ELEMENTS OF
STEAM AND GAS POWER
ENGINEERING

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ELEMENTS OF
STEAM AND GAS POWER ENGINEERING

BY

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PREFACE TO THE FOURTH EDITION

An effort was made to bring the contents of this book up to date. The social significance of power is considered in the first chapter with statistics of America's power-producing capacity and of the relative importance of different types of prime movers. This is followed by three chapters in which the elements of thermodynamics, fuels, and combustion are considered. Details of steam and gas power-plant machinery, auxiliaries, and accessories are treated in Chapters VI to XV, inclusive. The final chapter is devoted to mechanical power in transportation. The symbols throughout the book have been revised to conform to the accepted nomenclature in thermodynamics. A large number of the figures have been improved, as have also the problems at the end of each chapter.

Professors H. M. Jacklin, A. W. Cole, and H. L. Solberg of Purdue University have generously assisted in the preparation of this edition.

A. A. POTTER.

LAFAYETTE, INDIANA,
March, 1938.

PREFACE TO THE FIRST EDITION

In the preparation of this treatise the authors have attempted to present a clear and concrete statement of the principles underlying the construction and operation of steam and gas-power equipment.

The first chapter is devoted to a general survey of the field of power engineering and brings out the factors essential for the production of power, the principles governing the action of various mechanical motors, and a comparison of their performance.

The main portion of the book is divided into three parts. The first part takes up the subject of steam power and includes fuels, combustion, theory of steam generation, boilers, boiler auxiliaries, boiler accessories, steam engines, steam turbines, auxiliaries for steam engines and turbines, and the testing of steam-power equipment. The second part is devoted to gas power and includes a study of the internal-combustion engine, fuels for internal-combustion engines, gas producers, and the various auxiliaries found in connection with internal-combustion engine power plants. The last portion of the book treats of the application of steam and gas power to locomotives, automobiles, trucks, and tractors.

The method followed in each chapter was to give: first, the fundamental principles underlying the particular phase of equipment under consideration; second, the structural details; third, auxiliary parts; fourth, operation and management of the equipment considered.

This book has been prepared primarily as a textbook for students in engineering schools and colleges in order to familiarize them with power-plant equipment before they take up the more abstract study of thermodynamics and design. The subject matter of this treatise is so prepared that it should prove of considerable value to those who are reponsible for the operation of steam or internal-combustion engine power plants. Illustrative problems will be found at the close of each chapter. These problems are intended mainly as a guide in encouraging outside reference reading.

In the preparation of this text, the authors are particularly indebted to H. W. Davis and A. J. Mack of the Kansas State Agricultural College for their valuable assistance.

The authors are also grateful to E. M. Shealy, J. A. Moyer, A. J. Wood, C. F. Gebhardt, L. H. Morrison, R. H. Fernald, G. A. Orrok, and A. M. Greene for their permission to use certain illustrations from publications of which they are authors. The various manufacturers of power machinery have also been most liberal in giving the authors permission to use cuts.

ANDREY A. POTTER.
JAMES P. CALDERWOOD.

MANHATTAN, KANSAS.
January, 1920.

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CHAPTER I

FUNDAMENTALS OF POWER ENGINEERING

Mechanical Power.—The substitution of mechanical power for animal labor marks a most important epoch in the progress of civilization. The increase in the amount of mechanical power used for manufacturing, for transportation, and for other purposes has been enormous during the past fifty years and particularly so in the United States of America. The distribution of mechanical power available in this country in 1936 is indicated in Table 1.

TABLE 1.—APPROXIMATE MECHANICAL POWER, IN HORSEPOWER, AVAILABLE IN THE UNITED STATES IN 1936

Electric central stations	46,500,000
Industrial power plants	20,150,000
Electric railway plants	2,500,000
Isolated non-industrial plants	1,500,000
Mines and quarries	2,750,000
Agricultural prime movers	73,000,000
Automobiles, busses, trucks, and motorcycles	1,000,000,000*
Airplanes	3,500,000
Locomotives	88,000,000
Marine	30,000,000
Total horsepower	1,267,900,000

* The estimate of 1,000,000,000 is based upon an average of 30 hp. (the taxable horsepower of the two most used automobiles). Utilizing the average brake horsepower of American automobiles the power of motor vehicles would be about two billion horsepower.

If the total horsepower available (Table 1) is divided by the population of the United States in 1936, it will be found that over 10 hp. per capita of population are available in the United States in the form of mechanical power. The greatest factors which have contributed to the increased use of power are the development of electrical machinery and efficient electrical transmission systems, the perfection of the internal-combustion engine and steam turbine, the growth of the manufacturing industries, and the improvements in transportation equipment and systems.

Factors Essential for the Production of Power.—Two requirements are essential for the production of power: first, a source from which energy may be derived; and second, a motor which is capable of transforming this energy into work. Without energy all attempts to produce power would be futile; without a motor energy cannot be utilized, even when available, in producing power.

A motor is an apparatus capable of transforming energy into mechanical work.

A Motor Must Do Work.—By work is meant the production of motion against some external force. The mechanical motors available for the production of power are heat engines, including steam, gas, oil, hot-air, and solar engines; pressure engines, such as water wheels and water motors; windmills; electric motors.

Sources of Energy.—The principal source of all energy is the sun. The sun's rays are the fundamental source of all energy, they can be utilized directly by man only to a very limited extent. Heat engines have been built which transform the heat derived directly from the sun into mechanical energy; but, because of their bulk when compared with the energy transformed and because of the irregularities in the sun's rays, caused by clouds and the movement of the earth, this type of motor has not proved practicable. As a result, secondary sources of energy must be utilized. These secondary sources are: the wind; waterfalls; fuels in different form, such as coal, petroleum, or gas; and chemicals such as are used in electric batteries.

Principles Governing the Action of Various Mechanical Motors.—All mechanical motors do work by virtue of motion given to a piston, or to blades on a wheel, by some substance such as water, steam, gas, or air; or to a rotor by electricity. The first requirement in any of these cases is that the above-mentioned substance, often called the working substance, be under considerable pressure.

This pressure in the case of the water motor or waterwheel is obtained by collecting water in dams and tanks, or by utilizing the kinetic energy of natural waterfalls. The total power available in water when in motion depends on the weight of water discharged in a given time and on the head or distance through which the water is allowed to fall. The head of water can be utilized by its weight or pressure acting directly either on a piston, or on blades or paddles on wheels.

In the various forms of heat engines, work is accomplished by steam or gas under pressure, the pressure being obtained by utilizing the heat of some fuel or of the rays of the sun.

A motor utilizing the heat of the sun is called a solar motor or a solar engine. The action of this type of motor depends on the vaporization of water into steam by means of the rays of the sun, which are concentrated and intensified by means of reflecting surfaces. The steam thus generated is used in some form of heat motor.

In the case of the steam power plant (Fig. 1), a fuel, like coal, oil, or gas, is burned in a furnace and its heat of combustion is utilized in changing water into steam at high pressure in a special vessel called a boiler. This high-pressure steam is then conveyed by pipes to the engine cylinder where its energy is expended in pushing a piston, as in the case of the reciprocating engine. The sliding motion of the piston may be changed into rotary motion at the shaft by the interposition of a connecting rod and crank. Another method is to direct high-pressure steam so that it will strike blades on a wheel and produce rotary motion direct, as in the case of the steam turbine (Chap. IX).

In another type of heat engine, called a hot-air engine, air is heated in the engine cylinder by a fuel which is burned outside the cylinder. The air by its expansion drives a piston and does work.

In gas and oil engines, the fuel, which must be in a gaseous form as it enters the engine cylinder, is mixed with air in the proper proportions to form an explosive mixture. It is then compressed and ignited within the cylinder of the engine, the high pressure produced by the explosion pushing on a piston and doing work. These engines belong to a class called internal-combustion engines, and differ from the steam engines, which are sometimes called external-combustion engines, in that the fuel is burned inside the engine cylinder instead of in an auxiliary apparatus.

The windmill derives its high pressure for doing work from the moving atmosphere.

The electric motor converts electrical energy at high pressure into work; this electrical pressure or voltage is produced in an apparatus called an electrical dynamo, or a generator of electricity.

Comparison of Various Types of Motors.—The solar motor, as previously stated, is but little used on account of its high first cost and great bulk in relation to the small power developed.

In localities where the wind is abundant and little power is needed, the windmill is a cheap source of power. The only application of windmills is for the pumping of water for farms, and for such other work as does not suffer from suspension during calm weather. Electric storage and lighting on a small scale from the power of a windmill have been tried in several places with fair success, but probably will not be adopted to any great extent on account of the high first cost and the small practical capacity of such an installation.

The water motor or water turbine is very economical if a plentiful supply of water can be had at a fairly high head, but its reliability is affected by drought, floods, and ice in the water supply. For this reason, many of the hydraulic power stations must resort to the use of steam or gas power during certain seasons of the year.

The hot-air engine, on account of its high cost, bulk, and poor fuel economy, has been superseded by the oil engine, which uses gasoline or the heavier oils.

The internal-combustion engine (Chap. XII), whether using gas or oil, is well adapted for small and medium-sized powers. It finds its greatest application in the automobile, truck, bus, airplane, and in other power vehicles (Chap. XVI); also for uses in electric power generation, and on farms either as stationary engines or as oil-traction engines.

For the generation of electricity, especially in large units, the steam turbine (Chap. IX) has been found to be the most suitable type of motor, because of its low first cost when compared with other types of motors, and because of its greater reliability. By far the greatest amount of commercial power, other than transportation, is developed by steam motors. The reason for this fact is that the conversion of power from one form into another is always accompanied by losses; thus power developed from a cheap source is not necessarily the most economical from a commercial point of view. An example of this is the hydroelectric plant, where the cost of power would be small if no consideration had to be taken of the greater first cost of the installation and the cost of the long electric transmission lines As another illustration, the oil engine, of the Diesel type (Chap. XII), is conceded to have the highest efficiency as a motor for the transforming of heat energy into work, but commercially its application has been limited for stationary purposes to special uses or to those localities in which the cost of oil is low and the supply is large. When all factors are considered, it is usually found that the steam power plant is the cheapest producer of power in large quantities.

Electric generating stations had during 1936 an output of 113½ billion kilowatt-hours, of which about 59 per cent was developed in steam power plants and 41 per cent in hydroelectric plants. Less than 0 1 per cent was developed by oil or gas engines. The undeveloped water power of the United States that can be developed without expensive storage has been estimated at 53,000,000 hp. Of the undeveloped water power available much of it is in sections where the demands for power are small.

Principal Parts of a Steam Power Plant.—The principal parts of a simple steam power plant are illustrated in Fig. 1, and include the following:

1. A furnace, in which the fuel is burned. This consists of a chamber arranged with a grate (1), if coal or any other solid fuel is used, and with burners when the fuel is in the liquid or gaseous state. The furnace is connected through a flue or breeching (2) to a chimney. The function of a chimney is to produce sufficient draft so that the fuel will have the proper amount of air for

combustion; it also serves to carry off the obnoxious gases after the combustion process is completed. The flue leading to the chimney is provided with a damper (3), so that the intensity of the draft and, consequently, the air supply can be regulated.

2. A boiler (4), which is a closed metallic vessel filled to about two-thirds of its volume with water. The heat developed by the burning of the fuel in the furnace is utilized in converting the water contained in the boiler into steam. The boiler (4) is arranged with a water column (5) to show the water level, with a safety valve (6) to prevent the pressure from rising too high, and with a gage (7) to indicate the steam pressure.

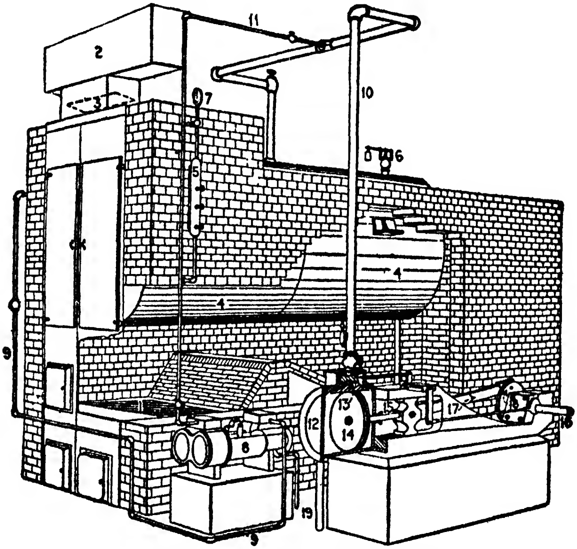

Fig. 1.—Elementary non-condensing power plant.

3. The function of a setting, which is the term usually used to designate the brickwork which surrounds the boiler, is to provide correct spaces for the furnace, combustion chamber, and ash pit, to prevent air from entering the furnace above the fuel bed, and to decrease the heat of radiation to a minimum. In some power plants the setting is also used to support the boiler shell, but this is poor practice.

4. The feed pump (8) supplies the boiler with water through the feed pipe (9).

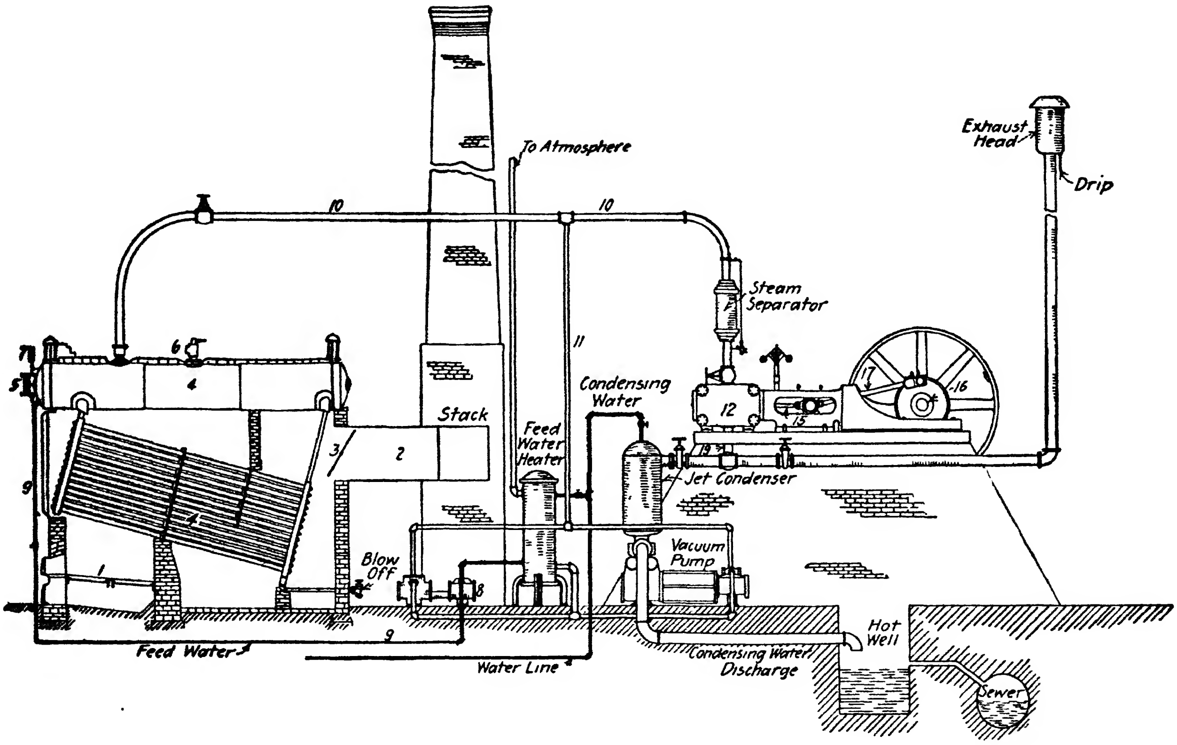

FIG. 2.—Condensing steam power plant.

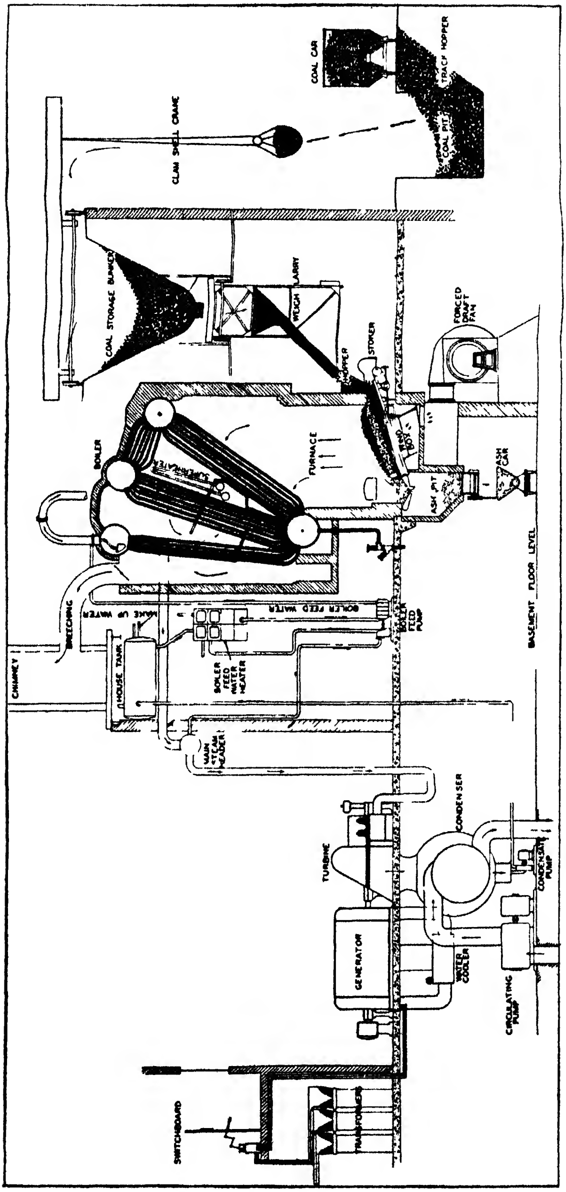

FIG. 3.—Steam-turbine power plant.

5. The steam lines (10) and (11) convey steam from the boiler to the engine and to the steam end of the pump, respectively.

6. In the engine the energy of the steam is expended in doing work. The steam enters the engine cylinder (12) through the valve (13) and pushes on the piston (14). The sliding motion of the piston, which is transmitted to the piston rod (15), is changed into rotary motion at the shaft (16) by means of a connecting rod (17) and crank (18).

7. The exhaust pipe (19) conveys the used steam to the atmosphere, or to some use where its heat is abstracted, converting the steam back into water.

Condensing Steam Power Plant.—In Fig. 2 is illustrated a reciprocating engine type of condensing power plant with a water-tube boiler. The various parts are numbered to correspond with similar parts in the simple power plant of Fig. 1.

Figure 3 is a descriptive layout of a steam turbine plant equipped with coal- and ash-handling machinery, mechanical stokers, and other labor-saving devices.

Internal-combustion Power Plants.—The equipment of an internal-combustion power plant depends upon the fuel used. The simplest type of gas power plant is the gasoline engine (Chap. XII), which consists of a cylinder and piston, a carburetor for preparing the explosive mixture, valves for admitting the mixture to the cylinder and for expelling the burnt gases to the atmosphere, a device for igniting the mixture at the proper time, a mechanism for changing the reciprocating motion of the piston into rotary motion, a governor to keep the speed constant at variable loads, a lubrication system for the cylinder and bearings, an arrangement for cooling the cylinder walls, a flywheel to carry the engine through the idle strokes, and bearings and a frame to support the various parts.

Details concerning various types of internal-combustion power plants will be given in Chap. XII.

Problems

1. Inspect some non-condensing or condensing steam power plant in your vicinity and hand in a report concerning the important details. State the type of service supplied by the plant, the method of introducing water to the boilers, whether any attempt is made to utilize the heat of

the exhaust steam, together with other details which differ from that illustrated in Fig. 1.

2. What is the relation between a kilowatt and a horsepower?
3. What is meant by the term kilowatt-hours?
4. What is meant by the term prime mover when applied to power generation?
5. Using the illustrations shown in Fig. 2, trace:
   (*a*) The path of the furnace gases from the furnace to the stack outlet.
   (*b*) The path of the steam from the boiler to the exhaust.
   (*c*) The path of the feed-water supply to the boiler.
6. Make a study of some internal-combustion engine power plant and hand in a report concerning fuel used and fundamental details of the engine.
7. How does the power available in the United States compare with that in other lands? Secure actual figures to prove your answer.
8. Prepare a table to show the power per capita in several countries.
9. The following are the items which enter into the yearly operating costs of a 5,500-kw. turbo-generating station:

Cost of building, equipment, and distributing system	$735,047
Operating costs per year exclusive of fuel..........	$ 24,791
Total coal burned per year......................	18,000 tons
Total electrical output per year..................	6,520,670 kw.-hr.

   (*a*) How many pounds of coal were required to produce 1 kw.-hr.?
   (*b*) If the coal costs $5 per ton, what was the cost of the fuel in producing 1 kw.-hr.?
   (*c*) Assuming 10 per cent of the cost of the building, equipment, and distributing system to cover interest on the money invested and depreciation, what was the total cost to produce 1 kw.-hr.?
   (*d*) What is the load factor, or the percentage ratio of average output, in kilowatt-hours, to the rated capacity of plant?
   (*e*) If the load factor in this plant could be raised to 50 per cent by the judicious addition of power load during off-peak periods and if the operating costs per kilowatt-hour would remain constant, what would be the total cost to produce 1 kw.-hr.? Assume 10 per cent of the investment costs as in (*c*).

10. The following data are taken from the yearly operating costs of a 270-kw. Diesel engine plant:

Cost of building, equipment, and distributing system	$108,000
Operating costs per year exclusive of fuel...........	$ 10,554
Total fuel oil consumed per year..................	62,899 gal.
Total electrical output per year...................	554,545 kw.-hr.

   (*a*) How many gallons of fuel oil were required to produce 1 kw.-hr.?
   (*b*) If the fuel oil cost is 5 cts. per gallon, what was the cost of the fuel in producing 1 kw.-hr.?

(*c*) Assuming 10 per cent of the cost of the building, equipment, and distributing system to cover interest on the money invested and depreciation, what was the total cost to produce 1 kw.-hr.?

(*d*) What is the load factor, or the percentage ratio of the average output in kilowatt-hours, to the rated capacity of plant?

(*e*) If the load factor in this plant could be raised to 50 per cent by the judicious addition of power load during off-peak periods and if the operating costs per kilowatt-hour would remain constant, what would be the total cost to produce 1 kw.-hr.? Assume 10 per cent of the investment costs as in (*c*).

11. In which respects has mechanical power contributed to human progress?

12. Why is water power of minor importance in this country as compared with power manufactured in fuel-burning plants?

CHAPTER II

FUNDAMENTAL PRINCIPLES

Heat.—Heat is a form of energy. Heat may pass from a body of higher temperature to that of a lower temperature in three different ways: by conduction, by radiation, or by convection.

The transfer of heat between the different particles of the same body is called conduction. Conduction may be internal or external. In internal conduction, heat is transmitted between the molecules of the same body, while in the case of external conduction heat is transmitted from one body to another when the two are in contact. The transfer of heat by conduction depends upon the difference in the temperature between the molecules of the different parts of the body, the material of which the body is composed, the size of the body, and the length of time during which the flow of heat occurs. The particles composing the body must be at different temperatures in order that the heat may flow by conduction. Different materials do not conduct heat equally well. The more dense the material the better its conductive power. Some substances such as cork or dry wood are poor conductors of heat. Metals are the best conductors of heat.

Radiation is the transfer of heat from one body to another through space when the two are not in contact. A steam boiler receives heat by radiation from the glowing fuel on the grate and from the heated fire brick of the furnace. Rough, dark, and opaque surfaces are good radiators of heat, while smooth, highly polished, and light surfaces are good reflectors of heat, but poor radiators.

Convection is the transfer of heat by the movement of the heated particles within a gaseous or fluid substance. Various heating and ventilating systems for buildings depend upon the convection of heat for their operation. Efficient operation of steam boilers depends upon convection for the heat transfer. The draft produced by chimneys also depends upon convection heat. The loss of heat from a body by convection depends upon the shape of the body and the velocity of the convection currents.

Temperature.—The heat intensity of a substance or body, or its tendency to transmit heat, is measured by its temperature. The temperature does not indicate the quantity of heat, but is a measure only of the sensible heat or of the degree of coldness or of hotness of a body. If the molecules of a body are vibrating rapidly, the temperature of the body is high; if the molecules vibrate slowly, the temperature is low.

Thermometric Scales.—The two thermometric scales which are most commonly used are the Fahrenheit (F.) and the Centigrade (C.).

On the Fahrenheit scale the melting point of ice is taken at 32°F., and the boiling of water at atmospheric pressure 212°. Thus the Fahrenheit degree is $\frac{1}{180}$ of the temperature interval between the melting of ice and the boiling of water at atmospheric pressure.

On the Centigrade scale the position of the mercury for the melting of ice is marked 0°, and that for the boiling of water at atmospheric pressure 100°. The Centigrade degree is then $\frac{1}{100}$ of the temperature interval between the melting of ice and the boiling of water at atmospheric pressure at sea level.

Absolute Zero.—The absolute zero is the lowest temperature theoretically attainable. The zero of the absolute scale or absolute zero is taken as a point at which there is an absence of heat energy or of molecular vibration.

Calling the absolute temperature T and the temperature as measured by a thermometer t, the absolute temperature on the Fahrenheit scale is

$$T = t + 460. \tag{1}$$

On the Centigrade scale, the absolute temperature is

$$T = t + 273. \tag{2}$$

Units of Heat.—Heat is measured in heat units. A heat unit is the amount of heat required to raise the temperature of a unit weight of water 1° in temperature. In English-speaking countries, heat is measured in British thermal units (B.t.u.).

The British thermal unit (B.t.u.) is defined as the heat required to raise the temperature of 1 lb. of water 1°F. In the metric system the unit of heat is the calorie and is defined as the heat required to raise the temperature of 1 kilogram of water 1°C. One calorie is equal to 3.968 B.t.u.

Specific Heat.—Specific heat (c) is the capacity of a substance for heat, or the resistance which a substance offers to a change in its temperature. It is defined in the English system as the number of B.t.u. required to raise the temperature of 1 lb. of a substance 1°F.; conversely, it will be the number of B.t.u. of heat given up by the same substance when its temperature is lowered 1°F.

The specific heat is not the same for all substances. Thus the specific heat of cast iron is about 0.123, of stone, 0.20; of water, 1.0; and of ice, 0.504. There is, furthermore, a change in the specific heat depending upon the conditions of the addition of heat. Air, for example, when heated in such a manner that its pressure remains constant has a specific heat (c_p) of 0.2375; when air is heated at constant volume its specific heat (c_v) is 0.1669.

Force.—Anything which produces or tends to produce, modifies or tends to modify motion is called force. In the English system, force is measured in pounds. A weight of 1 lb. produces a force of 1 lb. upon the object on which it rests.

Pressure.—Pressure is the measure of the intensity of force or the force per unit of area. It is equal to the total force divided by the area over which it acts. Conversely, the product of the pressure per unit area multiplied by the area over which it acts equals force. When a steam gage on a boiler registers a pressure of 180 lb., the steam exerts a force of 180 lb. for every square inch upon which it acts. If it is allowed to act upon a piston whose diameter is 12 in. (113.1 sq. in. area) the total force exerted is

$$180 \times 113.1 = 20{,}358 \text{ lb.}$$

In English practice, pressure is measured in pounds per square inch, pounds per square foot, inches of mercury, inches of water, or atmospheres. Gages always read pressures above or below atmospheric pressure. The total or absolute pressure is found by adding to the gage pressure the unit pressure exerted by the atmosphere.

The pressure exerted by the atmosphere is due to the weight of the envelope of air surrounding the earth and is called barometric pressure. The barometric pressure is 14.7 lb. per square inch at sea level and decreases as the altitude increases.

Work.—Work is the result of force acting through a given displacement and is equal to the product of the force and the distance through which the displacement acts. Work is, therefore, independent of time. When a body weighing 1 lb. is raised through a distance of 1 ft. the resulting work is a foot-pound, the unit of work.

Since the product of pressure and area over which it is exerted gives force, the pressure may be used in calculating work. Thus, if p is the pressure in pounds per square inch, A the area in square inches upon which it is exerted, and L the distance in feet through which the force acts, the work in foot-pounds is

$$\text{Work } (W) = p \times A \times L. \tag{3}$$

Where the pressure of force varies, work is calculated by determining the uniform pressure or force that would produce the same effect. This may be expressed mathematically,

$$\text{Work } (W) = \int F dS. \tag{4}$$

In equation (4), the letter F represents force, S is the space covered.

Work may also be expressed in terms of pressure p and volume v. In this case, equation (3) becomes

$$\text{Work } (W) = p \times 144 \times (v_2 - v_1). \tag{5}$$

Equation (5) applies when the pressure is constant and in pounds per square inch. $(v_2 - v_1)$ is the change in volume during the process in cubic feet. The work, equation (5), is expressed in foot-pound units.

When the pressure varies, equation (5) is expressed by

$$\text{Work } (W) = 144 \int P dV. \tag{6}$$

Mechanical Equivalent of Heat.—The principle of conservation of energy states that energy can neither be created nor destroyed, but can be transformed, without loss, from one form into another. This principle when limited to heat and work states that there is a definite relation between work expended and heat produced.

It has been found experimentally that 778 ft.-lb. of work produce 1 B.t.u. of heat when conditions are maintained for perfect transformation; similarly, 1 B.t.u. of heat produces 778 ft.-lb. of work. The value 778 is called the mechanical equivalent of heat.

Power.—Power is the rate of doing work. Work in itself is independent of time; power is the amount of work done in a unit of time. In the English system, the unit of power is the horsepower. Horsepower is the doing of work at the rate of 550 ft.-lb. per second or 33,000 ft.-lb. per minute. To determine the horsepower required in the doing of work, the foot-pounds of work done per minute must be divided by 33,000.

If work is expressed by equation (3), and if N is the number of times per minute the pressure p is applied and the distance L traversed, the horsepower (hp.) may be calculated.

$$\text{Horsepower (hp.)} = \frac{p \times A \times L \times N}{33,000}. \qquad (7)$$

Thermodynamics.—Thermodynamics deals with the relation between heat and work. A knowledge of thermodynamics enables one to analyze the factors which influence the performance and efficiency of heat engines.

Laws of Thermodynamics.—The two laws of thermodynamics, which are of major importance in connection with the study of heat engines, may be stated as follows:

1. The first law is a statement of the mechanical equivalent of heat which is usually expressed: *Heat and mechanical energy are mutually convertible and heat requires for its production and produces by its disappearance mechanical work in the ratio of the mechanical equivalent of heat.*

2. The second law is a statement of the fact that no heat engine can convert into work all the heat supplied to it. A portion of

the heat supplied must necessarily be rejected by the engine in the form of unused heat.

The second law of thermodynamics has been stated in many ways. The usual definition is as follows: "*In order to transform the heat of a body into work, heat must pass from the body into another at a lower temperature, and the maximum proportion of the heat which can be transformed into work is* $\frac{T_1 - T_2}{T_1}$ *when* T_1 *and* T_2 *are the absolute temperatures at the beginning and the end of the process.*"

The second law states in effect that the natural order of heat flow is from a hot to a cold body. In order to reverse this direction of flow some external means is necessary.

Absorption of Heat.—When heat Q is added to a substance its temperature increases and its volume becomes larger against an external resistance. Thus, two changes take place: one called internal or intrinsic energy change $(U_2 - U_1)$; and the other external work (W). The intrinsic energy change $(U_2 - U_1)$ is affected by the temperature and by the stored internal energy other than temperature. External work (W) increases the volume of the body against the resistance offered by external substances. Since the sum of $(U_2 - U_1)$ and W is equal to the heat added, the process may be expressed as:

Heat absorbed in B.t.u. (Q)

= intrinsic energy change $(U_2 - U_1)$ + the

heat equivalent of the work $\left(\frac{W}{778}\right)$. (8)

Reduced to an infinitesimal quantity, equation (8) becomes

$$dQ = dU + \frac{dW}{778}.$$

Integrating,

$$Q = \int dU + \int \frac{dW}{778}. \tag{9}$$

Since from equation (6)

$$W = \int PdV,$$

equation (9) becomes

$$Q = \int dU + \frac{1}{778}\int PdV. \tag{10}$$

Enthalpy.—The terms internal energy $(U_2 - U_1)$ and work (W) always appear together in a uniform flow process, as in the case of steam flowing through a steam turbine, and their sum is called *enthalpy* (h). Enthalpy is then expressed as:

$$h = U_2 - U_1 + AW. \tag{11}$$

Entropy.—Entropy S is one of the important dimensions of heat. It may be defined as the ratio of the heat per unit of weight absorbed by a substance to the average absolute temperature occurring during the process. The change in entropy may be expressed mathematically by

$$S_2 - S_1 = \int_1^2 \frac{dQ}{T}. \tag{12}$$

When the temperature varies during the process, the average or mean absolute temperature must be used in calculating entropy. When the temperature remains constant during the process, entropy is determined by dividing the heat absorbed by the absolute temperature during the process. Thus, if 10 units of heat are absorbed by a substance during which process the temperature of the substance is 200°F. and remains constant, the units of entropy change during the process are

$$\frac{10}{200 + 460} = 0.0151.$$

The Heat Engine.—A heat engine is a machine which converts the heat energy of fuel into work. This conversion is accomplished in one of two ways:

First, by "external combustion," in which case the fuel is burned outside of the engine cylinder; the heat developed by the combustion of the fuel is conducted to the working substance or heat medium through walls; this working substance does work on a piston in the case of a reciprocating engine or on a vane or "blade" in a turbine. To this class belong steam engines of the reciprocating, turbine, or rotary types and also external-combustion hot-air engines. Thus, in the case of the steam engine, the fuel, which may be coal, wood, petroleum, or gas, is burned outside of the boiler shell and the resulting heat is transmitted by conduction through the metal of the shell to the working substance, which is water. When enough heat has been added to the water to produce a change in its physical state, water vapor or steam is formed at the required pressure. This vapor, which may be dry, wet, or superheated, if allowed to act on the piston of the engine, will do work.

Another method of converting heat into mechanical energy is by burning the fuel rapidly or slowly inside of an engine cylinder or in a communicating vessel, the products of combustion being allowed to act directly on the piston of the engine. To this class belong gas, petroleum, and alcohol engines which are called internal-combustion engines.

The Working Substance of a Heat Engine.—In every type of heat engine a working substance or heat medium is used. The working substance, through which the heat engine derives its heat for transformation into work, may be in the condition of a gas or a vapor. Each of these mediums has special characteristics and obeys special laws.

A gas is a fluid which remains in a gaseous state when subjected to moderate changes in pressure and temperature. Air, oxygen, hydrogen, and nitrogen are examples of gases.

A vapor is a fluid which is near its point of condensation and which can be transformed into a liquid by a moderate reduction in temperature or increase in pressure. Steam, ammonia, and sulphur dioxide are the most common examples of vapors.

In the steam power plant the working substance is steam, the heat from the furnace being first absorbed in the generation of steam which in turn carries it to the engine for conversion into work. In the internal-combustion engine the heat medium is a mixture of air and gaseous fuel.

Laws of Gases.—If a gas is compressed or expanded in such a manner that its temperature remains constant, the pressure P varies inversely as the total volume V, or the product of the pressure and volume at any condition remains constant. This law may be stated:

$$P_1V_1 = P_2V_2 = \text{constant.} \tag{13}$$

When the pressure is maintained constant, the volume V of a given mass of gas varies directly as the absolute temperature T, or

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}. \tag{14}$$

When the volume is maintained constant, the pressure P of a given mass of gas varies as the absolute temperature, or

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}. \tag{15}$$

Combining equations (13) and (14) for gases, the following relation is obtained:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \text{constant} = R. \tag{16}$$

Limiting to unit weight and simplifying, equation (16) becomes

$$P_1v_1 = RT_1, \tag{17}$$

in which R is a constant depending upon the gas and v_1 is the volume of 1 lb.

Thus, if air at atmospheric pressure and a temperature of 32° F. has a volume of 12.39 cu. ft. per pound.

$$R = \frac{14.7 \times 144 \times 12.39}{32 + 460} = 53.3$$

If w is the weight of the gas in pounds involved in a process, equation (17) may be written:

$$P_1V_1 = wRT_1. \tag{18}$$

The use of equation (18) may be illustrated by the solution of the following problem:

What is the volume of 2 lb. of air if the pressure is atmospheric and the temperature 60°F?

The value of R for air is 53.3, therefore,

$$14.7 \times 144 \times V = 2 \times 53.3 \times (60 + 460),$$

from which

$$V = 26.4 \text{ cu. ft.}$$

Thermodynamics Processes for Gases.—There are four important thermodynamic processes: constant pressure, constant volume, isothermal, and adiabatic.

In all thermodynamic processes in which both the pressure and volume vary their relation may be represented by the equation

$$PV^n = \text{a constant}, \tag{19}$$

n, the power to which the volume is raised, is called the index of the process and has numerical values depending upon the character of the process.

Constant-pressure Processes.—If an expansion or compression takes place under constant pressure and the subscripts 1 and 2 be made to represent the initial and final conditions, respectively, of the working substance, the work W of the process becomes

$$W = P(V_2 - V_1). \tag{20}$$

The work in equation (20) is in foot-pounds if pressure P is in pounds per square foot and the volumes V_1 and V_2 are in cubic feet.

Since by equation (18), $P_1V_1 = wRT_1$, equation (20) may be expressed

$$W = wR(T_2 - T_1) = wR(t_2 - t_1). \tag{21}$$

The change in intrinsic energy $(U_2 - U_1)$ in B.t.u. during a constant-pressure process is

$$U_2 - U_1 = wc_v(t_2 - t_1), \tag{22}$$

in which c_v is the specific heat at constant volume of the working substance in B.t.u.

The heat absorbed or abstracted Q during a constant-pressure process may be expressed in two ways:

(1) $$Q = wc_p(t_2 - t_1) \tag{23}$$

where c_p is the specific heat at constant pressure of the working substance in B.t.u.

(2) $$Q = U_2 - U_1 + \frac{W}{778}. \tag{24}$$

To illustrate the application of the principles of constant-pressure processes, assume that 20 lb. of air receive heat at constant pressure, and the temperature is increased from 70 to 200°F.

The work done is

$$W = 20 \times 53.3 \times (200 - 70) = 138{,}580 \text{ ft.-lb.}$$

The internal energy change is

$$U_2 - U_1 = 20 \times 0.1669 \times (200 - 70) = 434 \text{ B.t.u.}$$

The heat absorbed during the process is

$$Q = 20 \times 0.2375 \times (200 - 70) = 617 \text{ B.t.u.},$$

or

$$Q = 434 + \frac{138{,}580}{778} = 612 \text{ B.t.u.}$$

The slight discrepancy in the quantity of heat Q by the two methods is due to discrepancies in the experimental values of c_p, c_v, and R.

Constant-volume Processes.—If heat is added or abstracted at constant volume, no external work is done and the heat is used up in internal energy change $U_2 - U_1$ which is calculated by equation (22).

Isothermal Processes.—An isothermal process is one in which the temperature remains constant. From equation (13), the relation between the pressure and volumes is

$$PV = \text{constant}. \tag{25}$$

In an isothermal expansion or compression of a gas, since by definition no temperature changes occur, no intrinsic energy change takes place. All heat involved during the process is that due to the external work W.

From equation (25),

$$P_1V_1 = P_2V_2$$

or

$$P_2 = \frac{P_1V_1}{V_2}.$$

Thus, the external work is

$$W = \int PdV = \int_1^2 \frac{P_1V_1}{V_2}dV = P_1V_1\int_1^2 \frac{dV}{V}$$

$$= P_1V_1 \log_e\frac{V_2}{V_1}. \tag{26}$$

$$= wRT_1 \log_e\frac{V_2}{V_1}. \tag{27}$$

Thus, if a gas is expanded isothermally from an absolute pressure of 100 lb. per square inch and a volume of 1 cu. ft. to an absolute pressure of 50 lb. per square inch, the volume at the end of the expansion is

$$100 \times 1 = 50 \times V_2$$
$$V_2 = 2 \text{ cu. ft.}$$

The work of the expansion is

$$W = 100 \times 144 \times 1 \times 2.3 \log_{10} \tfrac{2}{1}^{*}$$
$$= 9{,}980 \text{ ft.-lb.}$$

The heat Q added during the process is

$$Q = \frac{W}{778} = \frac{9.980}{778} = 13 \text{ B.t.u.}$$

Adiabatic Processes.—In an adiabatic expansion or compression the working substance neither receives nor rejects heat, all work being done at the expense of intrinsic energy. The equation for an adiabatic process of a gas is

$$PV^k = \text{constant} \qquad (28)$$

in which k is the relation between specific heats, or

$$k = \frac{c_p}{c_v}$$

For air and most gases, k is taken as 1.406.

Thus, the external work W for an adiabatic process of a gas is

$$W = \int P dV = \int_1^2 P_1 V_1^k \frac{dV}{V}$$
$$= \frac{P_1V_1 - P_2V_2}{k - 1} \qquad (29)$$
$$= \frac{wR(T_1 - T_2)}{k - 1}. \qquad (30)$$

The relations between temperatures and volumes and temperatures and pressures during an adiabatic expansion or compression may be expressed by the equations

---

* 2.3 × log base 10 = log base e.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} \tag{31}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}. \tag{32}$$

To illustrate the application of the principles of adiabatic processes, assume that 10 cu. ft. of air, at an absolute pressure of 100 lb. per square inch, is expanded adiabatically to an absolute pressure of 25 lb. per square inch. What are the final volume and work of the expansion?

From equation (28)

$$P_1V_1^k = P_2V_2^k.$$

Therefore,

$$V_2^k = \frac{P_1V_1^k}{P_2} = \frac{100 \times 10^{1.4}}{25}$$

$$V_2 = 26.9 \text{ cu. ft.}$$

From equation (29) the work is

$$W = \frac{100 \times 144 \times 10 - 25 \times 144 \times 26.9}{1.406 - 1}$$

$$= 33{,}640 \text{ ft.-lb.}$$

Thermal Efficiency of a Heat Engine.—The thermal efficiency of a heat engine is the ratio of the heat converted into work to the heat supplied. The thermal efficiencies of heat engines vary from 5 to 35 per cent. This low efficiency is due to the fact that only a part of the heat supplied to the engine can be converted into work, as will be explained in subsequent chapters.

Cycles of Heat Engines.—In the heat engine, the working substance or heat medium passes through a series of thermodynamic processes transferring heat into work. A series of such processes, in which the medium returns to its original or initial condition, constitute the heat engine cycle.

Carnot Cycle.—The Carnot cycle is the most efficient means of converting heat into work. It is the cycle of the ideal heat engine. Figure 4 illustrates the Carnot cycle on *P-V* coordinates.

Heat is added to the cycle along the isothermal ($PV = c$) curve *AB*, the total external work of the expansion being represented graphically by the area *EABG*. The process of expansion is continued between *BC* adiabatically ($PV^{1.406} = c$), the total external work being graphically represented by the area *GBCH*. Compression takes place between *CD* isothermally, the heat abstracted being equivalent to the external work (area *HCDF*). The final compression process occurs adiabatically between *DA*, the work of compression being the area *FDAE*. The net work of the cycle is represented by the area *ABCD*.

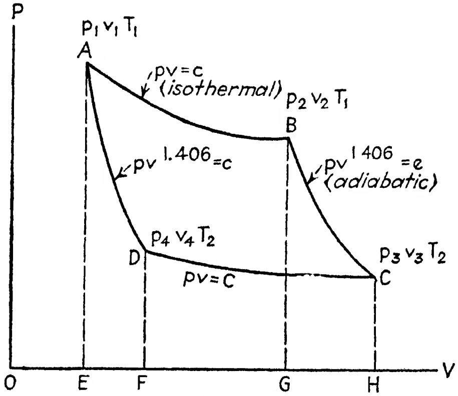

FIG. 4.—The Carnot cycle.

The efficiency *e*, of the Carnot cycle is expressed thus:

$$e = \frac{T_1 - T_2}{T_1}. \tag{33}$$

Thus if an engine operates between the temperatures of 350 and 100°F., its efficiency is

$$e = \frac{(350 + 460) - (100 + 460)}{(350 + 460)} = 0.308$$
$$= 30.8 \text{ per cent.}$$

Properties of Vapors.—Properties of steam and the thermodynamic principles of vapors are discussed in Chap. IV.

Problems

1. What are the principal sources of heat?
2. A bar of iron is being heated in a forge. Why does the protruding end of the bar remain cool?

3. In the case of a boiler furnace what rôle does radiation play?
4. In which manner does the principle of convection produce draft in a chimney?
5. Prove that the relations between the Centigrade and Fahrenheit thermometric scales are

$$\text{Degrees C.} = \tfrac{5}{9}\ (\text{degrees F.} - 32).$$
$$\text{Degrees F.} = \tfrac{9}{5}\ (\text{degrees C.}) + 32.$$

6. If the absolute zero of temperature measurement is 492°F. below the melting point of ice, prove that the same point is 273° below the zero of the Centigrade scale.
7. A certain coal is said to contain 13,200 B.t.u. per pound. What does this mean?
8. If the specific heat of a substance is 0.5 B.t.u., how many B.t.u. are required to raise the temperature of 100 lb., 20°F.?
9. If the B.t.u. is defined as the heat required to raise 1 lb. of water 1°F., what is the specific heat of water?
10. If the specific heat of a certain substance is 0.47 B.t.u., how many B.t.u. are required to raise the temperature of 1 lb. 50°F.?
11. If a cubic foot of water weighs 62.5 lb., what is the gage pressure exerted upon 1 sq. ft. area by a column of water 1 ft. high. What is the gage pressure per square inch of area?
12. Prove that the gage pressure in pounds per square inch exerted at the foot of a column of water h ft. high is expressed by the formula:

$$\text{Pressure in pounds per square inch} = 0.434 \times \text{head in feet.}$$

13. A gage registers 100 lb. per square inch. If the atmospheric pressure is 14.1 lb. per square inch, what is the absolute pressure?
14. If a cubic foot of mercury weighs 849 lb., prove that the pressure in pounds per square inch exerted by each inch of mercury is 0.491.
15. If 1 cu. ft. of water weighs 62.5 lb., how many foot-pounds of work will be necessary to raise 100 cu. ft. of water 100 ft. high?
16. How many foot-pounds of work are required to move 100 lb. of water against a head of 100 lb. per square inch?
17. A steam engine whose cylinder diameter is 12 in. and whose stroke is 16 in. is supplied with steam at a pressure of 100 lb. per square inch which acts throughout the stroke. How many foot-pounds of work is produced per stroke of the engine?
18. If 1 lb. of coal contains 14,500 B.t.u. of heat, how many foot-pounds of work is it capable of producing if all of the heat in the fuel could be changed into work?
19. An engine receives 100,000 B.t.u. of heat and produces 23,340,000 ft.-lb. of work. How many B.t.u. were lost?
20. An elevator weighing 3,000 lb. is moved vertically through a space of 100 ft. in 1 min., what horsepower is required?

21. The limit of human endurance in climbing treadmills is about 9,000 ft. in 24 hr. Taking the weight of a man at 150 lb., calculate the number of manpower which is equivalent to one mechanical horsepower.

22. The suction of a pump lifts 10,000 lb. of water per minute through a head of 10 ft. and discharges the same water against a pressure of 100 lb. per square inch. What horsepower is required?

23. Since 1 B.t.u. is the heat equivalent of 778 ft.-lb., prove that 2,545 B.t.u. is the heat equivalent of 1 hp.-hr.

24. A quantity of gas occupies 1 cu. ft. when the absolute pressure is 29.34 in. of mercury and the temperature is 72°F. What is the volume of the gas when the absolute pressure is 30.36 in. of mercury and the temperature 60°F.?

25. A tank whose volume is 10 cu. ft. contains air at an absolute pressure of 200 lb. per square inch and at 80°F. How many pounds of air does the tank contain?

26. If the tank in Problem 25 does not change in volume, what will be the pressure of the air if the temperature is increased to 150°F.?

27. Two pounds of air at a temperature of 100°F. are heated under constant pressure until the temperature reaches 300°F. How many foot-pounds of work are done during the process, how much heat is absorbed as internal energy and how much heat is required?

28. Air at an absolute pressure of 100 lb. per square inch and a volume of 2 cu. ft. expands isothermally to 25 lb. per square inch absolute. What is the work of the expansion and the heat required?

29. Air at an absolute pressure of 100 lb. per square inch and 2 cu. ft. expands adiabatically to 25 lb. per square inch. What is the final volume of the air and the work of the expansion?

30. A gasoline engine uses 1 lb. of fuel per hour to produce 1 hp. If 1 lb. of gasoline contains 19,200 B.t.u., and 1 hp. per hour is equivalent to 2,545 B.t.u., calculate the thermal efficiency of this engine.

31. What is the maximum theoretical (Carnot) efficiency of a heat engine operating between 600 and 100°F.?

32. Prepare a table of the symbols used in this chapter and explain their meaning. (This table will be helpful to the student in connection with other parts of this book.)

33. What is the difference between entropy (s) and enthalpy (h)?

34. Why cannot the Carnot engine efficiency be realized in an actual power plant?

CHAPTER III

STEAM POWER FUELS AND COMBUSTION

FUELS

The fuel in the case of the steam power plant is burned under the boiler, and its heat is utilized in changing water into steam.

Fuels may be used in their natural state, or may be prepared or manufactured in various ways. The chief natural fuels are coal, wood, petroleum oil, and natural gas. The chief prepared fuels are coke, made from the distillation of coal; manufactured gas, made from solid or liquid fuels; and the various petroleum distillates. Another prepared fuel is briquetted coal which is made by pressing finely ground coal into brick form, the particles being held together by some cementing material. There are a great many other materials which could be used for fuel, such as acetylene, alcohol, and benzol, that have valuable fuel properties, but their high cost makes their use prohibitive. Then again there is another class of fuel which is derived as a by-product in various industries. To this class belongs gas discharged from blast furnaces which has considerable value as a fuel.

The Heating Value of Fuels.—By the heating value of a fuel, often expressed by the terms, heat of combustion, calorific value, and heat content, is meant the amount of heat liberated by the perfect combustion of one unit weight of a solid or liquid fuel, or of a unit volume of a gaseous fuel. The value of the fuel for power purposes is dependent upon its heat content in a unit weight. Thus of two grades of coal, the one containing the greater heating value is the more desirable commercially, other things being equal.

The heating value of the fuel is measured in heat units. This calorific value or the heating value of a fuel may be determined by means of a chemical analysis, but a more satisfactory determination can be made by an instrument called a calorimeter.

Several different types of calorimeters are available, but those of the bomb type, similar to the one illustrated in Fig. 5, are the most satisfactory for determining the heating value of solid and heavy liquid fuels. This type of instrument consists of a steel vessel or bomb, lined with porcelain, platinum, or gold to prevent corrosion, and into which a weighed sample of the fuel is introduced. The bomb, after it has been charged with fuel, is filled with oxygen from the cylinder *O*, to which the bomb is connected through the union *U*. The quantity of oxygen admitted to the bomb is regulated by means of the valve *W* and the pressure gage *M*. The bomb is then placed in the calorimeter vessel *A*, which contains a known weight of water. The water is agitated by the stirring mechanism shown and the thermometer *T* indicates its rise in temperature when the fuel within the bomb is burned. The calorimeter vessel *A* is fitted with a water jacket which reduces the effect of external changes of temperature and causes a more uniform temperature of the thermometer *T*. The fuel charge is ignited electrically and burns in the presence of oxygen. The heating value of the fuel is calculated from the observed temperature rise of the water as indicated by thermometer *T*, since the heat gained by the water must equal the heat given up by the fuel, after making allowances for radiation and other similar factors which may produce a gain or loss of heat.

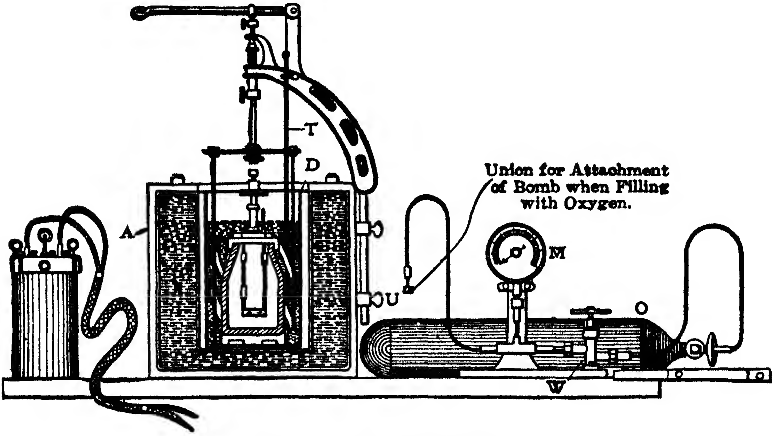

FIG. 5.—Bomb calorimeter.

The heating value of a fuel can be determined approximately from its chemical analysis by the following formula:

$$\text{Heating value in B.t.u. per pound} = 14{,}600C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000S. \qquad (34)$$

C, H, O, and S represent the proportionate weight of carbon, hydrogen, oxygen, and sulphur in 1 lb. of fuel.

As an illustration of the application of this formula:

Calculate the heating value of an Indiana coal which has 61.8 per cent carbon, 4.78 per cent hydrogen, 7.56 per cent oxygen, 4.53 per cent sulphur, and 1.35 per cent nitrogen.

Solution.—Heating value in B.t.u. per pound $= 14{,}600 \times 0.618 + 62{,}000\left(0.0478 - \frac{0.0756}{8}\right) + 4{,}000 \times 0.0453 = 9.942 + 2{,}381 + 181 = 12{,}504.$

The Proximate Analysis of Fuels.—While the heating value of a fuel is important in estimating its commercial value, other properties must be considered as well. Two different coals, for instance, may have the same heating value; but the properties of one, not disclosed by the heating value, may cause it to be more or less desirable than the other. The proximate analysis of a fuel has been devised to assist in this. Such an analysis is possible only with solid fuels. The proximate analysis determines the amount of moisture, volatile matter, fixed carbon, ash, and sulphur.

Moisture requires heat for its evaporation and is a direct loss. Ash, when present in large amounts, may form clinkers, and is also an item of expense in its disposal. Sulphur is usually considered a detrimental constituent, especially if present in amounts greater than 2 per cent. Coals containing large quantities of sulphur are usually avoided.

The volatile matter and the fixed carbon are the heat-producing constituents of the coal. The volatile matter represents that part which distills off at a comparatively low temperature, and may be considered the gaseous or flaming constituent. The amount of volatile matter gives some conception of the smoke-producing qualities of the fuel. If smokeless combustion must be secured in any particular plant, and no special furnaces have been installed which will insure the proper combustion of volatile gases, a coal with a large content of volatile matter should not be selected. The fixed carbon is just the reverse of the volatile matter; it being that part of the coal which burns with little flame and, consequently, gives no trouble from smoke.

Fuels for Steam Generation.—The fuels most commonly used for steam generation are coal, wood, petroleum oils, and natural gas.

Wood.—Wood is but little used for steam generation except in remote places, where timber is plentiful, or in special cases where sawdust, shavings, and pieces of wood are by-products of manufacturing operations. Wood burns rapidly and with a bright flame, but does not evolve much heat. When first cut, wood contains 30 to 50 per cent of moisture, which can be reduced by drying to about 15 per cent. One pound of dry wood is equal in heat-producing value to about one-half pound of soft coal. It is important that wood be dry, as each 10 per cent of moisture reduces its heat-producing value as a fuel by about 12 per cent. The chemical compositions and the calorific values of some of the more common woods are shown in Table 2.

TABLE 2.—ANALYSIS AND CALORIFIC VALUE OF DRY WOOD

Kind of wood	Carbon	Hydrogen	Nitrogen	Oxygen	Ash	B.t.u. per pound
Oak	50.16	6.02	0.09	43.36	0.37	8,316
Ash	49.18	6.27	0.07	43.91	0.57	8,480
Elm	48.99	6.20	0.06	44.25	0.50	8,510
Beech	49.06	6.11	0.09	44.17	0.57	8,591
Birch	48.88	6.06	0.10	44.67	0.29	8,586
Fir	50.36	5.92	0.05	43.39	0.28	9,063
Pine	50.31	6.20	0.04	43.08	0.37	9,153

Coal.—Coal is more extensively used as a fuel for steam generation than any other substance. It is a substance which results from collections of vegetable materials, which have been gradually changed in physical and chemical composition until they finally formed coal.

Coal was first discovered in this part of the world by Joliet and Marquette in 1673, near where the city of Utica, Illinois, is now located. The first bituminous coal mine was operated near Richmond, Virginia, in 1750. The first anthracite was mined in Pennsylvania in 1790.

The coal resources of the United States have been estimated at the end of 1925 as 3,419,324 million tons, of which 25,228 million tons have been mined; 34,807,000 tons were used during 1933 for the production of electricity. Coal is found in mineable quantities in 31 out of the 48 states in the United States.

In the first stages of the transformation coal is classed as peat. In its next stage it is known as lignite or brown coal. Following this in the proper order of transformation are soft or bituminous coal, semi-bituminous, semi-anthracite, and finally anthracite or hard coal.

Table 3 gives the proximate analyses and the calorific values of typical American coals.

TABLE 3.—COMPOSITION AND CALORIFIC VALUE OF AMERICAN COALS
(U. S. Bureau of Mines)

State	Classification	Proximate analysis					B.t.u. per lb., dry coal
		Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	
Pennsylvania	Anthracite	2.19	5.67	86.24	5.90	0.57	13,828
Pennsylvania	Anthracite	3.43	6.79	78.25	11.53	0.46	12,782
Pennsylvania	Semi-anthracite	5.48	7.53	81.00	11.47	....	13,547
Pennsylvania	Semi-bituminous	2.72	16.70	75.38	5.20	0.55	14,521
West Virginia	Semi-bituminous	3.17	18.46	70.86	7.51	1.07	13,995
Colorado	Bituminous	10.27	38.25	44.99	6.49	0.42	11,410
Illinois	Bituminous	7.12	34.55	50.68	7.65	2.23	12,481
Kansas	Bituminous	11.10	35.51	40.69	12.70	3.99	11,065
Kentucky	Bituminous	4.83	33.71	57.73	3.73	0.82	13,842
Missouri	Bituminous	5.87	30.98	51.67	11.48	5.00	12,339
Ohio	Bituminous	5.15	37.34	49.00	8.51	2.94	12,733
Oklahoma	Bituminous	4.83	35.76	55.55	3.86	1.34	13,829
Pennsylvania	Bituminous	3.48	35.15	55.45	5.92	1.18	13,700
West Virginia	Bituminous	3.36	22.50	68.86	5.28	0.52	14,369
Colorado	Lignites	20.71	31.82	43.98	3.45	0.45	9,941
North Dakota	Lignites	32.65	30.57	28.49	8.29	1.33	7,357
Wyoming	Lignites	23.46	35.64	35.73	5.17	0.49	9,050

The weight of coal per cubic foot will vary from 43 to 66 lb. An anthracite coal will have greater weight than a bituminous coal; the higher the amount of fixed carbon in the coal the greater is its weight. Ordinarily anthracite coal will weigh 55 to 66 lb. per cubic foot and bituminous coal 50 to 55 lb. per cubic foot.

Anthracite is commonly known as hard coal. It consists mainly of fixed carbon having little, and in some cases no volatile matter. Some varieties approach graphite in their characteristics, and are burned with difficulty unless mixed with other coals. This coal is slow to ignite, burns with a short flame, and gives an intense fire free from smoke. As it is available only in certain limited sections, its use is not common.

Semi-anthracite coal is softer and lighter than anthracite. It contains less carbon than anthracite coal, and its volatile matter ranges from 7 to 12 per cent. It ignites more readily than anthracite and makes an intense, free-burning fire.

Semi-bituminous coal has all the physical characteristics of bituminous coal, but it differs from it in that the volatile matter content is not so high. Semi-bituminous coal contains from 12 to 25 per cent volatile matter, and when compared with semi-anthracite coal its fixed carbon is less.

Bituminous coal is a classification intended to include coals which contain 25 per cent or more volatile matter and less than 65 per cent of fixed carbon. One objection to the use of bituminous coal as a fuel is its smoking quality. This may be an undesirable feature, especially if its use is in a city where smoke ordinances are enforced and when special smokeless furnaces have not been installed. Another feature which may be considered undesirable is the tendency for highly volatile coals to ignite spontaneously.

Bituminous coal constitutes over 85 per cent of the fuel used in manufacturing, when including the manufacture of coke. The term "bituminous coal" is broad in its interpretation, and includes a great variety of coals which have many different qualities. For this reason, many of the coals of this classification are given special names, depending upon some marked physical characteristic they possess. Dry or free-burning bituminous coal is one of the best of the bituminous varieties for steaming purposes. As compared with other bituminous coals, it is low in volatile matter and burns with a short bluish flame. Bituminous caking coals is the term applied to those varieties that swell up, become pasty and fuse together in burning. They contain a greater amount of volatile matter than do the dry bituminous coals and for that reason burn with a larger flame and have a greater tendency to smoke. Long-flaming bituminous coals are those containing the greatest amounts of volatile matter. They possess a strong tendency to produce smoke. Cannel coal is a variety rich in volatile matter. It is used principally in the manufacture of artificial gas. It differs in appearance from the other varieties in that it has a dull resinous luster. Its volatile content varies from 45 to 60 per cent. It is seldom used as a steaming coal, though it is sometimes mixed with other coals containing less volatile matter.

Lignite may be classified as coal in the process of formation. This coal contains a very large proportion of volatile matter and less than 50 per cent fixed carbon. It has a low heating value and burns freely, but owing to the high percentage of volatile-matter content it will not stand storage, but crumbles badly soon after exposure to air. Its use is restricted to those localities in which it is found.

Sulphur is an objectionable impurity as its presence causes slacking of lumps of coal as well as corrosion of breechings and other steel parts. Ash, like moisture, is inert and reduces the heating value directly in proportion to the amount present. It is not only necessary to pay freight on ash, but the operator must dispose of it after the coal is burned and, if present in large quantities, it chokes air passages and interferes with combustion.

Low-grade and Prepared Solid Fuels.—Other solid fuels used to some extent for steam generation are: peat, which is an intermediate between wood and coal and is found in bogs; sawdust; oak bark, after it has been used in the process of tanning; bagasse, or the refuse of cane sugar; and cotton stalks.

Coke is also used to some extent, the advantage of this fuel as compared with coal being that coke will not ignite spontaneously, will not deteriorate or decompose when exposed to the atmosphere, and produces no smoke when burned. Coke is manufactured by burning coal in a limited air supply, the volatile hydrocarbons being driven off during the process.

Low-grade solid fuels unsuitable for transportation as well as certain portions of waste due to the mining of coal are being used in European countries as fuel by briquetting or by pressing into solid blocks. In this country, because of the large deposits of natural fuels, briquetted fuels are used only to a very limited extent. With increasing fuel costs and improved methods of briquette manufacture, the demand for briquettes manufactured from low-grade fuels will increase.

The Storage of Solid Fuels.—The storage of coal is made necessary by market conditions, the possibility of labor difficulties at mines and on railroads, and the crowding of transportation facilities. Coal is stored to insure a continuous and uninterrupted supply and to take advantage of fluctuations in price.

Anthracite coal is easiest to store. It is not subject to spontaneous combustion, and for this reason is unlimited in amount that may be stored in one pile. Bituminous coal is more difficult to store, as the majority of bituminous coals will ignite if placed in large enough piles and will suffer to some extent from disintegration. The higher the volatile content of the coal, the greater will be the loss in heating value due to storage and the more subject will the fuel be to spontaneous combustion.

The storing of large sizes of coal will reduce the loss due to disintegration. Large lumps of coal are less liable to spontaneous combustion than are small sizes. It is best not to pile bituminous coal over 10 ft. high. Storage under water is used to some extent in order to prevent losses from spontaneous combustion, but this method is expensive.

Fuel Oil.—Petroleum fuels, either in the form of crude petroleum or as the refuse left from its distillation may be used for steam generation. Due, however, to the demand for gasoline and the more volatile fractions, very little of the crude oils are used and practically all commercial fuel oils have passed through some stage of distillation. Oil is used as a fuel in steam generation chiefly in the midwestern and western parts of the United States, in which localities its relative cost is less than other fuels. In estimating the relative value of oil and coal, 4 bbl. of oil may be considered as equivalent to 1 ton of coal. One barrel of oil contains about 42 gal.

The advantages of oil as a fuel for steam generation as compared with solid fuels are: ease of handling, less labor in firing, better combustion by a more intimate mixture of air and fuel, cleanliness, and almost total absence of smoke after combustion.

A survey of the American Petroleum Industry by the American Petroleum Institute indicates that on Jan. 1, 1935, the United States had 12.2 billion bbl. of proven reserves of petroleum, or *a supply sufficient for less than* 15 *years* if the present rate of consumption and the known producing methods are continued. The United States produced in 1935 over 993 million bbl. of petroleum and the rest of the world only about 615 million bbl. Thus it seems socially undesirable to use petroleum as fuel for steam generation or even for household heating when this fuel and its distillates are so important for lubrication purposes and for motor vehicle propulsion.

In selecting a fuel oil, the following characteristics are usually considered: flash point, or the temperature at which the oil gives off inflammable vapors; viscosity, which is an index of the ease with which the oil will flow; gravity, or its relative weight per unit of volume, as compared with water; moisture; sulphur; sediment; and heating value.

TABLE 4.—ANALYSIS AND CALORIFIC VALUE OF OILS (C. E. LUCKE)

Classification	Density at 60°F.		Ultimate analysis				Heating value B.t.u. per lb.	
	gr.	°Bé.	C	H_2	O_2+N_2	S	High	Low
California fuel	0.966	14.93	81.52	11.61	6.92	0.55	18,926	17,903
Texas, Beaumont fuel	0.926	21.25	83.26	12.41	3.83	0.50	19,654	18,570
California crude	0.957	16.24	86.30	16.70	....	0.80	21,723	21,254
Texas, Beaumont crude	0.924	21.56	84.60	10.90	2.97	1.63	18,977	18,025
Pennsylvania crude	0.914	23.18	86.10	13.90	....	0.06	20,949	19,735
Kansas crude	0.866	31.67	85.40	13.07	....	....	20,345	19,203
West Virginia crude	0.841	36.47	84.30	14.10	1.6	....	20,809	19,578
Ohio crude	0.829	38.89	85.00	13.80	0.6	0.6	20,752	19,547

The heating value of petroleum fuels can best be determined by a calorimeter. From the chemical analysis of a fuel the heating value, in B.t.u. per pound, can be determined, approximately, by a formula similar to that used for solid fuel. Thus the heating value of a fuel oil is

$$\text{B.t.u. per pound} = 14{,}600C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000S. \qquad (35)$$

C, H, O, and S represent the proportionate weights of carbon, hydrogen, oxygen and sulphur in 1 lb. of fuel oil.

Colloidal Fuel.—The term colloidal fuel is applied to an emulsion of powdered coal and oil fuel. Most oils in their natural state can be mixed with pulverized solid fuels to make a smokeless colloidal fuel. It is also possible to combine oil, tar, and powdered coal and obtain a stable colloidal fuel. Colloidal fuel for steam generation requires much additional experimentation before it can be definitely compared with the fuels now in use.

Gaseous Fuels.—Blast-furnace gas, by-product coke-oven gas, and natural gas are used to some extent for steam generation.

Blast-furnace gas is a by-product of the blast furnace of the iron and steel industry. The volume of blast-furnace gas produced per ton of iron varies between 130,000 and 150,000 cu. ft.

By-product coke-oven gas is the product of the destructive distillation of coal in the by-product coke oven. The volume of coke-oven gas produced per ton of coal coked is about 6,000 cu. ft.

Natural gas is used for steam generation only in natural-gas regions, where its cost is very low. The extension of pipe-line systems is constantly increasing the use of this fuel.

Illuminating gas and other manufactured gases are too expensive for steam generation and cannot compete with other fuels.

The heating values of various gaseous fuels will be found in Table 5.

TABLE 5.—HEATING VALUE OF GASEOUS FUELS

Character of gas	B.t.u. per cubic foot
Coke-oven gas	600
Water gas	275
Blast-furnace gas	100
Natural gas	950
Producer gas	120

Fuels suitable for internal-combustion engines are treated in Chap. XIII.

COMBUSTION

Combustion is a chemical combination of the heat-producing constituents of a fuel with oxygen, accompanied by the evolution of heat.

Carbon, hydrogen, and sulphur are the main combustible constituents of all fuels. Of these, the sulphur is of minor importance in contributing to the heating value because it is present in small quantities in fuels suitable for steam power plants.

Carbon is present either in a free, uncombined state or in combination with hydrogen as a hydrocarbon.

Oxygen, the supporter of combustion, is one of the most common substances found in nature. The largest supply of oxygen is found in the atmosphere, and it is from this source that the supply required for the combustion of fuel is derived. Air is chiefly a mixture of oxygen and nitrogen, although small amounts of other gases are usually present.

Air contains 0.23 parts by weight of oxygen and 0.77 parts by weight of nitrogen. Only the oxygen is used in the combustion of the fuel; nitrogen is an inert gas and has no chemical effect upon the combustion of the fuel.

In order to secure good combustion, the combustible constituents of the fuel must be brought into intimate contact with sufficient oxygen to complete their combustion; also the temperature must be sufficiently high to support combustion, and time must be available for the completion of the combustion reactions.

Chemistry of Combustion.—In the process of combustion, the heat-producing elements of the fuel, which are carbon, hydrogen, and sulphur, unite with oxygen from the air.

If the combustion is perfect, the combustibles unite with the greatest amount of oxygen. Thus in the case of carbon, if the combustion is perfect, every atom of carbon unites with two atoms of oxygen forming carbon dioxide ($C + O_2 = CO_2$), and liberates 14,600 B.t.u. per pound.

If there is a lack of oxygen, combustion is imperfect, every atom of carbon unites only with one atom of oxygen forming carbon monoxide ($2C + O_2 = 2CO$) and liberating only 4,400 B.t.u. for each pound of carbon burned.

The importance of proper air supply in the burning of a fuel is quite evident from the above. Each pound of carbon when completely burned is capable of liberating 14,600 B.t.u. If carbon is burned to carbon monoxide, only 4,400 B.t.u. will be liberated, producing a loss of 10,200 B.t.u., which is about 70 per cent of the original heating value of the carbon. While it would be an extremely inefficient furnace that would produce much carbon monoxide, any furnace, unless properly operated, produces more or less incomplete combustion, with the consequent lower efficiency in the utilization of the fuel.

The complete combustion of carbon is expressed by the reaction:

$$C + O_2 = CO_2. \tag{36}$$

The combining weights involved are: C, 12 and O_2, 32. Introducing these in equation (36), we have

$$12 + 32 = 44. \tag{37}$$

Thus, 12 lb. of carbon require 32 lb. of oxygen and produce 44 lb. of carbon dioxide. Reducing to 1 lb. of carbon the statement becomes, 1 lb. of carbon requires $^{32}/_{12}$ or 2.66 lb. of oxygen and produces $^{44}/_{12}$ or 3.66 lb. of carbon dioxide.

Hydrogen, when burned, enters into combination with oxygen forming water (H_2O), and liberating 62,000 B.t.u. per pound of hydrogen burned This process is indicated by the chemical reaction:

$$H_2 + O = H_2O. \tag{38}$$

Introducing the combining weights of H_2, 2 and O, 16, we have

$$2 + 16 = 18. \tag{39}$$

Thus, 2 lb. of hydrogen require 16 lb. of oxygen and produce 18 lb. of water, or 1 lb. of hydrogen requires 8 lb. of oxygen and produces 9 lb. of water.

In the case of the combustion of all fuels, the oxygen in the fuel is assumed to be combined with hydrogen in the form of water. The difference between the total hydrogen and that combined with the oxygen present in the fuel is termed "the available hydrogen." Thus from equation (39) it may be seen that 16 lb. of oxygen combine with 2 lb. of hydrogen, or each pound of oxygen makes inert $^1/_8$ lb. of hydrogen. The available hydrogen of a fuel may then be determined from the expression:

$$H - \frac{O}{8}. \tag{40}$$

Sulphur unites with oxygen to form sulphur dioxide and liberates 4,050 B.t.u. per pound of sulphur burned. This process is indicated by the chemical reaction:

$$S + O_2 = SO_2. \tag{41}$$

Introducing the combining weights of S, 32 and O_2, 32, we have

$$32 + 32 = 64.$$

Thus, 32 lb. of sulphur require 32 lb. of oxygen producing 64 lb. of sulphur dioxide, or 1 lb. sulphur requires 1 lb. oxygen and produces 2 lb. of sulphur dioxide.

Air Required for Combustion.—For the complete combustion of 1 lb. of carbon 2.66 lb. of oxygen, or $\frac{2.66}{0.23} = 11.5$ lb. of air will be theoretically required. For the complete combustion of 1 lb. of hydrogen 8 lb. of oxygen will be required, or $\frac{8}{0.23} = 34.8$ lb. of air.

The theoretical amount of air required to burn any fuel may be approximately determined from the chemical analysis by the following formula:

$$\text{Weight of air required per pound fuel} = 11.5C + 35\left(H - \frac{O}{8}\right) + 4.35S. \qquad (42)$$

C, H, S, and O represent the proportionate weights of carbon, hydrogen, sulphur, and oxygen in 1 lb. of the fuel.

As an illustration of the application of this formula:

Calculate the approximate theoretical amount of air required to burn a coal which has 68.1 per cent carbon, 5 per cent hydrogen, 0 per cent sulphur, and 8 per cent oxygen.

Solution.—Air required per pound fuel, by equation (42), =

$$11.5 \times 0.681 + 35\left(0.05 - \frac{0.08}{8}\right) = 7.82 + 1.40 = 9.22 \text{ lb.}$$

Complete combustion will not be obtained in a boiler furnace if only this theoretical amount of air is supplied. An excess of air varying from 20 to 100 per cent will be required, depending upon the draft and upon the fuel used. With natural draft, a greater excess of air is required than with mechanical draft.

Too much air will produce a great loss of heat by diluting the gases arising from the furnace. Air should be added to the furnace so that each atom of carbon has sufficient opportunity to unite with as much air as possible. When this is accomplished no further excess air is needed. Ordinarily, bituminous coal requires about 15 lb. of air per pound of fuel, or about 200 cu. ft. of air per pound of fuel.

Flue-gas Analysis.—The analysis of the gases leaving the boiler is made to ascertain whether the fuel is being burned economically. If there is an excess of air, too much oxygen will be present in the flue gases; if there is a deficiency there will be carbon monoxide present.

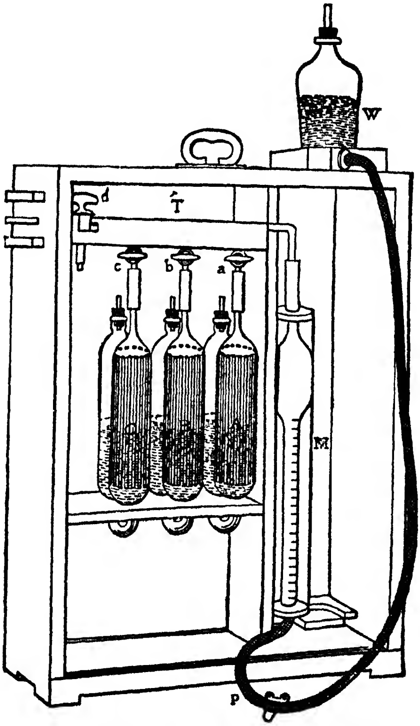

Fig. 6.—Orsat apparatus.

Several instruments have been devised to facilitate this analysis. The fundamental principles upon which they operate are much the same. A simple device, called an Orsat apparatus and shown in Fig. 6, is commonly used. It consists of three pipettes, *A*, *B*, and *C*, filled, respectively, with caustic potash, a mixture of caustic potash and pyrogallic acid, and cuprous chloride. A measuring burette *M* and a displacement bottle *W* are also provided. The sample of the flue gas to be analyzed is drawn into the measuring burette. It is then passed into the pipette *A* containing the caustic potash where the carbon dioxide is absorbed. The gas is then drawn back into the measuring burette and the shrinkage in volume represents the amount of carbon dioxide present. The remaining gas is similarly treated in pipette *B* where the oxygen is absorbed, and is finally passed to pipette *C* where the carbon monoxide is removed.

The sample of flue gas is usually taken from the breeching, and preferably at a point where the flue gases are just leaving the boiler.

The method of calculating the air required for combustion by the aid of a flue-gas analysis is shown by the following example:

A flue-gas analysis gives by volume 13 per cent carbon dioxide, 6 per cent oxygen, 0.5 per cent carbon monoxide, and 80.5 per cent nitrogen.

Solution.—Assume the flue-gas sample has a volume of 100 cu. ft. and compute the weights as follows:

Carbon dioxide has a volume of 13 cu. ft., a density per cubic foot of 0.12345; its weight is $13 \times 0.12345 = 1.604$.

Carbon monoxide has a volume of 0.5 cu. ft., a density of 0.07806; its weight is $0.5 \times 0.07806 = 0.0390$.

Oxygen has a volume of 6 cu. ft., a density of 0.08928; its weight is $6 \times 0.08928 = 0.5357$.

One pound of carbon dioxide contains $8/11$ lb. of oxygen; 1 lb. of carbon monoxide contains $4/7$ lb. of oxygen.

Thus the total weight of oxygen in 100 cu. ft. of flue gas will be

In the carbon dioxide $8/11 \times 1.604$	= 1.1668
In the carbon monoxide $4/7 \times 0.0390$	= 0.0223
Free oxygen	= 0.5357
Total weight of oxygen	= 1.7248 lb.

The weight of carbon in 100 cu. ft. of flue gas will be

In the carbon dioxide $3/11 \times 1.604$	= 0.4375
In the carbon monoxide $3/7 \times 0.0390$	= 0.0167
Total weight of carbon	= 0.4542 lb.

Since air contains 23.0 per cent of oxygen by weight, the air per pound of carbon by the flue-gas analysis will be

$$\frac{1.7248}{0.4542} \text{ divided by } 0.23 = 16.4 \text{ lb.}$$

If the coal used in the furnace of the boiler contains 76.5 per cent carbon, 5 per cent hydrogen, and 8 per cent oxygen, the total air required for complete combustion per pound of coal can be calculated by the formula previously given as follows:

$$\begin{aligned} \text{Air} &= 16.4 \times 0.765 + 35\left(0.05 - \frac{0.08}{8}\right) = 12.5 + 1.5 \\ &= 14 \text{ lb.} \end{aligned}$$

Perfect combustion is indicated by a flue-gas analysis, which shows about 1 per cent of carbon dioxide for every 4 per cent of nitrogen. Low carbon dioxide may be due to excessive air, air holes in the fuel bed, or to the infiltration of air through cracks in the setting. Dirty heating surfaces and the presence of soot will be indicated by a low carbon dioxide in the flue gases. Too much oxygen in the flue gases shows excess of air. A good flue-gas analysis will show 4 to 8 per cent oxygen, 10 to 13 per cent carbon dioxide, and no carbon monoxide. Fuels high in hydrogen have more nitrogen in the flue-gas and the percentages of carbon dioxide and oxygen are proportionately reduced.

Problems

1. Calculate the heating value in B.t.u. of a Pennsylvania coal which contains 86.5 per cent carbon, 2.7 per cent hydrogen, 3.6 per cent oxygen, and 0.6 per cent sulphur.
2. Calculate the heating value of a North Dakota coal of the following composition: carbon 39.5 per cent, hydrogen 6.75 per cent, oxygen 43.8 per cent, sulphur 0.68 per cent.
3. Compile a table showing composition and heating value of the fuels most commonly used in your locality.
4. Coal costs $3 a ton (2,000 lb.). If the coal in question has a heating value of 12,000 B.t.u. per pound, what is the cost in cents of 1000 B.t.u.?
5. Calculate the space in square feet required to store 9,000 tons of bituminous coal in piles 6 ft. high.
6. Fuel oil whose heating value is 18,500 B.t.u. per pound and whose weight is 7 lb. per gallon sells at 5 cts. per gallon. Coal with a heating value of 13,000 B.t.u. per pound may be purchased at a price of $4 per ton.

Which would be the cheaper fuel if the estimate is based upon the cost of an equal number of heat units?

7. Calculate the approximate heating value in B.t.u. of a fuel oil which contains 86 per cent carbon, 14 per cent hydrogen, and 0.07 per cent sulphur.

8. From a study of Table 4 explain how petroleum from Texas differs from that which comes from Pennsylvania or from Kansas.

9. What is meant by volatile matter in coal?

10. Natural gas costs 25 cts. per 1,000 cu. ft. If its heating value is 950 B.t.u. per cubic foot, what is the cost of 1000 B.t.u.?

11. Distillate, a liquid fuel used extensively in the production of heat, weighs about 6.78 lb. per gallon and has a heating value of 18,000 B.t.u. per pound. If coal has an average heating value of 12,000 B.t.u. per pound and 1 bbl. of oil contains 42 gal., how many barrels of distillate are equivalent in heat to 1 ton of coal?

12. If the coal, in Problem 11, sells for $10 per ton, what would be the maximum price per gallon and per barrel that could profitably be paid for distillate? The calculations in this problem to be based on equivalent heats alone.

13. Prove that 2⅔ lb. of oxygen will be required to burn 1 lb. of carbon into carbon dioxide.

14. Prove that 8 lb. of oxygen will be required to burn 1 lb. of hydrogen.

15. Calculate the approximate theoretical amount of air required to burn 1 lb. of coal which contains 53 per cent carbon, 5.5 per cent hydrogen, and 21.3 per cent oxygen.

16. A flue-gas analysis shows 12 per cent carbon dioxide, 7 per cent oxygen and 0.3 per cent carbon monoxide. Calculate the air actually supplied per pound of carbon.

17. Find the air required per pound of coal, Problem 16, if the coal contains 80 per cent carbon, 4 per cent hydrogen, and 2.2 per cent oxygen.

18. Calculate the size of bin, in cubic feet, needed to store 50 tons of bituminous coal.

19. Why should the use of oil for steam generation be discouraged?

20. Is it practical and socially desirable to use natural gas for steam generation? Give reasons for your answer.

CHAPTER IV

STEAM

Theory of Steam Generation.—If heat is added to ice, the effect will be to raise its temperature until the thermometer registers 32°F. When this point is reached, a further addition of heat does not produce an increase in temperature until all the ice is changed into water, or in other words, the ice melts. It has been found experimentally that 144 B.t.u. are required to change 1 lb. of ice into water at the constant temperature of 32°F. This quantity is called the latent heat of fusion of ice.

After the given quantity of ice, which for simplicity may be taken as 1 lb., has all been turned into water, it will be found that if more heat is added the temperature of the water will again increase, though not so rapidly as did that of the ice. While the addition of each B.t.u. increases the temperature of ice 2°F., in the case of water an increase of only about 1° will be noticed for each B.t.u. of heat added. This difference is due to the fact that the specific heat, or the resistance offered by ice to a change in temperature is only one-half that offered by water. That is, the specific heat of ice is 0.5.

If the water is heated in a vessel open to the atmosphere, its temperature will continue to rise until it reaches a temperature of about 212°F., the boiling point of water, when further addition of heat will not produce any temperature changes, but steam will issue from the vessel. It has been found that about 970 B.t.u. are required to change 1 lb. of water at atmospheric pressure and at 212°F. into steam at the same temperature. This quantity of heat which changes the physical state of water from that of a liquid to steam without changing the temperature is called the enthalpy of vaporization.

If the above operations are performed in a closed vessel, such as an ordinary steam boiler, water will boil at a higher temperature than 212°F., since the steam driven off cannot escape and is compressed, raising the pressure and, consequently, the temperature.

The fact that the boiling point of water depends on the pressure is well known. Thus, in a locality where the altitude is 6,000 ft. above sea level and the barometric pressure is 12.6 lb. per square inch absolute the boiling point of water is about 204°F. as compared with 212°F. at sea level where the barometric pressure is 14.7 lb. per square inch absolute.

Assuming that the pressure is increased to 60 lb. per square inch by the gage, it will be found that the boiling point of water is 307.2°F. At 100 lb. per square inch water will boil at 337.8°F. and at 150 lb. the temperature will read 365.8°F. before steam will be formed.

Quality of Steam.—Steam formed in contact with water is known as saturated steam, which may be wet or dry.

In the first case, steam carries with it a certain amount of water which has not been evaporated. The percentage of this water determines the dryness or the quality of the steam (x); that is, if the steam contains 3 per cent by weight of moisture, the steam is spoken of as being 97 per cent dry, or $x = 0.97$. A stationary steam boiler, properly erected and operated and of suitable size, should generate steam that is 98 per cent dry. If there is more than 3 per cent moisture, there is every reason to believe that the boiler is improperly installed, inefficiently operated, has too small a space for the disengagement of the steam from the water, or is too small for the work to be done.

In the second condition, that of being dry steam, the vapor carries with it no water that has not been evaporated; that is, it is dry. Any loss of heat, however small, not accompanied by a corresponding reduction in pressure, will cause condensation, and wet steam will be the result. Saturated steam, whether wet or dry, has a definite temperature corresponding to its pressure.

An increase in temperature not accompanied by an increase in pressure will cause the steam to acquire a condition that will permit a small loss of heat at constant pressure without condensation necessarily following. This condition is called superheat. The advantage of superheated steam lies in the fact that its temperature may be reduced by the amount of superheat without causing condensation. This makes it possible to transmit the steam through mains and still have it dry and saturated at the time it reaches the engine cylinder. Superheated steam may be secured by passing saturated steam through coils of pipe in the path of the hot flue gases from the boiler to the chimney. An apparatus for superheating steam is called a superheater.

The pressure of steam will remain constant if it is used as fast as it is generated. If an engine uses steam too rapidly, the boiler pressure will drop, and similarly if the fuel is burned at a constant rate and an insufficient amount of steam is used the pressure of the steam in the boiler will increase.

Steam Tables.—The relations existing between pressure, volume, and temperature of saturated and superheated steam as well as the energy required to produce vaporization under various conditions have been determined experimentally. These experimental results have been expressed in the form of empirical equations from which steam tables have been computed.

In Tables 6 and 7 are given the most important properties of saturated steam which include:

1. Pressure (p) of steam in pounds per square inch absolute, or inches of mercury for low pressures.

2. Temperature (t) of saturated steam in degrees Fahrenheit. This column shows the vaporization temperature or the boiling point, at each of the given pressures.

3. Specific volumes. These include the specific volume of the saturated liquid (v_f) and the specific volume of saturated steam (v_g).

4. Enthalpy. The three columns for enthalpy are: the enthalpy of the liquid (h_f), enthalpy of evaporation (h_{fg}), and enthalpy of saturated steam (h_g). The enthalpy of the liquid (h_f) is the energy required to raise the temperature of 1 lb. of water from freezing point to the vaporization temperature, or boiling point, at the given pressure. The enthalpy of evaporation (h_{fg}) is the energy required to change 1 lb. of water at its point of vaporization to dry saturated steam at the given pressure. The enthalpy of saturated steam (h_g) is the sum of h_f and h_{fg}, or the energy required to change 1 lb. of water from freezing point to dry saturated steam at the given pressure.

5. Entropy. The three columns for entropy include entropy of the liquid (S_f), entropy of evaporization (S_{fg}), and entropy of saturated steam (S_g).

TABLE 6.—PROPERTIES OF SATURATED STEAM (TEMPERATURES)*

Temp. Fahr., t	Abs. press., lb. per sq. in., p	Specific volume			Enthalpy			Entropy			Temp., Fahr., t
		Sat. liquid, v_f	Evap., v_{fg}	Sat. vapor, v_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, S_f	Evap., S_{fg}	Sat. vapor, S_g	
32	0.08854	0.01602	3306	3306	0.00	1075.8	1075.8	0.0000	2.1877	2.1877	32
35	0.09995	0 01602	2947	2947	3.02	1074.1	1077.1	0.0061	2.1709	2.1770	35
40	0.12170	0.01602	2444	2444	8.05	1071.3	1079.3	0.0162	2.1435	2.1597	40
45	0 14752	0 01602	2036.4	2036.4	13.06	1068.4	1081.5	0.0262	2.1167	2.1429	45
50	0.17811	0.01603	1703.2	1703.2	18.07	1065.6	1083.7	0.0361	2.0903	2.1264	50
60	0.2563	0.01604	1206.6	1206.7	28.06	1059.9	1088.0	0.0555	2.0393	2.0948	60
70	0.3631	0 01606	867.8	867.9	38.04	1054.3	1092.3	0.0745	1.9902	2.0647	70
80	0.5069	0.01608	633.1	633.1	48.02	1048.6	1096.6	0.0932	1.9428	2.0360	80
90	0.6982	0.01610	468.0	468.0	57.99	1042.9	1100.9	0.1115	1.8972	2.0087	90
100	0.9492	0.01613	350.3	350.4	67.97	1037.2	1105.2	0 1295	1 8531	1.9826	100
110	1.2748	0.01617	265.3	265.4	77.94	1031.6	1109.5	0.1471	1.8106	1.9577	110
120	1.6924	0.01620	203.25	203.27	87.92	1025 8	1113.7	0.1645	1.7694	1.9339	120
130	2 2225	0.01625	157.32	157.34	97.90	1020.0	1117.9	0.1816	1.7296	1.9112	130
140	2.8886	0.01629	122.99	123.01	107.89	1014 1	1122.0	0.1984	1.6910	1.8894	140
150	3.718	0.01634	97.06	97 07	117.89	1008.2	1126.1	0.2149	1.6537	1 8685	150
160	4.741	0.01639	77.27	77.29	127.89	1002.3	1130.2	0.2311	1.6174	1.8485	160
170	5.992	0 01645	62.04	62.06	137.90	996.3	1134 2	0.2472	1.5822	1.8293	170
180	7 510	0.01651	50.21	50.23	147 92	990 2	1138.1	0.2630	1.5480	1.8109	180
190	9.339	0 01657	40.94	40.96	157.95	984.1	1142.0	0.2785	1.5147	1.7932	190
200	11.526	0.01663	33.62	33.64	167.99	977.9	1145.9	0.2938	1.4824	1.7762	200
210	14.123	0.01670	27.80	27.82	178.05	971.6	1149.7	0.3090	1 4508	1.7598	210
212	14.696	0.01672	26.78	26.80	180.07	970 3	1150.4	0.3120	1.4446	1.7566	212
220	17 186	0.01677	23.13	23.15	188.13	965 2	1153 4	0.3239	1.4201	1.7440	220
230	20.780	0.01684	19.365	19.382	198 23	958 8	1157.0	0.3387	1 3901	1.7288	230
240	24.969	0.01692	16.306	16.323	208.34	952.2	1160.5	0.3531	1.3609	1 7140	240
250	29 825	0.01700	13.804	13.821	218 48	945.5	1164.0	0.3675	1.3323	1.6998	250
260	35.429	0.01709	11.746	11.763	228.64	938.7	1167.3	0.3817	1.3043	1.6860	260
270	41.858	0 01717	10.044	10.061	238.84	931.8	1170 6	0.3958	1.2769	1.6727	270
280	49.203	0.01726	8.628	8.645	249.06	924.7	1173.8	0.4096	1.2501	1.6597	280
290	57.556	0.01735	7.444	7.461	259.31	917.5	1176.8	0.4234	1 2238	1.6472	290
300	67.013	0.01745	6.449	6.466	269.59	910.1	1179.7	0.4369	1.1980	1.6350	300
310	77.68	0.01755	5.609	5 626	279.92	902.6	1182.5	0.4504	1.1727	1.6231	310
320	89.66	0.01765	4.896	4.914	290.28	894.9	1185.2	0.4637	1.1478	1.6115	320
330	103.06	0.01776	4.289	4.307	300.68	887.0	1187.7	0.4769	1.1233	1.6002	330
340	118.01	0.01787	3.770	3.788	311.13	879.0	1190.1	0.4900	1.0992	1.5891	340
350	134.63	0.01799	3.324	3.342	321.63	870.7	1192.3	0.5029	1.0754	1 5783	350
360	153.04	0.01811	2.939	2 957	332.18	862.2	1194.4	0.5158	1.0519	1.5677	360
370	173.37	0.01823	2.606	2 625	342.79	853.5	1196 3	0.5286	1.0287	1.5573	370
380	195 77	0.01836	2.317	2.335	353 45	844.6	1198.1	0.5413	1.0059	1.5471	380
390	220.37	0.01850	2.0651	2.0836	364.17	835.4	1199.6	0.5539	0.9832	1.5371	390
400	247.31	0.01864	1.8447	1.8633	374.97	826.0	1201.0	0.5664	0.9608	1.5272	400
410	276 75	0.01878	1.6512	1.6700	385.83	816.3	1202.1	0.5788	0.9386	1.5174	410
420	308.83	0.01894	1.4811	1.5000	396.77	806.3	1203.1	0.5912	0.9166	1.5078	420
430	343.72	0.01910	1.3308	1.3499	407.79	796.0	1203.8	0.6035	0.8947	1.4982	430
440	381.59	0.01926	1.1979	1.2171	418.90	785.4	1204.3	0.6158	0.8730	1.4887	440
450	422.6	0.0194	1.0799	1.0993	430.1	774.5	1204.6	0.6280	0.8513	1.4793	450
460	466.9	0.0196	0.9748	0.9944	441.4	763.2	1204.6	0.6402	0.8298	1.4700	460
470	514.7	0.0198	0.8811	0.9009	452.8	751.5	1204.3	0.6523	0.8083	1.4606	470
480	566.1	0.0200	0.7972	0.8172	464.4	739 4	1203.7	0.6645	0.7868	1.4513	480
490	621.4	0.0202	0.7221	0.7423	476.0	726.8	1202.8	0.6766	0.7653	1.4419	490
500	680.8	0.0204	0.6545	0.6749	487.8	713.9	1201.7	0.6887	0.7438	1.4325	500
520	812.4	0.0209	0.5385	0.5594	511.9	686.4	1198.2	0.7130	0.7006	1.4136	520
540	962.5	0.0215	0.4434	0.4649	536.6	656.6	1193.2	0.7374	0.6568	1.3942	540
560	1133.1	0.0221	0.3647	0.3868	562.2	624.2	1186.4	0.7621	0.6121	1.3742	560
580	1325.8	0.0228	0.2989	0.3217	588.9	588.4	1177.3	0.7872	0.5659	1.3532	580
600	1542.9	0.0236	0.2432	0.2668	617.0	548.5	1165.5	0.8131	0.5176	1.3307	600
620	1786.6	0.0247	0.1955	0.2201	646.7	503.6	1150.3	0.8398	0.4664	1.3062	620
640	2059.7	0.0260	0.1538	0.1798	678.6	452.0	1130.5	0.8679	0.4110	1.2789	640
660	2365.4	0.0278	0.1165	0.1442	714.2	390.2	1104.4	0.8987	0.3485	1.2472	660
680	2708.1	0.0305	0.0810	0.1115	757.3	309.9	1067.2	0.9351	0.2719	1.2071	680
700	3093.7	0.0369	0.0392	0.0761	823.3	172.1	995.4	0.9905	0.1484	1.1389	700
705.4	3206.2	0.0503	0	0.0503	902.7	0	902.7	1.0580	0	1.0580	705.4

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* Abridged from "Thermodynamic Properties of Steam," by Joseph H. Keenan and Frederick G. Keyes, John Wiley & Sons, Inc., New York.

TABLE 7.—PROPERTIES OF SATURATED STEAM (PRESSURES)*

Abs. press., lb. per sq. in., p	Temp. Fahr., t	Specific volume		Enthalpy			Entropy			Internal energy		Abs. press., lb. per sq. in., p
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, S_f	Evap., S_{fg}	Sat. vapor, S_g	Sat. liquid, u_f	Sat. vapor, u_g	
1.0	101.74	0.01614	333.6	69.70	1036.3	1106.0	0.1326	1.8456	1.9782	69.70	1044.3	1.0
2.0	126.08	0.01623	173.73	93.99	1022.2	1116.2	0.1749	1.7451	1.9200	93.98	1051.9	2.0
3.0	141.48	0.01630	118.71	109.37	1013.2	1122.6	0.2008	1.6855	1.8863	109.36	1056.7	3.0
4.0	152.97	0.01636	90.63	120.86	1006.4	1127.3	0.2198	1.6427	1.8625	120.85	1060.2	4.0
5.0	162.24	0.01640	73.52	130.13	1001.0	1131.1	0.2347	1.6094	1.8441	130.12	1063.1	5.0
6.0	170.06	0.01645	61.98	137.96	996.2	1134.2	0.2472	1.5820	1.8292	137.94	1065.4	6.0
7.0	176.85	0.01649	53.64	144.76	992.1	1136.9	0.2581	1.5586	1.8167	144.74	1067.4	7.0
8.0	182.86	0.01653	47.34	150.79	988.5	1139.3	0.2674	1.5383	1.8057	150.77	1069.2	8.0
9.0	188.28	0.01656	42.40	156.22	985.2	1141.4	0.2759	1.5203	1.7962	156.19	1070.8	9.0
10	193.21	0.01659	38.42	161.17	982.1	1143.3	0.2835	1.5041	1.7876	161.14	1072.2	10
14.696	212.00	0.01672	26.80	180.07	970.3	1150.4	0.3120	1.4446	1.7566	180.02	1077.5	14.696
15	213.03	0.01672	26.29	181.11	969.7	1150.8	0.3135	1.4415	1.7549	181.06	1077.8	15
20	227.96	0.01683	20.089	196.16	960.1	1156.3	0.3356	1.3962	1.7319	196.10	1081.9	20
25	240.07	0.01692	16.303	208.42	952.1	1160.6	0.3533	1.3606	1.7139	208.34	1085.1	25
30	250.33	0.01701	13.746	218.82	945.3	1164.1	0.3680	1.3313	1.6993	218.73	1087.8	30
35	259.28	0.01708	11.898	227.91	939.2	1167.1	0.3807	1.3063	1.6870	227.80	1090.1	35
40	267.25	0.01715	10.498	236.03	933.7	1169.7	0.3919	1.2844	1.6763	235.90	1092.0	40
45	274.44	0.01721	9.401	243.36	928.6	1172.0	0.4019	1.2650	1.6669	243.22	1093.7	45
50	281.01	0.01727	8.515	250.09	924.0	1174.1	0.4110	1.2474	1.6585	249.93	1095.3	50
55	287.07	0.01732	7.787	256.30	919.6	1175.9	0.4193	1.2316	1.6509	256.12	1096.7	55
60	292.71	0.01738	7.175	262.09	915.5	1177.6	0.4270	1.2168	1.6438	261.90	1097.9	60
65	297.97	0.01743	6.655	267.50	911.6	1179.1	0.4342	1.2032	1.6374	267.29	1099.1	65
70	302.92	0.01748	6.206	272.61	907.9	1180.6	0.4409	1.1906	1.6315	272.38	1100.2	70
75	307.60	0.01753	5.816	277.43	904.5	1181.9	0.4472	1.1787	1.6259	277.19	1101.2	75
80	312.03	0.01757	5.472	282.02	901.1	1183.1	0.4531	1.1676	1.6207	281.76	1102.1	80
85	316.25	0.01761	5.168	286.39	897.8	1184.2	0.4587	1.1571	1.6158	286.11	1102.9	85
90	320.27	0.01766	4.896	290.56	894.7	1185.3	0.4641	1.1471	1.6112	290.27	1103.7	90
95	324.12	0.01770	4.652	294.56	891.7	1186.2	0.4692	1.1376	1.6068	294.25	1104.5	95
100	327.81	0.01774	4.432	298.40	888.8	1187.2	0.4740	1.1286	1.6026	298.08	1105.2	100
110	334.77	0.01782	4.049	305.66	883.2	1188.9	0.4832	1.1117	1.5948	305.30	1106.5	110
120	341.25	0.01789	3.728	312.44	877.9	1190.4	0.4916	1.0962	1.5878	312.05	1107.6	120
130	347.32	0.01796	3.455	318.81	872.9	1191.7	0.4995	1.0817	1.5812	318.38	1108.6	130
140	353.02	0.01802	3.220	324.82	868.2	1193.0	0.5069	1.0682	1.5751	324.35	1109.6	140
150	358.42	0.01809	3.015	330.51	863.6	1194.1	0.5138	1.0556	1.5694	330.01	1110.5	150
160	363.53	0.01815	2.834	335.93	859.2	1195.1	0.5204	1.0436	1.5640	335.39	1111.2	160
170	368.41	0.01822	2.675	341.09	854.9	1196.0	0.5266	1.0324	1.5590	340.52	1111.9	170
180	373.06	0.01827	2.532	346.03	850.8	1196.9	0.5325	1.0217	1.5542	345.42	1112.5	180
190	377.51	0.01833	2.404	350.79	846.8	1197.6	0.5381	1.0116	1.5497	350.15	1113.1	190
200	381.79	0.01839	2.288	355.36	843.0	1198.4	0.5435	1.0018	1.5453	354.68	1113.7	200
250	400.95	0.01865	1.8438	376.00	825.1	1201.1	0.5675	0.9588	1.5263	375.14	1115.8	250
300	417.33	0.01890	1.5433	393.84	809.0	1202.8	0.5879	0.9225	1.5104	392.79	1117.1	300
350	431.72	0.01913	1.3260	409.69	794.2	1203.9	0.6056	0.8910	1.4966	408.45	1118.0	350
400	444.59	0.0193	1.1613	424.0	780.5	1204.5	0.6214	0.8630	1.4844	422.6	1118.5	400
450	456.28	0.0195	1.0320	437.2	767.4	1204.6	0.6356	0.8378	1.4734	435.5	1118.7	450
500	467.01	0.0197	0.9278	449.4	755.0	1204.4	0.6487	0.8147	1.4634	447.6	1118.6	500
550	476.94	0.0199	0.8424	460.8	743.1	1203.9	0.6608	0.7934	1.4542	458.8	1118.2	550
600	486.21	0.0201	0.7698	471.6	731.6	1203.2	0.6720	0.7734	1.4454	469.4	1117.7	600
650	494.90	0.0203	0.7083	481.8	720.5	1202.3	0.6826	0.7548	1.4374	479.4	1117.1	650
700	503.10	0.0205	0.6554	491.5	709.7	1201.2	0.6925	0.7371	1.4296	488.8	1116.3	700
750	510.86	0.0207	0.6092	500.8	699.2	1200.0	0.7019	0.7204	1.4223	498.0	1115.4	750
800	518.23	0.0209	0.5687	509.7	688.9	1198.6	0.7108	0.7045	1.4153	506.6	1114.4	800
850	525.26	0.0210	0.5327	518.3	678.8	1197.1	0.7194	0.6891	1.4085	515.0	1113.3	850
900	531.98	0.0212	0.5006	526.6	668.8	1195.4	0.7275	0.6744	1.4020	523.1	1112.1	900
950	538.43	0.0214	0.4717	534.6	659.1	1193.7	0.7355	0.6602	1.3957	530.9	1110.8	950
1000	544.61	0.0216	0.4456	542.4	649.4	1191.8	0.7430	0.6467	1.3897	538.4	1109.4	1000
1100	556.31	0.0220	0.4001	557.4	630.4	1187.8	0.7575	0.6205	1.3780	552.9	1106.4	1100
1200	567.22	0.0223	0.3619	571.7	611.7	1183.4	0.7711	0.5956	1.3667	566.7	1103.0	1200
1300	577.46	0.0227	0.3293	585.4	593.2	1178.6	0.7840	0.5719	1.3559	580.0	1099.4	1300
1400	587.10	0.0231	0.3012	598.7	574.7	1173.4	0.7963	0.5491	1.3454	592.7	1095.4	1400
1500	596.23	0.0235	0.2765	611.6	556.3	1167.9	0.8082	0.5269	1.3351	605.1	1091.2	1500
2000	635.82	0.0257	0.1878	671.7	463.4	1135.1	0.8619	0.4230	1.2849	662.2	1065.6	2000
2500	668.13	0.0287	0.1307	730.6	360.5	1091.1	0.9126	0.3197	1.2322	717.3	1030.6	2500
3000	695.36	0.0346	0.0858	802.5	217.8	1020.3	0.9731	0.1885	1.1615	783.4	972.7	3000
3206.2	705.40	0.0503	0.0503	902.7	0	902.7	1.0580	0	1.0580	872.9	872.9	3206.2

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* Abridged from "Thermodynamic Properties of Steam," by Joseph H. Keenan and Frederick G. Keyes, John Wiley & Sons, Inc., New York.

6. Internal energy. u_f is internal energy of liquid, and u_g that of vapor.

Example 1.—Water at 200°F. is fed to a boiler in which the pressure is 155.3 lb. per square inch gage. How much heat must be supplied by the fuel to evaporate each pound of water into dry steam?

Solution.—A pressure of 155.3 lb. per square inch gage = 155.3 + 14.7 = 170 lb. per square inch absolute, if the barometer reading is 30 in.

The enthalpy (h_g) required to evaporate 1 lb. of water from freezing point into dry steam at a pressure of 170 lb. per square inch absolute is 1196 (Table 7). Since the water fed to the boiler has a temperature of 200°F., the total amount of heat to be supplied by the fuel to evaporate 1 lb. of water into dry steam is

$$1196 - (200 - 32) = 1028 \text{ B.t.u.}$$

Example 2.—If the steam in Example 1, contained 3 per cent moisture, calculate the heat which must be supplied by the fuel to evaporate each pound from feed water at 200°F.

Solution.—The enthalpy of the liquid (h_f), or the heat required to raise the temperature of a pound of water from 200°F. to the boiling point corresponding to a pressure of 170 lb. per square inch absolute is

$$341.1 - (200 - 32) = 173.1 \text{ B.t.u.}$$

The enthalpy required to vaporize a pound of water into dry steam at 170 lb. per square inch absolute, after the boiling point is reached, or the enthalpy of evaporation (h_{fg}), is 854.4 B.t.u.

Since the steam in this example contains 3 per cent moisture, it is 97 per cent dry, and the heat required to vaporize it is

$$854.9 \times 0.97 = 829.2 \text{ B.t.u.}$$

The total heat required to change 1 lb. of water at 200°F. into steam, 3 per cent wet, and at a pressure of 170 lb. per square inch absolute, is

$$173.1 + 829.2 = 1002.3 \text{ B.t.u.}$$

Example 3.—What is the volume of 1 lb. of steam at 150 lb. per square inch absolute, if it is 20 per cent wet?

Solution.—Dry steam at a pressure of 150 lb. per square inch absolute has a volume of 3.015 cu. ft. per pound.

The volume of 1 lb. of steam which is 20 per cent wet, or 80 per cent dry, at a pressure of 150 lb. per square inch absolute is

$$3.015 \times 0.80 = 2.41 \text{ cu. ft.}$$

Determination of the Quality of Saturated Steam.—The quality, or the per cent of moisture in saturated steam x, is determined by means of a calorimeter. There are three types of steam calorimeters in general use—the throttling calorimeter, the separating calorimeter, and the electrical calorimeter.

The throttling calorimeter is an accurate instrument for measuring the amount of moisture in steam if the moisture content of the steam is not too great. This instrument depends for its action upon the fact that steam, nearly dry, becomes superheated when its pressure is reduced by throttling, since slightly wet saturated steam at high pressure contains more heat than at low pressure. A simple type of throttling calorimeter is illustrated in Fig. 7. O is the orifice discharging into the chamber C, into which a thermometer T_2 is inserted. A mercury manometer is attached at V_2.

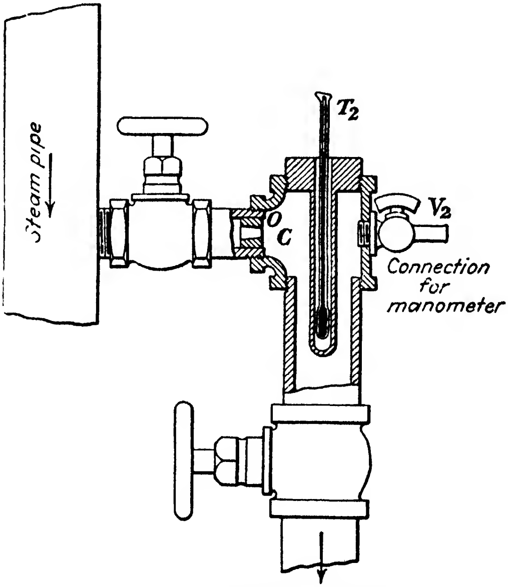

Fig. 7.—Throttling steam calorimeter.

Let P_1 equal the absolute pressure of the steam in the main steam pipe. The enthalpy of 1 lb. steam at the pressure P_1 (h_1) would be the sum of the enthalpy of the liquid (h_{f_1}) and the enthalpy of evaporation (h_{fg_1}) corrected for the moisture, or

$$h_1 = h_{f_1} + xh_{fg_1},$$

where x is the quality of the steam.

If the steam has a pressure P_2, as indicated by the manometer, attached to V_2, after it passes the orifice O, and a temperature t_s, as registered by the thermometer T_2, the enthalpy of 1 lb. of steam at the pressure P_2 would be the enthalpy of dry saturated steam at the lower pressure (h_{g_2}) plus the heat due to the superheat. The heat due to the superheat is calculated by multiplying the degrees of superheat by the specific heat of superheated steam at the given pressure and temperature. The average value of the specific heat of superheated steam C_p at the temperatures and pressures common in calorimeters is about 0.47. The degrees of superheat are determined by subtracting the saturated temperature t_2 corresponding to the lower pressure P_2, as measured by the manometer at V_2, from the temperature t_s, as indicated by the thermometer T_2 of the steam calorimeter. The enthalpy of superheated steam at the lower pressure is

$$h_{g_2} + 0.47(t_s - t_2).$$

Since the heat contained in 1 lb. of the steam in the main steam pipe is the same as that contained in 1 lb. of steam at the calorimeter pressure, or since the enthalpy of the steam is the same on both sides of the calorimeter:

$$h_{f_1} + xh_{fg_1} = h_{g_2} + 0.47(t_s - t_2).$$

Solving for x, the quality of steam is calculated as follows:

$$x = \frac{h_{g_2} + 0.47(t_s - t_2) - h_{f_1}}{h_{fg_1}} \tag{43}$$

Example.—Steam is tested by means of a throttling calorimeter. Find the per cent of moisture in the steam if the gage pressure of the steam in the main steam pipe is 115.3, the pressure in the calorimeter, as indicated by the manometer at V_2 (Fig. 7), 2 in. of mercury, and the temperature of the calorimeter thermometer at T_2 (Fig. 7) 250°F.

Solution.

$P_1 = 115.3 + 14.7 = 130$ lb. per square inch absolute

$P_2 = 14.7 + (2 \times 0.491) = 15.68$ lb. per square inch absolute

$h_{f_1} = 318.81$

$h_{fg_1} = 872.9$

$h_{g_2} = 1151.2$

$t_2 = 215.2$

$t_s = 250.$

Making use of equation (43),

$$x = \frac{1151.2 + 0.47(250 - 215.2) - 318.81}{872.9}$$

$$= 0.97.$$

Percentage of moisture = 100 − 97 = 3.

The throttling calorimeter is unsuitable for measuring the quality of steam which contains more than 3 or 4 per cent moisture.

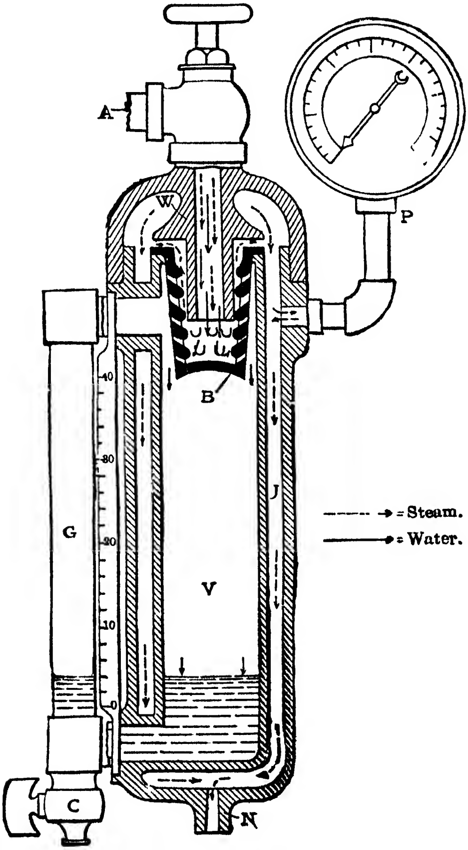

Fig. 8.—Separating calorimeter.

The amount of moisture in very wet steam can best be determined by a separating calorimeter, illustrated in Fig. 8. Steam enters the separating calorimeter at A (Fig. 8), passes down the vertical pipe, plugged at the lower end, from which it escapes through a large number of holes as indicated. The moisture collects at the bottom of the vessel V and can be measured by the calibrated glass gage G. The steam leaves the calorimeter at N and can be collected, condensed, and weighed. The gage P indicates the pressure in the jacket J. This pressure is roughly proportional to the flow of steam through the nozzle N. The gage P is usually provided with a scale to indicate the approximate flow of steam. The percentage of moisture is calculated by dividing the weight of water collected in the gage glass G by the sum of the weights of steam passing out at N and of the water at G.

The electrical calorimeter consists of an electric heater which is used for drying and for superheating the steam. The amount of electrical energy required to dry the steam is proportional to the amount of moisture in the steam.

Superheated Steam.- -Superheated steam has a temperature which is higher than the saturation temperature corresponding to its pressure as taken from the steam tables (Table 7). Thus, if steam at a pressure of 250 lb. per square inch absolute has a temperature of 600°F., the degree of superheat may be found as follows:

The saturation temperature corresponding to 250 lb. is, by Table 7, equal to 400.97°F. Thus, the degree of superheat is

$$600 - 400.95 = 199°\text{F}.$$

In Table 8 are given the properties of superheated steam. At each pressure and at superheated steam temperatures up to 1600°F. values are given for the specific volume (v), enthalpy (h), and entropy (S) of superheated steam. The saturation temperatures are given in parentheses below each pressure.

The following examples will illustrate the use of Table 8.

Example 1.—Calculate the temperature and the specific volume of steam at a pressure of 220 lb. absolute and 200° superheat.

Solution.—Steam at a pressure of 200 lb. absolute and 200° superheat has a temperature of $389.9 + 200 = 589.9$°F., and a specific volume of 2.737 cu. ft.

TABLE 8.—PROPERTIES OF SUPERHEATED STEAM*

Abs. press., lb per sq. in. (sat. temp.)		Temperature-degrees Fahrenheit												
		200°	300°	400°	500°	600°	700°	800°	900°	1000°	1100°	1200°	1400°	1600°
	v	392.6	452.3	512 0	571 6	631.2	690.8	750.4	809.9	869.5	929.1	988.7	1107.8	1227.0
1	h	1150.4	1195 8	1241 7	1288.3	1335.7	1383.8	1432.8	1482.7	1533.5	1585.2	1637.7	1745.7	1857.5
(101 74)	s	2.0512	2.1153	2.1720	2.2233	2.2702	2.3137	2 3542	2 3923	2.4283	2 4625	2.4952	2.5566	2 6137
	v	78.16	90.25	102 26	114 22	126 16	138 10	150 03	161 95	173.87	185.79	197.71	221.6	245 4
5	h	1148.8	1195.0	1241.2	1288 0	1335.4	1383 6	1432.7	1482 6	1533.4	1585 1	1637.7	1745.7	1857 4
(162 24)	s	1 8718	1.9370	1 9942	2.0456	2.0927	2.1361	2 1767	2.2148	2 2509	2.2851	2.3178	2.3792	2 4363
	v	38 85	45.00	51.04	57 05	63.03	69 01	74 98	80.95	86 92	92 88	98 84	110 77	122 69
10	h	1146 6	1193.9	1240 6	1287 5	1335 1	1383 4	1432 5	1482 4	1533.2	1585.0	1637 6	1745 6	1857 3
(193 21)	s	1.7927	1.8595	1.9172	1 9689	2.0160	2 0596	2.1002	2.1383	2.1744	2.2086	2.2413	2.3028	2 3598
	v		30.53	34 68	38 78	42 86	46.94	51.00	55.07	59 13	63.19	67.25	75.37	83 48
14 696	h		1192 8	1239.9	1287 1	1334.8	1383 2	1432 3	1482.3	1533 1	1584 8	1637.5	1745.5	1857 3
(212.00)	s		1 8160	1.8743	1.9261	1.9734	2.0170	2 0576	2.0958	2.1319	2 1662	2.1989	2.2603	2.3174
	v		22 36	25 43	28 46	31 47	34.47	37.46	40 45	43.44	46.42	49 41	55.37	61 34
20	h		1191 6	1239 2	1286 6	1334 4	1382 9	1432 1	1482.1	1533 0	1584.7	1637 4	1745 4	1857 2
(227 96)	s		1.7808	1 8396	1.8918	1.9392	1.9829	2.0235	2 0618	2 0978	2 1321	2.1648	2.2263	2 2834
	v		11 040	12 628	14.168	15.688	17.198	18.702	20.20	21.70	23 20	24 69	27.68	30 66
40	h		1186 8	1236 5	1284 8	1333.1	1381 9	1431.3	1481.4	1532 4	1584 3	1637.0	1745.1	1857 0
(267 25)	s		1 6994	1.7608	1 8140	1.8619	1.9058	1.9467	1.9850	2.0212	2.0555	2 0883	2.1498	2.2069
	v		7 259	8.357	9.403	10 427	11.441	12 449	13 452	14 454	15 453	16.451	18 446	20 44
60	h		1181 6	1233.6	1283 0	1331 8	1380.9	1430.5	1480.8	1531.9	1583 8	1636 6	1744 8	1856 7
(292 71)	s		1 6492	1.7135	1.7678	1.8162	1.8605	1.9015	1.9400	1.9762	2.0106	2.0434	2.1049	2 1621
	v			6 220	7.020	7.797	8.562	9.322	10.077	10.830	11.582	12 332	13 830	15 325
80	h			1230 7	1281 1	1330.5	1379 9	1429.7	1480.1	1531.3	1583 4	1636 2	1744 5	1856 5
(312 03)	s			1.6791	1.7346	1.7836	1.8281	1.8694	1 9079	1 9442	1 9787	2.0115	2.0731	2.1303
	v			4 937	5 589	6 218	6 835	7.446	8 052	8.656	9 259	9 860	11 060	12 258
100	h			1227.6	1279 1	1329.1	1378 9	1428 9	1479 5	1530.8	1582 9	1635 7	1744 2	1856.2
(327 81)	s			1 6518	1.7085	1 7581	1.8029	1.8443	1.8829	1 9193	1.9538	1.9867	2.0484	2 1056
	v			4.081	4 636	5 165	5 683	6 195	6.702	7 207	7.710	8 212	9 214	10.213
120	h			1224.4	1277 2	1327.7	1377 8	1428 1	1478.8	1530.2	1582 4	1635.3	1743.9	1856 0
(341 25)	s			1.6287	1 6869	1 7370	1 7822	1.8237	1.8625	1.8990	1.9335	1.9664	2.0281	2.0854
	v			3 468	3 954	4 413	4 861	5 301	5 738	6 172	6 604	7 035	7 895	8 752
140	h			1221 1	1275 2	1326 4	1376 8	1427 3	1478.2	1529 7	1581 9	1634 9	1743.5	1855 7
(353 02)	s			1 6087	1.6683	1 7190	1.7645	1.8063	1.8451	1.8817	1 9163	1.9493	2.0110	2 0683
	v			3 008	3.443	3 849	4.244	4 631	5.015	5.396	5.775	6 152	6 906	7 656
160	h			1217.6	1273 1	1325 0	1375.7	1426.4	1477.5	1529 1	1581.4	1634.5	1743.2	1855.5
(363 53)	s			1 5908	1 6519	1.7033	1 7491	1.7911	1.8301	1.8667	1.9014	1.9344	1.9962	2 0535
	v			2 649	3 044	3 411	3 764	4.110	4.452	4.792	5 129	5 466	6 136	6 804
180	h			1214 0	1271 0	1323 5	1374.7	1425.6	1476.8	1528 6	1581.0	1634 1	1742.9	1855 2
(373 06)	s			1 5745	1.6373	1 6894	1.7355	1.7776	1.8167	1.8534	1.8882	1.9212	1.9831	2.0404
	v			2.361	2.726	3.060	3.380	3.693	4.002	4 309	4 613	4.917	5 521	6.123
200	h			1210 3	1268.9	1322.1	1373.6	1424.8	1476 2	1528.0	1580 5	1633.7	1742.6	1855 0
(381.79)	s			1 5594	1.6240	1.6767	1.7232	1.7655	1.8048	1.8415	1.8763	1.9094	1.9713	2.0287
	v			2.125	2.465	2.772	3 066	3 352	3.634	3.913	4.191	4.467	5 017	5 565
220	h			1206.5	1266.7	1320.7	1372.6	1424.0	1475.5	1527.5	1580 0	1633.3	1742.3	1854.7
(389.86)	s			1.5453	1.6117	1.6652	1.7120	1.7545	1.7939	1.8308	1.8656	1.8987	1.9607	2.0181
	v			1 9276	2.247	2.533	2 804	3.068	3.327	3.584	3.839	4.093	4.597	5.100
240	h			1202.5	1264.5	1319.2	1371.5	1423.2	1474 8	1526.9	1579.6	1632.9	1742.0	1854 5
(397.37)	s			1.5319	1.6003	1.6546	1 7017	1.7444	1.7839	1.8209	1.8558	1.8889	1.9510	2 0084
	v				2.063	2.330	2 582	2.827	3.067	3.305	3.541	3 776	4.242	4 707
260	h				1262.3	1317.7	1370 4	1422.3	1474.2	1526.3	1579.1	1632.5	1741.7	1854 2
(404.42)	s				1.5897	1.6447	1.6922	1.7352	1.7748	1.8118	1.8467	1.8799	1.9420	1.9995

TABLE 8.—PROPERTIES OF SUPERHEATED STEAM.*—(*Continued*)

Abs. press., lb. per sq. in. (sat. temp.)		Temperature-degrees Fahrenheit												
		200°	300°	400°	500°	600°	700°	800°	900°	1000°	1100°	1200°	1400°	1600°
	v				1.9047	2.156	2.392	2.621	2.845	3.066	3.286	3.504	3.938	4.370
280	*h*				1260.0	1316.2	1369.4	1421.5	1473.5	1525.8	1578.6	1632.1	1741.4	1854.0
(411.05)	*s*				1.5796	1.6354	1.6834	1.7265	1.7662	1.8033	1.8383	1.8716	1.9337	1.9912
	v				1.7675	2.005	2.227	2.442	2.652	2.859	3.065	3.269	3.674	4.078
300	*h*				1257.6	1314.7	1368.3	1420.6	1472.8	1525.2	1578.1	1631.7	1741.0	1853.7
(417.33)	*s*				1.5701	1.6268	1.6751	1.7184	1.7582	1.7954	1.8305	1.8638	1.9260	1.9835
	v				1.4923	1.7036	1.8980	2.084	2.266	2.445	2.622	2.798	3.147	3.493
350	*h*				1251.5	1310.9	1365.5	1418.5	1471.1	1523.8	1577.0	1630.7	1740.3	1853.1
(431.72)	*s*				1.5481	1.6070	1.6563	1.7002	1.7403	1.7777	1.8130	1.8463	1.9086	1.9663
	v				1.2851	1.4770	1.6508	1.8161	1.9767	2.134	2.290	2.445	2.751	3.055
400	*h*				1245.1	1306.9	1362.7	1416.4	1469.4	1522.4	1575.8	1629.6	1739.5	1852.5
(444.59)	*s*				1.5281	1.5894	1.6398	1.6842	1.7247	1.7623	1.7977	1.8311	1.8936	1.9513

		500°	550°	600°	620°	640°	660°	680°	700°	800°	900°	1000°	1200°	1400°	1600°
	v	1.1231	1.2155	1.3005	1.3332	1.3652	1.3967	1.4278	1.4584	1.6074	1.7516	1.8928	2.170	2.443	2.714
450	*h*	1238.4	1272.0	1302.8	1314.6	1326.2	1337.5	1348.8	1359.9	1414.3	1467.7	1521.0	1628.6	1738.7	1851.9
(456.28)	*s*	1.5095	1.5437	1.5735	1.5845	1.5951	1.6054	1.6153	1.6250	1.6699	1.7108	1.7486	1.8177	1.8803	1.9381
	v	0.9927	1.0800	1.1591	1.1893	1.2188	1.2478	1.2763	1.3044	1.4405	1.5715	1.6996	1.9504	2.197	2.442
500	*h*	1231.3	1266.8	1298.6	1310.7	1322.6	1334.2	1345.7	1357.0	1412.1	1466.0	1519.6	1627.6	1737.9	1851.3
(467.01)	*s*	1.4919	1.5280	1.5588	1.5701	1.5810	1.5915	1.6016	1.6115	1.6571	1.6982	1.7363	1.8056	1.8683	1.9262
	v	0.8852	0.9686	1.0431	1.0714	1.0989	1.1259	1.1523	1.1783	1.3038	1.4241	1.5414	1.7706	1.9957	2.219
550	*h*	1223.7	1261.2	1294.3	1306.8	1318.9	1330.8	1342.5	1354.0	1409.9	1464.3	1518.2	1626.6	1737.1	1850.6
(476.94)	*s*	1.4751	1.5131	1.5451	1.5568	1.5680	1.5787	1.5890	1.5991	1.6452	1.6868	1.7250	1.7946	1.8575	1.9155
	v	0.7947	0.8753	0.9463	0.9729	0.9988	1.0241	1.0489	1.0732	1.1899	1.3013	1.4096	1.6208	1.8279	2.033
600	*h*	1215.7	1255.5	1289.9	1302.7	1315.2	1327.4	1339.3	1351.1	1407.7	1462.5	1516.7	1625.5	1736.3	1850.0
(486.21)	*s*	1.4586	1.4990	1.5323	1.5443	1.5558	1.5667	1.5773	1.5875	1.6343	1.6762	1.7147	1.7846	1.8476	1.9056
	v		0.7277	0.7934	0.8177	0.8411	0.8639	0.8860	0.9077	1.0108	1.1082	1.2024	1.3853	1.5641	1.7405
700	*h*		1243.2	1280.6	1294.3	1307.5	1320.3	1332.8	1345.0	1403.2	1459.0	1513.9	1623.5	1734.8	1848.8
(503.10)	*s*		1.4722	1.5084	1.5212	1.5333	1.5449	1.5559	1.5665	1.6147	1.6573	1.6963	1.7666	1.8299	1.8881
	v		0.6154	0.6779	0.7006	0.7223	0.7433	0.7635	0.7833	0.8763	0.9633	1.0470	1.2088	1.3662	1.5214
800	*h*		1229.8	1270.7	1285.4	1299.4	1312.9	1325.9	1338.6	1398.6	1455.4	1511.0	1621.4	1733.2	1847.5
(518.23)	*s*		1.4467	1.4863	1.5000	1.5129	1.5250	1.5366	1.5476	1.5972	1.6407	1.6801	1.7510	1.8146	1.8729
	v		0.5264	0.5873	0.6089	0.6294	0.6491	0.6680	0.6863	0.7716	0.8506	0.9262	1.0714	1.2124	1.3509
900	*h*		1215.0	1260.1	1275.9	1290.9	1305.1	1318.8	1332.1	1393.9	1451.8	1508.1	1619.3	1731.6	1846.3
(531.98)	*s*		1.4216	1.4653	1.4800	1.4938	1.5066	1.5187	1.5303	1.5814	1.6257	1.6656	1.7371	1.8009	1.8595
	v		0.4533	0.5140	0.5350	0.5546	0.5733	0.5912	0.6084	0.6878	0.7604	0.8294	0.9615	1.0893	1.2146
1000	*h*		1198.3	1248.8	1265.9	1281.9	1297.0	1311.4	1325.3	1389.2	1448.2	1505.1	1617.3	1730.0	1845.0
(544.61)	*s*		1.3961	1.4450	1.4610	1.4757	1.4893	1.5021	1.5141	1.5670	1.6121	1.6525	1.7245	1.7886	1.8474
	v			0.4532	0.4738	0.4929	0.5110	0.5281	0.5445	0.6191	0.6866	0.7503	0.8716	0.9885	1.1031
1100	*h*			1236.7	1255.3	1272.4	1288.5	1303.7	1318.3	1384.3	1444.5	1502.2	1615.2	1728.4	1843.8
(556.31)	*s*			1.4251	1.4425	1.4583	1.4728	1.4862	1.4989	1.5535	1.5995	1.6405	1.7130	1.7775	1.8363
	v			0.4016	0.4222	0.4410	0.4586	0.4752	0.4909	0.5617	0.6250	0.6843	0.7967	0.9046	1.0101
1200	*h*			1223.5	1243.9	1262.4	1279.6	1295.7	1311.0	1379.3	1440.7	1499.2	1613.1	1726.9	1842.5
(567.22)	*s*			1.4052	1.4243	1.4413	1.4568	1.4710	1.4843	1.5409	1.5879	1.6293	1.7025	1.7672	1.8263
	v			0.3174	0.3390	0.3580	0.3753	0.3912	0.4062	0.4714	0.5281	0.5805	0.6789	0.7727	0.8640
1400	*h*			1193.0	1218.4	1240.4	1260.3	1278.5	1295.5	1369.1	1433.1	1493.2	1608.9	1723.7	1840.0
(587.10)	*s*			1.3639	1.3877	1.4079	1.4258	1.4419	1.4567	1.5177	1.5666	1.6093	1.6836	1.7489	1.8083

TABLE 8.—PROPERTIES OF SUPERHEATED STEAM.*—(*Continued*)

Abs. press., lb. per sq. in. (sat. temp)		Temperature-degrees Fahrenheit													
		500°	550°	600°	620°	640°	660°	680°	700°	800°	900°	1000°	1200°	1400°	1600°
	v				0.2733	0.2936	0.3112	0.3271	0.3417	0.4034	0.4553	0.5027	0.5906	0.6738	0.7545
1600	*h*				1187.8	1215.2	1238.7	1259.6	1278.7	1358.4	1425.3	1487.0	1604.6	1720.5	1837.5
(604.90)	*s*				1.3489	1.3741	1.3952	1.4137	1.4303	1.4964	1.5476	1.5914	1.6669	1.7328	1.7926
	v					0.2407	0.2597	0.2760	0.2907	0.3502	0.3986	0.4421	0.5218	0.5968	0.6693
1800	*h*					1185.1	1214.0	1238.5	1260.3	1347.2	1417.4	1480.8	1600.4	1717.3	1835.0
(621.03)	*s*					1.3377	1.3638	1.3855	1.4044	1.4765	1.5301	1.5752	1.6520	1.7185	1.7786
	v					0.1936	0.2161	0.2337	0.2489	0.3074	0.3532	0.3935	0.4668	0.5352	0.6011
2000	*h*					1145.6	1184.9	1214.8	1240.0	1335.5	1409.2	1474.5	1596.1	1714.1	1832.5
(635.82)	*s*					1.2945	1.3300	1.3564	1.3783	1.4576	1.5139	1.5603	1.6384	1.7055	1.7660
	v							0.1484	0.1686	0.2294	0.2710	0.3061	0.3678	0.4244	0.4784
2500	*h*							1132.3	1176.8	1303.6	1387.8	1458.4	1585.3	1706.1	1826.2
(668.13)	*s*							1.2687	1.3073	1.4127	1.4772	1.5273	1.6088	1.6775	1.7389
	v								0.0984	0.1760	0.2159	0.2476	0.3018	0.3505	0.3966
3000	*h*								1060.7	1267.2	1365.0	1441.8	1574.3	1698.0	1819.9
(695.36)	*s*								1.1966	1.3690	1.4439	1.4984	1.5837	1.6540	1.7163
	v									0.1583	0.1981	0.2288	0.2806	0.3267	0.3703
3206.2	*h*									1250.5	1355.2	1434.7	1569.8	1694.6	1817.2
(705.40)	*s*									1.3508	1.4309	1.4874	1.5742	1.6452	1.7080
	v								0.0306	0.1364	0.1762	0.2058	0.2546	0.2977	0.3381
3500	*h*								780.5	1224.9	1340.7	1424.5	1563.3	1689.8	1813.6
	s								0.9515	1.3241	1.4127	1.4723	1.5615	1.6336	1.6968
	v								0.0287	0.1052	0.1462	0.1743	0.2192	0.2581	0.2943
4000	*h*								763.8	1174.8	1314.4	1406.8	1552.1	1681.7	1807.2
	s								0.9347	1.2757	1.3827	1.4482	1.5417	1.6154	1.6795
	v								0.0276	0.0798	0.1226	0.1500	0.1917	0.2273	0.2602
4500	*h*								753.5	1113.9	1286.5	1388.4	1540.8	1673.5	1800.9
	s								0.9235	1.2204	1.3529	1.4253	1.5235	1.5990	1.6640
	v								0.0268	0.0593	0.1036	0.1303	0.1696	0.2027	0.2329
5000	*h*								746.4	1047.1	1256.5	1369.5	1529.5	1665.3	1794.5
	s								0.9152	1.1622	1.3231	1.4034	1.5066	1.5839	1.6499
	v								0.0262	0.0463	0.0880	0.1143	0.1516	0.1825	0.2106
5500	*h*								741.3	985.0	1224.1	1349.3	1518.2	1657.0	1788.1
	s								0.9090	1.1093	1.2930	1.3821	1.4908	1.5699	1.6369

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* Abridged from "Thermodynamic Properties of Steam," by Joseph H. Keenan and Frederick G. Keyes, John Wiley & Sons, Inc., New York.

Example 2.—Calculate the enthalpy and entropy at the conditions in Example 1.

Solution.—Enthalpy (h) = 1314.0.
Entropy (S) = 1.6590.

Thermodynamic Processes for Vapors.—Vapors undergo pressure, volume, temperature, and entropy changes. These changes may be studied graphically by means of pressure-volume P-V, entropy-temperature T-S, and entropy-total-heat, H-S diagrams.

An entropy-temperature diagram for steam is illustrated in Fig. 9. For convenience 32°F. or 492°F. absolute has been adopted as the point of zero entropy. The water line represents the relation between the entropy and temperature of the liquid state, the dry steam or saturation line representing the same relation for dry saturated steam. The temperature at which the two lines intersect is called the critical temperature and in the case of steam occurs at about 706.1°F. or 1166°F. absolute. The critical temperature is a condition where water is changed to steam without the addition of enthalpy of evaporation.

The shaded areas in Fig. 9 represent the enthalpy of saturated steam (h_g in Table 6). The area *ABCD* is the enthalpy of the liquid (h_f). The area *DCEF* is the enthalpy of evaporation (h_{fg}).

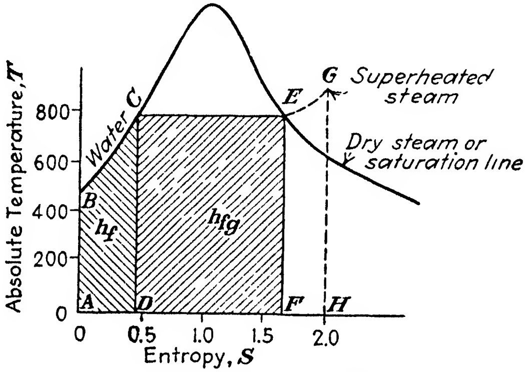

Fig. 9.—Temperature-entropy diagram of steam.

The entropy-enthalpy diagram, called the *Mollier chart*, is given in Fig. 10. In this chart the ordinates represent the enthalpy of steam above 32°F. and the abscissas the entropy. The saturation curve marks the boundary between the superheated and saturated regions. In the region of wet steam lines of constant quality and pressure are drawn. In the superheated region lines of equal superheats appear. In both the saturated and superheated regions, lines of constant pressure are drawn and the absolute pressure in pounds per square inch of the various curves are labeled.

To illustrate the use of the Mollier diagram,* calculate the enthalpy of 1 lb. of dry steam at a pressure of 150 lb. per square

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* For accurate results use should be made of an enlarged Mollier diagram similar to those which are found in connection with Keenan and Keyes' steam tables.

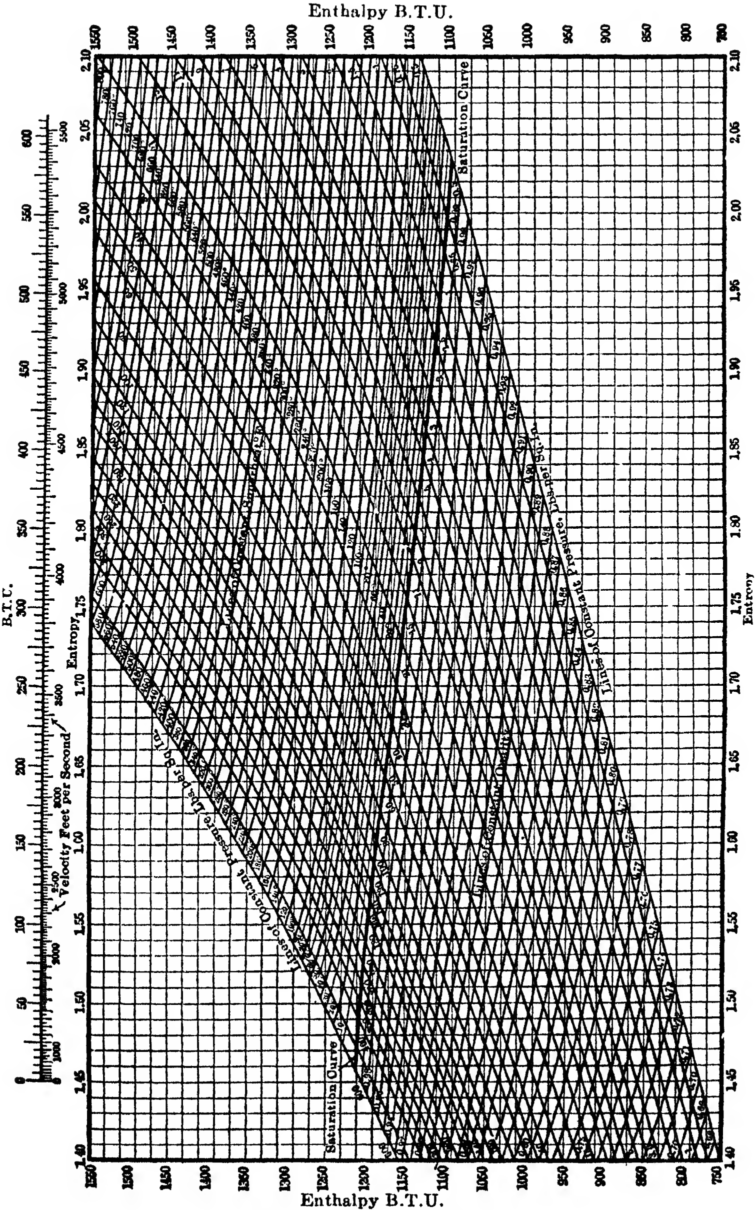


FIG. 10.—Mollier chart.

inch absolute. This is found to be 1,195 as compared with 1,194.1 as given in Table 7.

If the steam in the above problem has a temperature of 500°F., the enthalpy by the chart is 1,275 as compared with 1274.1 as given in Table 8.

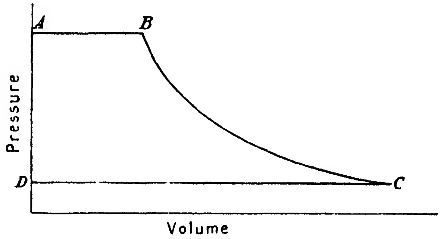


Fig. 11.—Pressure-volume diagram of Rankine cycle.

The Mollier chart (Fig. 10) is particularly useful for obtaining the approximate enthalpy of a vapor if its pressure and quality are known.

The Rankine Steam Cycle.—This cycle is the standard for comparing steam power plant economies. It is illustrated on pressure-volume P-V and temperature-entropy TS diagrams in Figs. 11 and 12.

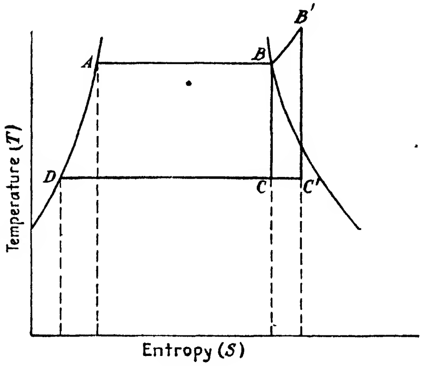


Fig. 12.—Temperature-entropy diagram of Rankine cycle.

In this cycle, steam is admitted at constant pressure (AB) and is expanded adiabatically (BC) to the exhaust pressure. It is then exhausted at constant pressure (CD). In this cycle, it is assumed that the prime mover has no losses due to radiation, conduction, throttling, clearance, or friction. In the ideal Rankine cycle the working substance is restored to the initial condition by raising the feed water from the temperature of the engine exhaust to the temperature of the admission steam.

If the steam is initially superheated, the point B on the entropy-temperature diagram (Fig. 12) is changed to B' and C to C'.

Problems pertaining to the Rankine cycle may best be solved by the use of steam tables (Tables 6 and 7) or by means of the Mollier chart (Fig. 10).

As an Illustration.—If a steam plant operates non-condensing between a pressure of 200 lb. per square inch absolute and a temperature of 600°F. the net work AW of the cycle is by the Mollier diagram

$$AW = 1321 - 1094 = 227 \text{ B.t.u.}$$

The efficiency of the Rankine cycle is calculated by dividing the heat converted into work AW by the heat supplied above the feed-water temperature, or

$$e = \frac{AW}{h_1 - h_f}. \tag{44}$$

In the formula (44) h_1 is the enthalpy of a pound of steam (at admission conditions), as found from the steam tables or the Mollier chart, h_f is the enthalpy corresponding to the feed-water temperature (at exhaust conditions).

In the above problem,

$$= \frac{227}{1321 - 180.1} = 19.9 \text{ per cent.}$$

Problems

1. A boiler generates steam at a pressure of 120 lb. by the gage. If the barometric pressure is 28.5 in., calculate the absolute pressure in pounds per square inch.
2. Calculate the heat required to change 20 lb. of water at a temperature of 190°F. into dry steam at 150 lb. per square inch absolute.
3. If the steam in Problem 2 contains 5 per cent moisture, calculate the heat required.
4. Compare the volumes of 1 lb. of dry steam at the following pressures in pounds per square inch absolute: ½, 1, 2, 14.7, 100, 150, 200, 300.

5. A plain cylindrical boiler has a diameter of 30 in. and a length of 12 ft. If two-thirds of the volume of the boiler is filled with water at a temperature of 270°F., the other third with dry and saturated steam, calculate:

(*a*) Boiler pressure in pounds per square inch gage if the barometer is 29.2 in.

(*b*) The weight of the water and the weight of the steam contained in the boiler.

6. The quality of steam at a pressure of 140 lb. per square inch gage is measured by means of a throttling calorimeter. If the calorimeter thermometer reads 270°F. and the manometer registers 3 in. of mercury calculate the quality of the steam.

7. Prove that the throttling calorimeter will be unsuitable for measuring the quality of steam which has 10 per cent moisture at a steam pressure of 150 lb. per square inch gage.

8. Steam is tested by means of a separating calorimeter (Fig. 8) and gives the following results:

Water collected in the glass gage *G*................	0.25 lb.
Steam collected at *N*..........	0.90 lb.

Calculate the quality of the steam.

9. A boiler generates steam at a pressure of 150 lb. per square inch absolute from a feed-water temperature of 70°F.

(*a*) How many B.t.u. of heat are required to evaporate 1 lb. of the water into steam 3 per cent wet?

(*b*) If the feed-water temperature was raised by waste heat to 200°F. what would be the percentage of heat saved?

10. A boiler evaporates 10,000 lb. of water per hour from a feed-water temperature of 200°F., into steam at 175 lb. per square inch absolute and 150° superheat.

(*a*) How many B.t.u. of heat must be supplied per hour?

(*b*) If the fuel used in this boiler contains 12,000 B.t.u. per pound and all of this heat is absorbed by the water, how many pounds of water will be evaporated into steam per pound of fuel?

11. Calculate the size of a pipe which will deliver 10,000 lb. of steam per hour. The steam has a pressure of 165 lb. per square inch absolute and 98 per cent quality. If the maximum velocity of steam is to be 6,000 ft. per minute, what will be the inside diameter of the pipe?

12. Prepare charts to show the following:

(*a*) Variation in the temperature of saturated steam with a change in pressure.

(*b*) Variation in the enthalpy of evaporation of steam with a change in pressure.

(*c*) Variation in the volume of dry saturated steam with a change in pressure.

13. One pound of steam at 300 lb. per square inch absolute expands adiabatically to a back pressure of 1 lb. absolute. If the steam is initially superheated 150°F. and using the Mollier chart (Fig. 10) calculate:
  (*a*) Final condition of the steam.
  (*b*) The heat made available for work.

14. If the steam in Problem 13 is initially 3 per cent wet, what is the final condition of the steam and the resulting velocity?

15. Calculate the efficiency of a Rankine cycle operating under the conditions stated in Problem 14.

16. Calculate the Rankine cycle efficiency for the conditions in Problem 13.

CHAPTER V

BOILERS

The function of a boiler is to generate steam to be used either in engine cylinders, or for heating purposes. The term boiler is commonly applied to the combination of the furnace in which the fuel is burned and the boiler proper, which is a closed vessel containing water and steam.

Classification of Boilers.—Boilers are divided into two classes, the fire tube and the water tube. In the fire-tube boiler (Fig. 13) the hot gases developed by the combustion of the fuel pass through the tubes, while in the water-tube boiler (Fig. 20) these gases pass around the tubes. Either type may be constructed as a vertical or as a horizontal boiler, depending on whether the axis of the shell is vertical or horizontal.

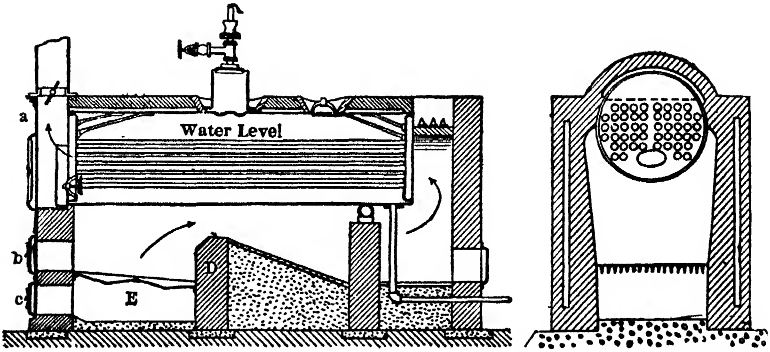


Fig. 13.—Return tubular boiler and setting.

The fire-tube boiler may be externally or internally fired. In the externally fired boiler (Fig. 14) the furnace is in the brick setting entirely outside of the boiler shell, while in the internally fired types (Figs. 16 and 17) the furnace is in the boiler shell, no brick setting being necessary. For stationary work the externally fired boiler is the more common, while the internally fired types are always used for locomotive and traction engine purposes, and generally for small marine power plants. Vertical fire-tube boilers are usually internally fired.

(Boilers are also classified as to their use.) Locomotive, stationary, marine, and portable boilers are some of the classifications used.

Horizontal Return Tubular Boiler.—Boilers of this type are popular in this country and are extensively used for pressures below 125 lb. per square inch They are simple, inexpensive, have a large overload capacity, and are economical when properly handled. The general appearance of a return tubular boiler is shown in Fig. 13. Figure 14 illustrates the details of the setting.

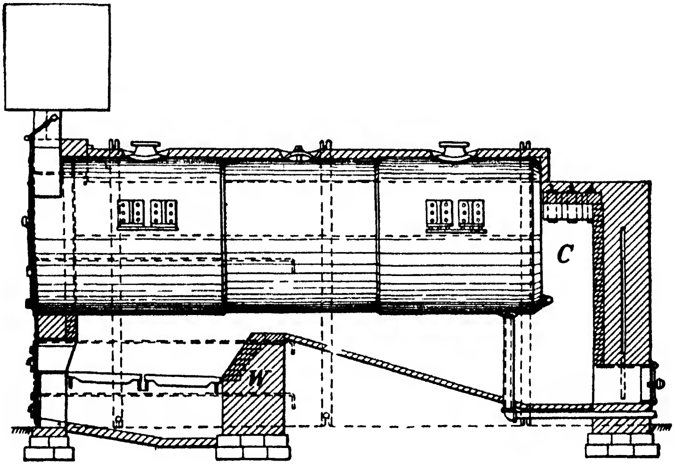


FIG. 14.—Details of horizontal return tubular boiler setting.

These boilers consist of a cylindrical shell closed at the ends by two flat heads, and of numerous small fire tubes which extend the whole length of the shell. The fire tubes are 3 or 4 in. in diameter and 14 to 18 ft. long. About two-thirds of the volume of the shell is filled with water, the other third, called the steam space, being left for the disengagement of the steam from the water. The water line is about 6 in. above the top row of fire tubes.

The coal is burned upon the grates which, as shown in Fig. 14, rest upon the bridge wall *W* and upon the front of the setting.

The hot gases, formed by the combustion of the fuel, pass from the furnace under and along the boiler shell to the back connection, or combustion chamber *C*, from there to the front through the tubes, and up the uptake to the breeching or flue, which leads to the chimney.

The distance between the grates and the boiler shell should be greater for bituminous than for anthracite coal, on account of the volatile content of such coals. This distance in the case of the best anthracite coal, may be as little as 24 in., but for bituminous coal the distance between the grates and the boiler should be approximately equal to the diameter of the boiler shell. The greater this distance the more opportunity will be given for the proper combustion of the fuel.

This type of boiler is usually provided with a handhole or a manhole in front below the tubes, and with a manhole in the top of the boiler.

The flat heads, or tube sheets of the boiler, are stayed below the water line by the tubes. Above the water line special stays must be provided to prevent the tube sheets from distorting. In Fig. 13, the distortion of the tube sheet above the tubes is prevented by the use of diagonal stays which transfer the strain to the shell of the boiler.

Boilers of this type are usually set in brick settings. In some cases the boiler is supported by brackets, as shown in Fig. 14. In this case the front brackets rest on metal plates embedded in the brickwork of the side walls, while the back brackets are placed on rollers, which in turn rest on horizontal plates, this method allowing the back of the boiler to move as the shell expands or contracts. A better method is to support the boiler independent of the setting, on steel framework, as shown in Fig. 15.

The setting should be constructed so that the hot gases will not come in contact with the shell above the water line.

Scotch Marine Boiler.—A single-ended, two-furnace Scotch marine boiler is shown in Fig. 16. This boiler differs from those previously described in that it is internally fired. The boiler consists of a cylindrical shell enclosed at its two ends by flat plates. The furnace flues are connected to a combustion chamber. Numerous fire tubes fill the upper portion of the boiler. The travel of gases is first through the furnace flues, then to the combustion chamber, and finally through the tubes to the uptake and stack.

Boilers of this type are self-contained, require little overhead room, and no setting. The rear surface of the combustion chamber is stayed by connecting it to the rear head by means of short bolts, termed stay bolts. The front surface of the combustion chamber is stayed by the furnace flues and the tubes, while the top of the chamber is supported by a bar which transmits the strain to the two side sheets and is termed a girder stay. The heads of the boiler above the tubes are supported by through stays, which are rods connecting both heads as shown. Large boilers of this type are provided with furnaces at both ends which open into a common combustion chamber in the middle of the boiler.

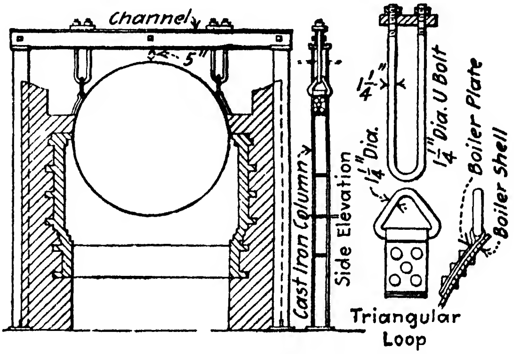


FIG. 15.—Independent method of setting boiler.

Locomotive Boiler.—Figure 17 illustrates a locomotive boiler. A type similar to the one shown is used to some extent in stationary work. The stationary type, however, is made only in comparatively small sizes and finds its application only in isolated locations, or where steam is required temporarily. The type used in locomotive practice as well as that used in stationary work is classified as a fire-tube, internally fired boiler.

The locomotive boiler consists of a cylindrical-shaped barrel or shell which contains a large number of fire tubes. The furnace or fire box is constructed by extending the shell downward to form the sides. The walls of the fire box are made double, the space thus created being connected to the water space in the shell.

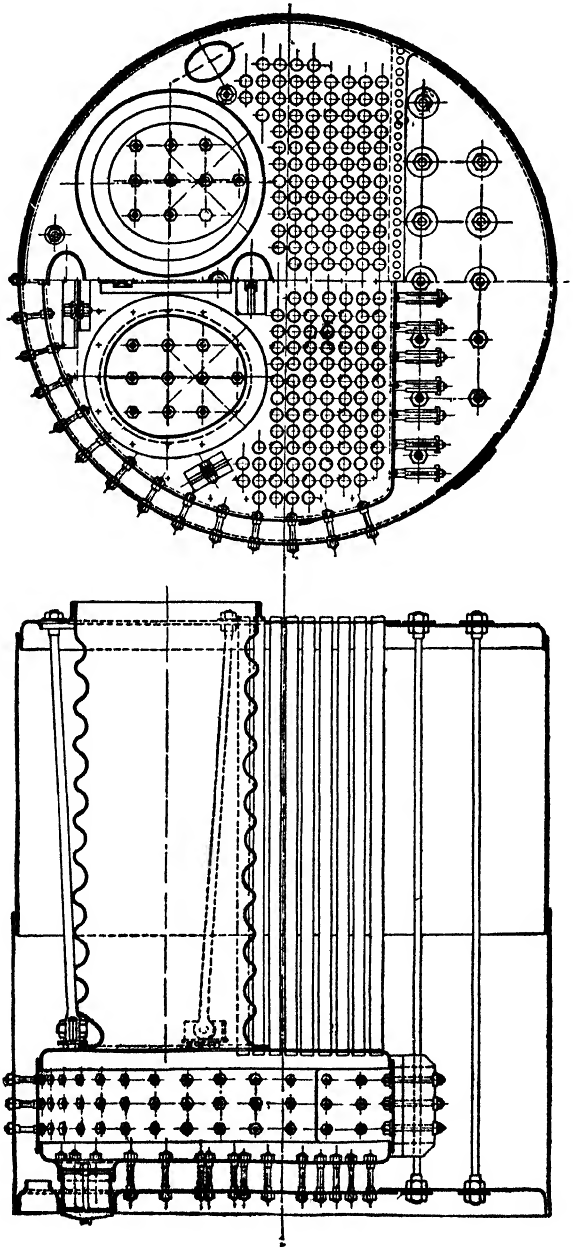


FIG. 16 —Scotch marine boiler.

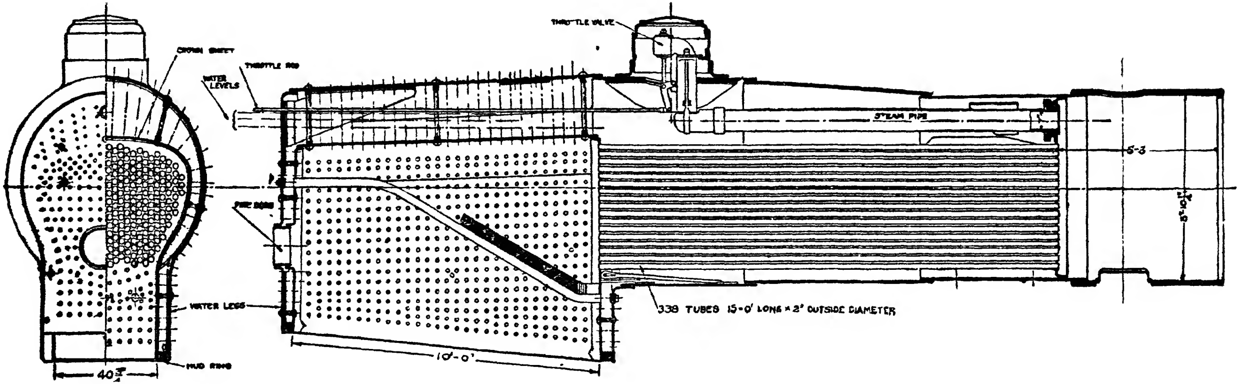


FIG. 17.—Locomotive boiler.

This extension of the plates to form the sides of the fire box produces two narrow sections which are filled with water, forming what is usually termed a water leg. These boilers are constructed with a steam dome from which the steam is taken.

The hot gases leave the furnace, pass through the small tubes to the smoke box at the front of the boiler, and from there to the stack.

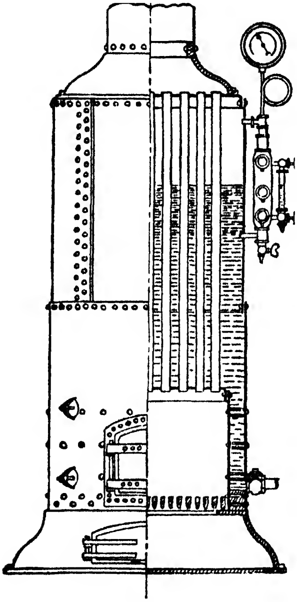


FIG. 18.—Vertical boiler exposed tube type.

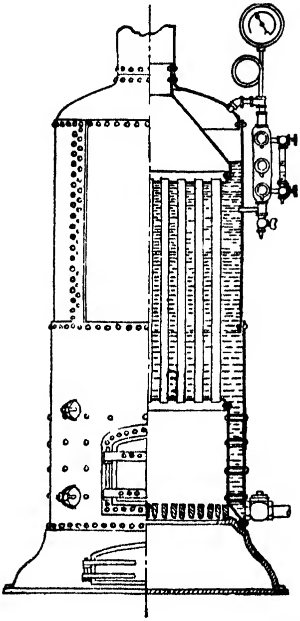


FIG. 19 Vertical boiler submerged tube type.

The flat sheets composing the water legs are stayed by the use of small stay bolts. The same method of staying is applied to the sheet forming the top of the fire box, but in this case the name "crown stays" is usually applied.

Vertical Fire-tube Boilers.—Two forms of vertical boilers are shown in Figs. 18 and 19. In the type shown in Fig. 19 the tops of the tubes are ended in a submerged tube sheet, which is kept below the water line.

The essential parts of all forms of vertical boilers are a cylindrical shell with a fire box and ash pit in the lower end. The tubes lead directly from the furnace to the upper head of the shell. The hot gases from the furnace pass through the tubes and out of the stack.

Vertical boilers occupy little floor space, require no setting except a light foundation, and are inexpensive. To offset these advantages, vertical boilers, as ordinarily constructed, are uneconomical, have small capacity, have too little space for the disengagement of the steam, and are inaccessible for thorough inspection and cleaning.

Water-tube Boilers.—Water-tube boilers are used in large power plants on account of their adaptability to higher steam pressures and larger sizes, decreased danger from serious explosions, greater space economy, and rapidity of steam generation. For small power plants and for steam pressures of 125 lb. or less the fire-tube boiler is usually used on account of its lower first cost. Also in a fire-tube boiler, if a tube should burst, the boiler can be repaired by plugging without seriously interrupting service, which is not the case with most types of water-tube boilers. Numerous tests show that either type, when properly designed and operated, will give good economy.

There are many different types of water-tube boilers, but the essential parts of all are much the same. They consist of numerous tubes filled with water, and one or more drums for the disengagement of the steam from the water. No tubes run through the drums, consequently dished heads may be used, thus eliminating the necessity for staying.

Figure 20 shows the Babcock and Wilcox sectional header type of water-tube boiler unit including boiler, superheater, economizer, and air heater with Bailey slag-tap furnace, fired by pulverized coal. The equipment other than the boiler is described in Chap. VI. The boiler (Fig. 20) consists of a number of straight tubes fastened into several sets of headers which are connected to a common drum. Opposite the end of each tube there is provided a handhole through which the tubes may be inspected or cleaned. The hot gases from the furnace are deflected by means of fire-brick baffle plates and the bridge wall and pass across the tubes three times before reaching the uptake at the rear of the boiler. In some cases the baffling is arranged so that the gases are directed along the tubes. The boiler is supported by steel beams resting on columns independent of the setting

The tubes are usually 4 in in diameter and 18 ft in length They are inclined at an angle of about 22° with the horizontal The number of tubes varies with the size of the boiler

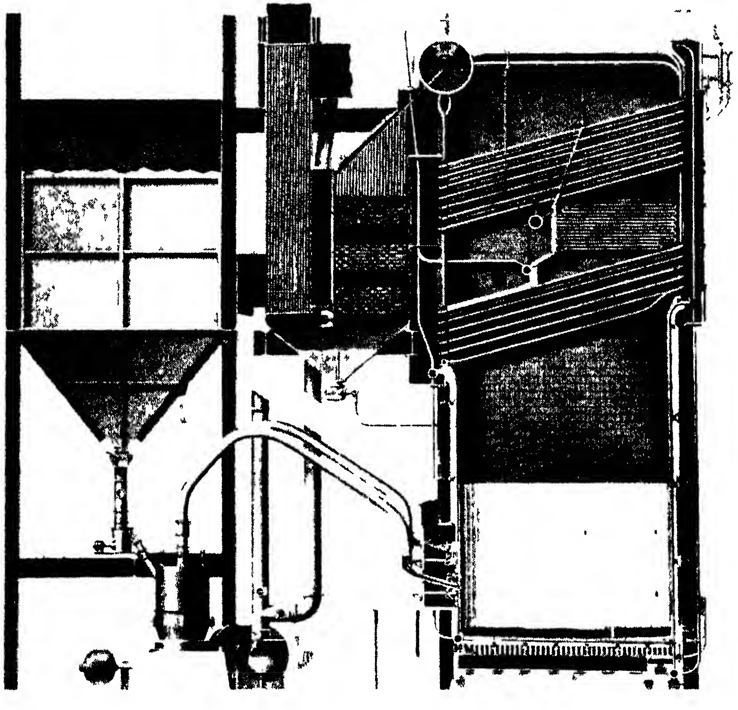


Fig 20 —Complete Babcock and Wilcox boiler unit

The Heine box-header type boiler is illustrated in Fig 21 It consists of a number of straight tubes, expanded into two water legs or headers of flanged steel plate, which are connected to drums. The tubes are parallel to the drums. Opposite the end of each tube is a handhole to facilitate cleaning and inspection. The feed water enters the boiler through the top of the drums, passes into small mud drums, where the impurities are deposited, circulates from the front toward the back in the drum, and from the back toward the front in the tubes. The baffle plates in this type of boiler are usually arranged horizontally so that the hot gases pass first to the rear of the boiler, then back through the nest of tubes to the front, and finally back to the stack, coming in contact with the drum of the boiler in this last pass This boiler is supported independently of the setting at the front end, while the rear water leg rests upon a roller support

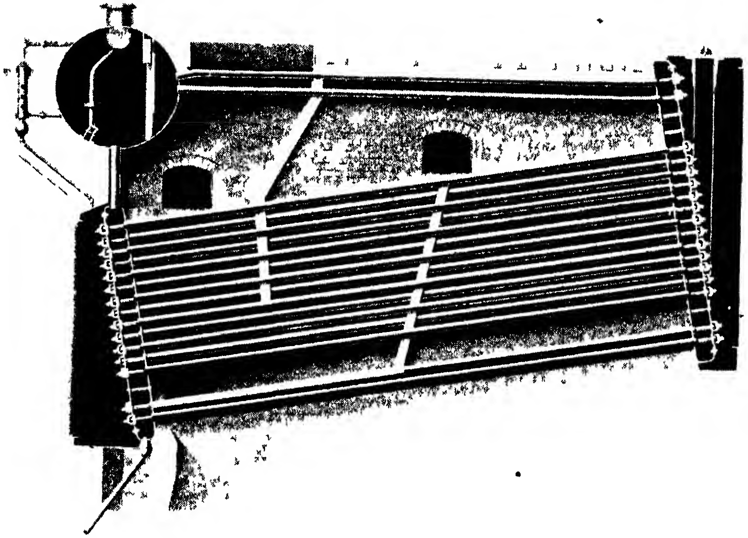


FIG 21 —Heine type cross-drum boiler (*Combustion Engineering Co Inc*)

Figure 22 shows a sectional elevation of the Babcock and Wilcox Stirling type water-tube boiler equipped with a superheater and oil burner This boiler consists of four horizontal cylindrical drums, three at ~~the top~~ and one large drum at the bottom A series ~~of in~~clined water tubes connect the upper drums with ~~the~~ lower. Tubes are used to connect the steam spaces ~~of th~~e upper drums so that any steam formed in these may be transmitted to the middle drum Similarly, a series of tubes connects the front and middle drums below the water line Such a connection limits the main circulation within the boilers to the front and middle bank of tubes.

The feed water enters the rear upper drum, which is the cooler part of the boiler, flows downward through the rear bank of tubes to the bottom drum, upward through the front bank of tubes, and downward through the middle bank. The rear system of tubes acts as a feed-water heater The steam formed during the passage upward through the front tubes becomes separated from the water in the front drum and passes into the rear drum, which is connected with the steam main. The safety valve is located on the top of the rear drum.

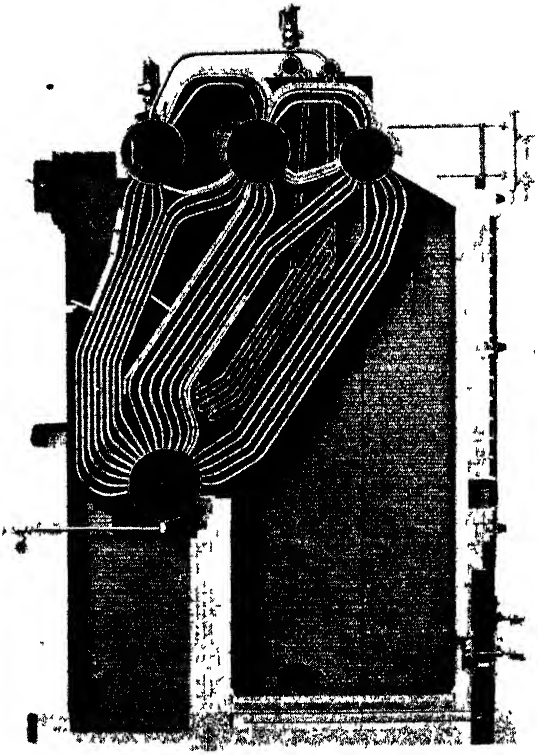


FIG. 22.—Stirling type boiler (*Babcock & Wilcox Co.*)

The baffle walls are set so that the hot gases from the furnace pass over the bridge wall, and thence upward through the first bank of tubes. The gases then pass downward through the second set of tubes, and finally upward through the remaining set to the stack. Thus the water and hot gases circulate in opposite directions in the rear set of tubes

The boiler is supported on a structural steel framework independent of the setting The drums can be easily cleaned through manholes located at the ends.

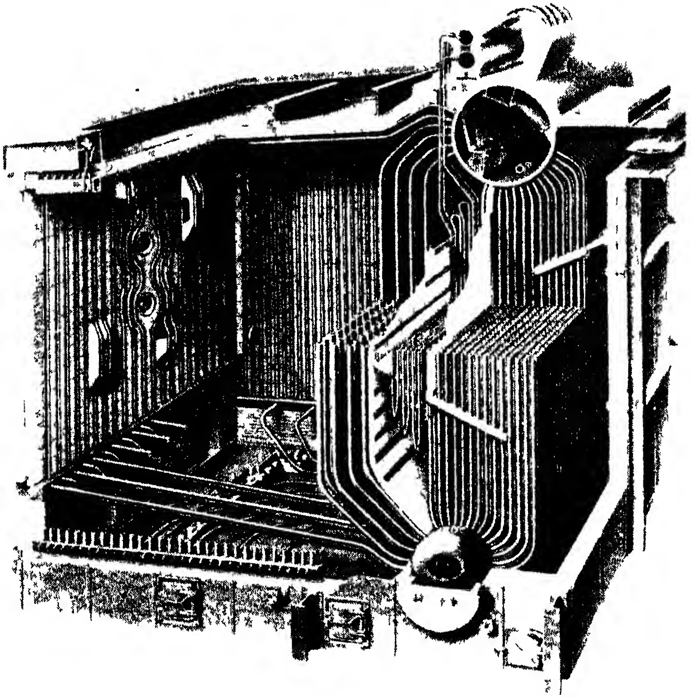


FIG 23 – Two-drum steam generator (*Combustion Engineering Co., Inc.*)

Figure 23 illustrates a two-drum water-tube boiler of the Combustion Engineering Co. V.U. type, built in sizes ranging from 20,000 to 250,000 lb. of steam per hour.

Marine Water-tube Boilers.—The service to which a boiler is to be applied modifies its design. Several types of water-tube boilers have been designed and have been found well adapted to marine work. The main requirements for a successful boiler in this class of service are that it should occupy little space and have a large evaporative capacity.

Figure 24 illustrates a water-tube boiler designed for marine service. It consists of a cylindrical drum whose axis is at right angles to those of the tubes, or is crossed The tubes are connected to headers, but the size of these tubes is smaller and the number of them larger than is common in the stationary type. This boiler is for oil fuel and is equipped with a superheater.

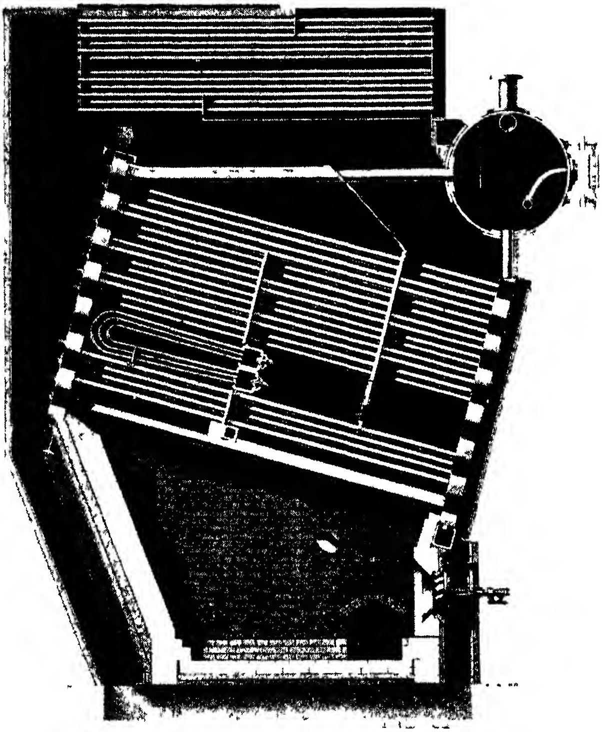


FIG. 24 —Babcock and Wilcox marine water-tube boiler.

Large-sized and High-pressure Boilers.—Units of 1,000 to 2,500 boiler hp. are becoming quite common in modern steam power plants. New installations include boilers greater than 35,000 sq. ft. of heating surface each, which corresponds to about 3,500 boiler hp. Many boilers have steaming capacities of 600,000 lb per hour each, with some few, whose maximum output is 1,200,000 lb steam per hour

The tendency for large central stations is to install boilers which operate at pressures of 450 lb per square inch and higher Many operate at pressures of 1,200 to 1,400 pounds pressure, and one industrial power plant is designed for 1,800 lb. per square inch at the boiler. Research is being carried on by boiler manufacturers and at Purdue University with steam pressures in excess of 3,000 lb. per square inch and at steam temperatures of 900 to 1200°F.

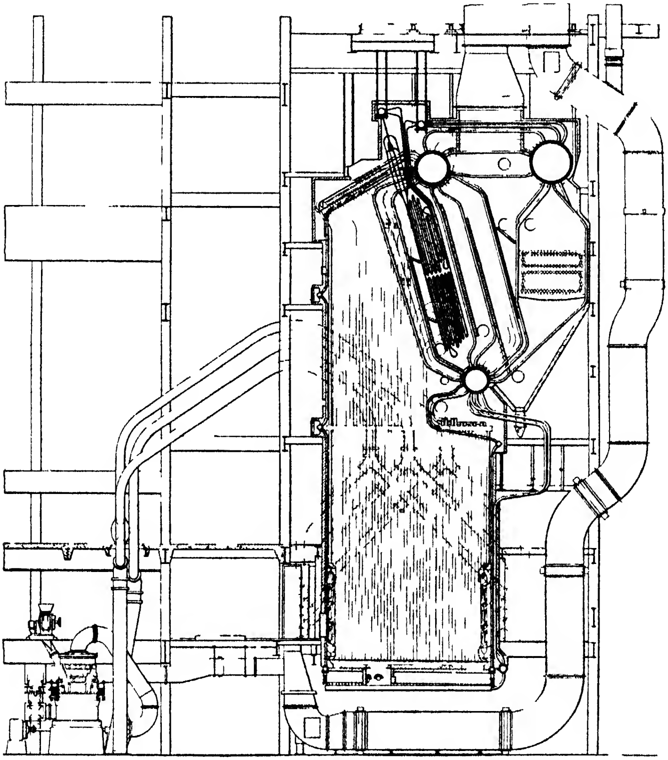


FIG 25 — Three-drum bent-tube high-pressure steam generator (*Combustion Engineering Co, Inc*)

Figure 25 illustrates a three-drum bent-tube steam generator, designed for pressures of 1,200 to 1,400 lb., fired with pulverized coal and slagging bottom. An economizer is contained within the boiler casing. The air heater, above the boiler, is tangentially fired.

Materials.—The drums of boilers intended for power purposes are made of rolled-steel plates forged together. Steel is the most desirable material for the construction of a boiler because of its strength and cheapness, and also because of its ductility, which permits the material to be formed into the irregular shapes necessary in constructing the boiler. Boiler tubes are made of steel and are usually seamless.

Cast iron is not considered a suitable material for boilers. It is brittle, possesses practically no ductility, and often produces unsound castings. It is used only in the construction of house-heating boilers, as in this class of service high pressures are not necessary.

Copper is used in boiler construction in special cases, as in fire-engine boilers, where the use of a material of less strength and greater cost is permissible in order to obtain a quick steaming boiler.

Heating Surface.—The heating surface of a boiler is that surface which is exposed to the flame and hot gases. This term is expressed in square feet, and the general rule employed in its calculation is to measure that part of the surface which is in contact with the flame or gases. For example, the heating surfaces of a boiler tube would be calculated by multiplying the internal circumference of the tube in feet by its length in feet if the tube was surrounded by water upon its external surface, and its internal surface was in contact with hot gases, as is the case in fire-tube boilers. If this condition is reversed, as is the case in water-tube boilers, the heating surface would be calculated by multiplying the external circumference of the tube by its length.

In a horizontal return tubular boiler, the heating surface is calculated by taking two-thirds of the cylindrical surface of the shell, adding to this the internal area of all the tubes, plus two-thirds of the area of both tube sheets, and subtracting from the result twice the combined external cross-sectional area of all the tubes.

In a water-tube boiler the surface below the mean water level, which is in direct contact with the hot gases, is used in calculating the heating surface of the boiler. The remaining exposed and heated area is the superheating surface.

The heating surface of a boiler is proportional to its capacity, or to the ability of a boiler to evaporate water into steam. The larger the quantity of water to be evaporated by a boiler, the larger must be its heating surface.

Staying.—Cylindrical or spherical surfaces retain their shape when subjected to either a bursting or to a collapsing pressure. Surfaces having a flat shape tend to become circular or spherical when a pressure is exerted. This tendency of flat boiler plates to distort when pressure is applied is prevented by the use of stays, as was pointed out in connection with the various types of boilers. There are many different types of stays; but in general they consist of small rods which connect the surfaces to be stayed and transfer the strain either to the shell of the boiler or to some other surface. These stays are given special names, depending upon their general construction, their mode of connection, or the type of surface to which they are best suited.

Settings and Furnaces.—In building a boiler setting, the solid brick wall is preferable to the hollow wall. If the wall is built in two parts, the space should be filled with ash, crushed brick, or sand, as loose material reduces air leakage by its plasticity.

Proper furnace design will aid in the economical combustion of coal. The design of a furnace should be modified to suit local fuels. To burn coals rich in volatile matter, the furnace must be so designed that the gases given off from the fuel bed remain at a high temperature until the combustion process is complete. This means that the combustion chamber for a high volatile coal must be large enough for the air to mix with the gases given off from the fuel bed and before such gases come into contact with the cool heating surfaces of the boiler. This can be accomplished by the use of an extension furnace, such as the Dutch-oven type, or by having the heating surfaces elevated at a considerable distance above the grate. The more volatile matter the coal contains, the greater should be the distance between the grate and the shell or the tubes of the boiler. The baffling for water-tube boilers should be arranged so that the hot gases from the fuel bed come first into contact with the baffles at the bottom of the tubes.

Air infiltration through cracks in boiler setting reduces the economy of a boiler plant. Visible cracks in the setting should be covered. The practice of encasing the whole setting in sheet steel, or the application of asbestos cement on the outside of the setting, should be employed more generally. Radiation losses can be reduced by the use of insulating brick.

Sufficient ash-pit capacity should be available to handle the refuse from at least a 12-hr. run. In calculating the size of an ash pit, the weight of ashes can be assumed at 40 to 50 lb per cubic foot. In plants where the ashes have to be handled by hand, it is important that the ash pit be so arranged as to be readily cleaned.

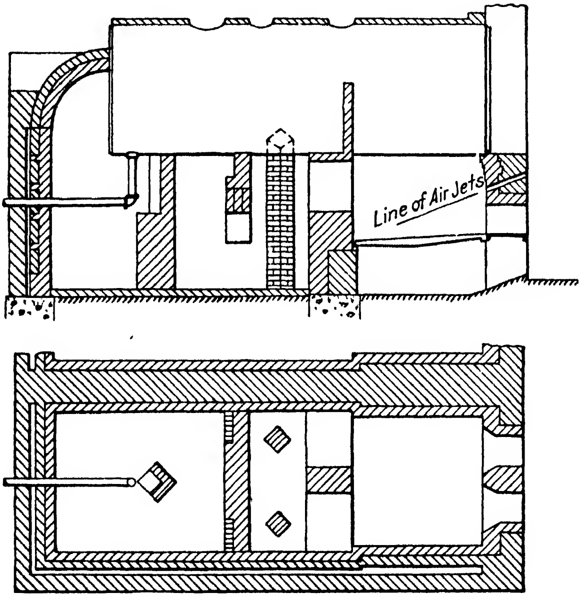


Fig. 26.—Chicago setting.

A setting recommended by the Chicago Smoke Inspection Department for fire-tube boilers is illustrated in Fig. 26. This type of setting is used when head room is small. Complete combustion is accomplished by thoroughly mixing the gases by the use of air jets, deflecting arches, and piers.

Water-cooled walls are a necessity in modern power plants, as the high temperatures used involve high upkeep costs of refractory furnaces. Furthermore, water walls increase the economy of steam generation by absorbing the surplus radiant heat which is ordinarily not utilized in the refractory furnace. Water walls consist of a series of parallel tube elements which extend within the furnace wall. These water tubes connect with the steam and water drums of the boiler proper. A water wall is illustrated in the steam generator (Fig. 25).

The Steam Accumulator.—In any steam-generating station the demand for steam that the load imposes upon the boilers varies from time to time. The steam accumulator takes care of fluctuations in steam demand by storing heat energy in a body of hot water. When the pressure and also the temperature of the hot water are decreased, steam formed by the reevaporation of the water is discharged. Thus the variation in the heat content of the water with temperature is utilized for heat accumulation purposes. The steam delivered by an accumulator is saturated, but by the provision of a special tank superheated steam may be stored.

The steam accumulator is used to a considerable extent in Europe in connection with sugar refineries, paper mills, and in other industrial plants which require considerable steam for process work.

Capacity and Efficiency of Steam Boilers.—Boilers are rated in square feet of heating surface, in pounds of steam per hour, or in horsepower. The term horsepower in this connection is a misnomer and does not represent the rate of doing work; boiler horsepower is an arbitrary unit which is applied to the evaporation of a definite amount of water. The amount of power developed by a steam power plant per unit weight of steam generated by the boiler depends upon the engine or turbine used. A boiler horsepower is equivalent to the evaporation of 34½ lb. of water per hour from feed water at 212°F. into dry steam at the same temperature.

A more logical method of expressing boiler horsepower is in terms of heat. To evaporate 1 lb. of water from a temperature of 212°F. into steam at 212°F., only the enthalpy of evaporation at that temperature is required. From the steam tables (Table 6), it is found that the enthalpy of steam at 212°F. is 970.3 B.t.u. The amount of heat required to evaporate 34.5 lb. from and at 212°F. is called the *unit of evaporation* and is equal to

$$34.5 \times 970.3 = 33{,}475 \text{ B.t.u.}$$

Thus a boiler horsepower may be stated as the absorption by the water within the boiler of 33,475 B.t.u. per hour.

Boiler manufacturers usually rate boilers in square feet of heating surface. For fire-tube boilers it is customary to assume 10 to 12 sq. ft. of heating surface as representing one boiler horsepower; in water-tube boilers 10 sq. ft. of heating surface is equivalent to one boiler horsepower. It should be noted, however, that the arrangement and not the area of the heating surface of a boiler affects its steam-making capacity. The evaporation per square foot of heating surface varies within wide limits, and may be as low as 3 lb. in small boilers and as great as 50 lb in large modern steam generators.

Under good working conditions, a boiler will evaporate 8 to 12 lb. of water per pound of coal, and 11 to 18 lb. of water per pound of petroleum fuel. The economy of a boiler plant depends upon the quality of the fuel used, the design of the furnace and boiler, the condition of setting, and the care in firing.

The efficiency of a boiler is the ratio of the heat units absorbed by the steam per pound of fuel fired, to the heat units supplied by 1 lb. of the fuel. Tests show that the efficiencies of boilers will vary under ordinary working conditions from about 40 per cent for small vertical boilers to 85 per cent or even higher when well-designed boilers are carefully handled. A boiler under average conditions should show an efficiency of about 70 per cent. The main losses in a boiler are the heat carried away by the flue gases, the loss of fuel through grates, the loss due to poor combustion of the fuel, and the heat lost by radiation.

The amount of heat required to produce 1 lb. of steam depends upon the temperature of the feed water, the steam pressure, and the quality of the steam. In order to compare boilers working under different conditions, the economy of boilers is expressed as the equivalent evaporation from and at 212°F. This means that the actual evaporation per pound of fuel is reduced to the number of pounds of water which would be evaporated if the feed water had been supplied to the boiler at 212°F., and that dry steam was formed at that temperature which is the boiling point of water at atmospheric pressure.

Example.—A boiler generates 9 lb. of steam per pound of fuel from feed water at 203°F. Calculate the equivalent evaporation from and at 212°F., if the steam pressure is 160 lb. per square inch absolute and the quality steam 0.98 dry.

Solution.—The heat required to evaporate 9 lb. of feed water at 203°F. into steam which has a pressure of 160 lb. absolute and a quality 0.98 is equal to

$$9[335.9 - (203 - 32) + 0.98(859.2)] = 9062 \text{ B.t.u.}$$

In order to evaporate water at 212°F. into steam at the same temperature, 970.3 B.t.u. will be required; therefore, the equivalent evaporation in accordance with the conditions of the above problem will be

$$\frac{9062}{970.3} = 9.33 \text{ lb.}$$

The ratio of the total heat actually used for changing water into steam to that necessary for the equivalent evaporation from and at 212°F. is called the *factor of evaporation.* Calling F the factor of evaporation, h_f and h_g, respectively, the enthalpy of water and of evaporation corresponding to the steam pressure, x the quality of the steam, and h_1 the enthalpy of the liquid corresponding to the feed water:

$$F = \frac{xh_g + (h_f - h_1)}{970.3}. \tag{45}$$

In the above problem,

$$\begin{aligned} F &= \frac{0.98 \times 858.7 + 335.9 - (203 - 32)}{970.3} \\ &= 1.036. \end{aligned}$$

In the case of superheated steam, equation (45) becomes

$$F = \frac{h - h_1}{970.3}. \tag{46}$$

Thus, in the above problem, if the steam at a pressure of 160 lb. per square inch was superheated to a temperature of 500°F., the enthalpy in a pound of steam under these conditions is $h = 1273.1$, (Table 8) and

$$F = \frac{1273.1 - (203 - 32)}{970.2}.$$
$$= 1.15$$

If w is the amount of water evaporated by the boiler per hour, the boiler horsepower in terms of the factor of evaporation F may be calculated by the following formula:

$$\text{Boiler horsepower} = \frac{wF}{34.5}. \qquad (47)$$

Thus, if a boiler evaporates 100,000 lb. of water per hour and has a factor of evaporation $F = 1.15$, the boiler horsepower is

$$\text{Boiler horsepower} = \frac{100{,}000 \times 1.15}{34}.$$
$$= 3{,}333$$

Hand-firing.—To the average person, firing consists merely of opening the furnace door and throwing fuel on the grate. This is, however, a fallacy. It has been found that some system of firing must be adopted in order to produce economical combustion of coal. The method to be adopted depends mainly on the kind of fuel used.

The spreading method consists of distributing a small charge of coal in a thin layer over the entire grate. This system of firing will give satisfactory results with anthracite coal and with some bituminous coals. With this method, if the fuel is fed in large quantities and at long intervals, incomplete combustion will result.

The alternate method consists of covering first one side of the grate with fresh fuel and then the other. The volatile gases that pass off from the fresh fuel on one side of the grate are burned with the hot air coming from the bright side of the fire. This system is best applied to a boiler with a broad furnace.

The coking method is best adapted for the smoky and for the caking varieties of bituminous coal. In this method the coal is put in the front part of the furnace, and allowed to remain there until the volatile gases are driven off; it is then pushed back and spread over the hot part of the furnace, and a new charge is thrown in the front.

Either one of the three systems of hand-firing explained will produce good results, if properly carried out and if the fire is kept bright and clean. Smoke indicates incomplete combustion and with bituminous coal occurs if the volatile gases are allowed to pass off unburned.

Mechanical stokers will be explained in Chap. VI.

Management of Boilers.—Before a boiler is started for the first time, its interior should be carefully cleaned, care being taken that no oily waste or foreign material is left inside the boiler. The various manholes and handholes are then closed and the boiler is filled to about two-thirds of its volume with water. The fire is started with wood, oily waste, or some other rapidly burning materials, keeping the damper and ash-pit door open. The fuel bed is then built up slowly.

While getting up the steam pressure, the water gage glass should be blown out to see that it is not choked, the gage cocks should be tried, and all auxiliaries such as pumps, injectors, pressure gages, piping, etc. carefully inspected. The safety valve should be carefully examined and tried out before cutting the boiler into service.

When cutting a boiler into service with others, its pressure should be the same as that of the other boilers. Steam valves should be opened and closed very slowly, in order to prevent water-hammer and stresses from rapid temperature changes.

During the operation of a steam boiler the safety valve should be kept in perfect condition and tried daily by allowing the pressure to rise gradually until the valve begins to simmer. Each boiler should have its own safety valve and under no condition should a stop valve be placed between it and the boiler. The steam gage should be calibrated from time to time with a standard gage, or still better by means of some form of dead-weight tester. It is best not to depend on the water gage glass entirely; gage cocks are more reliable and should be used for checking the water level of a boiler.

In case of low water, do not turn on the feed, but shut the damper, cover the fuel bed with ashes, or if that is not available, with green coal. The safety valve should not be lifted until the boiler has cooled down, as an explosion may occur. Also do not change operating conditions as regards the use of steam. If the engine is running allow it to continue but do not open valves to reduce the pressure.

A boiler should be cleaned often and kept free from scale. If water free from impurities is used, a boiler may be run several months without fear of serious scale formation, but in most places boilers should be cleaned at least once a month. When preparing to clean a boiler, allow it to cool down, and the water to remain in the shell until you are ready to commence cleaning.

In emergencies split tubes of fire-tube boilers may be plugged without throwing the boiler out of service. Also if a tube becomes leaky in the tube sheet the fault can be remedied by inserting a tapering sleeve slightly larger than the inside diameter of the tube.

A boiler should always be thoroughly inspected before it is started. In the case of the locomotive type of boiler the crown sheet should be given particular attention.

Boilers should be kept free from scale-forming material. Scale deposits decrease the conductivity of the boiler heating surfaces and may cause the overheating of the boiler metal. Heating feed water before it is admitted to the boiler will reduce the formation of scale. Boilers should also be blown down at frequent intervals. Water purifiers are a necessity in cases where the water is poor.

Problems

1. Calculate the heating surface of a fire-tube boiler, to which you have access, after taking the necessary measurements.
2. A boiler plant operating under a pressure of 225 lb. per square inch gage generates 18,000 lb. of saturated steam per hour. If the feed-water temperature is 203°F. and the quality of the steam 3 per cent wet, calculate the boiler horsepower of the plant.
3. Calculate the approximate heating surface of the boiler plant in Problem 2, assuming fire-tube boilers.
4. Prove that 34½ lb. of water per hour from and at 212°F. is the same as the evaporation of 30 lb. of water per hour from feed water at 100°F. into steam at 70 lb. gage pressure.
5. Compare the equivalent evaporation from and at 212°F. and the factor of evaporation of the following boilers:
   Boiler *A* evaporates 7½ lb. of water per hour per pound of coal from feed water at 140°F. and into steam at a pressure of 140 lb. gage, with 2 per cent priming.
   Boiler *B* evaporates 8½ lb. of water per hour per pound of coal from feed water at 205°F. and into steam at a pressure of 150 lb. gage, with 4 per cent priming.

6. Calculate the approximate boiler horsepower of a boiler which has a steaming capacity of 800,000 lb. steam per hour. Steam pressure 600 lb. per square inch; feed-water temperature 205°F. (Steam is 3 per cent wet.)
7. What is the approximate heating surface of the boiler in Problem 6?
8. If the steam in Problem 6 had a temperature of 600°F., calculate the boiler horsepower.
9. Calculate the factor of evaporation for conditions in Problems 7 and 8.
10. Calculate the efficiency of the boiler in Problem 6 if 1,200 lb. of coal are used per hour; heat value of coal 12,481 B.t.u.
11. Why will air infiltration through cracks in a boiler setting interfere with the economy of a boiler plant?
12. Examine some power plant to which you have access and hand in report showing the following: type of boilers used, steam pressure carried, methods used for setting boilers (use sketches), and temperature of feed water; also the relation between the rating of the boilers in horsepower and the maximum capacity of the power plant in horsepower or kilowatt.
13. What causes a boiler to explode?
14. Is a solid wall or a hollow wall preferable for a boiler setting? Give reasons for your conclusion.
15. Why are water walls a necessity in boilers of large capacity?

CHAPTER VI

BOILER AUXILIARIES

SUPERHEATERS

Advantages of Superheaters.—A superheater, which consists of tubes or steam passages, receives the steam after it passes the boiler proper and heats it to a temperature greater than the saturation temperature corresponding to its pressure. The installation of a superheater makes greater economies possible in the utilization of the steam in steam engines and in steam turbines. Superheated steam decreases the steam consumption of reciprocating engines 5 to 20 per cent. In the case of steam turbines the steam economy is improved about 1 per cent for every 8 to 12°F. of superheat. Superheated steam also reduces the losses of heat in piping systems, as superheated steam gives heat less readily than saturated steam.

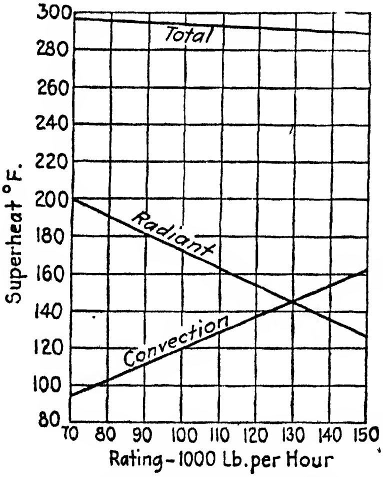


FIG. 27.—Characteristics of radiant and convection superheaters.

The cost of a superheater depends upon the type and size, as well as upon the degree of superheat maintained. Ordinarily the installation of a superheater will add about one-third to the cost of a steam boiler.

Types of Superheaters.—Two types of superheaters are used, the independently fired and the built-in or attached type. The independently fired superheater, as its name indicates, is placed in an independent setting and is fired by a separate furnace.

The attached superheaters are located directly in the boiler setting, derive their heat from the same furnace as the boiler, and are consequently subject to the fluctuating temperatures of the furnace. In the independently fired superheater the degree of superheat is independent of the boiler furnace. By means of the independently fired superheaters the final temperatures can be varied more easily than with the attached superheaters. The independently fired superheater is, however, more expensive in first cost, costs more to operate, and occupies considerable space, as compared with the attached superheater. In either type of superheater the steam passes through the superheater on its way from the boiler to the engine.

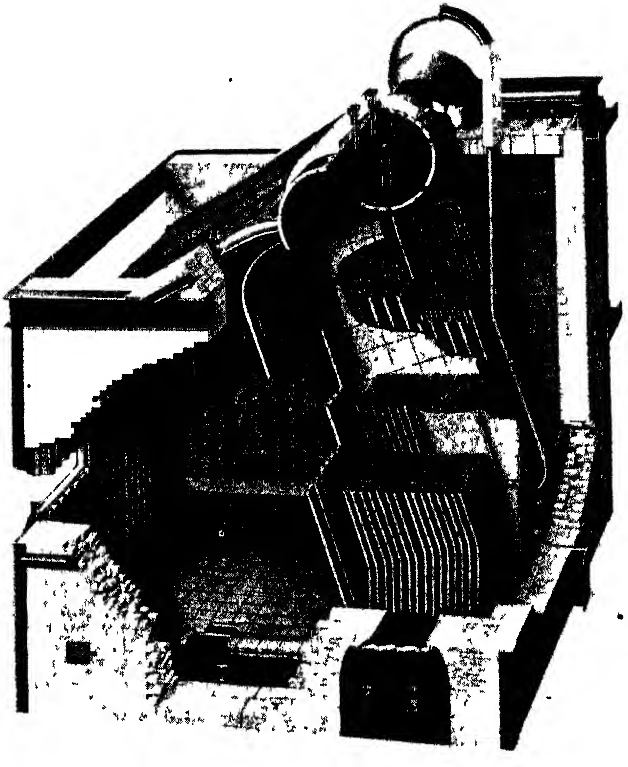


FIG. 28.—Babcock and Wilcox integral-furnace boiler unit in perspective.

The attached superheater is installed so as to be exposed to the fire, to the hot gases, or partially to both This class of superheater is further divided into convection, interdeck, and radiant types, depending upon their location in the setting. The convection type is located in the gas path between the first and second passes of the boiler. The convection type receives its heat primarily by convection and is usually used for moderate amounts of superheat The interdeck type is placed after a

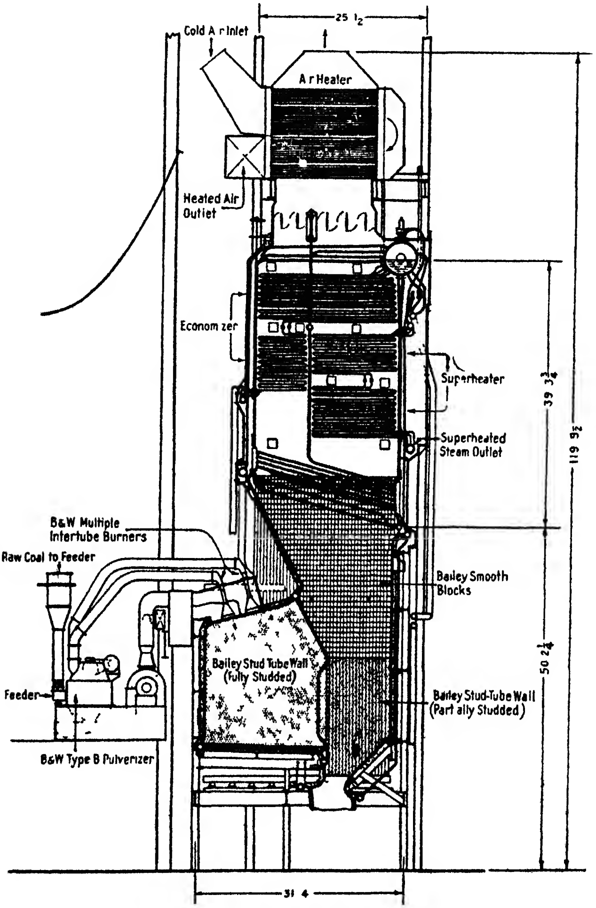


FIG 29—Babcock and Wilcox single-pass boiler with superheater, air heater and economizer

shallow bank of tubes in the first pass. The interdeck type being nearer the furnace receives heat by radiation as well as by convection and provides a higher degree of superheat with a reasonable amount of heating surface. The radiant type is located in one or more sides of the furnace and receives most of its heat by direction radiation. The radiant type is suitable for installations where the temperature in the furnace is so high that the furnace walls need protection. The characteristics of radiant, convection and combination types of superheaters are illustrated in Fig. 27. The combination type of superheater insures a fairly uniform degree of superheat.

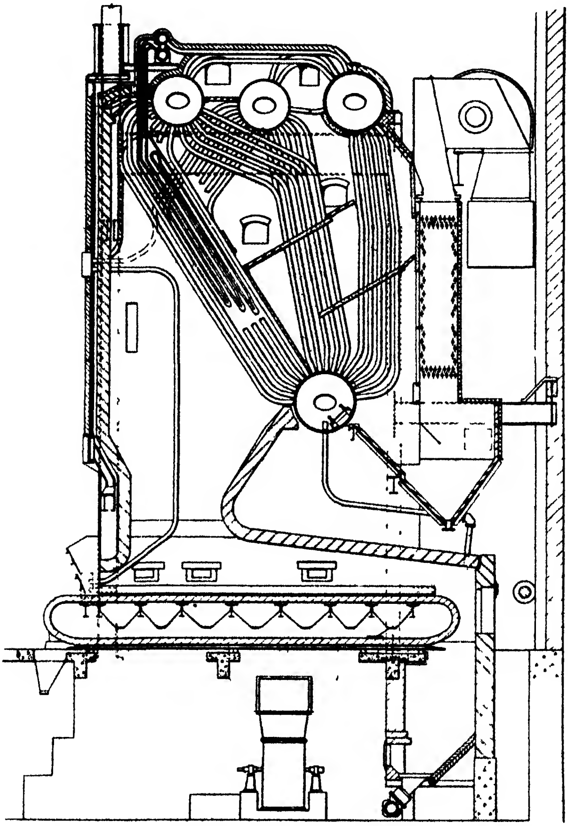


Fig. 30.—Four-drum boiler with superheater. (*Combustion Engineering Co., Inc.*)

Practically all superheaters consist of a series of tubes expanded into steel headers through which the steam from the boiler passes before entering the piping leading to the engine. Heat from the furnace gases is thus absorbed by the flowing steam and its temperature is raised above that at which it left the boiler.

Figure 28 illustrates the Babcock and Wilcox integral-furnace boiler unit in perspective, sectionalized to show the sizes and arrangement of the tubes comprising the boiler heating surface, the self-draining convection type superheater, and the integral water-cooled furnace.

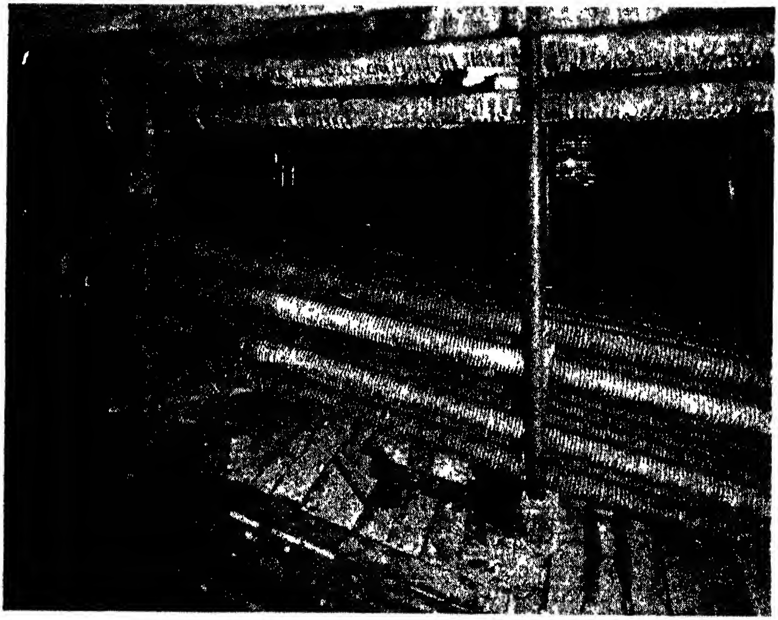


FIG. 31.—Cross-drum boiler with Foster-Wheeler superheater.

In Fig. 29 is illustrated a boiler unit, which includes a single-pass boiler, equipped with a superheater, economizer, and air heater, and which is fired by pulverized fuel. A safety valve is placed near the outlet of the superheater and is to provide a flow of steam through the superheater in case the load is suddenly thrown off the boiler, thereby preventing the overheating of the superheater tubes. The superheater safety valve should be set

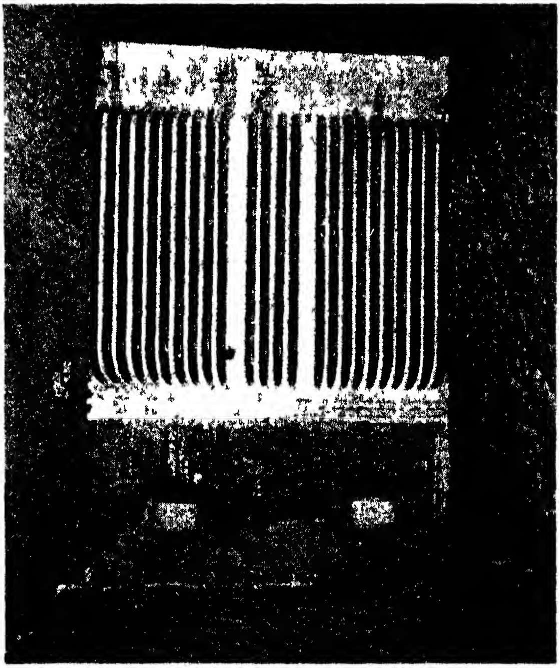


Fig 32 —Foster-Wheeler radiant superheater

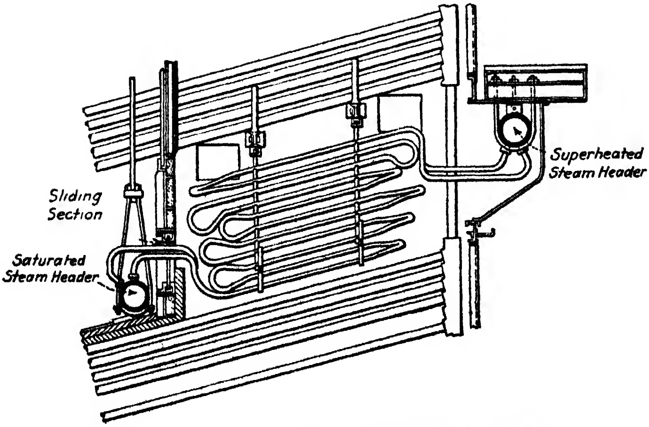


Fig. 33 —Principle of the interdeck superheater

to pop at a pressure lower than that of the valves on the boiler, as otherwise no protection to superheater tubes would result.

Figure 30 illustrates the application of the Elesco superheater to a bent-tube boiler. This design is found in industrial plants operating at pressures up to 600 lb. per square inch.

In Fig. 31 is illustrated an installation of cast-iron armored superheaters in a cross-drum sectional header boiler.

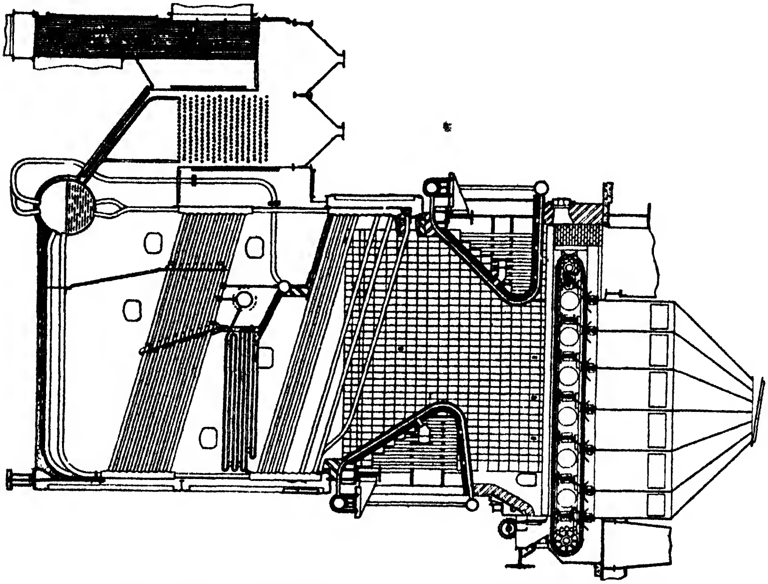


Fig. 34.—Babcock and Wilcox boiler with interdeck superheater.

The application of the radiant superheater element in the rear wall of a boiler is shown in Fig. 32.

The principle of an interdeck superheater is shown in Fig. 33.

Figure 34 illustrates a Babcock and Wilcox boiler with an interdeck superheater.

Superheater Construction.—The Foster-Wheeler superheater makes use of a U-bent element, illustrated in Fig. 35. The superheater tubes are provided with cast-iron grilled rings which augment heat transfer by breaking up the gas flow, while increasing the external surface in contact with the hot gases.

The Elesco superheater consists of cold-drawn, seamless tubing of small diameter so that no cores are required. The headers are made of extra heavy pipe and the headers as well as the unit joints are protected from the direct action of the gases by being placed either outside the setting or in a protected part. The location of the headers and the method used in making the unit joints give excellent accessibility for inspection and maintenance.

The tubes for convection superheaters suitable for temperatures up to about 700°F. are ordinarily constructed of mild steel, but for higher temperatures special steel alloys are employed. The headers in the best designs are made of forged steel.

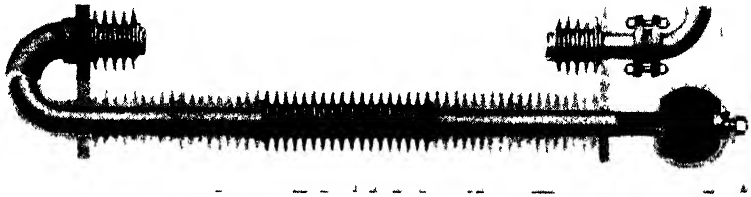


Fig. 35.— Foster-Wheeler superheater element.

GRATES FOR BOILER FURNACES

Grates for hand-fired furnaces are formed of cast-iron bars and are illustrated in Fig. 36. Plain grates (*b*), Fig. 36, are best adapted for caking coals and are usually provided with iron bars, cast in pairs, and with lugs at the side. The Tupper type of grate (*c*), Fig. 36, is more suitable for the burning of hard coal, which does not cake. The grates of a boiler furnace can be easily interchanged to suit the fuel burned.

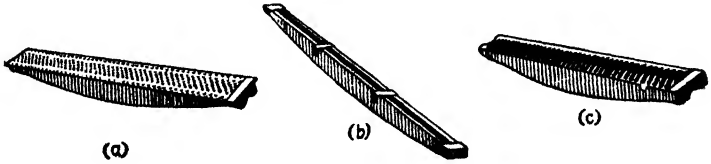


Fig. 36.—Grate bars.

For most economical results some form of rocking and dumping grate, as shown in Fig. 37, should be used. This type of grate permits stoking without opening the fire doors; it also requires less labor than stationary grates.

MECHANICAL STOKERS

The Field of Mechanical Stokers.—Greatest fuel economy can be secured by firing coal frequently and in small quantities. With hand firing this is difficult to accomplish and usually more coal is put into the furnace at one time than is desirable for economical combustion. Mechanical stokers make possible the feeding of small quantities of fuel at regular intervals, the time between the charges being so regulated that the fuel is completely burned. When using mechanical stokers, the rate of firing is even, smoke can be greatly reduced, the furnace doors can be kept closed, and the air supply regulated to suit the fuel and the load. Low-grade fuels, which cannot be burned without smoke by hand-firing methods, are frequently used successfully with certain types of mechanical stokers.

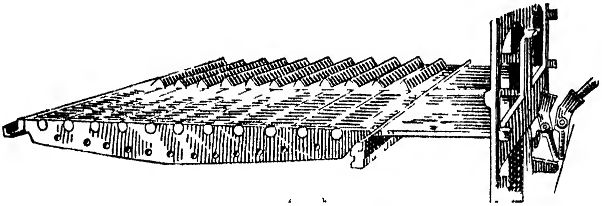


Fig. 37.—Dumping grate.

Mechanical stokers are an absolute necessity in modern power plants which involve high rates of combustion and large boiler capacities.

The cost of upkeep is influenced by the size and by the composition of the fuel used. For best results lumps 3 in. in size or smaller should be used. The initial cost of stoker equipment depends upon the size and number of stokers installed, the draft available, and the kind of fuel.

The types of mechanical stokers usually used are the chain-grate and the underfeed. The type of stoker to be selected depends upon the kind of fuel to be burned.

Chain-grate Stokers.—Figures 38 and 39 illustrate chain-grate stokers. The entire grate surface is made of a large number of chain links, which form the fuel bearing surface. Sagging of the upper grate surface is prevented by supporting the weight of the upper grate on small rollers.

Power for driving the stoker is applied at the front This causes the top side of the grate to revolve slowly from the front of the furnace toward the rear Coal is fed upon the moving grate through the hopper in the front and is burned as it passes toward the bridge wall Under proper operating conditions, the speed of the traveling grate is adjusted so that the coal will have been completely burned to ash when it reaches the end of the grate and will drop down into the ash pit below. The speed of the chain grate must be regulated in accordance with the load on the boiler and the grade of coal used. Care must be taken in regulating the speed of the grate to prevent loss of fuel to the ash pit. Leakage of air between the grate and the bridge wall

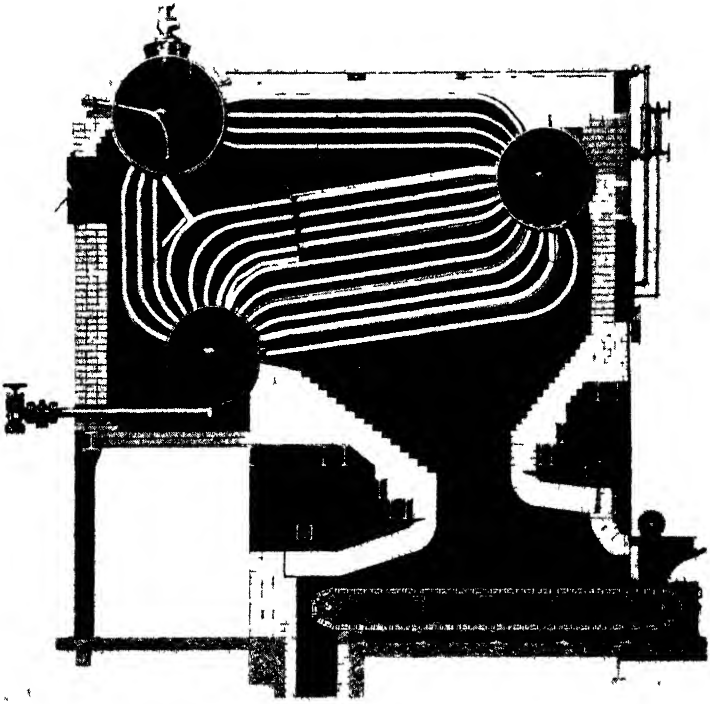


Fig. 38 —Babcock and Wilcox type *H* Stirling boiler with chain-grate stoker.

and through the fire bed at the rear must be reduced to a minimum by regulating the depth of the fuel and ash beds.

This type of stoker can be secured to operate either with forced draft or with natural draft. In the case of natural-draft stokers of this type, the entire grate is generally mounted upon wheels so that it can be removed from the furnace for the purpose of making repairs. A coking arch or an ignition arch of fire brick extends over the top of the grate and acts as an incandescent surface upon which the volatile gases strike as they are distilled from the coal. This promotes the complete combustion of the gases, which, if allowed to strike the cooler boiler surface, would be cooled below their ignition temperature and smoke would result.

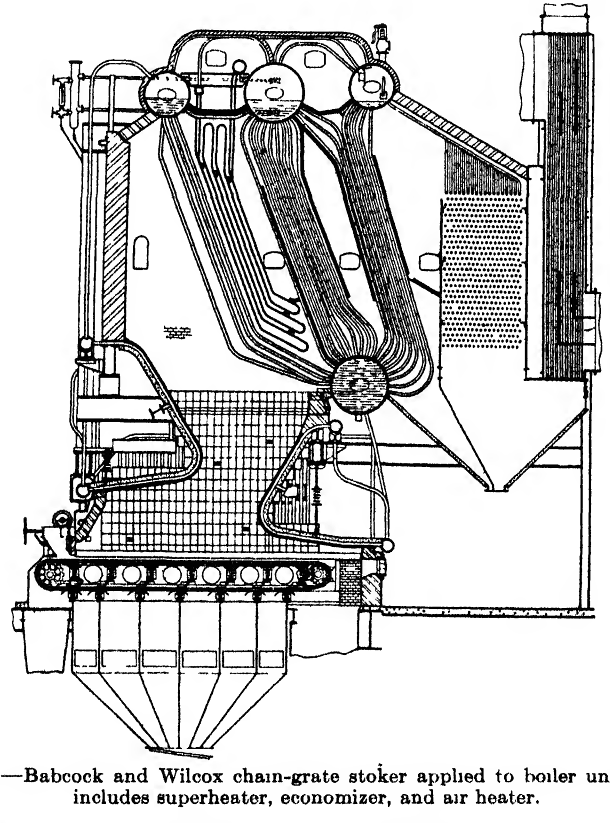


Fig. 39.—Babcock and Wilcox chain-grate stoker applied to boiler unit which includes superheater, economizer, and air heater.

Figure 38 illustrates the application of a chain-grate stoker to a Babcock and Wilcox Stirling boiler. In Fig. 39 is shown a chain-grate stoker as applied to a Babcock and Wilcox boiler unit, which includes a superheater, economizer, and air heater.

The chain-grate stoker is best suited for small sizes of free-burning, non-caking, and high-ash bituminous coals. It is also satisfactory for anthracite screenings and has been used for coke breeze. This type of stoker is not very satisfactory with high-coking, low-ash coals on account of the fusing action of the fuel under the fire-brick arch For coking coals the natural-draft chain-grate stoker is not suitable unless provided with coking plates under the front of the arch upon which the coal drops from the hopper. Forced-draft chain-grate stokers burn moderately coking coal satisfactorily.

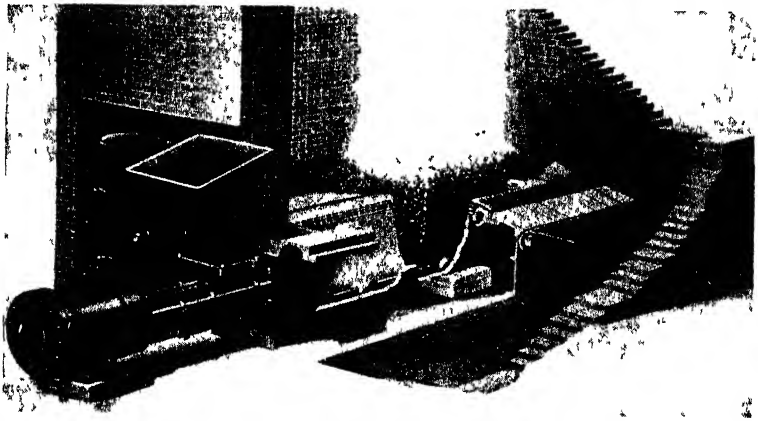


FIG 40 —Single-retort side-dump underfeed stoker

Natural-draft chain-grate stokers are installed in plants where the load demand is steady and where rates of combustion of about 30 lb. per square foot of grate surface per hour are satisfactory. Forced-draft chain-grate stokers lend themselves to considerable overloads and rates of combustion as high as 60 lb. per square foot of grate surface per hour.

Underfeed Stokers.—Figure 40 illustrates the single-retort underfeed stoker. It consists of a retort placed inside the furnace and of an external feeding mechanism. The retort is trough shaped and along each side are placed tuyère blocks for admitting the air. The feeding mechanism is a steam cylinder in which works a piston. A coal ram is attached to the same piston rod. As the ram forces coal into the retort, the coal already there is forced upward. To prevent the coal from heaping up near the front of the furnace, pusher blocks, connected to the piston rod, are placed in the bottom of the retort. These tend to maintain a level fire.

The operation of this stoker is such that the clinkers and ash are worked to the top of the fire and are removed from the furnace through the dumping grates at the sides. The green fuel is fed below the burning coal, and the hottest part of the furnace is at the top of the fuel bed. As the burning coal gradually works its way toward the top, any volatile matter is distilled off and is consumed before reaching the furnace.

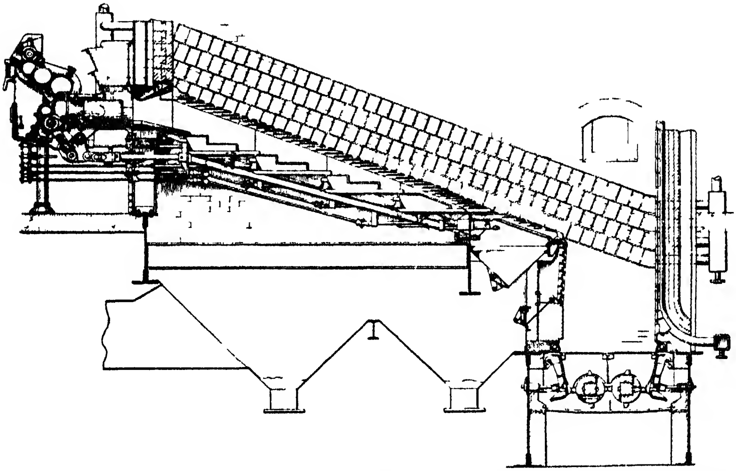


FIG. 41.—Combustion Engineering Co multiple-retort underfeed stoker.

Air for this stoker is supplied by a forced-draft fan. A duct from the fan leads the air to the stoker where it passes into the furnace through the tuyères in the retort. This class of stoker has a high forcing capacity and is suitable for coking bituminous coals.

In another type of underfeed stoker the piston is replaced by a worm, which continuously feeds the coal beneath the fire.

Figures 41 and 42 illustrate two types of multiple-retort underfeed stokers.

In the stoker, Fig. 41, fuel from the hopper is fed into the retort, which is located in the bottom of the coal hopper. A ram in the retort pushes the green fuel outward and beneath the burning fuel, which rests upon an inclined grate. The green fuel being introduced under the fire is slowly coked. The lower ram forces the fuel bed and refuse toward the dump plates at the rear. Air for the combustion of the fuel is supplied by a forced-draft fan, and enters the fuel bed through openings in the tuyère boxes.

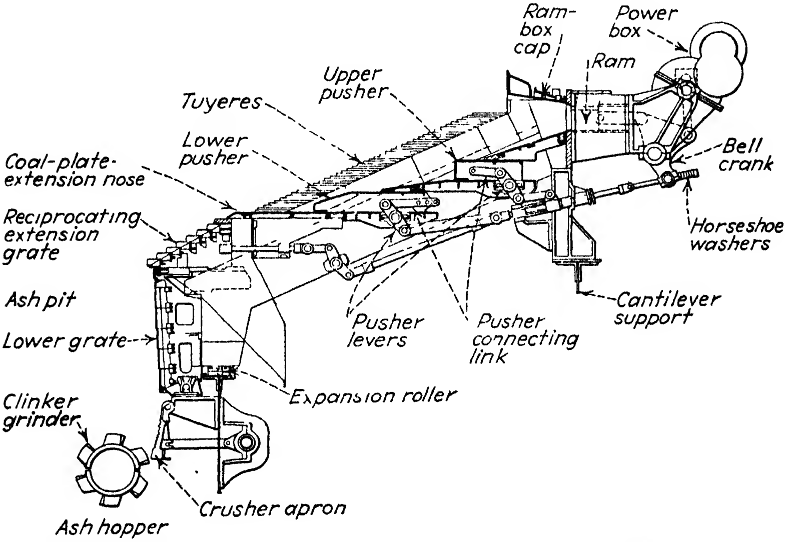


FIG. 42.—Taylor multiple-retort underfeed stoker. (*American Engineering Co.*)

The stoker in Fig. 42 is built up of a series of alternate retorts and tuyère or air boxes. Each retort is fitted with plungers or rams. Coal is fed from the hoppers into the retorts by the upper ram; the lower ram forces the fuel bed and refuse toward the rear. The air for combustion is forced through the tuyères to the fuel bed.

POWDERED COAL

Advantages of Powdered Coal.—Coal in the powdered form has been used for many years in certain metallurgical processes and in the cement industry. In recent years there has also been a rapidly growing tendency toward the use of powdered coal for steam generation in large steam-electric power plants. The advantages claimed for powdered coal are: complete combustion, absence of smoke, decreased labor costs, flexibility of furnace control, decrease in the banking losses, possibility of utilizing for steam generation low-grade fuels, and high thermal efficiency. The objections to powdered fuel are: cost of preparation, furnace depreciation, the difficulty of providing adequate fuel storage and

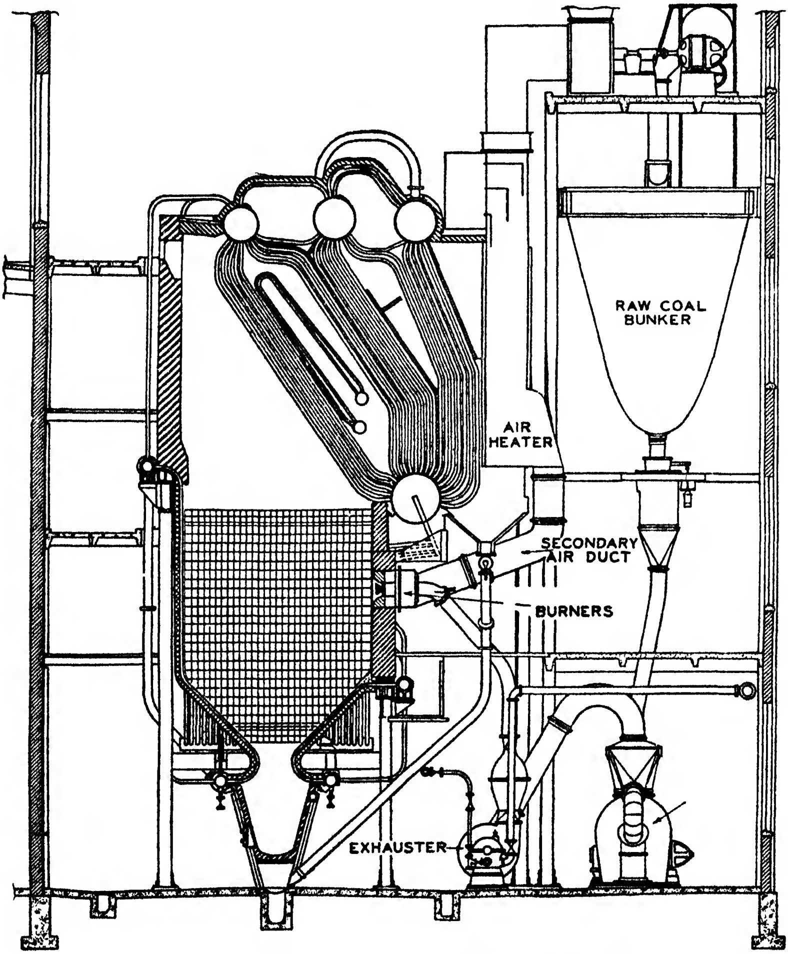


Fig. 43.—Unit system of powdered-coal equipment.

the refuse discharging through the stack In large installations, there is little if any difference in the cost of underfeed mechanical stokers and of powdered coal Improvements in furnace design, use of water-cooled walls, electrical ash precipitation methods

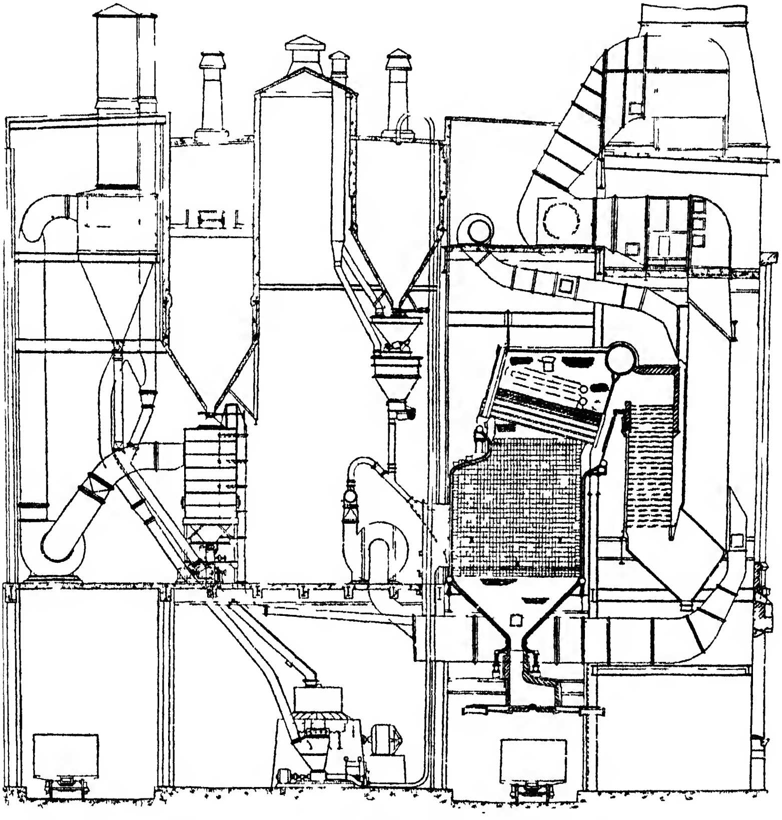


Fig 44 —Bin-and-feeder powdered coal system

and new safety appliances are rapidly overcoming the objections to powdered fuel for steam power plants.

Coals high in volatile matter and low in ash content are well suited for burning in the powdered form.

Powdered Coal Systems.—The systems used in preparing and burning powdered fuel are divided into the unit and the central or bin-and-feeder systems. In the unit system, one or more machines, located near each boiler, prepare and deliver the powdered coal to each furnace as needed, with the necessary air supply for combustion. The central system consists of an independent pulverizing plant, located more or less remote from the boilers, together with conveying systems, pulverized-coal bins and feeders The powdered coal is delivered and stored in the bins from which it is fed to the several boilers as needed The central system is the older of the two methods.

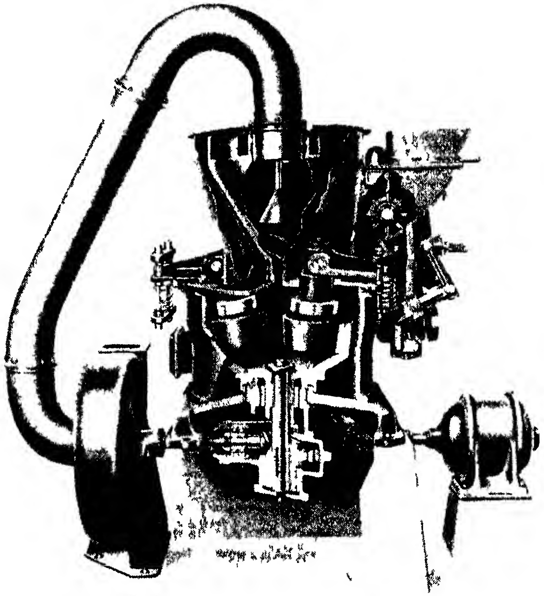


FIG 45—Raymond "bowl" type pulverizer (*Combustion Engineering Co, Inc*)

In the unit system, the fuel goes to a crusher, thence to the raw-coal bunker, to the pulverizer, and to the burners. In the unit system preliminary drying is usually dispensed with, the mills being usually supplied with preheated air. Figure 43 illustrates a unit system. This system is suitable for small as well as large installations

The central or the bin-and-feeder system is illustrated in Fig. 44. The path of the fuel in this system is to the crusher, thence to the raw-coal bunker, then to the dryer, the pulverizer, the pulverized-coal conveying system, powdered coal storage bin, feeders, and to the burners

The powdered coal as it enters the burner meets a current of air, supplied by a blower. In one type of burner, called the turbulent, all the air and fuel are intimately mixed as they enter the furnace; in another type the fuel and air are forced into the furnace in streams, the long flame being depended upon to secure the proper mixing of the powdered coal with air

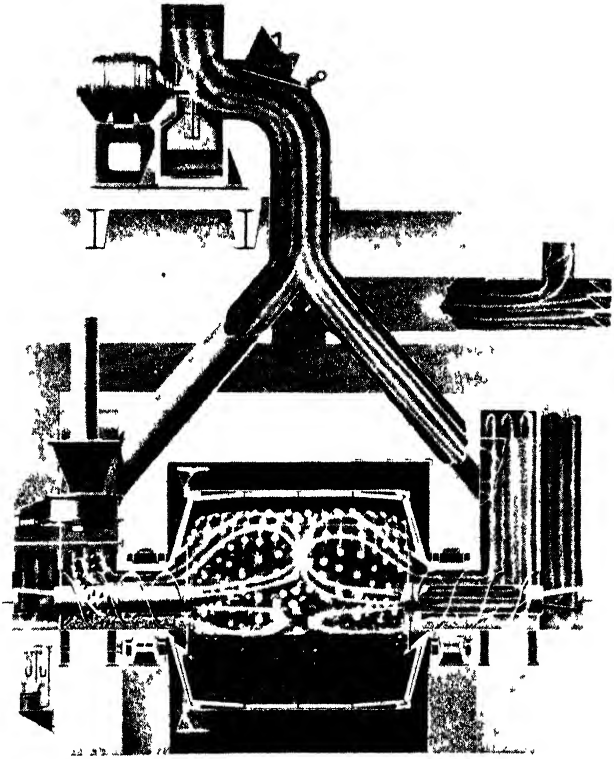


FIG. 46.—Foster-Wheeler double classifier mill pulverizer.

The furnaces for powdered coal are constructed with walls which are cooled by air, water, or steam. In cases where solid refractory walls are used they are protected by water screens Air-cooled hollow refractory walls are found in some plants, but the best practice is to use water- or steam-cooled metal walls.

Figure 45 illustrates the Raymond bowl-mill type of pulverizer. This type makes use of a revolving bowl or grinding chamber.

Figure 46 shows a double classifier mill in which coal may be fed from both ends, giving increased pulverizer capacity.

More than half of the ash from powdered coal is carried out of the stack unless electric or other types of precipitators are used. In some powdered-fuel plants slagging furnaces are installed; in such cases the ash is tapped off in molten state, cooled, and carried away by water

OIL AND GAS FUEL

Advantages of Oil and Gas As Fuel.—Where economical and commercial conditions permit, oil or gas is a desirable substitute for coal. In small plants, higher boiler efficiencies and greater capacities can be obtained with oil or gas as fuel than those usually obtained with coal. As the size of the plant increases and boilers are operated at high ratings, equally good results can be secured with either fuel The saving in labor in the oil-fired or gas-fired plant is considerable as compared with the coal-fired plant, because of the elimination of coal and ash handling. As compared with coal, oil fuel is cleaner, is easier to store and to transfer, permits more accurate regulation of the air supply, and leaves no ash after combustion.

Fuel Oil Furnaces and Burners.—To burn oil most economically, it must be thoroughly atomized by the burner, it must be brought in contact after atomization with the correct amount of air for complete combustion, the boiler furnace must be constructed with sufficient volume so that the gases are completely burned before they strike the boiler heating surfaces, and the burners must be located so that overheating or blistering of the boiler tubes will be obviated.

Furnaces for oil fuel are of simple construction, as they require no grates, ash pits, or ignition arches.

Oil burners are of two types, steam and mechanical atomizing burners. Steam atomizing burners are either of the outside mixing or of the inside mixing type. In outside mixing burners, the oil is picked up by the steam as it leaves the burner tip. In the inside mixing type, the steam and oil come into contact within the burner. The outside mixing type of steam burner is most commonly used and the air for combustion is introduced through checkerwork beneath the burner. In the mechanical atomizing burners the oil, preferably heated, is forced out under pressure through a distributing tip, or by the whirling action of a revolving carrier. Steam atomizing burners are usually used for stationary plants.

Figure 47 illustrates one type of steam inside mixing-type burner.

In Figs. 22 and 24 are shown applications of the mechanical-atomizing burners to stationary and marine types Babcock and Wilcox boilers.

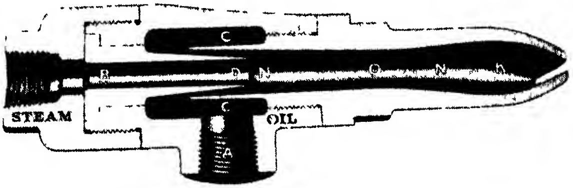


Fig. 47. National Airfoil type steam atomizing burner (patented).

The equipment for oil burning includes an oil pump, filter or strainer, an oil heater, oil burners, and oil piping. The pressure at which oil is brought to steam atomizing burners varies from 40 to 60 lb. The temperature to which the oil must be heated depends upon the oil used and varies from 150 to 275°F.

Gas-burning Equipment.—Gas fuel is used to some extent for steam generation in natural-gas regions and in certain industries which produce gas as a by-product. Thus blast-furnace gas is used in the steel industry for steam generation.

Gas burners are similar to oil burners and depend upon the gas used. Some types mix the gas and air inside the burner jet; others admit the air outside and around the jet.

In some plants pulverized-coal and blast-furnace gas are burned in combination. An example of this is the Ford Company Plant at River Rouge, Michigan.

FEED-WATER HEATING

Feed-water Heaters.—If cold water is fed to a boiler, there will be a difference in temperature at the various parts of the boiler shell, and strains will be set up by the unequal expansion and contraction, which will decrease the life of the boiler, besides impairing the tightness of the setting. With hot feed water, strains, due to unequal expansion and contraction, are reduced. Modern power plants are usually provided with feed-water heaters, which heat the water by exhaust steam. The use of a feed-water heater will increase the economy of a steam power plant by utilizing exhaust steam, which would otherwise be wasted. Under ordinary conditions, heating feed water 11° will produce about 1 per cent gain in economy. The capacity of a boiler plant can be increased more cheaply by the installation of a feed-water heater, outside the boiler, than by increasing the

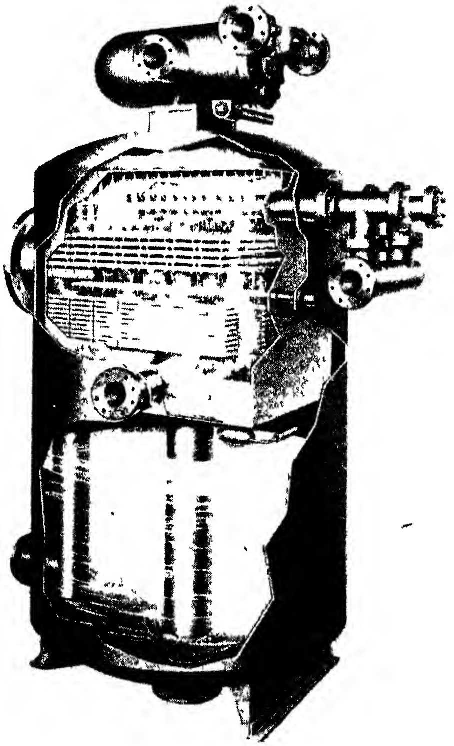


Fig. 48.—Cochrane deaerator type open feed-water heater.

size of the boiler. Heating the feed water outside of the boiler serves also to purify the water before it enters the boiler.

Feed water can be heated by live steam, by exhaust steam, or by the waste chimney gases.

The heating of feed water by live steam is not recommended, as no use is made of the waste heat.

Feed-water heaters which utilize the heat of exhaust steam from engines and pumps are most commonly used. Heaters may be constructed so that the exhaust steam and water come into direct contact and the steam gives up its heat by condensation. Such heaters are called open feed-water heaters One type of open feed-water heater is illustrated in Fig 48. In this form, water passes over trays upon which the impurities thrown out of the water by the heat are deposited, and can be easily removed. Open feed-water heaters are provided with oil separators through which the exhaust steam passes before entering the heater. The heater illustrated in Fig. 48, is of deaerator type. Open feed-water heaters are usually placed on the suction side of the feed pump and at a higher elevation than the pump cylinders as a feed pump cannot lift hot water.

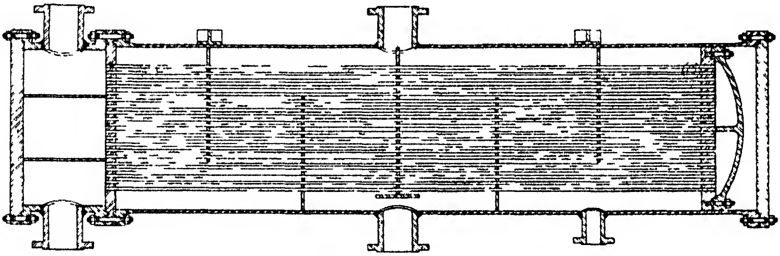


FIG 49 —Foster-Wheeler closed feed-water heater.

If it is desired to pass the water through the heater under pressure or to prevent the steam and water from coming into contact with each other, some form of closed heater should be used. Figure 49 illustrates a heater of this type. Here the steam on one side of the tubes heats the water on the other. Such heaters may be constructed so that either the steam or the water flows through the tubes. Closed feed-water heaters are more expensive than the open types, more difficult to clean, and are used only in special cases.

The general arrangement of the feed-water heating equipment and the source from which the exhaust steam is obtained lead to a great number of possibilities. In the small power plant, the auxiliaries are usually steam operated and their exhaust used in feed-water heating.

In the larger plants, the auxiliaries are mainly electrically driven and the feed water heated by bleeding steam from several intermediate stages of the main turbine. This method is generally accepted as the most efficient. The advantage of bleeding steam from various stages of the turbine and, consequently, at various temperatures instead of at one point will be appreciated when it is remembered that the steam for heating the feed water at the lowest temperature can do considerable work in the turbine before passing to the feed-water heater. Theoretically, the steam for feed-water heating should be bled from the turbine at points where its temperature is slightly above that of the feed water to be heated, gradually bringing the temperature of the water to the point where it enters the boiler.

Economizers.—A feed-water heater which derives its heat from the flue gases as they leave the boiler is termed an economizer. Economizers increase the capacity of a boiler plant while providing a means for storing large quantities of hot water

An economizer, besides providing a large storage of hot water for sudden demands, increases the economy of a steam power plant by utilizing the heat in the flue gases. The reduction of the flue-gas temperature, due to the absorption of heat by the economizer, may necessitate the addition of mechanical draft apparatus, or an increase in the height of the chimney. The purity of the feed water, the sulphur content in the coal, and the cost of producing additional draft should be considered in connection with the installation of economizers. With impure feed water, the cost of keeping the economizer tubes clean may be excessive.

The present tendency is to use economizers in large plants. These are usually installed as an individual economizer for each boiler. The economizer installations may be in the same setting as the boiler or in a setting separate from the boiler.

The economizer illustrated in Fig. 50 is of the independent type and is placed apart from the main boiler setting. In this type, the flue gases flow from top to bottom while the water passes through the whole economizer from bottom to top. The economizer consists of forged steel boxes which are connected by straight steel tubes. In another type of steel economizer, sections similar to those for water-tube boilers are used in place of the steel boxes. In some types of steel economizers, the heating surface is composed of elements similar to those used for superheaters and as illustrated in Fig. 35. The steel-tube economizer illustrated in Fig. 50 is placed at the back of the boiler as indicated. Steel-tube economizers are usually equipped with steam jet blowers or water sprays for soot removal.

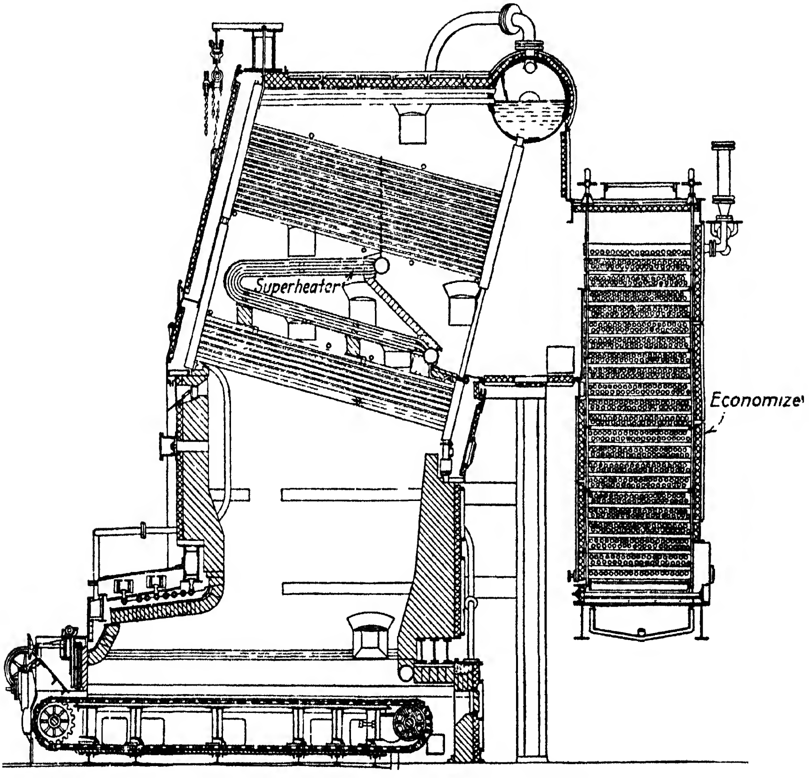


Fig. 50.—Steel-tube economizer installation.

Economizers consist of a series of steel tubes connected by headers. The boiler feed water enters at the end nearest the chimney, passes through the sections of tubes, and is heated by the hot gases that circulate through them.

For many years cast iron was used as the material for economizers, as the pressures in power plants were low and cast iron is non-corrosive. Modern plants use steel-tube economizers, which are protected from internal and external corrosion by removing the air from the water entering the tubes, by protective coverings, and by maintaining of a minimum inlet water temperature in excess of 160°F.

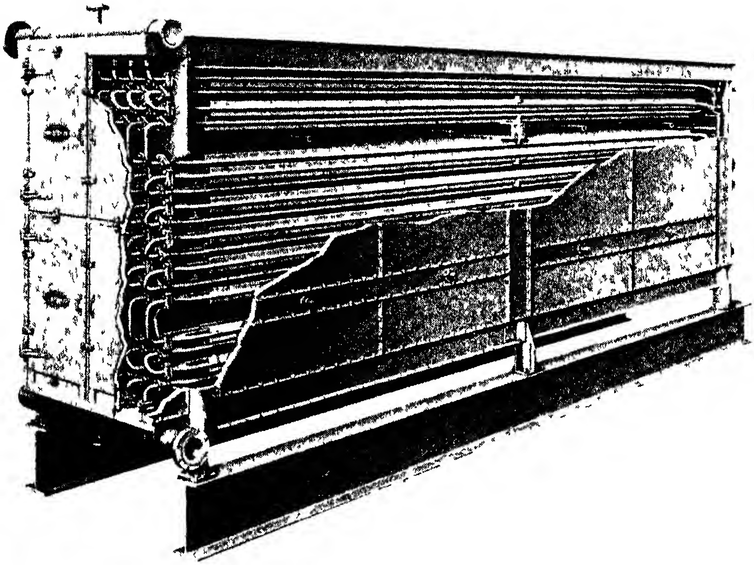


Fig. 51.—Elesco economizer (*Combustion Engineering Co., Inc.*)

Figure 51 illustrates the fin-tube flanged-joint type Elesco economizer.

The Foster-Wheeler extended-surface economizer is illustrated in Fig. 52. Figure 53 shows the construction details of this type of economizer.

AIR HEATERS

One of the largest losses of heat in a boiler plant is that escaping in the flue gas. The use of an economizer reduces this loss to a certain extent. The use of air heaters or preheaters attempts to reduce the flue-gas losses further. Preheating the air for combustion raises the efficiency of the boiler due to the smaller

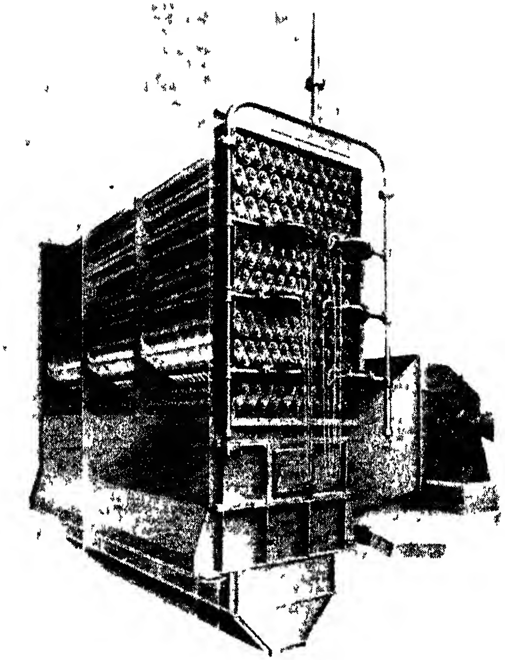


Fig. 52.—Foster-Wheeler extended-surface economizer.

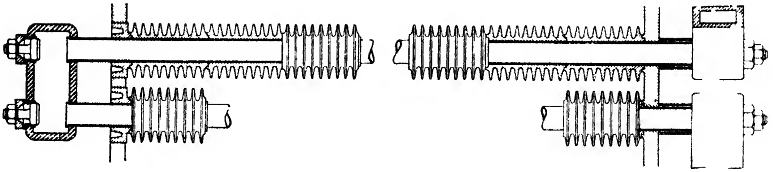


Fig. 53.—Economizer details. (*Foster-Wheeler.*)

amount of heat required to raise the temperature of the air after it enters the furnace.

Two types of air heaters are shown in Figs. 54 and 55. The type shown in Fig. 54 is the plate air heater of the recuperative

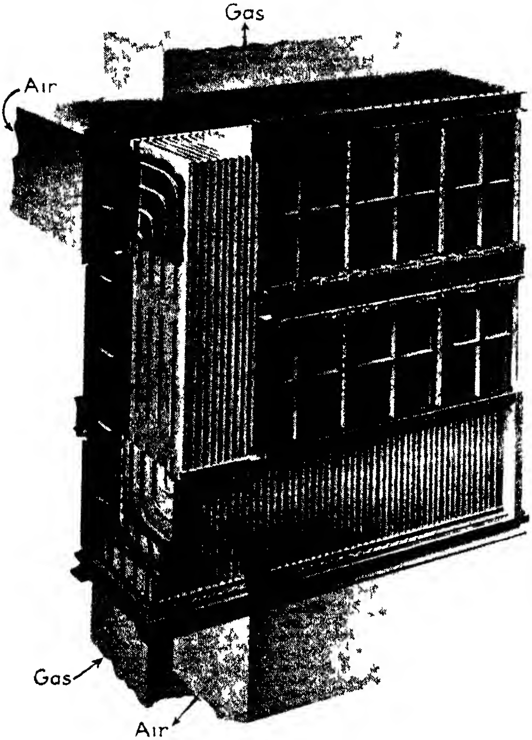


FIG 54 —Plate type air heater (*Combustion Engineering Co Inc*)

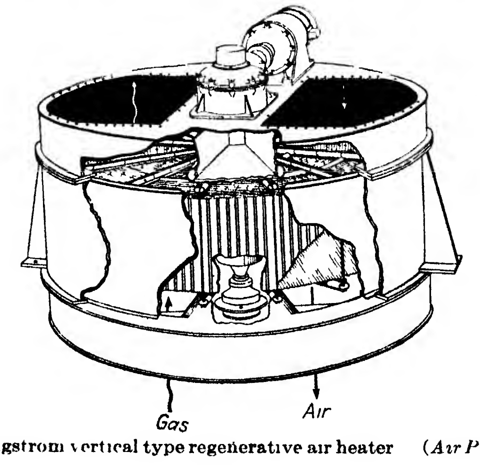


FIG 55 —Ljungstrom vertical type regenerative air heater (*Air Preheater Corp*) group. In this type of air heater the air enters at the point where the cooler gases from the boiler furnace leave, and the exit of the air from the heater is at the point of the hottest gases from the boiler furnace. Thus the air and hot gases flow in opposite directions.

The air heater illustrated in Fig. 55 is of the regenerative type. In this heater the heating elements rotate, absorbing heat from one section and giving up this heat to the air of another section.

DRAFT-PRODUCING EQUIPMENT

Chimneys.—A chimney or stack is used to carry off the obnoxious gases formed during the process of combustion, to discharge them at such an elevation as will render the gases unobjectionable, and to create sufficient draft to cause fresh air, carrying oxygen, to pass through the fuel bed, producing continuous combustion. The majority of power plants depend upon chimneys, at least in part, for draft.

The draft produced by a chimney is due to the fact that the hot gases inside the chimney are lighter than the outside cold air. In the boiler plant, the cold air is heated in passing through the fuel bed, rises through the chimney, and is replaced by cold air entering under the grate. This means that the amount of draft produced by a chimney depends upon the flue-gas temperature.

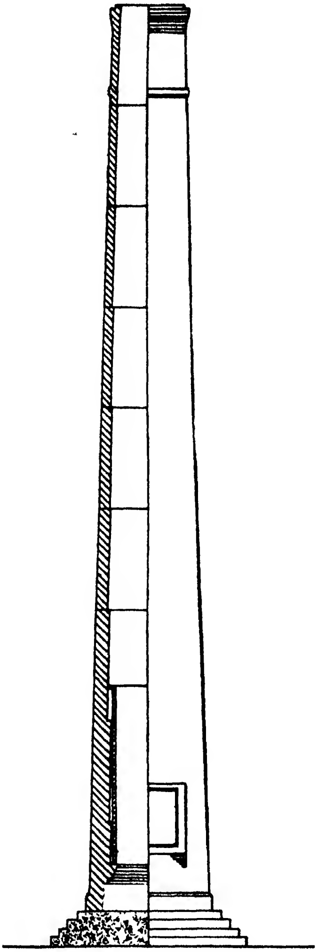


Fig. 56.—Brick chimney.

The intensity of the draft produced by a chimney depends also on its height; the taller the chimney, the greater is the draft produced, since the difference in weight between the column of the air inside and that of the air outside increases as the height of the chimney.

The intensity of chimney draft is measured in inches of water, which means that the draft is strong enough to support a column of water at the height given. The draft produced by chimneys is usually $\frac{1}{2}$ to $\frac{3}{4}$ in. of water.

Chimneys are made of steel, brick, or reinforced concrete. For small plants steel stacks are most desirable on account of lower first cost and ease of construction and erection. Self-sustaining steel stacks are used in some large power plants on account of the smaller space required as compared with other stacks. Steel stacks will rust and corrode unless they are kept well painted.

Brick is most commonly used where permanent chimneys are desired. A brick chimney, unless carefully constructed, will allow large quantities of air to leak in, which will interfere with the intensity of the draft. Brick chimneys are built round, octagonal, or square, and are usually constructed with two walls and an air space between them. The inside wall is lined with firebrick. In some cases chimneys are built of hard burned brick and without lining. The thickness of the chimney wall decreases by a series of steps, as illustrated in Fig. 56.

The use of concrete chimneys, reinforced with steel rods, is increasing on account of the absence of joints, light weight, and space economy as compared with brick chimneys. Ordinarily, a reinforced concrete chimney is less expensive to build than a brick chimney.

Draft produced by chimneys is called natural draft, and varies as the square root of the height. The approximate boiler horsepower a chimney will serve in a hand-fired installation, can be determined by the following formula, in which A is the internal section area of the chimney in square feet, and H is its height above the grate in feet:

$$\text{Boiler horsepower} = 3.33(A - 0.6\sqrt{A})\sqrt{H}. \qquad (48)$$

The height of a chimney depends upon the kind of fuel, the amount of fuel burned per square foot of grate surface, the frictional losses in the boiler setting and flue-gas passages, the temperature of the flue gas in the chimney, and whether economizers, preheaters, and forced-draft fans are used in the installation.

Mechanical Draft.—In modern large power plants equipped with mechanical stokers or economizers, the draft produced by chimneys is insufficient and some artificial method has to be used. A chimney once built is limited in capacity and will seldom be capable of producing a draft greater than 0.75 in. of water, or about 0.43 oz. pressure. Draft produced by a fan may have a large range of pressures, depending upon the speed at which it is operated.

Artificial draft may be produced by steam jets. In some cases the jets discharge beneath the grates, forcing the air and steam up through the fuel bed. In locomotives the jets of steam from the engine exhaust are directed upward from the base of the stack. Steam jets beneath the grates are cheap to install and with certain varieties of coal are absolutely necessary in order to prevent the formation of clinkers. Steam jets are uneconomical, and in stationary practice preference is given to the fan or the blower systems of artificial draft.

The method by which the fan produces draft gives rise to the forced- and induced-draft systems, both of which are shown in Fig. 57.

In the forced system (Fig. 57) the air delivered to the furnace is usually taken from the boiler room, and a duct from the fan discharges it into the ash pit. The air is thus forced into the furnace, which is under a slight pressure. The fact that the pressure within the furnace is greater than that of the atmosphere is one of the objections to the forced-draft system. It may cause the gas to leak into the boiler room through the cracks in the setting, and the flames from the furnace to flare out when the fire doors are opened. To overcome this latter objection, the system must be equipped with suitable dampers for shutting off the air when the furnace doors are opened.

The forced-draft system alone lends itself well to old plants when the draft produced by chimneys becomes insufficient on account of increased demands for power. The forced-draft system is also used in connection with the underfeed types of stokers.

In the induced-draft system, Fig. 57, the suction side of the fan is connected with the breeching of the boiler, and the products of combustion are discharged through a short chimney. The breeching is usually provided with a by-pass direct to the stack to be used in case of accident to the fan. The furnace and ash pit, in the case of the induced-draft system, are under a slight vacuum, any tendency for air leakage being inward.

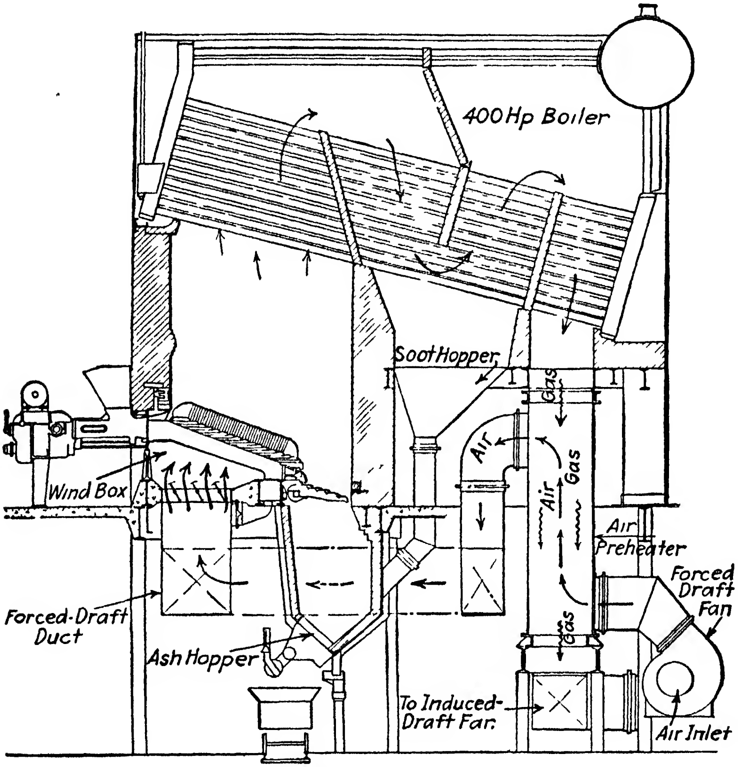


FIG. 57.— Forced- and induced-draft systems.

Since the induced-draft fan handles gases at temperatures of 400 to 500°F., it must be much larger than a forced-draft fan delivering cold air. This means that the cost of the induced-draft system is greater than that of the forced-draft system for the same size of power plant.

The induced-draft system is generally installed with economizers and is also used extensively in large steam-electric power plants which have high peak loads.

Mechanical draft permits a higher rate of combustion with less air per pound of fuel than is possible with natural draft produced by chimneys. A forced-draft system for a large power plant will cost about one-third of a brick chimney. Induced-draft system will cost from 40 to 60 per cent less than a brick chimney. To offset the above advantages is the cost of operating the mechanical-draft system. The power required to operate a fan will amount to from 2 to 5 per cent of the total boiler steaming capacity. The mechanical-draft systems have also greater depreciation and maintenance costs than well-constructed chimneys.

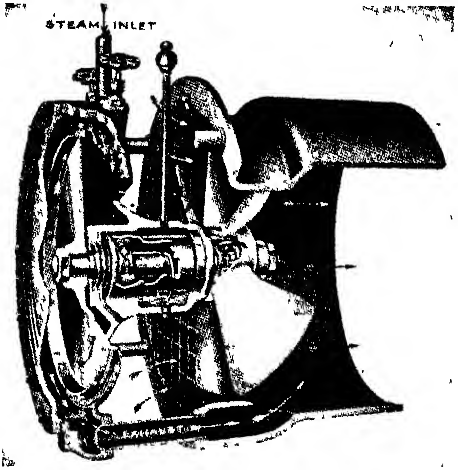


FIG. 58.—Undergrate turboblower.

Undergrate blowers, suitable for small plants, consist of a propeller operated by a direct-connected steam turbine or electric motor. Figure 58 illustrates an undergrate turboblower.

Undergrate blowers are usually installed in the side wall of the boiler ash pit, one blower to each boiler. The draft for each boiler is under separate control and may be varied to meet individual boiler requirements. Undergrate blowers are well adapted to small boiler plants in which an increased draft is required without extensive alterations.

FEED PUMPS AND INJECTORS

Water is forced into steam boilers by pumps or injectors. A pump will handle hot water, while an injector can be used only when the water is cold. The injector is not so wasteful of steam as a pump, and for feeding cold water has the additional advantage that it heats the water while feeding it to the boiler.

Direct-acting Feed Pumps.—Feed pumps may be driven from the crosshead of an engine. Such pumps are very simple, but can supply water to the boiler only when the engine is in operation.

Direct-acting steam pumps, driven by their own steam cylinders, are most commonly used for feeding small stationary boilers, as they can be operated independently of the main engine and their speed can be regulated to suit the feed-water demand of the boilers. With a tight suction pipe a direct-acting pump will lift cold water about 15 ft. Centrifugal pumps are frequently used in large power plants and are generally driven by steam turbines or by electric motors.

The details of construction of two forms of direct-acting pumps are shown in Fig. 59. The essential difference between these pumps is that the one uses a piston and the other a plunger. Both types are extensively used. The piston pattern occupies less floor space, but is more difficult to pack.

In the pump shown in Fig. 59, 1 is the steam cylinder and 2 is the water cylinder. The valve *E* is moved by the vibrating arm *F*, and admits steam into the cylinder, 1. If steam is admitted at the left of the piston *A*, the piston will be moved to the right, pushing the plunger *B*, driving the water through the valve *K*, and into the feed line at *D*. While the plunger is moving to the right, a partial vacuum is formed at its left which action opens the valve *N* and draws the water from the supply at *C*. When the plunger *B* reaches the extreme position to the right, the vibrating arm *F* moves the valve *E* to the left, admitting steam which pushes the piston and plunger to the left, driving the water through the valve *L* and taking a new supply through *M*. The function of the air chamber *P* is to secure a steady flow of water through the discharge and to prevent excessive pounding at high speeds by providing a cushion for the water.

The pump shown in Fig. 60 differs from the one just described in that the steam valve *G* is operated by the steam in the steam chest and not by a vibrating arm outside of the cylinder. The piston *C* is driven by steam admitted under the slide valve *G*, this valve being moved by a plunger *F*. This plunger *F* is hollow at the ends and the space between it and the head of the

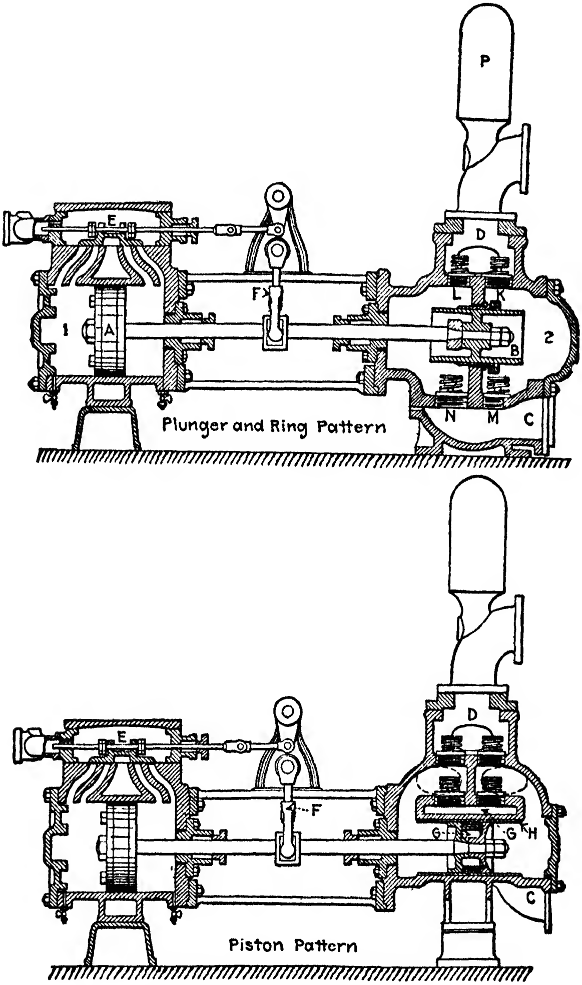


Fig. 59.—Boiler feed pumps.

steam chest is filled with steam. Thus the plunger remains motionless until the piston *C* strikes one of the valves *I*, exhausting the steam through the port *E* at one end The water end is similar to that of the pump in Fig. 59.

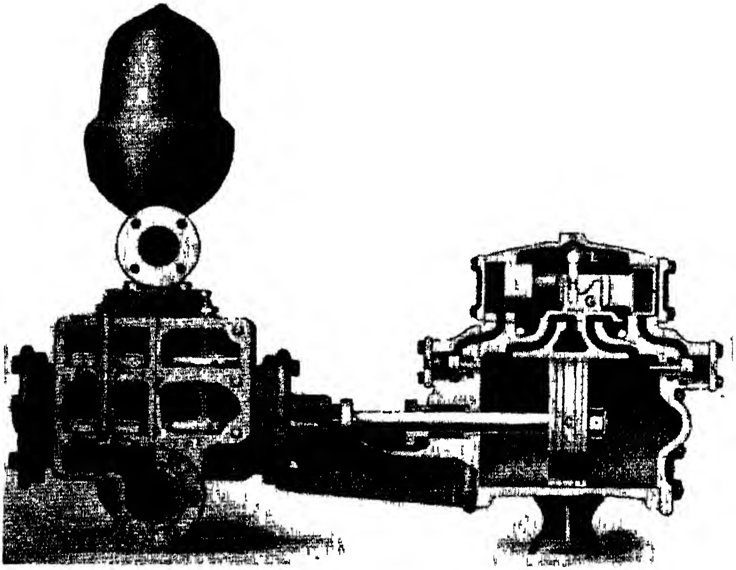


Fig. 60 —Boiler feed pump.

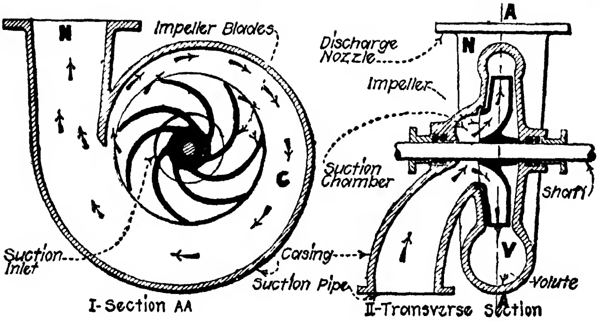


Fig 61 — Single-stage centrifugal pump.

Direct-acting feed pumps are inexpensive and simple in design, but have poor steam economy by reason of the fact that steam consumed is not used expansively.

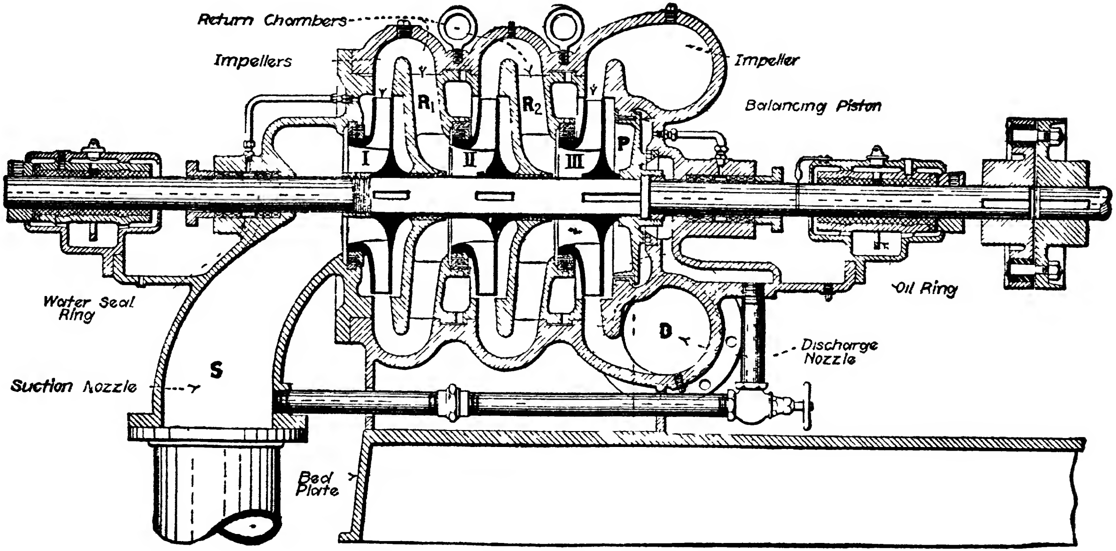


FIG 62 —Multi-stage centrifugal pump

Centrifugal Pumps.—Centrifugal feed pumps are in general use in large power plants. They consist of from two to five stages, depending upon the delivery pressure required. They are continuous in their action, set up no pulsating strains in the feed line, occupy small floor space, and can be operated with more economical driving power. Centrifugal pumps may be either turbine or motor driven.

In Figs. 61 and 62 are illustrated single-stage and multi-stage centrifugal pumps. In the case of Fig. 61, water enters the impeller around its center and is discharged into the case *C*. The multi-stage pump (Fig. 62) consists of two or more single-stage pumps connected in series. Multi-stage pumps are suitable for pumping against high heads.

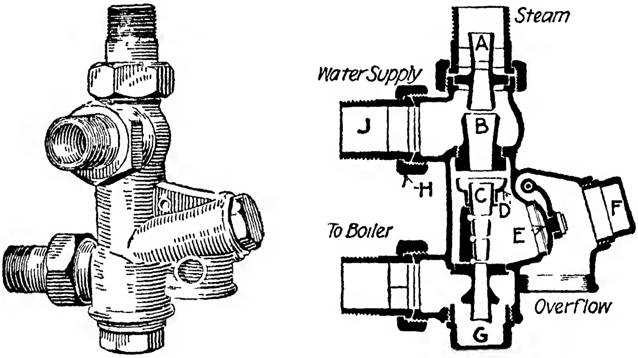


FIG. 63.—Injector.

Injectors.—Injectors are used very commonly for the feeding of locomotive, portable, and small stationary boilers. In some power plants, injectors are used in conjunction with pumps as an auxiliary method of feeding boilers.

The general construction of an injector is illustrated in Fig. 63. When priming the injector, steam from the boiler enters the injector nozzle at *A*, flows through the combining tube *BC*, and out to the atmosphere through the check valve *E* and overflow. The steam in expanding through the nozzle *A* attains considerable velocity, and forms sufficient vacuum to cause the water to rise to the injector. The steam jet at a high velocity coming into contact with the water is condensed, gives up its heat to the water, and imparts a momentum which is great enough to force the water into the boiler against a steam pressure equal to or greater than that of the steam entering the injector.

As soon as a vacuum is established in the injector and the water begins to be delivered to the boiler, the check valve E at the overflow closes. Should the flow of feed water to the boiler be interrupted, due to air leaking into the injector or to some other cause, the overflow will open and the steam will escape to the atmosphere.

Due to the fact that the vacuum in an injector is broken as the temperature of the water increases, injectors can work only when the feed water is 150°F. or cooler.

Duty of Pumps.—The duty of a pump is measured in foot-pounds of work done in moving water for each 1,000 lb. of steam used, or for each 1,000,000 B.t.u. delivered in the steam.

Duty per 1,000,000 B.t.u. is

$$\frac{\text{Water horsepower} \times 33{,}000 \times 60 \times 1{,}000{,}000}{\text{B.t.u. in steam used per hour}}. \qquad (49)$$

Small direct-acting pumps have duties as low as 15,000 ft.-lb. per 1,000 lb. of steam used. Large pumping engines have shown results as high as 181,000,000 ft.-lb. per 1,000 lb. of steam.

COAL- AND ASH-HANDLING SYSTEMS

In small power plants the coal is delivered to the furnace and the refuse is removed from the ash pit by hand shoveling. In such cases the coal pockets or coal bunkers should be located opposite the boilers, so that the rehandling of coal is reduced to a minimum. If the coal cannot be stored in front of the boilers, coal tip carts are found very satisfactory for conveying the fuel to the boiler room.

As plants increase in size, mechanical coal- and ash-handling systems are warranted. The coal-handling system usually consists of the following equipment: a receiving hopper, into which the coal is delivered; a crusher, which reduces the fuel to such a size as can conveniently be handled by stokers; elevating and conveying systems for raising the coal from the crusher and for distributing it to the bunkers, which are placed over the boilers; and spouts which deliver the fuel from the bunkers to the stokers.

The endless chain bucket conveyor (Fig. 64) is frequently used for handling both coal and ashes. This system consists of a continuous series of buckets suspended between two endless chains The discharge of the coal from the buckets into the bunkers over

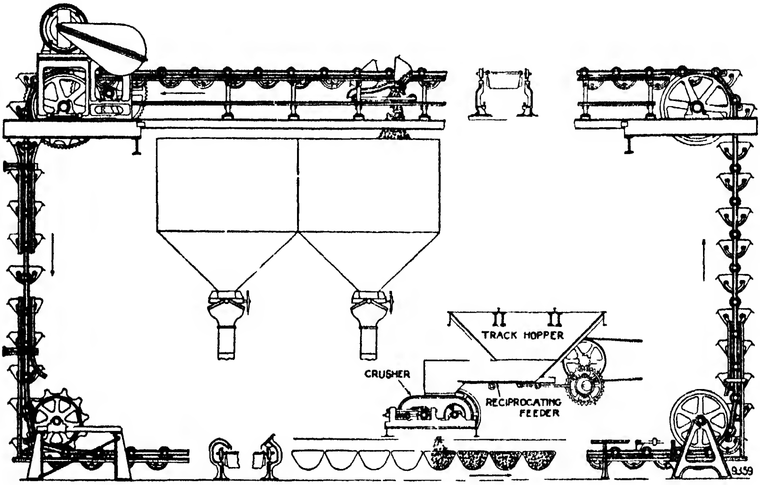


FIG 64.—Coal- and ash-handling system (Link-Belt Peck bucket carrier)

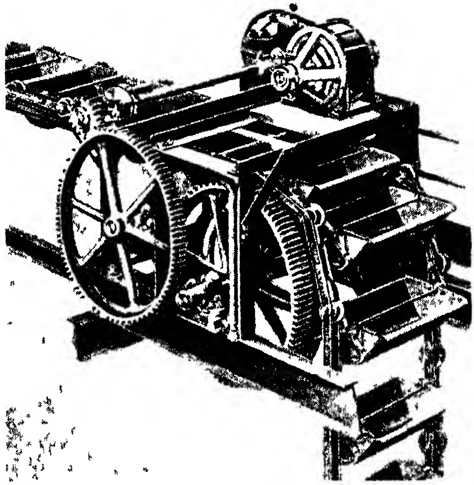


FIG. 65.—Mechanism of bucket carrier (Peck Link-Belt conveyor.)

the boilers is effected by a tripping device which turns the buckets over. The buckets pass beneath ash hoppers under the boilers.

Figure 65 illustrates the upper corner of the Link-Belt Peck overlapping pivoted bucket carrier.

The ashes are elevated by the buckets and discharged into an ash-storage bin. Hoist and trolley systems, scraper conveyors, screw conveyors, and belt conveyors are also used in handling coal and ashes. Vacuum or steam conveyors are used for handling ashes and fine coal. Vacuum and steam conveying systems consist of a pipe line through which the ashes or fine coal are carried by air or steam at high velocity.

Problems

1. Discuss the advantages of superheaters for large power plants.

2. Report on the uses of mechanical stokers in the power plants in your vicinity.

3. Calculate the percentage of gain which will result from preheating feed water to 200°F., from a temperature of 70°F., if a boiler plant is operated at a steam pressure of 140 lb. gage.

4. Examine the draft-producing systems in the power plants in your vicinity, and hand in a complete report, showing types of stacks, mechanical-draft systems, and the intensity of the draft used.

5. A pumping engine pumps 8,000,000 gal. of water per day of 24 hr., against a head of 110 ft. It uses 2,500 lb. of steam per hour. If the steam pressure is 140 lb. per square inch gage, and the feed-water temperature is 202°F., calculate the duty of the pumping engine per 1,000,000 B.t.u.

6. Name the parts in Fig. 44.

7. A power plant having a total capacity of 2,000 boiler hp. installed is equipped with a stack 125 ft. high and 8 ft. in diameter. Is this stack of sufficient size?

8. What boiler capacity will a stack 100 ft. high and 5 ft. in diameter supply?

9. A 1,000-hp. boiler is to be equipped with a stack. If it is decided that the stack should have a height of 200 ft., what diameter should it have?

10. Using data as in Problem 5 calculate the duty of the pumping engine in terms of 1,000 lb. of steam used.

11. To what extent are economizers used in the plants in your vicinity? Report reasons for this practice.

12. What methods are used in the power plants in your vicinity for handling coal and ashes? Include sketches.

13. Why is the ash-disposal problem in large power plants of major concern to the public?

14. Secure data which will enable you to compare the cost of coal at the mine per ton with the cost of delivering the same ton of coal to the boiler furnace.

15. Why are both air heaters and economizers used in large power plants?

16. Under what conditions must a closed feed-water heater be used?

17. Is a stack absolutely necessary in a power plant equipped with mechanical draft? Give reasons for your answer.

18. Is powdered coal replacing the stoker in large power plants? If not give reasons.

19. What is meant by the statement that "steam is not used expansively" in direct-acting steam pumps?

20. Why cannot steam be used expansively in direct-acting steam pumps?

CHAPTER VII

PIPING AND BOILER-ROOM ACCESSORIES

Grades and Sizes of Piping.—Piping used to convey the steam generated in a boiler is made of wrought iron or of mild steel. Wrought-iron pipe is more expensive and more difficult to secure than steel pipe. The largest portion of piping used in power plants is of mild steel, lap or butt welded, riveted or seamless drawn depending upon the size of pipe and pressures used.

The various grades of pipe are: standard, extra heavy, and double extra heavy. Extra heavy and double extra heavy have the same outside diameter as standard pipe, but the inside diameters are smaller, due to the greater thickness of the pipe. Taking the thickness of standard pipe as 1, that of extra heavy pipe is about 1.4 and that of double extra heavy 2.8. Extra heavy pipe is suitable for pressures up to 250 lb. per square inch, while double extra heavy pipe can be used for pressures up to about 1,000 lb. per square inch.

Sizes of standard steam pipe up to 12 in. are named by their insider diameter; above 12 in. they are designated by their outside diameter. The sizes of boiler tubes are given by their outside diameter.

Standard steam pipe is made in sizes of $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{4}$, $1\frac{1}{2}$, 2, $2\frac{1}{2}$, 3, $3\frac{1}{2}$, 4, 5, 6, 8, 10, and 12 in. Standard pipe is suitable for pressures up to 125 lb. per square inch.

The size of a pipe may be calculated approximately by the following formula:

$$d = 13.54\sqrt{\frac{W}{DV}}. \qquad (50)$$

In formula (50), d is the inside diameter of the pipe, W is the steam flowing in pounds per minute, D is the density corresponding to the pressure and quality of the steam (Table 6 or 7), and V is the steam velocity in feet per minute. For saturated steam V is 6,000 to 8,000 and for superheated steam up to 15,000 ft. per minute. V for exhaust steam is about 4,000 ft. per minute.

In piping designed to deliver 180,000 lb. of steam per hour at a pressure of 150 lb. per square inch at a velocity of 8,000 ft. per minute, if the steam is dry, the density D is from the steam tables $1/v_9 = 0.3319$. Then, by formula (50)

$$d = 13.54\sqrt{\frac{180{,}000}{60 \times 0.3319 \times 8{,}000}}$$
$$= 14.24, \text{ or a 14-in. pipe.}$$

Pipe Fittings.—Two kinds of fittings are used in steam power plants, the screwed and the flanged fittings. For saturated steam and for pressures less than 150 lb., all fittings 2½ in. and under may be screwed. Fittings 3 in. and over should have flanged ends. Screwed fittings, when properly installed, are less liable to leak than flanged fittings, which are put together with gaskets. Flanged fittings are easily taken apart and are most generally used in modern power plants.

For pressures up to 250 lb. per square inch fittings made of gray cast iron may be used if the total steam temperature is below 450°F. Cast iron is not used in the steam piping systems of modern high pressure power plants. Forged steel, straight or alloyed, is used for fittings and valve bodies in steam power plants which operate at pressures in excess of 200 lb. and temperatures higher than 400°F.

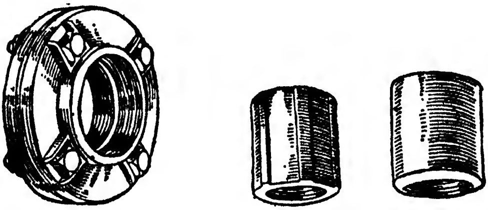


FIG. 66.—Pipe unions and coupling.

The pipe fittings most commonly used are illustrated in Figs. 66 to 74.

Figure 66 illustrates several forms of pipe fittings which are used for uniting two lengths of pipe.

The elbow or ell shown in Fig. 67 is employed for connecting two pipes, of the same size, at an angle to each other. If the pipes are of different diameters a reducing ell, as shown in Fig. 68 should be used.

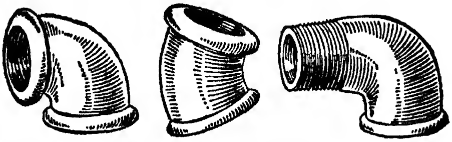


Fig. 67.—Ells.

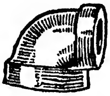


Fig. 68.—Reducing ell.

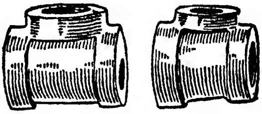


Fig. 69.—Tees.

The tees shown in Fig. 69 are used for making a branch at right angles to a pipe line.

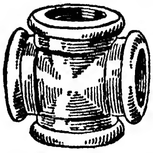


Fig. 70.—Cross.

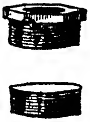
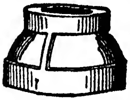


Fig. 71.—Bushing.



Reducing Coupling

Fig. 72.

The cross shown in Fig. 70 is used when two branches must be connected in opposite directions.

In order to reduce the size of a pipe line, a bushing (Fig. 71) or a reducer (Fig. 72) can be used.

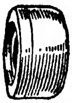


Fig. 73.—Cap.

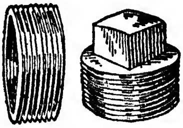


Fig. 74.—Plug.

To close the end of a pipe, a cap, (Fig. 73) is used, while the plug shown in Fig. 74, is used to close a fitting threaded on the inside.

In cast-iron flanged fittings the flange is always a part of the casting. For joining two ends of a pipe, the pipe and flange are threaded, the pipe is screwed beyond the face of the flange, and the two are faced off together. Another method is to weld the flanges on the pipe.

Autogenously welded butt joints are used to an increasing extent in long pipe lines. Outlets and connections are also being welded to piping.

Expansion of Piping.—In piping systems, provision must be made to allow for the expansion and contraction due to variation in the temperature of the steam within the pipe. Unless a pipe expands freely, distortion or injurious strains on the joints and fittings will occur.

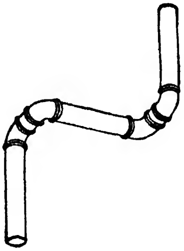


FIG 75.—Double-swing expansion joint.

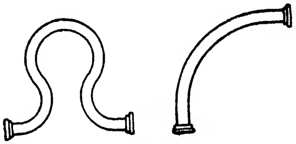


FIG. 76 –Long radius bends.

The simplest method for low pressures is to permit the expansion to adjust itself in a threaded joint. Such an arrangement is shown in Fig. 75. Any expansion or contraction in the piping is adjusted by a slight movement in the screwed joints.

Another method quite extensively used in high pressure piping is to utilize the elasticity of piping by the employment of a long radius bend, as illustrated in Fig. 76. A long radius bend, besides taking care of the expansion after the piping is in place, reduces the number of joints, decreases friction, and is much easier to erect than pipe fittings. One of the objections against the use of long radius bends is the space required.

The slip expansion joint illustrated in Fig. 77 overcomes the above objection. The main casting of this expansion joint is divided into two parts. The expansion or moving element consists of a non-corrodible bronze sleeve, made steam tight by the long stuffing box. The sleeve is supported at the outer end by flanges. In installing a slip expansion joint, the pipe must be securely anchored to prevent the steam pressure from forcing the joint apart.

Pipe Covering.—All pipes carrying steam and hot water should be covered with some heat-insulating material in order to reduce the loss of heat to a minimum. If saturated steam is conveyed in uncovered steam pipes, some of it will condense, reducing the economy of the plant. Tests demonstrate that pipe covering will pay for itself in a very short time.

Pipe covering is usually applied in sections, molded to the required size of the pipe, and secured to the pipe by bands. Valves and fittings are usually covered with a plastic insulating mortar.

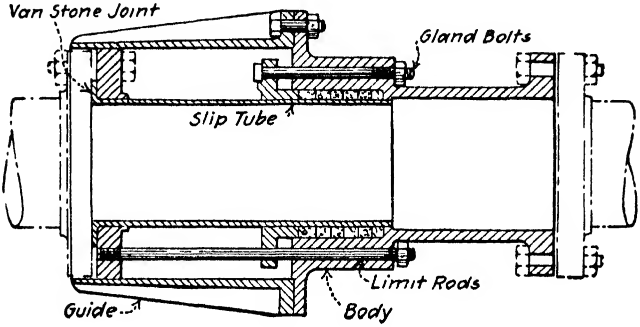


FIG. 77.—Expansion joint.

The pipe-covering material commonly used is 85 per cent magnesia for temperatures up to 600°F. Power plants which operate with highly superheated steam usually use, in addition to the 85 per cent magnesia, asbestos fiber or some substance of high insulating efficiency.

Erecting Pipe.—Steam-pipe lines should always be laid with a gradual slope in the direction in which the steam flows. This will allow the condensation and the steam to flow in the same direction. If this is not done water may accumulate, will be picked up by the steam, and may cause much damage either to the fittings or to the engine.

Care must be taken that the pipe lines have the proper alignment in order to prevent strain on the fittings. Pipe lines must be supported by wall brackets, hangers, or floor stands to guard against excessive deflection and vibration.

Valves.—The function of a valve is to control and regulate the flow of water, steam, or gas in a pipe. In the globe valve (Fig. 78), the fluid usually enters at the left, passes under the valve, and out at the left. This method of installation permits the valve stem to be packed, when the valve is closed, without cutting the steam pressure off the entire line.

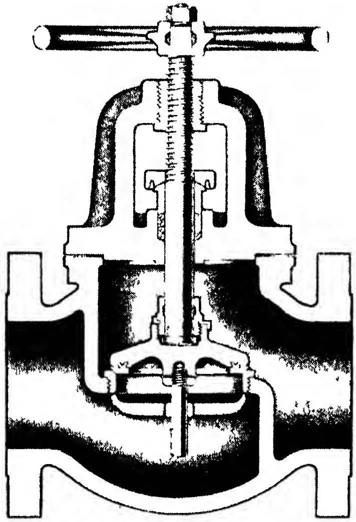


FIG. 78.—Crane globe valve.

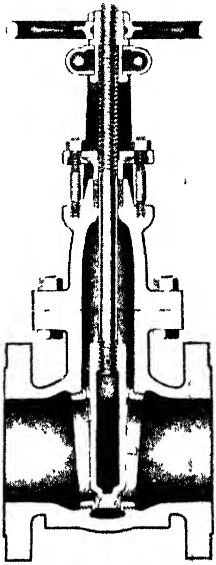


FIG. 79.—Crane gate valve.

If a globe valve is installed so that the fluid enters at the right (Fig. 78), the pressure of the steam, when the valve is closed, tends to keep it in that position and there is much less likelihood of the valve leaking, but the valve cannot be opened if it should become detached from the stem.

Globe valves in sizes up to 3 in. have brass bodies; large valves are made of cast iron for ordinary pressures and temperatures, and of forged steel for high temperatures and pressures.

A gate valve is shown in Fig. 79. This form of valve gives a straight passage through the valve, and is preferable for most purposes to the globe valve. For high-pressure work and in large sizes, gate valves are usually of the outside-screw type, which means that the stem protrudes beyond the hand wheel. This enables the operator to tell at a glance whether the valve is open or closed.

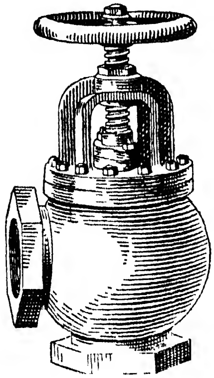


Fig. 80.—Angle valve.

Figure 80 illustrates an angle valve which takes the place of an ordinary valve and ell.

The function of a check valve, illustrated in Fig. 81, is to allow water or steam to pass in one direction but not in the other.

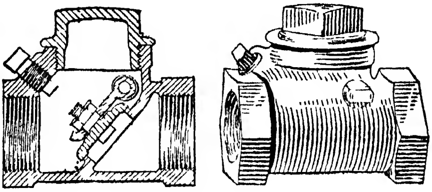


Fig. 81.—Check valve.

A boiler feed line should always be provided with a check valve and also with some form of globe or gate valve to enable the operator to examine and repair the check valve.

Blow-off Valves.—A boiler should always be provided with a blow-off connection at its lowest point for removing mud and sediment, as well as for the purpose of draining the boiler. The blow-off connections must be provided with blow-off valves, which can be easily opened, which will give a free passage for scale and sediment when open, and which will not leak when

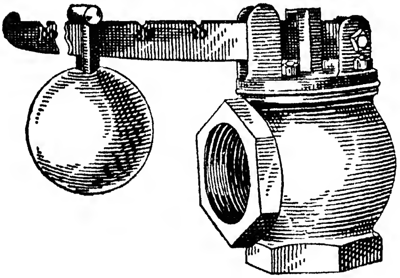


Fig. 82.—Lever safety valve.

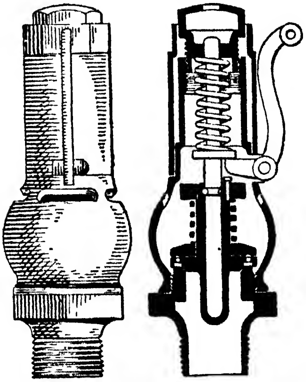


Fig. 83.—Pop safety valve.

closed. Best practice recommends the use of two valves or of a valve and a blow-off cock in the blow-off line of each boiler.

Safety Valves.—The function of a safety valve is to prevent the steam pressure from rising to a dangerous point.

The lever safety valve shown in Fig. 82, now seldom used, consists of a valve disc which is held down on the valve seat by means of a weight acting through a lever, the steam pressing against the bottom of the disc. The lever is pivoted at one end to the valve casing, and is marked at a number of points with the pressures at which the boiler will blow off if the weight is placed at that particular point. Lever safety valves are seldom used in modern power plants.

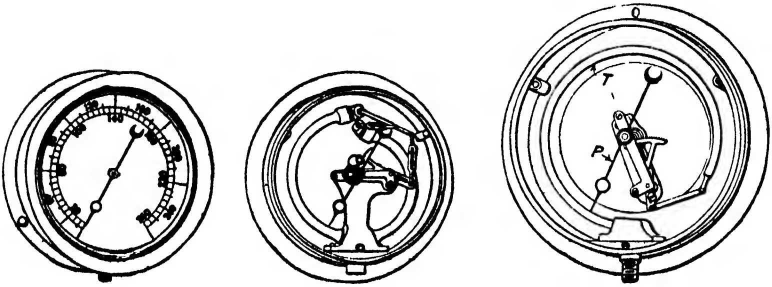


Fig. 84.—Steam gages.

The pop safety valve shown in Fig. 83 differs from the lever valve in that the valve disc is held on its seat and the steam pressure is resisted by a spring, in place of a weight and levers. Pop safety valves can be adjusted to blow off at various pressures by tightening or loosening the spring pressure on the valve disc.

The American Society of Mechanical Engineers recommends that two or more safety valves be installed on every boiler, except in the case of small boilers which require a safety valve 3 in. or smaller.

Steam Gages.—A steam gage indicates the pressure of the steam in a boiler. The most common form, shown in Fig. 84, consists of a curved spring tube closed at one end. One end of the tube is free, while the other is fastened to the fitting which is secured into the space where the pressure is to be measured. The cross-section of the tube is made elliptical or irregular in shape so that pressure applied to the inside of the tube causes the free end to move. This motion is communicated by means of levers and small gears to the needle which moves over a graduated dial face, and records the pressure directly in pounds per square inch.

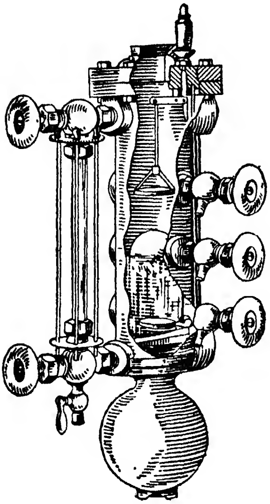


FIG. 85.—Water column

Water Glass and Gage Cocks.—The height of the water level in a boiler is indicated by a water glass, one end of which is connected to the steam space and the other end to the water space in the boiler. All boilers should also be provided with three gage cocks, one of which is set at the desired water level, one above it and one below. These are more reliable than the water glass and should be used for checking the glass.

Water Column.—The steam gage, water glass, and gage cocks are usually fastened to a casting called a water column. One form of water column is shown in Fig. 85. This water column is fitted with a float and a whistle to notify the operator should the water in the boiler become too low or too high. An operator who takes proper care of the boilers in his charge will never allow the water to be at a height that will necessitate audible warnings.

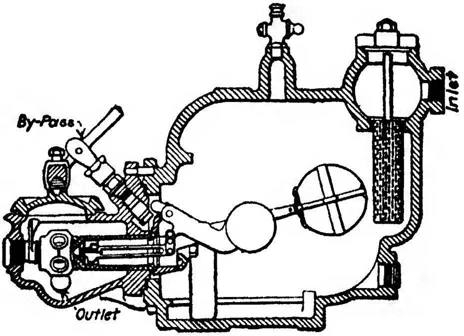


FIG. 86.—Steam trap.

Steam Traps.—The object of a steam trap is to drain the water from pipe lines without allowing the steam to escape. One form of steam trap is shown in Fig. 86; in this case the valve is controlled by a float when the water in the trap rises to a sufficient height. In another type of trap, called the bucket type, there is a bucket in the interior of the trap, which when filled with the condensed steam operates as a float and opens a valve.

Traps which receive the condensed steam and return it to the boiler are called return traps.

Fusible Plugs.– Plugs with a core of some fusible metal are used to protect boilers from overheating. If a plate, into which a fusible plug is screwed, becomes overheated, the fusible metal melts and runs out allowing the steam and hot water to run into the boiler furnace.

Fusible plugs are placed about 3 in. above the top row of tubes in a cylindrical tubular boiler and in the lower side of the upper drum of a water-tube boiler. Fusible plugs are not recommended for boilers carrying pressures in excess of 250 lb. per square inch.

Problems

1. Make a clear sketch showing the location of the boiler stop valve with reference to the piping from the boiler.
2. Make an inspection of some plant in your vicinity and report on the following:
   (*a*) Types of fittings used.
   (*b*) Are the steam pipes covered? If so, with what material?
3. Make a clear sketch showing how you would arrange the piping and fittings in connection with a boiler blow-off connection.
4. Where should safety valves be placed on fire-tube boilers? On water-tube boilers?
5. Sketch three forms of pipe supports.
6. Why place a fusible plug about 3 in. above the top row of tubes in a cylindrical tubular boiler?
7. Show by means of sketches how expansion of piping is taken care of in the power plants in your vicinity.
8. What guide has the engineer to aid him in conforming to the best practice in selecting piping and fittings for power plants.
9. Calculate the approximate size of piping which should be used to carry 250,000 lb. of steam per hour with a velocity of 12,000 ft. per minute if the steam has a pressure of 250 lb. and a temperature of 650°F.
10. If the steam in Problem 9 has a quality of 0.97, calculate the approximate diameter of the piping.
11. Why are fusible plugs not advisable for high-pressure-boiler plants?

12. Compile a table of pipe dimensions, giving the approximate internal and external diameter as well as thickness of pipe sizes from 1/8 to 10 in.

13. Why are flanged fittings preferable to screwed fittings?

14. In plants operating at pressures of 1,200 lb. per square inch and higher, will the water column shown in Fig. 81 have to be modified, and if so, how?

CHAPTER VIII

STEAM ENGINES

Description of the Steam Engine.—A steam engine is a motor which utilizes the energy of steam. It consists essentially of a piston and cylinder with valves to admit and to exhaust the steam, a governor for regulating the speed, some lubricating system for reducing friction, and stuffing boxes for preventing steam leakage.

In the steam engine working as a motor, continuous rotary motion of the shaft is essential. This is accomplished by the interposition of a mechanism consisting of a connecting rod and crank, which changes the to-and-fro, or reciprocating, motion of the piston into mechanical rotation at the shaft. A steam engine in which the reciprocating motion of the piston is changed into rotary motion at the crank is called a reciprocating steam engine to differentiate it from the steam turbine to be described in a later chapter.

The various parts of a steam engine are illustrated in Figs. 87 88, and 89.

Steam from the boiler at high pressure enters the steam chest *A* (Fig. 87) and is admitted alternately through the ports *BB* to either end of the cylinder by the valve *C*. The same valve also releases and exhausts the steam used in pushing the piston *D*. *E* is the cylinder in which the steam is expanded. The motion of the piston *D* (Fig. 88), is transmitted through the piston rod *F* to the crosshead *G*, and through the connecting rod *H* to the crank *I*, which is keyed to the shaft *K*.

The shaft is connected directly, or by means of intermediate connectors, such as belts or chains, to the machines to be driven.

The shaft carries the flywheel *L* (Fig. 88), the function of which is to make the rate of rotation as uniform as possible and to carry the engine over the dead centers. The dead center occurs when the crank and connecting rod are in a straight line at either end of the stroke, at which time the steam acting on the piston will not turn the crank. A flywheel is sometimes used as a driving pulley, as shown in Fig. 89.

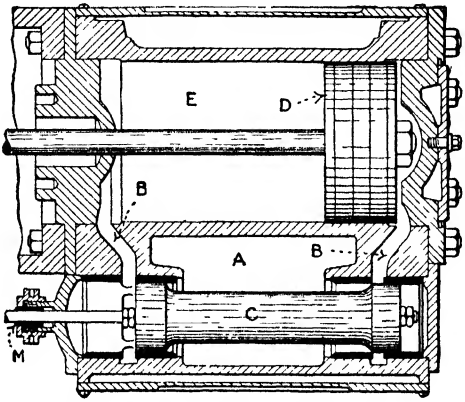


FIG. 87.—Engine cylinder and steam chest.

The eccentric shown in Fig. 89 also rotates with the shaft, and its function is to impart a reciprocating motion to the valve. The eccentric consists of a circular iron disc, so keyed to the shaft that its center is eccentric to the center of the shaft. Around the eccentric fits a ring, called the eccentric strap. The eccen-

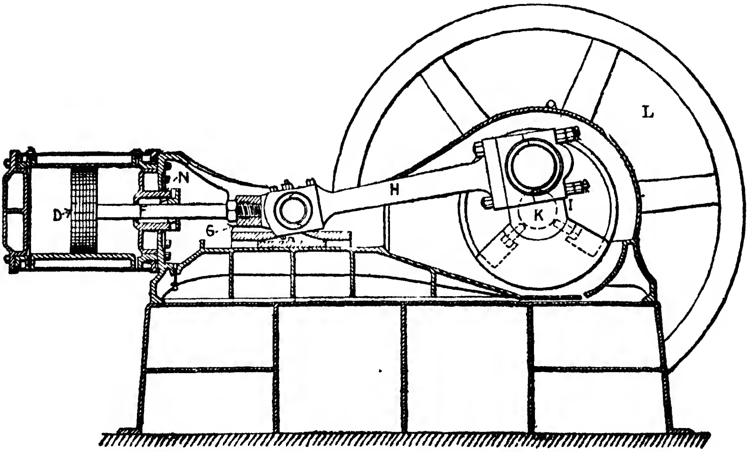


FIG. 88.—Steam engine.

tric strap is bolted to a rod, called the eccentric rod. The eccentric imparts a backward and forward motion to the valve through the eccentric rod and valve stem. This motion given to the valve is dependent upon the eccentricity of the eccentric. The eccentricity is the distance between the center of the eccentric and the center of the shaft. Changing the eccentricity changes the travel of the valve. The travel of the valve, or the total distance it moves, is equal to the throw of the eccentric, or to twice the eccentricity.

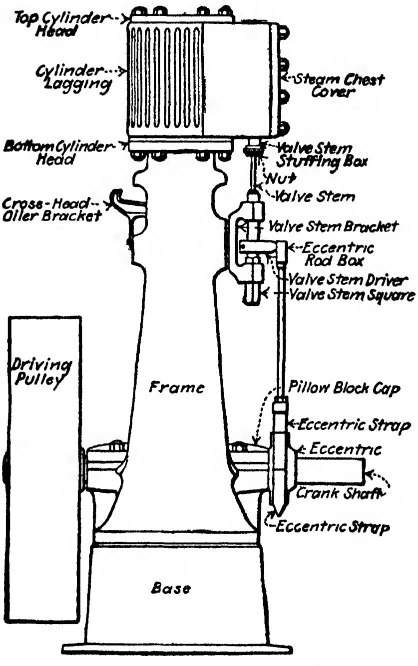


FIG. 89.—Vertical steam engine.

Stuffing boxes which prevent the escape of steam around the rods are illustrated at *M* and *N* in Figs. 87 and 88, respectively.

Early History of the Steam Engine.—The use of steam for the pumping of water dates back to about 1700. The operation of the engines of that time differed from the modern steam engine in that steam was admitted into a closed vessel, at atmospheric pressure, and was condensed by throwing cold water over the external surface of that vessel. The vacuum thus created was utilized in the production of work.

The Newcomen engine of 1705 first made use of a cylinder and piston, but worked on the same principle as the engines mentioned above.

In 1712, Newcomen designed a steam engine in which the condensation of the steam was effected by introducing water into the cylinder. The operation of the valves in the Newcomen engine was by hand and steam at only atmospheric pressure was utilized.

In 1718, Henry Brighton invented a self-acting machine. The valves consisted of a series of tappets operated by the beam of the engine.

James Watt, in 1769, laid the foundation for many of the important features of the modern steam engine. His greatest improvements consisted in transferring the steam to another vessel for condensation, making use of pressure greater than atmospheric, constructing the steam-engine double acting, and in inventing the steam engine indicator. Watt was the first to realize the advantages resulting from using steam expansively, although this was applied to an actual engine by Wolfe in 1804.

George H. Corliss introduced the Corliss valve gear in 1845.

Classification of Steam Engines.—Reciprocating steam engines are classified in the following ways:

1. According to the rotative speed in revolutions per minute, engines are designated as high speed, medium speed and slow speed. A high-speed engine usually operates at a speed of 175 to 400 r.p.m., a medium-speed engine at 125 to 175 r.p.m., and a slow-speed engine at less than 125 r.p.m.
2. Depending upon the position of the cylinder, with reference to the crank, engines are either horizontal or vertical.
3. With reference to the valve gear employed, engines are classed as slide-valve, Corliss-valve, and poppet-valve types.
4. On the steam-flow basis, an engine is either a counterflow or a uniflow.
5. Depending upon the number of cylinders through which the steam passes, engines are classified as simple, compound, or triple expansion.
6. According to the operating basis, engines are either condensing or non-condensing.

7. Depending upon the type of governor, engines are either throttling or automatic.

8. On the basis of use, engines are classified as stationary, locomotive, and marine.

Losses in Steam Engines. The main losses in a steam engine are:

1. Loss in pressure as the steam is trānsferred from the steam boiler to the engine cylinder, owing to the throttling action in the steam pipe and ports. Steam in passing through a small port loses part of its energy in overcoming friction. To reduce such losses to a minimum, the pipes and ports must be ample and all steam passages must be as straight as possible.

2. Leakage past piston and valves. The losses due to leakage past the piston and valves are usually very small in well-designed engines and may be kept so by proper attention.

3. Loss due to the condensation of the steam in the cylinder. This loss takes place when the entering steam comes in contact with the cylinder walls, which have been cooled by the exhaust steam which previously filled the cylinder. Cylinder condensation becomes greater as the difference between the admission and exhaust pressures is increased. When steam is sufficiently superheated, no condensation takes place, but the loss, though somewhat lessened, is still present.

Losses due to condensation of steam with the cylinder may also be decreased by increasing the engine speed, by regulating the point of cut-off, by compounding, using steam jackets, increasing the size of the units, or by employing the uniflow principle, to be described later.

4. Radiation losses. Radiation losses take place when the steam passes through the steam pipes from the boiler to the cylinder and also while the steam is in the cylinder. Radiation losses in the steam pipes leading from the boiler to the engines may be reduced by the use of a good pipe covering. The radiation losses from the cylinder of the engine are reduced by jacketing the cylinder with some non-conducting material.

5. Losses of heat in the exhaust steam. Seventy-five per cent or more of the heat available in the steam when it enters the engine cylinder is carried away in the exhaust. Part of this heat can be recovered by using the exhaust steam for the heating

of feed water before it enters the boiler, for the heating of buildings, or in employing the exhaust steam in connection with various manufacturing processes.

6. Mechanical losses due to the friction of the moving parts. These losses may be kept at a minimum by proper lubrication.

Action of the Plain Slide Valve.—Figure 90 shows a section through a steam-engine cylinder with the slide valve in mid-position. *A* and *B* are the steam ports, which lead to the two ends of the cylinder; *C* is the exhaust space. The steam ports are separated from the exhaust space by the two bridges, *D* and *E*. *F* is the steam chest. *V* is a plain slide valve, commonly called a D slide valve. The amount *S* that the valve *V* extends over the outside edge of the port, when the valve is at the center of its travel, is called the steam lap. Similarly, the amount *X* by which the valve overlaps the inside edge of the port when it is in mid-position is called the exhaust lap. *M* and *N* are the steam and exhaust pipes, respectively.

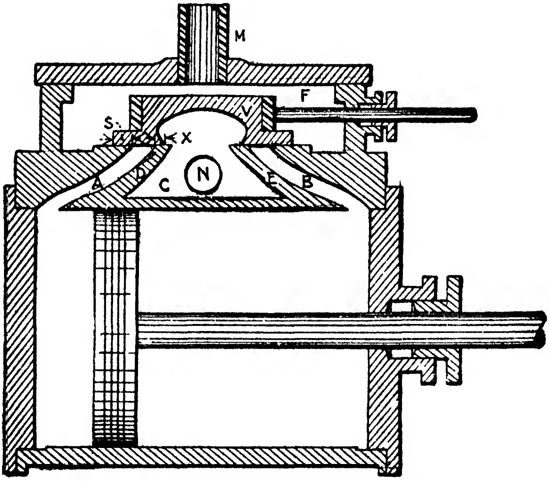


Fig. 90.—Engine cylinder and plain slide valve.

A term frequently used in connection with the operation of valves is "lead." By lead is meant the amount that the port is uncovered when the engine is on either dead center. The object of lead is to supply full-pressure steam to the piston as soon as it passes the dead center.

The motion of the valve produces four events: admission, cut-off, release, and compression. Admission is that point at which the valve is just beginning to uncover the port. The position of the valve for this event is shown in Fig. 91. Cut-off occurs, Fig. 92, when the valve covers the port, preventing further admission of steam. This is followed by the expansion of the steam until the cylinder is communicated with the exhaust opening, at which time release, as shown by Fig. 93, occurs. Compression occurs when communication between the cylinder and exhaust opening is interrupted, Fig. 94, and the steam remaining in the cylinder is slightly compressed by the piston. The valve is in the same position at cut-off as it is at admission, only it is traveling in the opposite direction. Similarly, the positions of the valve are the same at release and compression.

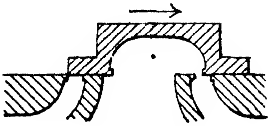


FIG. 91.—Admission.

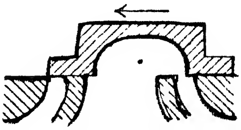


FIG. 92 Cut-off.

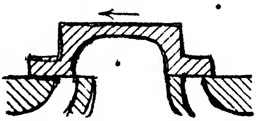


FIG. 93.—Release.

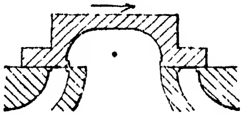


FIG. 94. Compression.

Types of Plain Slide Valves.—If the valve is constructed without laps, as shown in Fig. 95, there is no period of valve closure, and the steam acts non-expansively. The release and the cut-off of the steam occur at practically the same instant. The steam admission in one end of the cylinder takes place throughout the entire stroke, while the steam in the opposite end of the cylinder is exhausted at the same time. Such a valve would be uneconomical because of its failure to provide for the expansion of the steam, and, as a result, is only resorted to in the direct-acting steam pump, which is essentially a special case.

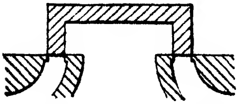


FIG. 95.—Valve without laps.

For best economy, a steam engine should be provided with a valve which cuts off the steam at about one-third of the stroke and releases it somewhere near the end of the stroke.

The simplest type of valve for steam engines is the plain slide valve, illustrated in Fig. 90. This type of valve is not used where steam economy has to be considered. The plain slide valve is used to a limited extent in connection with portable engines, traction engines, or small stationary steam engines. The chief objection to its use on engines of large sizes is that it is not balanced. If the difference between the steam and the exhaust pressure is large, the force of the steam holding the valve upon its seat is also large, and consequently the force required to move the valve backward and forward may be excessive. This consumes a part of the work developed by the engine, needlessly strains the valve gear, and makes it difficult to keep the valve steam-tight. The objections to the plain slide valve are remedied by the use of balanced valves.

Balanced Valves.—The piston valve, illustrated in Fig. 87, is one form of balanced valve. The pressures upon all sides that would force the valve against its seat are balanced by equal and opposite forces. When well made, and properly fitted with packing rings, little leakage occurs, but small piston valves are often made without packing rings and in such a case leakage is very likely to occur.

The balancing of the flat slide valve is accomplished by the addition of balancing plates. Such a device is shown in Fig. 96. It consists of a machined plate, arranged so that it excludes the high-pressure steam from the top of the valve. This eliminates the pressure that would force the valve upon its seat, and the only friction theoretically present is that due to the weight of the valve itself. Various valves employing this principle have been devised. Some are only partially balanced. Others differ in the method of maintaining a steam-tight joint between the valve and the balancing plate. The principle involved in all balanced valves is the same.

Balanced valves are employed in connection with the so-called automatic high-speed engines. This type of engine usually operates at speeds up to 350 r.p.m. In the automatic high-speed engine, the speed is controlled by changing the point of cut-off, or by regulating the volume of steam admitted to suit the engine load

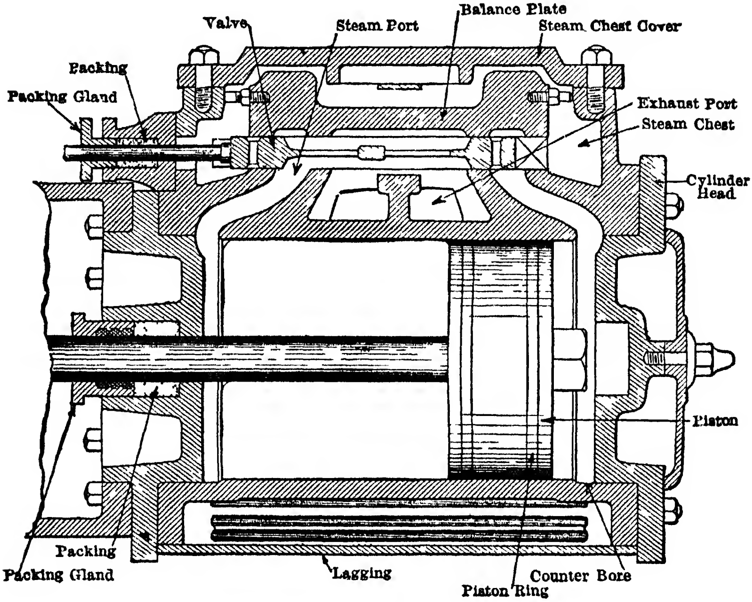


Fig 96 —Balanced valve

The Double-ported Valve.—One difficulty in the use of the plain slide valve is that a large movement or travel of the valve is necessary in order to fully open the port This makes it difficult to use the plain slide valve in engines having a large diameter and short stroke. The double-ported valve, Fig. 97, overcomes this difficulty. Instead of using one large port for the

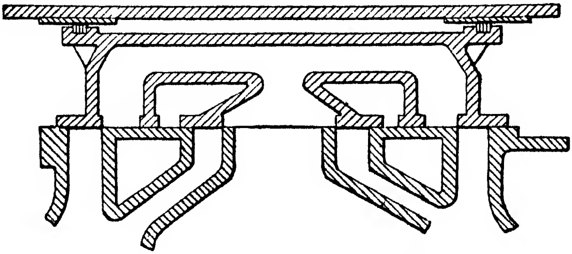


Fig 97 —Double-ported valve.

passage of the steam, two ports, whose combined areas would equal that of a single port, are used.

The Corliss Engine.—The slide-valve engine requires long ports or passages for the steam. This increases the amount of surface to which the steam is exposed. Another fault of the slide valve is that the same port is used for the live steam entering the cylinder, after it has been cooled by the exhaust steam. To overcome these objections, four-valve engines have been introduced. One of the earliest and best of these types is the Corliss engine.

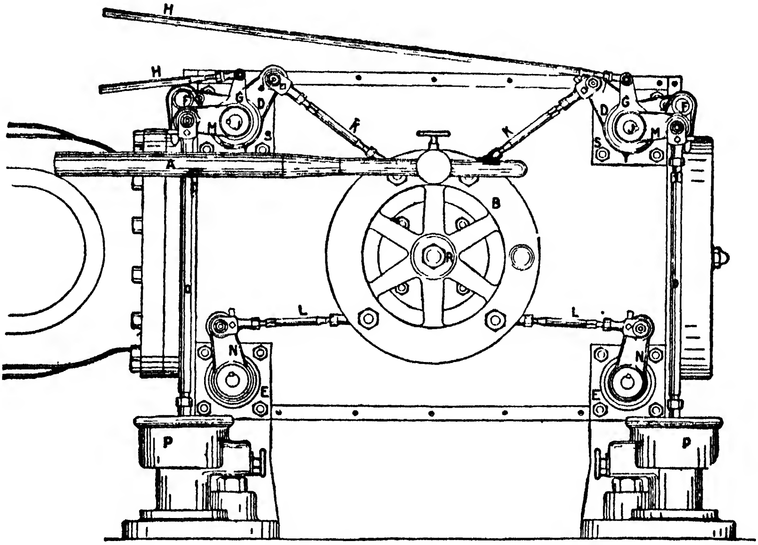


Fig. 98.—Corliss engine cylinder and valve gear.

The cylinder of a Corliss engine is illustrated in Fig. 98. It includes four valves, two for the control of the entering steam, and two for the exhaust. The valves are cylindrical in shape and are located at the top and bottom of the cylinder at the extreme ends of the stroke of the engine. The steam and exhaust valves operate, respectively, in the chambers *S* and *E*. The bell-crank levers *D* work loosely on the valve stems; they are connected to the wrist plate *B* by the rods *K*. The steam-valve levers *M* are keyed to the valve stem *J*, and are also connected by the rods *O* to the dash pots *P*. The bell-crank levers *D* carry at their outer ends V-shaped steam hooks *F*, which are provided with steel catch plates that engage with the arms *M*. The levers *G* are connected by the rods *H* to the governor, and carry upon their outer faces small cams which release the steam hooks. The exhaust-valve levers *N* are connected directly through the rods *L* to the wrist plate; their motion being identical with that of a plain slide valve.

In the operation of the engine, the wrist plate is given an oscillating motion by the eccentric to which it is connected through the rod *A*. This causes the bell-crank lever *D* to oscillate upward and downward about the spindle *J* as an axis. Upon the extreme downward movement, the steam hook engages the main valve lever *M*, and the upward movement of the hook lifts the lever *M* and opens the valve. The opening of the valve continues until the hook is disengaged by coming in contact with the knock-off cam on lever *G*. The instant the valve is released, the vacuum created in the dash pot *P* causes the quick return of the valve to its normal position. The governor controls the position of the knock-off cam, thus regulating the cut-off by varying the point at which the valve is released.

The Corliss engine is one of the most efficient types of reciprocating steam engines.

The valve gear of the Corliss engine, illustrated in Fig. 98, is operated by a single eccentric. With the single eccentric valve gear the point of cut-off of the steam may be varied up to about 40 per cent of the stroke. If a longer cut-off is desired, the Corliss engine must be equipped with two eccentrics, one to operate the inlet valves and the other to control the exhaust valves. In the double eccentric Corliss engine, the setting of the exhaust valves may be altered independent of the position of the admission valves.

The Non-releasing Corliss Engine.—The Corliss engine with the releasing or trip gear described becomes impractical when the speed of the engine is high. Consequently, most Corliss engines, with trip or releasing valve gears, operate at low speeds, usually about 85 to 100 r.p.m. To meet the field for direct connection to electric generators, the non-releasing Corliss engine has been developed. This engine has a positive connection between the eccentric and valve gear. This type of engine is equipped with

Corliss types of valve, but is governed by a flywheel governor in a manner similar to that used in the case of automatic high-speed engines. Figure 99 illustrates a non-releasing Corliss engine. Two eccentrics are employed. The admission valves are connected to a reach rod which is operated by an eccentric rod from the eccentric connected to the flywheel governor. The exhaust valves are operated by a separate eccentric.

Poppet Valves.—Superheated steam decreases cylinder condensation and increases the economy of the steam engine, but highly superheated steam causes slide valves and those of the Corliss type to warp. To overcome this objectionable feature, and at the same time to take advantage of the gain that may be derived from superheated steam, the poppet-valve engine was designed.

Details of one type of poppet-valve engine are shown in Fig. 100. The cylinder has four double-seat poppet valves, two are used for regulating the inlet steam, and two for regulating the exhaust. The operation of the valves is accomplished by the movement of an eccentric acting through a series of levers. The eccentric is attached to a lay shaft, which runs longitudinally along the outside of the cylinder and is finally geared to the main shaft.

The Uniflow Steam Engine.—The reciprocating steam engines previously described are of the counter- or double-flow type. The steam, after its expansion in this type of engine, is reversed in its course, the cylinder walls are subjected to the cooling action of the exhaust steam during the entire exhaust stroke, and the economy of the engine is greatly decreased by the losses due to the condensation and re-evaporation of the steam. The uniflow engine (Fig. 101) has been designed to decrease the above mentioned losses. In the uniflow engine, the steam enters at the ends of the cylinder as in the counter-flow engine, but is exhausted through special ports arranged around the center of the cylinder at the farthest point from the heads. The piston acts as an exhaust valve uncovering and covering the exhaust ports. The cylinder heads are exposed to the temperature of the exhaust steam for a very short time. The steam caught in the clearance space is compressed against the cylinder heads, which are jacketed with live steam. The incoming steam is not

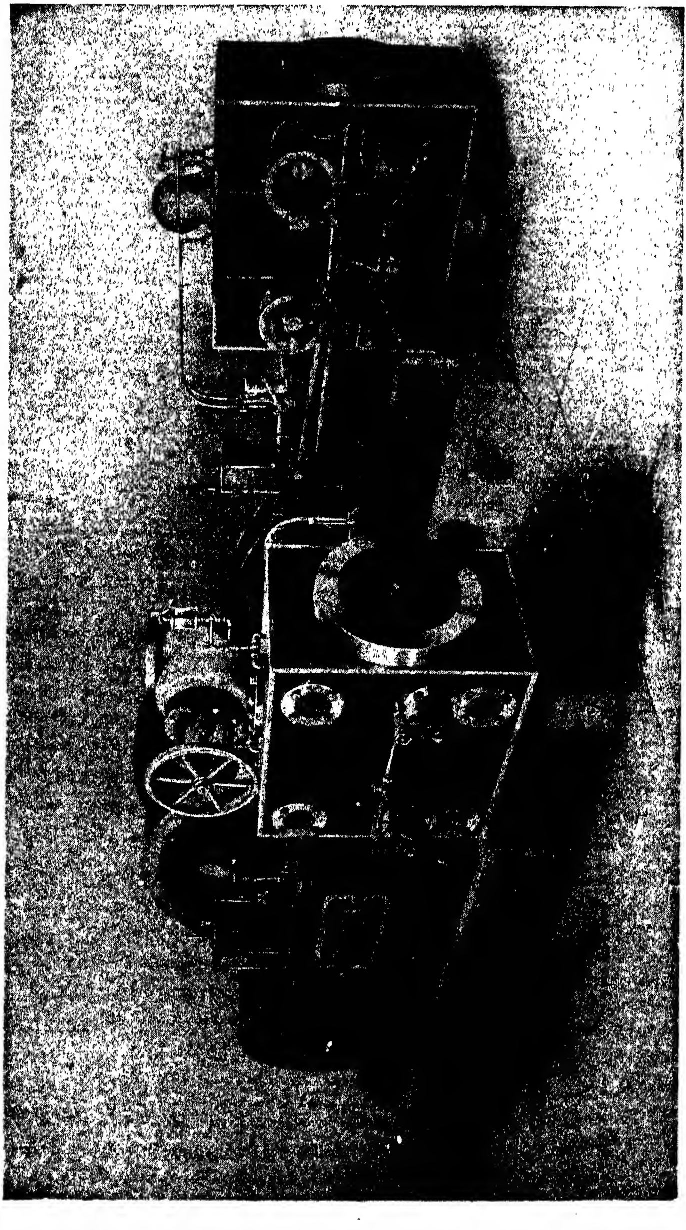


FIG. 99.—Non-releasing Corliss engine.

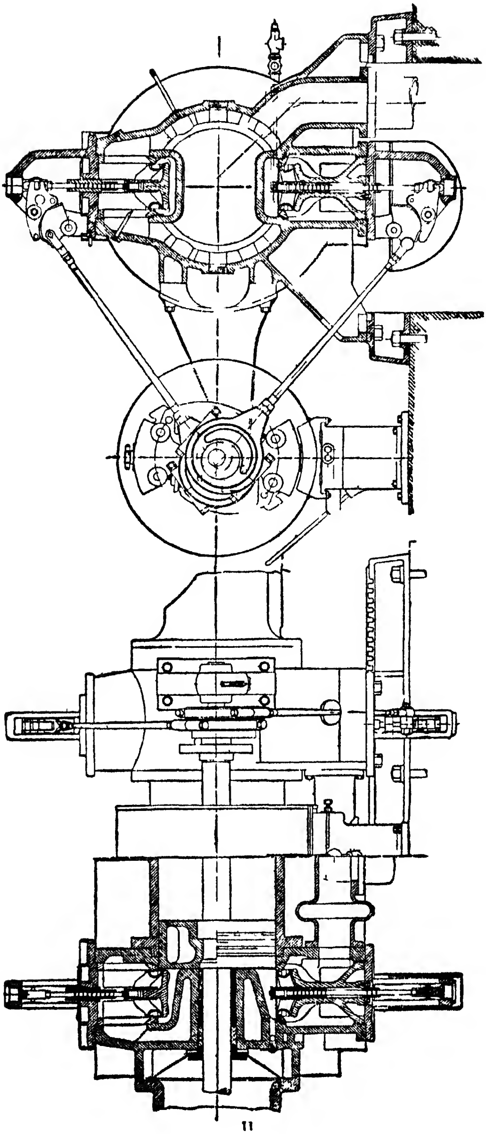


Fig 100 —Valve gear of poppet-valve engine

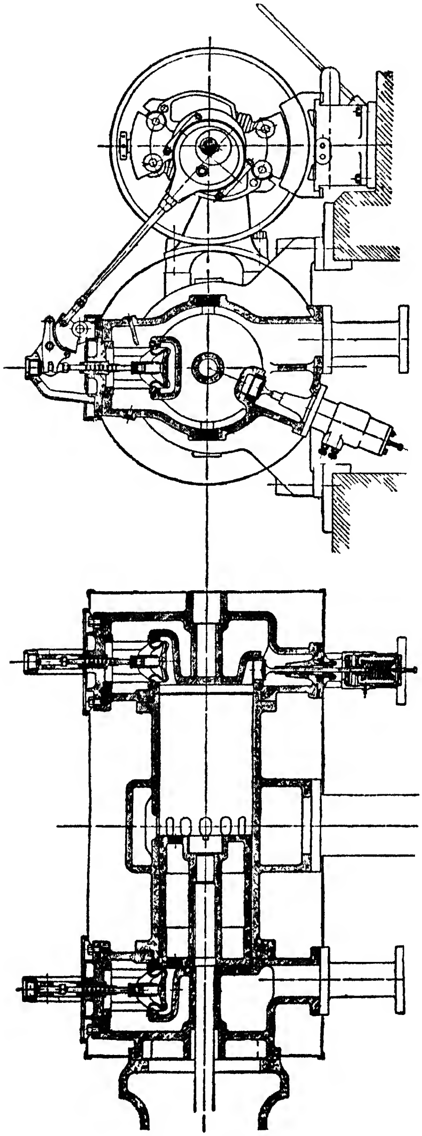


FIG. 101.—Uniflow engine.

to the lap and lead lever, which in turn is connected to the crosshead by a small link.

The motion derived from the crosshead moves the valve an amount equal to the lap plus the lead. The position of the link block with respect to the link is varied by raising or lowering the radius rod. By this means, the motion of the engine can be reversed. When the link block is in the mid-position of the link, the motion derived from the eccentric is neutralized and the valve is moved by the crosshead an amount equal to the lap plus the lead. *A* and *B* show two positions of the valve gear. The Walschaert valve gear is used on nearly all modern American steam locomotives.

Condensing and Non-condensing Engines.—Non-condensing engines exhaust directly into the atmosphere, into heating coils, or into feed-water heaters, where the heat contained in the exhaust steam is utilized in heating buildings or in raising the temperature of the feed water, as the case may be. Owing to the frictional resistance caused by the steam flowing through the exhaust ports, as well as the resistance introduced by the piping and other equipment, the pressure of the exhaust steam in non-condensing engines exceeds atmospheric pressure.

In the operation of a condensing engine, the exhaust steam from the engine cylinder escapes into a condenser, where it is cooled and condensed to water, thus producing a vacuum or a reduction in the back pressure. The reduction in the back pressure increases the work done in the cylinder, if the cut-off remains constant, by increasing the mean effective or unbalanced pressure. If the cut-off is decreased, the same work can be developed by using a smaller quantity of steam.

Generally, a condensing engine will use about 25 per cent less steam than a non-condensing engine of the same size on account of the lower back pressure. Small engines are very seldom operated condensing, as the gain in economy is usually more than balanced by the increased first cost of the equipment and by the greater complications of the power plant. A compound engine when operated condensing will show a greater gain in economy, as compared with non-condensing operation, than will a simple engine. The uniflow engine is very economical when operated condensing. Where the exhaust steam can be used for heating or for manufacturing purposes, the non-condensing installation is practical, but care must be taken to remove the oil used in cylinder lubrication.

Multiple-expansion Engines.—The use of multiple-expansion engines is another method for reducing cylinder condensation losses. In the simple engine, in which the total expansion of the steam is accomplished in one cylinder, the cylinder walls are first exposed to the high temperature of the inlet steam and then are exposed to the low temperature of the exhaust steam. This causes an excessive loss due to the condensation, which can be decreased by dividing the expansion into several pressure stages.

As there is a direct relation between the pressure of steam and its temperature, the decreasing of the pressure range of steam in a cylinder decreases the temperature range and hence decreases the condensation losses also. If steam, instead of being expanded completely in one cylinder, is expanded down to some intermediate pressure in one cylinder and then is exhausted into a second cylinder, where its pressure is reduced to that of the exhaust of a simple engine, the temperature range and condensation losses within each cylinder are decreased. Such an arrangement of cylinders forms a multiple-expansion engine. If the pressure range takes place in two stages, the engine is called a compound; if in three stages, triple expansion; and if in four stages, quadruple expansion. Obviously, the greater the number of pressure stages, the less will be the temperature range and hence the better the economy. A triple expansion engine is, for that reason, more economical than one operating compound, but the gain in economy when using triple expansion engines is usually more than offset by the increased cost of the equipment, the extra floor space required for the additional cylinder, and the greater complications of the power plant. Triple expansion engines are used in marine practice and in pumping plants, but are seldom found in stationary power plants; ordinarily, the compound engine is preferable when conditions warrant a multiple-expansion engine.

There are two different types of compound engines—the tandem- and the cross-compound. This classification depends upon the arrangement of the cylinders.

In the tandem-compound engine (Fig. 106) the axes of the low- and high-pressure cylinders are in one straight line. The piston rod is common to both cylinders and the total force transmitted to the single crank is the sum of the forces exerted in each cylinder.

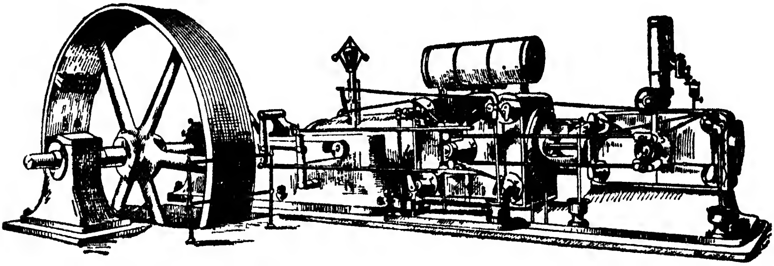


Fig. 106.—Tandem-compound engine.

The cross-compound engine (Fig. 107) has its cylinders arranged side by side, and the force exerted in each cylinder is transmitted to the separate crankpins, usually set at an angle of 90 deg. By this arrangement, the turning effort at the crankpin is more nearly uniform.

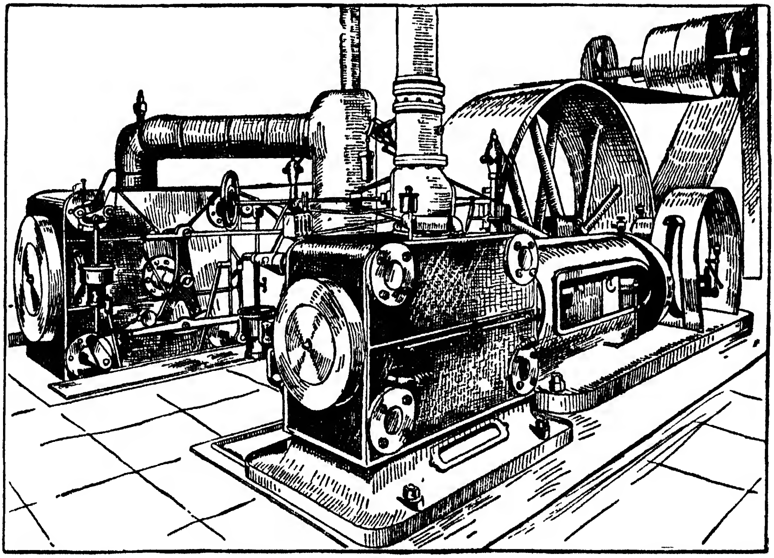


Fig. 107.—Cross-compound engine.

Valve Setting.—The object of setting valves on an engine is to equalize the work done on both ends of the piston. The method of procedure will vary with the type of valve, but the general principles will be understood from the following method used in setting the plain slide valve.

Before a valve can be set, the dead centers for both ends of the engine must be accurately determined.

The method of setting an engine on dead center can best be understood by referring to Fig. 108. *H* represents the engine crosshead which moves between the guides marked *G*, *N* is the connecting rod, *R* the crank, *F* the engine flywheel, and *O* is a stationary object.

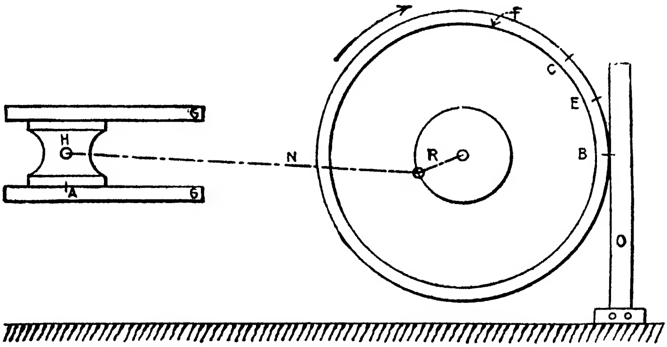


Fig. 108.—Valve setting.

To set the engine on dead center, turn the engine in the direction in which it is supposed to run, as shown by the arrow, until the crosshead is near the end of its head-end travel, and make a small scratch mark on the crosshead and guide as at *A*. At the same time, mark the edge of the flywheel and the stationary object opposite each other, as at *B*. Turn the engine past dead center, in the same direction as shown by the arrow, until the mark on the crosshead and that on the guide again coincide at *A*, and mark the flywheel in line with the same point on the stationary object, obtaining the mark *C*. The distance between the two marks on the flywheel is now bisected at *E*. If the mark *E* on the flywheel is now placed in line with the mark on the stationary object, the engine will be on the head-end dead center. Similarly, the crank-end dead center can be found.

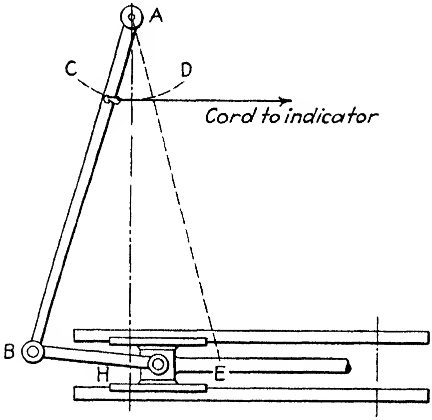


FIG. 111.—Pendulum reducing motion.

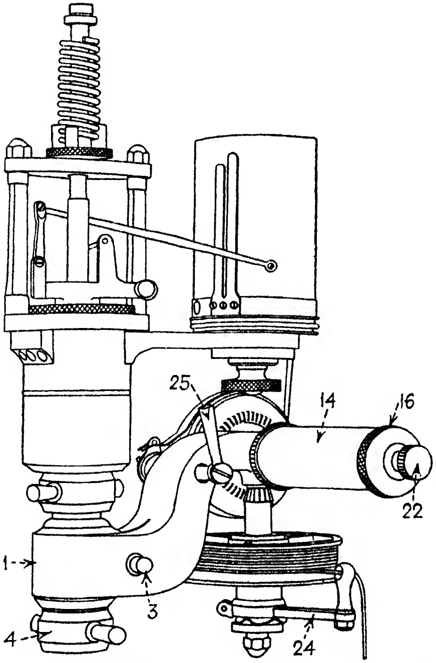


FIG. 112.—Reducing wheel attached to engine indicator.

are connected to each other through gears. The cord from the indicator drum is attached to the smaller wheel, while the larger wheel is connected to the crosshead. Changing the diameters of the two wheels permits of indicating engines having strokes between wide limits.

The Indicator Card.—A card taken from a steam engine by means of an indicator is shown in Fig. 113. The total length of the card is proportional to the stroke of the engine, and the height at any point is proportional to the pressure of the steam in the cylinder. The events of the stroke in the card are marked: admission A, cut-off C, release R, compression K. The pressure may be measured at any point on this card if the scale of the spring is known. Springs are provided so that various pressures are required to compress the spring sufficiently to cause the pencil to be moved 1 in. A 60-lb. spring, for instance, will require a pressure of 60 lb. per square inch to cause the pencil point to move 1 in. Or conversely, if the height of an indicator card is $1\frac{1}{2}$ in. at some point in the diagram and a 60-lb. spring is used in making the card, the pressure exerted by the steam in the cylinder is

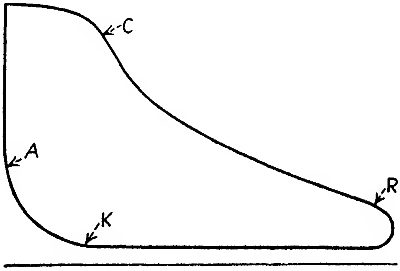


Fig. 113.—Steam-engine indicator card.

$$60 \times 1\frac{1}{2} = 90 \text{ lb. per square inch.}$$

The Measurement of Power from Indicator Cards.—A close analysis of an indicator card will show that certain pressures are exerted in the cylinder during the forward stroke and that lesser pressures exist in the cylinder during the return stroke. The two series of pressures differ in that those exerted during the forward stroke act upon the piston of the engine and are transmitted to the main shaft or flywheel, while on the return stroke the engine itself, due to the momentum which has been stored in the various parts during the forward stroke, must force the steam out of the cylinder and compress it. Thus, the total forward pressure exerted in the cylinder is not effective in producing power, but some must be utilized to exhaust the steam and to produce the compression. The effective pressure is the difference between the total pressure and the back pressure. This difference is graphically represented by the pressure within the indicator diagram. To use this value in determining the foot-pounds of work, it must be reduced to the mean effective pressure exerted throughout the stroke. The mean effective pressure (m.e.p.) can best be found by the use of a planimeter (Fig. 114) which is an instrument for measuring areas. Thus,

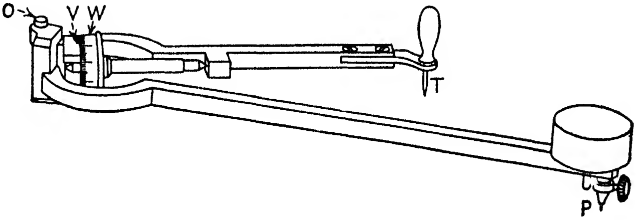


Fig. 114.—Polar planimeter.

$$\text{M.e.p.} = \frac{\text{area of card}}{\text{length of card}} \times \text{scale of spring.} \qquad (51)$$

Another means often employed in the absence of a planimeter is to divide the length of the card into 10 equal parts, as shown in Fig. 115, and obtain the average of the heights in inches of the 10 trapezoids formed. Thus, from Fig. 115,

$$\text{M.e.p.} = \frac{a+b+c+d+e+f+g+h+i+j}{10} \times \text{scale of spring.} \qquad (52)$$

The indicated horsepower developed by one end of the cylinder is

$$\text{i. hp.} = \frac{plan}{33{,}000} \qquad (53)$$

where p = mean effective pressure in pounds per square inch.
l = length of stroke in feet.
a = area of piston in square inches.
n = number of revolutions per minute.

In the crank end of the cylinder this same formula will apply with the exception that the effective area of the piston is reduced by the area of the piston rod.

Illustration.—The following data were obtained from the test of a steam engine:

Diameter of engine cylinder 10 in. (area 78.54 sq. in.).
Diameter of piston rod $1\frac{3}{4}$ in. (area 2.405 sq. in.).
Stroke of engine 12 in.
Speed of engine 280 r.p.m.

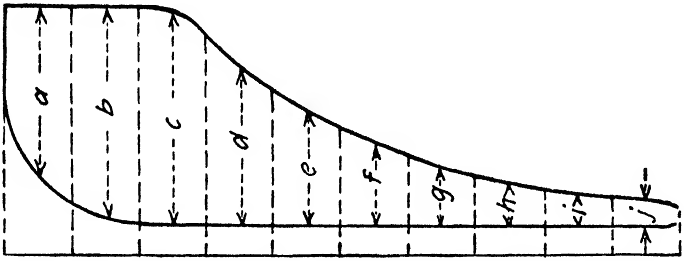


FIG. 115.—Ordinate method of measuring mean effective pressure.

If the mean effective pressure in the head-end side of the cylinder is found to be 41.64, the indicated horsepower in the head-end side is then

$$\frac{41.64 \times 1 \times 78.54 \times 280}{33{,}000} = 27.73 \text{ i. hp.}$$

The indicated horsepower in the crank-end side of the cylinder is obtained in the same manner, but the effective area in this side of the cylinder, which is found by deducting the area of the piston rod, must be used.

If the mean effective pressure in the crank end is 35.76, the indicated horsepower in the crank end is then

$$\frac{35.76 \times 1 \times (78.54 - 2.405) \times 280}{33{,}000} = 23.10 \text{ i. hp.}$$

The total indicated horsepower developed by the engine is:

$$27.73 + 23.10 = 50.83 \text{ i. hp.}$$

Valve Setting by Indicator Cards.—In general, one of the best methods of setting the valve of a steam engine is by means of the steam engine indicator. Any distortion in the events of the stroke is easily detected, and a little study of such diagrams suggests the proper steps to correct the difficulty.

Figure 116 shows indicator cards taken from the two ends of a cylinder when the valve is properly set. The four events in each cylinder occur at very nearly the same point in each stroke, and the cards compare favorably with that of an ideal diagram.

Figure 117 shows indicator cards taken from two ends of a cylinder when the valve is poorly set. Comparing the cards from the two ends of the cylinder, the same events in the two ends occur at different points in the stroke; this indicates that an adjustment of the valve is necessary.

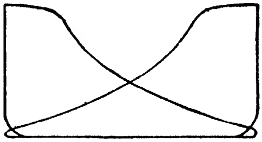


Fig 116 — Indicator cards, valves properly set

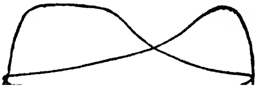


Fig. 117.—Indicator cards, valves improperly set.

Figure 118 shows samples of good and imperfect indicator diagrams. The cause of each defect is explained.

Brake Horsepower.--Brake horsepower represents the actual effective power which a motor or engine can deliver for the purpose of work at a shaft or a brake. An instrument for the measurement of the brake horsepower of motors, called a Prony brake, is shown in Fig. 119. This brake consists of two wooden blocks *BB* which fit around the pulley *P*, and are tightened by means of the thumb nuts *NN*. A projection of one of the blocks, the level *L*, rests on the platform scale *S*. When the brake is balanced, the power absorbed is measured by the weight, as registered on the scales, multiplied by the distance through which it would pass in a given time if free to move. If l is the length of the brake arm in feet, measured from the center of the shaft to the point of support on the scales, w the net weight as registered on the scales in pounds, and n the revolutions per minute of the motor, the horsepower absorbed can be calculated by the formula

$$\text{Brake horsepower} = \frac{2\pi l w n}{33{,}000}. \qquad (54)$$

Illustration.—If, in the test of an engine, the length of the brake arm is $5\frac{1}{4}$ ft., the net weight on scales 80 lb., and the speed 250 revolutions per minute, calculate the brake horsepower developed.

$$\text{Brake horsepower} = \frac{2 \times 3.1416 \times 5.25 \times 80 \times 250}{33{,}000} = 20.00.$$

Friction Horsepower.—The indicated horsepower of an engine would be equal to that of the brake horsepower if no losses occurred in the engine. The indicated horsepower is, however, always in excess of the brake horsepower by an amount equivalent to the power consumed in friction. The difference between the indicated horsepower and the brake horsepower is consequently the friction horsepower.

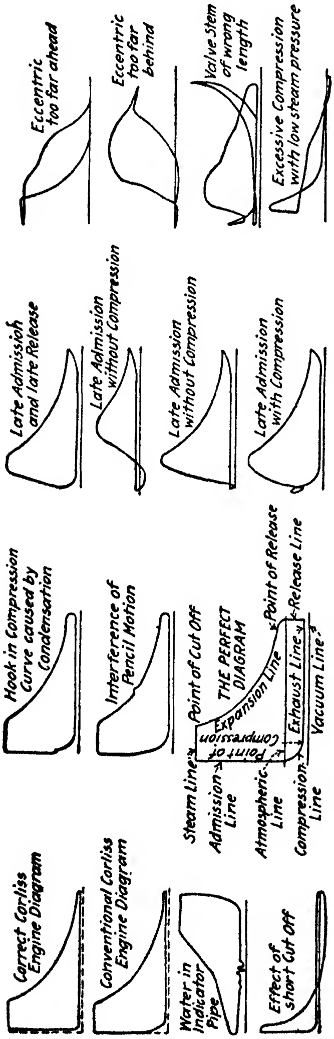


FIG. 118.—Samples of ideal and imperfect indicator diagrams.

$$\text{Friction horsepower} = \text{indicated horsepower} - \text{brake horsepower} \qquad (55)$$

Mechanical Efficiency.—The mechanical efficiency of an engine is the ratio of the brake horsepower (b.hp.) to the indicated horsepower (i.hp.)

$$\text{Mechanical efficiency} = \frac{\text{brake horsepower}}{\text{indicated horsepower}}. \qquad (56)$$

The mechanical efficiency is the percentage of the indicated horsepower that is delivered to the shaft as effective work. One hundred minus the percentage of mechanical efficiency gives the percentage of the indicated horsepower that is lost in friction

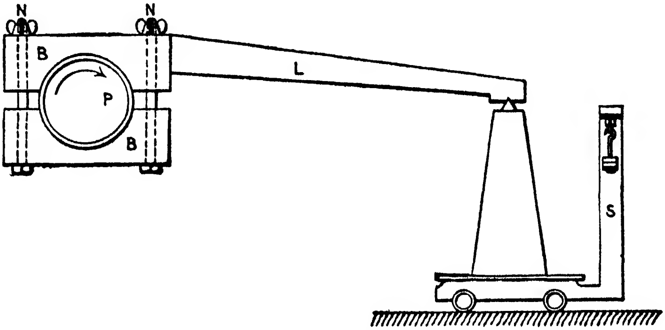


FIG. 119.—Prony brake.

Steam-engine Governors.—The function of a governor is to control the speed of rotation of a motor irrespective of the power which it develops. In the steam engine, the governor maintains a uniform speed of rotation either by varying the initial pressure of the steam supplied, or by changing the point of cut-off and hence the portion of the stroke during which steam is admitted.

Governors, which regulate the speed of an engine by varying the initial pressure of the steam supplied to the engine, are called throttling governors. The throttling governor is the simplest form of governor, and is used mainly on engines of the plain slide-valve type. In Fig. 120 is given a section of a throttling governor, showing details. This form of governor is attached to the steam pipe at A, and is connected to the engine cylinder at B, so that the steam must pass the valve V before entering the engine. The valve V is a balanced valve and is attached to a valve stem S, at the upper end of which are two balls CC. The valve stem and balls are driven from the engine shaft by a belt, which is connected to the pulley *P*, and which in turn runs the bevel gears *D* and *E*. As the speed of the engine is increased, the centrifugal force makes the balls fly out, and in so doing they force down the valve stem *S*, thus reducing the area of the opening through the valve, and the steam to the engine is throttled. As soon as the engine begins to slow down, the balls drop, increasing the steam opening through the valve *V*. The speed at which the steam is throttled can be changed within certain limits by regulating the position of the balls by means of the nut *N*.

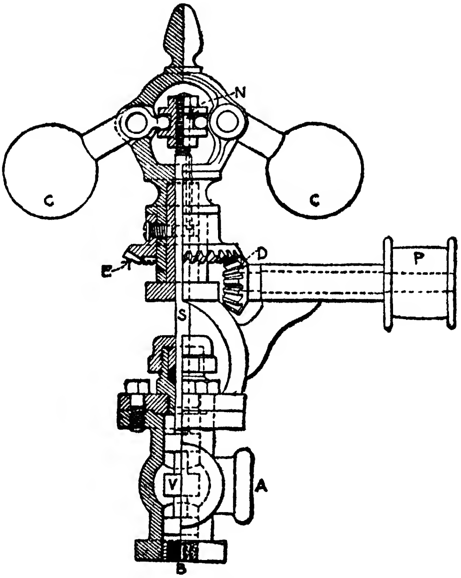


Fig. 120.—Steam-engine governor.

Most of the better engines are governed by varying the point of cut-off and hence the total volume of steam supplied to the cylinder. In high-speed automatic engines, as well as in Corliss non-releasing engines, this is accomplished by some form of flywheel or shaft governor, which controls the point of cut-off by changing the position of the eccentric.

One form of flywheel governor is shown in Fig. 121. The sheave of the eccentric is mounted upon an arm which is pivoted to the flywheel. The eccentric sheave contains a slot which passes over the shaft, and the outer end of the arm is attached to the weight as shown. In the operation of the governor, centrifugal force causes a movement of governor weight, and in so doing the position of the eccentric, and hence the cut-off, is changed As the speed of the engine increases, the cut-off is reduced; and when the speed slows down, the cut-off is increased.

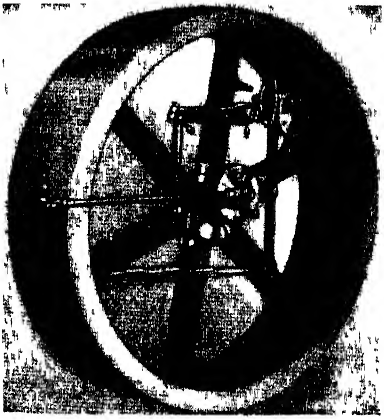


Fig. 121.—Shaft governor.

Engine Details.—The general construction of steam-engine cylinders can be seen from the previous illustrations. Steam-engine cylinders are made of cast iron As the cylinder wears, it has to be rebored so as to maintain true inside surfaces The thickness of the cylinder walls should be not only sufficient to withstand safely the maximum steam pressure, but should allow for reboring All steam-engine cylinders should be provided with drip cocks at each end in order to drain the cylinder and steam chest when starting.

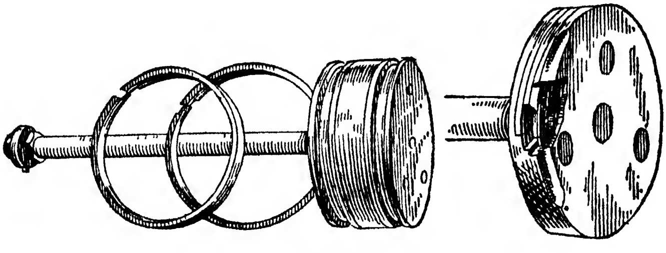


Fig. 122 —Steam-engine piston

A good piston should be steam-tight, and at the same time should not produce too much friction when sliding inside the engine cylinder. The piston is usually constructed somewhat smaller than the inside diameter of the engine cylinder and is made tight by the use of split cast-iron packing rings. In Fig. 122 is illustrated a piston with its packing rings.

The general construction of steam-engine crossheads is illustrated in Fig. 123. All crossheads should be provided with shoes which can be adjusted for wear.

Figure 124 shows a connecting rod. A connecting rod should be so constructed that the wear on its bearings can be taken up. This is usually accomplished by wedges and set screws as illustrated.

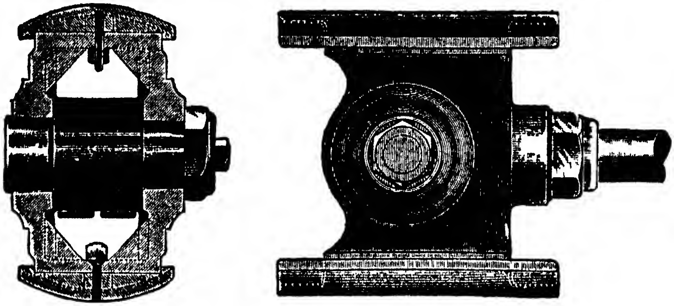


Fig. 123.—Steam-engine crosshead.

Some engines have their cranks located between the two bearings of an engine, and are called center-crank engines. Engines which have their cranks located at the end of the shaft and on one side of the two bearings are called side-crank engines.

The eccentric is a special form of crank. It is usually set somewhat more than 90 deg. ahead of the crank and gives motion to the valve or valves in the steam chest of the engine. Figure 125 shows an eccentric rod and strap.

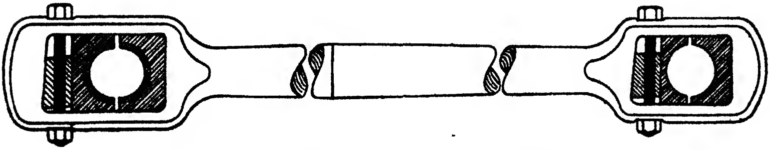


Fig. 124.—Steam-engine connecting rod.

The main bearings of steam engines are illustrated in Fig. 126. These bearings are usually made in three or four parts and can be adjusted for wear by means of wedges and set screws fastened with locknuts.

Lubricators.—The function of lubrication is to decrease the frictional losses which occur in steam-engine operation. All rubbing surfaces at which friction is produced must be lubricated.

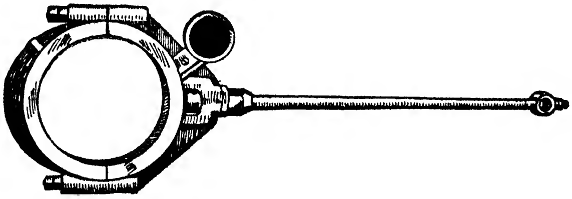


Fig. 125 Eccentric rod and strap

Bearings may be lubricated by grease cups as illustrated in Figs. 127 and 128. The first type is used on stationary bearings, the grease being forced out by screwing the cap down by hand. The type illustrated in Fig. 128 is automatically operated, and is used for the lubrication of crankpins.

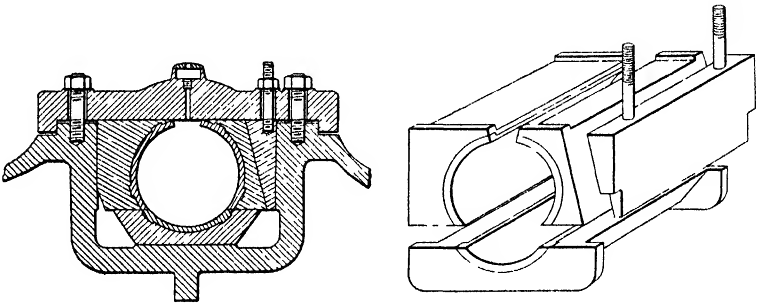


Fig. 126.— Main engine bearings.

If oil is used, a sight-feed lubricator is employed, as shown in Fig. 129. By means of the sight-feed types the flow of oil can be regulated and the drops of oil issuing from the lubricator can be seen.

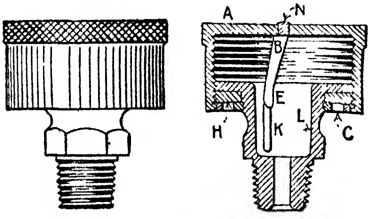


Fig. 127. —Grease cups.

For the lubrication of steam-engine cylinders, some form of sight-feed automatic steam lubricator, as illustrated in Fig. 130, should be employed. This form of lubricator is used to introduce a heavy oil into the steam entering the cylinder. This oil is a specially refined heavy petroleum oil which will neither decompose, vaporize, nor burn when exposed to the high temperature of steam. Steam from the pipe *B* leading to the engine cylinder is admitted through the pipe *F* to the condensing chamber *L*, where it is condensed and flows through the pipe *P* to the bottom of the chamber *A*. The oil which is contained in chamber *A* rises to the top, is forced through the tube *S*, ascends in drops through the water in the gage glass *H*, and into the steam pipe *K* leading to the steam chest. The amount of oil fed is regulated by the needle valve *E*. The gage glass *J* shows the amount of oil in the chamber *A*. In order to fill the chamber *A*, the valves on the pipes *F* and *H* are closed, the water is drained out through *G*, and the cap *D* is removed for receiving the oil.

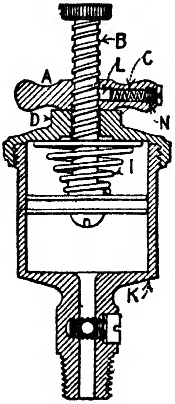


Fig. 128.—Automatic grease cup.

Mechanical Force-feed Lubricators.—These lubricators (Figs. 131 and 132) consist of one or more pumps immersed in a reservoir of oil. The pumps are operated from some moving part of the engine and each pump controls the lubrication of some particular bearing, the rate of flow being regulated by the stroke of the pump. This type of lubricator is positive in action and the

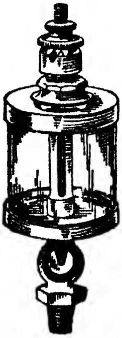


Fig. 129.—Sight-feed lubricator.

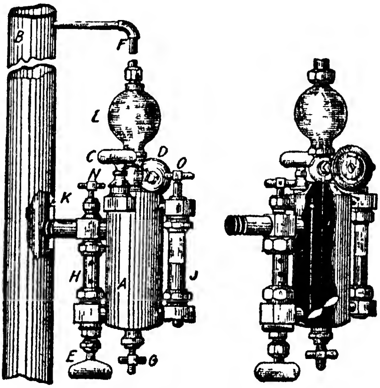


Fig. 130.—Sight-feed automatic lubricator.

flow of oil is more uniform than in the other types of lubricators discussed.

Steam-engine Economy.—The economy of steam engines is usually expressed in pounds of steam consumed per horsepower per hour. In the case of steam-electric power plants, the economy is expressed in pounds of steam consumed per kilowatt-hour. The steam consumption of simple, non-condensing engines will vary, under good operating conditions and at full load, from 20 to 35 lb. per horsepower per hour, depending upon the type of valve gear used. Compound condensing engines consume 12 to 20 lb. of steam per horsepower per hour.

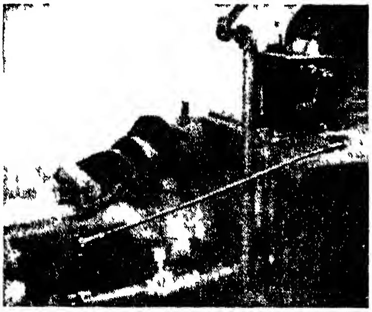


Fig. 131—Force-feed lubricator

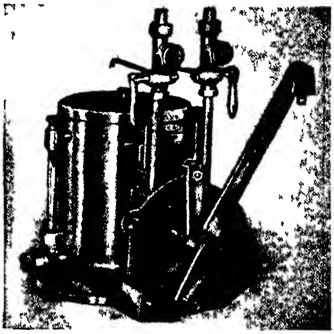


Fig 132.—Force-feed lubricator.

The steam consumption, or water rate, is not an accurate method for comparing economies of steam engines, unless suitable corrections can be made for steam pressure and for steam quality. The economy of steam engines is best expressed in terms of the heat consumption (B t u.) per horsepower per minute or per kilowatt per minute measured above the temperature at which the condensation can be returned to the boiler.

Example—A steam engine develops 1 b hp-hr at a steam consumption of 15 lb. The initial pressure is 125 lb absolute, quality 98 per cent dry, exhaust pressure 2 lb. absolute. Calculate the heat consumption per brake horsepower per minute.

Solution.—From the steam tables, the heat of 1 lb. of steam under the conditions given is

$$315.6 + 0.98 \times 873.4 = 1172.2 \text{ B.t.u}$$

Assuming that the condensation will be returned to the boiler at a temperature corresponding to the exhaust pressure of 2 lb. absolute, the enthalpy of water corresponding to an absolute pressure of 2 lb. is 93.97.

Thus the heat supplied per brake horsepower per hour is

$$15(1172.6 - 94) = 16{,}177 \text{ B.t.u.}$$

The heat supplied per brake horsepower per minute is

$$\frac{16{,}177}{60} = 269.6 \text{ B.t.u.}$$

Reciprocating steam engines are usually operated at steam pressures varying from 75 to 200 lb. per square inch. In one industrial plant a steam engine of special design operates at 1,800 lb. per square inch. The gain produced in economy by increasing the steam pressure from 80 to 100 lb. per square inch is about twice as great as that resulting from increasing the steam pressure from 180 to 200 lb. per square inch. In general, the practical limit for steam pressure is mainly one of expense. The first cost and the cost of upkeep of steam-power-plant equipment increase with the steam pressure.

The exhaust pressure at which an engine is operated depends upon the use to which the exhaust steam can be put. If the exhaust steam can be used for heating or for manufacturing purposes, engines are operated non-condensing. With large compound engines, the gain due to condensing is considerable. Condensing reciprocating engines give best economy with back pressures of about 2 lb. absolute (26-in. vacuum).

The quality of the steam influences the losses due to condensation and re-evaporation. The use of superheated steam, considering the cost of producing the superheat, will increase the net economy of steam engines by about 5 per cent for every 100° superheat.

Installation and Care of Steam Engines.—Foundations for stationary steam engines are usually put in by the purchaser, the manufacturer furnishing complete drawings for that purpose. Drawings of a board template are also included. A template is a wooden frame which is used in locating the foundation bolts and for holding them in position while holding the foundation.

Before starting on the foundation, a bed should be prepared for receiving it. The depth of bed depends on the soil. If the soil is rocky and firm, the foundation can be built without much difficulty. When the soil is very soft, piles may have to be driven.

The wooden template is then constructed from the drawings, holes being bored for the insertion of foundation bolts.

Foundations are usually built of concrete. The concrete mixture should consist of 1 part of cement, 2 parts of sharp sand, and 4 parts of crushed stone. The stone should be of a size that will pass through a 2-in. ring. In starting on a concrete foundation, a wooden frame of the exact shape of the foundation is built. The template is then placed in position in the manner shown by Fig. 133, and the bolts are put in, the heads of the bolts being at the bottom in recesses of cast-iron anchor plates marked *P*. Often the foundation bolts are threaded at both ends and the anchor plates are held in place by square nuts. A piece of pipe should be placed around each bolt, so as to allow the bolts to be moved slightly to pass through the holes in the engine bedplate, in case an error should occur in the placing of the bolts, or in the location of the bolt holes in the engine bedplate.

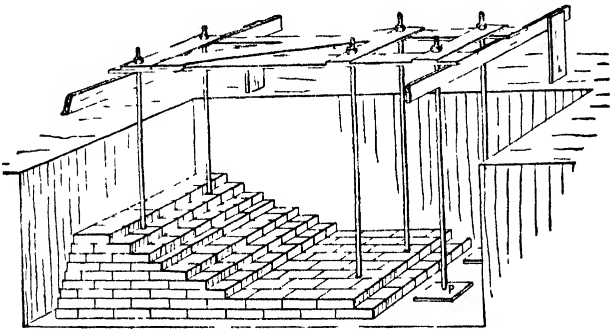


Fig. 133.—Foundation in the process of construction.

With the frame, template, and foundation bolts in place, the concrete can now be poured and tamped down. After the concrete has set, the template is removed and the foundation is made perfectly level. It is well to allow a concrete foundation to set several weeks before placing the full weight of the engine on it.

When the foundation is ready, the engine is placed in position and leveled by means of wedges. The nuts on the bolts are now screwed down and the engine is grouted in place by means of neat cement, this serving to fill any crevices and to give the engine a perfect bearing on the foundation.

After erecting the engine and all its auxiliaries, including pipes, valves, cocks, and lubricators, all the parts should be carefully examined and cleaned, and a coating of oil should be applied to all rubbing surfaces, cylinder oil being used for the wearing parts in the valve chest and cylinder.

Before the engine is operated for the first time, it is well to adjust bearings and to turn the engine over slowly until an opportunity has been given for any inequalities due to tool and file marks to be partially eliminated, and also to prevent heating that might occur if there was an error in adjustment.

When the engine is ready to start, the steam throttle valve should be slowly opened to allow the piping to warm up, but leaving the drain cock in the steam pipe, above the steam chest, open to permit the escape of condensation. While the piping is being warmed up, all the grease cups and lubricators are filled. Before opening the throttle valve, all cylinder and steam-chest drain cocks should be opened to expel water, and the flow of oil started through the various lubricators. The throttle valve is then opened gradually, and both ends of the engine warmed up. This can be accomplished in the case of a single-valve engine by turning the engine over slowly by hand to admit steam in turn to each end of the cylinder. In starting a Corliss engine the eccentric is disconnected from the wrist plate, and the wrist plate is rocked by hand sufficiently to allow steam to pass through each set of valves. The drain cocks are closed soon after the throttle is wide open and the engine is gradually brought up to speed.

When stopping an engine, close the throttle valve. As soon as the engine stops, close the lubricators, wipe clean the various parts, examine all bearings, and leave the engine in perfect condition ready to start.

The above instructions apply to non-condensing engines. If the engine is to be operated condensing, the circulating and air pumps should be started while the engine is warming up. The other directions apply with slight modifications to all types of steam engines.

In regard to daily operation, cleanliness is of great importance. No part of the engine should be allowed to become dirty and all parts must be kept free from rust. It is well to draw off all the oil from bearings quite frequently and to clean them with kerosene before refilling with fresh oil. In starting, it is well to give the various parts plenty of oil, but the amount should be decreased as the engine warms up. An excess of oil should be avoided.

Competent engine operators usually make a practice of going over and cleaning every bearing, nut, and bolt, immediately on shutting down. This practice not only keeps the engine in first-class condition, as regards cleanliness, but enables the operator to detect the first indication of any defect that, if overlooked, might result seriously.

If a knock develops in a steam engine, it should be located and remedied at once. Knocking is usually due to lost motion in bearings, worn journals, or crosshead shoes, water in the cylinder, loose piston, or to poor valve setting. Locating knocks in steam engines is to a great extent a matter of experience, and no definite rules can be laid down which will meet all cases.

One may, by careful attention to the machine, however, learn to trace out the location of a knock in a comparatively short time. He must bear in mind that he cannot rely on his ear for locating it, as the sound produced by a knock is, in many cases, transmitted along the moving parts, and apparently comes from an entirely different point.

A knock due to water in the cylinder is usually sharp and crackling in its nature, while that in the case of a crank or a crosshead pin is more in the nature of a thud. If the knock should be due to looseness of the main bearings, the location may be detected by carefully watching the flywheel. If the crosshead is loose in the guides, the observer may be able to detect a motion crossways of the crosshead, but it is not likely that he can do this with accuracy in the case of a high-speed engine; in such cases the crosshead should be tested when the engine is at rest. No adjustment should be made in bearings or moving parts of an engine unless the machine is at a standstill or is being turned by hand; never when under its own power.

The heating of a bearing is always due to one of five causes:

1. Insufficient lubrication due to insufficient quantity of oil, wrong kind of oil, or lack of proper means to distribute the oil about the bearings.
2. The presence of dirt in the bearings.
3. Bearings out of alignment.
4. Bearings improperly adjusted. (They may be either too tight or too loose)
5. Operation in a place where the temperature is excessive.

In case a bearing should run hot and it is very undesirable to shut down, it is generally possible to keep going by a liberal application of cold water upon the entire heated surface or surfaces. It is sometimes possible to stop heating by changing from machine oil to cylinder oil which has a higher flash point.

Should a bearing, particularly a large one, be overheated to the extent that it is necessary to shut down the engine, do not shut down suddenly or allow the bearing to stand any length of time without attention. This is particularly important in the case of babbitted bearings, as the softer metal of the bearings will tend to become brazed to, or fused with, the harder metal of the shaft, and it may be necessary to put the engine through the shop before it can be used again.

In case of the necessity of shutting down for a hot bearing, first remove the load, then permit the engine to revolve slowly under its own steam until the bearing is sufficiently cool to permit the bare hand to rest upon it.

The presence of water in the cylinder is always a source of danger, and care should be taken that the water of condensation is thoroughly drained from the cylinder when the engine is first started, at shutting down, and at regular intervals throughout the operation. An accumulation of water may readily cause the blowing out of a cylinder head with its resultant loss to property and possibly to life. There are several appliances now on the market which automatically safeguard the cylinder head by providing a weak point in the drain system which will relieve the excess pressure before the cylinder head gives way.

Problems

1. Examine the power plants in your vicinity and report upon the types of valve gears used. If the valve mechanisms in any case differ from those in this textbook, hand in clear sketches of such valve gears.

2. Examine the locomotives entering your city and report upon the reversing mechanisms used.
3. Check and correct the valve setting of some engine, accessible to you, and report upon the method used.
4. Explain, using clear sketches, how a Corliss engine is governed.
5. Calculate the indicated horsepower of an 18- × 24-in. steam engine operating at a speed of 110 r.p.m., if the head-end mean effective pressure is 30 lb. per square inch, the crank-end mean effective pressure 30.5 lb., size of piston rod is 2 in.
6. An engine operating at a speed of 200 r.p.m. is tested by means of a Prony brake. If the length of the brake arm is 42 in. and the net weight as registered on platform scales 35 lb., calculate the brake horsepower of the engine.
7. If the mechanical efficiency of the engine in Problem 6 is 87 per cent, calculate the indicated horsepower and the friction horsepower of the engine.
8. Secure an indicator card and calculate its mean effective pressure by the "ordinate" method. If the proper data can be secured, calculate also the indicated horsepower for this card.
9. A steam engine develops a brake horsepower per hour at a steam consumption of 22 lb. The initial steam pressure is 135 lb. gage, quality 97 per cent dry, and exhaust pressure 15 lb. absolute. Calculate the heat consumption per brake horsepower per minute.
10. Prepare a table showing economies which can be expected at full load, half load, and quarter load, from the following types of engines:
    (*a*) Simple high-speed automatic engines, sizes 50 to 150 hp.
    (*b*) Corliss engines, simple and compound non-condensing.
    (*c*) Compound condensing engines in large units.
    (*d*) Uniflow engines, condensing and non-condensing.
11. Compare the advantages and disadvantages of the Stephenson and Walschaert reversing gears.
12. Give directions for starting a steam engine.
13. If a slide valve should have its steam lap decreased, what would be the effect upon the events of the valve and upon the lead?
14. What would be the effect of decreasing the exhaust lap upon the lead?
15. Under what conditions should the following types of engines be installed:
    (*a*) Simple high-speed automatic.
    (*b*) Corliss.
    (*c*) Compound.
    (*d*) Uniflow.
16. Why is the slide valve not suitable for highly superheated steam?
17. Why cannot the exhaust from reciprocating steam engines be condensed and returned to the boiler without special treatment?
18. What is the field of the compound steam engine?
19. What is the field of the uniflow engine?
20. Under what conditions are the uniflow engines in Fig. 103 preferable to those illustrated in Fig. 102?

CHAPTER IX

STEAM TURBINES

The Steam Turbine.—The steam turbine differs from the reciprocating steam engine, in that it produces rotary motion directly and without any reciprocating parts. The simple steam turbine is a wheel which is given rotary motion by a steam jet impinging on its blades. The elastic force of the steam in the turbine does not act upon the surface of a moving piston, but upon the mass of the steam itself, converting nearly all of the available energy in the steam between certain pressure limits, into velocity.

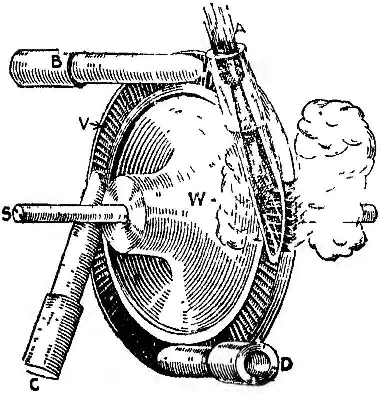


Fig. 134.—De Laval steam turbine.

In one type of steam turbine (Fig. 134), the jet of steam from a fixed expanding nozzle is directed upon moving curved blades. All the expansion occurs in a nozzle, resulting in a steam jet of high velocity which does work. This is called the impulse type of steam turbine. *A*, *B*, *C*, and *D* are stationary expanding nozzles in which the steam is completely expanded and the steam jet of high velocity strikes the blades *V*, giving a direct rotary motion to the wheel *W* and also to the shaft *S*.

In another type, called the reaction turbine (Fig. 153), the steam is expanded within the stationary and the moving blades of the machine, and work is partly produced by the reaction of the expanding steam as it flows from the moving blades to the stationary or guide blades. No commercial steam turbines operate upon the pure reaction principle, but work by both the impulse of the steam against the blades and by the reaction of the steam as it leaves the blades.

Advantages of the Steam Turbine.—As compared with the reciprocating engine, the steam turbine has the following advantages:

1. The speed of the steam turbine is practically uniform This makes the steam turbine a very desirable motor for electric central stations.

2. The steam turbine requires no internal lubrication, and the exhaust steam may be used for heating or industrial purposes without oil filtration.

3. The steam turbine can operate at lower back pressures, that is at higher vacua, than reciprocating engines. It is not practical to operate steam engines at vacua greater than 26 in Steam turbines are commonly operated at a vacuum of 28 in. and some turbine installations maintain a vacuum greater than 29 in. Increasing the vacuum from 26 to 29 in. increases the energy of the steam very nearly the same amount as does the increase in steam pressure from 75 to 150 lb.

4.' The steam turbine is better adapted to use highly superheated steam than are reciprocating engines equipped with slide valves or with Corliss valves. With stationary reciprocating steam engines, other than those equipped with poppet valves, steam temperatures above 450°F. are seldom exceeded. Above such temperatures lubrication is unsatisfactory, and distortion of parts may take place. Temperatures of 750°F. or even higher are common in steam turbine practice.

5. The steam turbine occupies less space than the reciprocating engine and weighs less per unit capacity.

6. The steam turbine can be built in very large sizes. Reciprocating engines of capacities as great as 10,000 hp. are very rare. Steam turbines, each of which has a capacity of 160,000 kw. (over 213,000 hp.) and greater, are found in large generating stations. In 1929, a 210,000-kw. steam turbine was installed. Other steam turbines, varying in capacity from 10,000 to 130,000 kw., have been in service in large central stations operating continuously without trouble, for several years.

7. Steam turbines in large sizes are cheaper than reciprocating engines.

8. Where turbines of large capacities can be utilized, electric current can be generated cheaper than with reciprocating engines. The steam turbine is the most important prime mover for the generation of electricity, as the development of power has been in the direction of more powerful generating units, the operating costs decreasing with the size of prime movers. The steam turbine, more than any one factor, made possible the modern electric central station.

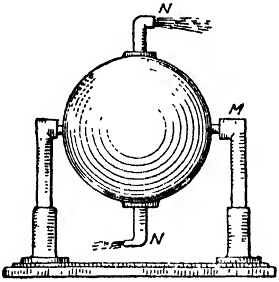


Fig. 135.— Hero's turbine.

History of the Steam Turbine. The history of the steam turbine dates back to the second century before the birth of Christ, when Hero of Alexandria contrived a steam motor which is illustrated in Fig. 135. The Hero turbine consisted of a hollow spherical vessel rotating on two supports. The steam was delivered to the vessel through one of the supports M, and escaped from it through two bent pipes or nozzles N, N pointed in opposite directions. Rotation of the sphere was produced by the reaction due to the steam escaping from the nozzles. The modern reaction turbine is a modification of the Hero motor.

The Branca wheel, Fig. 136 which was designed in 1629, resembled a water wheel and was driven by a jet of steam directed by means of a nozzle upon buckets attached to the wheel.

The steam turbine did not become a commercial success until near the end of the nineteenth century. The delay in the practical utilization of the turbine was due to the following causes:

1. There was very little demand for a high-speed motor of large capacity until the development of the electric central station.

2. Lack of scientific knowledge concerning the laws governing the flow of steam has prevented the perfection of a machine which could operate at practical speeds. All the earlier turbines were single-stage machines and operated at very high speeds. The method of reducing the speed of the turbine shaft, by passing the steam through a number of wheels in series, was not discovered until about the middle of the nineteenth century.

3. The simple one-wheel turbines, of which the Branca turbine was the prototype, could not be built as commercial motors until the developments in the science of metallurgy made possible the manufacture of materials which were capable of bearing without rupture the high rotative speeds.

The De Laval Simple-impulse Steam Turbine.—The De Laval steam turbine (Fig. 134) was the first successful simple-impulse turbine. This type of turbine is now obsolete, but its principle of operation is embodied in modern commercial-impulse turbines

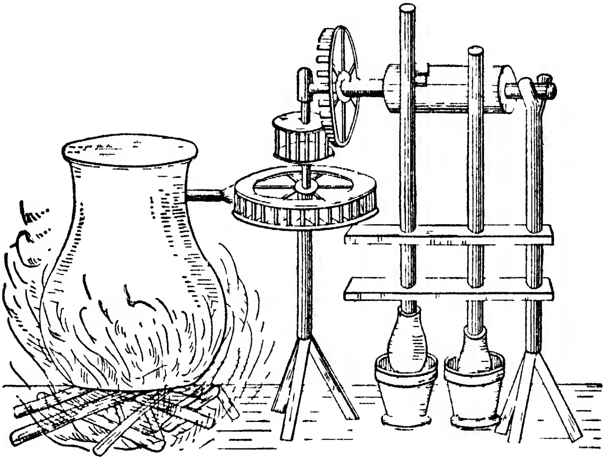


FIG. 136.– Branca turbine.

The inventor of this turbine, Dr. Gustaf De Laval, designed the expanding nozzle in 1889. He also patented the principle of flexible supports for turbines or other bodies intended to rotate at high velocities.

Figure 137 illustrates a sectional plan of an early type of De Laval turbine. Steam enters the steam chest, where it is distributed to one or more nozzles, depending on the size, is expanded to the exhaust pressure, and strikes the blades on the turbine wheel *C*, as illustrated in Fig. 137. The nozzles are generally fitted with stop valves by which one or more nozzles can be cut out when the turbine is not loaded to its fullest capacity. The turbine wheel *C* is mounted on a flexible shaft *D* which is supported at the bearings *K* and *I*. After performing its work, the steam passes

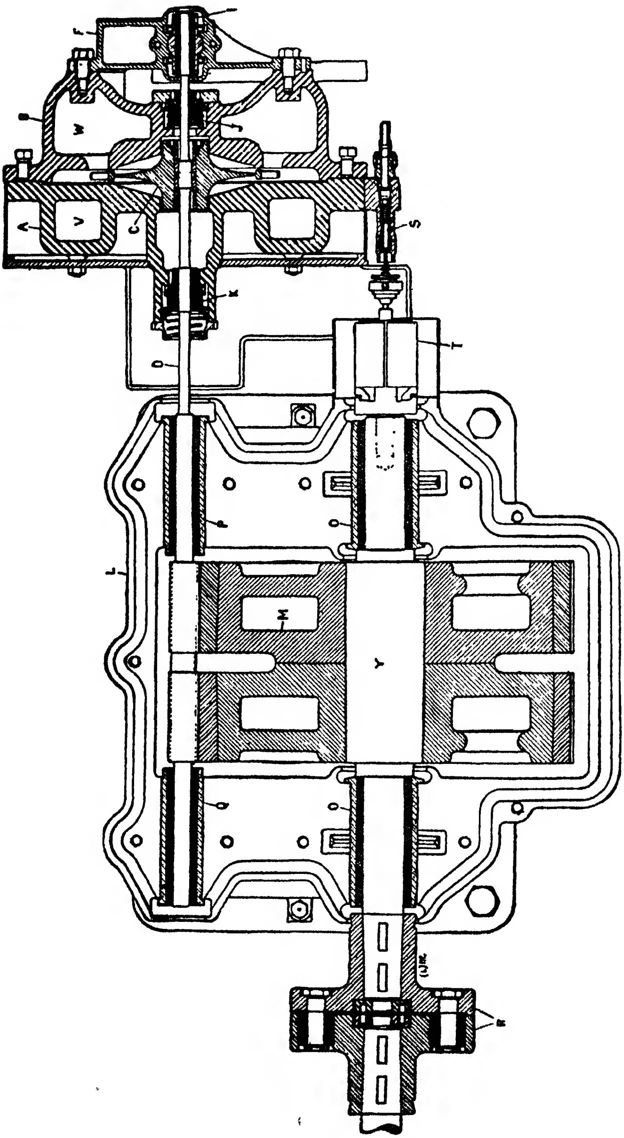


FIG. 137.—Sectional plan of an early type of De Laval steam turbine.

into the chamber *W*, and out through the exhaust pipe into the open air or condenser. Since the total expansion of the steam takes place in one set of nozzles, the velocity of the wheel in this type of turbine is very high, and this must be reduced by gearing. The turbine shaft *D* is connected to the pinion which engages a gear wheel *M*, thus reducing the speed of the shaft *Y* to that required by the machine to be driven. A throttling governor *T* is used for speed regulation.

Different nozzles are used for condensing and for non-condensing operation, as illustrated in Fig. 138. The difference in the taper of the two nozzles shows graphically the relative ratios of expansion of steam when expanding against atmospheric pressure or into a vacuum. *A* is the steam inlet and *B* is the outlet from the nozzle.

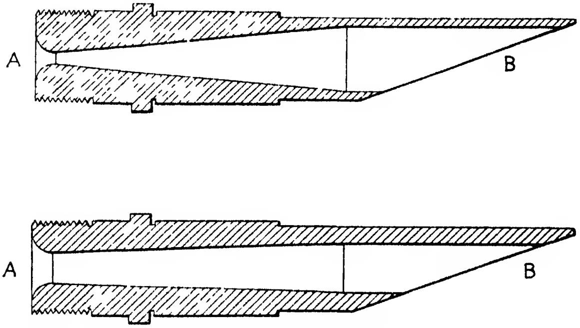


FIG. 138.—Nozzles for condensing and non-condensing operation.

Figure 139 shows the details of the De Laval governor. It consists of two weights *D* which are pivoted on the knife edge with hardened pins *M* which bear upon the spring seat *J*. When the speed exceeds normal, the weights, affected by centrifugal force, spread apart, pressing on the spring seat *J*, push the governor pin *I* to the right, which moves with it the bell-crank lever *L*. The bell-crank lever *L* operates the main admission valve, throttling the steam pressure.

When the turbine is operated condensing and overspeeds, the vacuum valve *P* is operated by the governor allowing air to enter the turbine exhaust pipe, checking the turbine speed.

Multi-stage Impulse Turbines.—Simple-impulse turbines are not efficient, as it is difficult to utilize in a single wheel the energy developed by the expansion of steam in a nozzle between wide pressure limits. Thus steam expanding in a nozzle between a pressure of 200 lb. per square inch absolute and a vacuum of 28 in. attains a velocity of over 4,000 ft. per second, which corresponds to more than one-fourth of a million foot-pounds of energy per pound of steam. To utilize efficiency the energy of the steam in a turbine, in which the complete expansion of the steam occurs in one set of nozzles and the steam at high velocity is allowed to impinge against a single set of blades, the speed of the revolving blades should approximately equal one-half the velocity of the steam. A turbine operating at such a high speed cannot be utilized for direct connection to machines, but requires the interposition of a set of reducing gears.

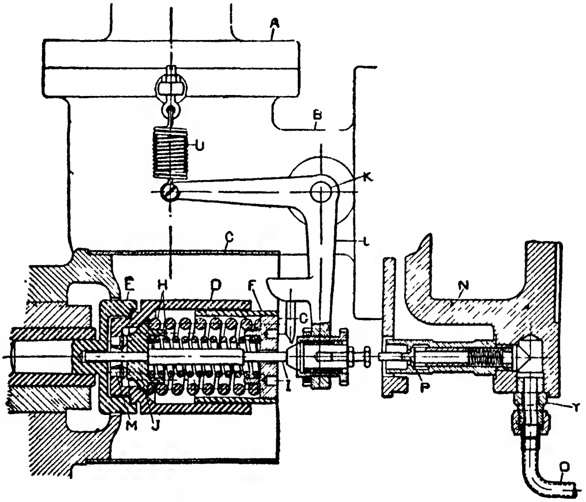
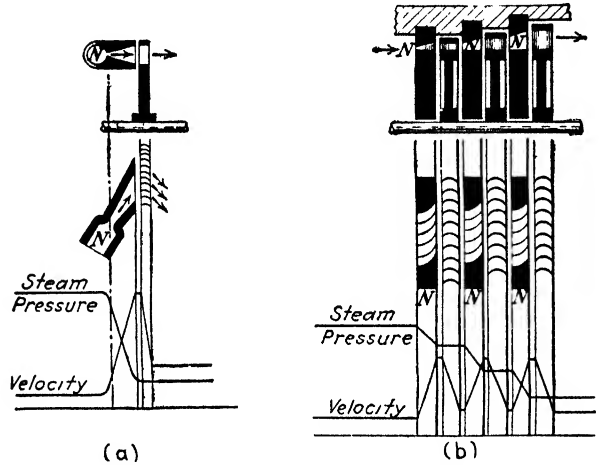


FIG. 139.—De Laval governor.

The various multi-stage turbines have been perfected in order to do away with the reduction gearing of the simple-impulse types.

Multi-pressure, Single-velocity Stage Impulse Turbines.—In the simple-impulse turbine, the complete expansion of the steam from boiler pressure to exhaust pressure takes place in one set of nozzles and the velocity acquired in the nozzles is given up to a single revolving wheel. In one type of multi-stage impulse turbine, the expansion of the steam takes place in a series of steps or stages, each stage being provided with a set of nozzles and a single revolving wheel. This type is called multi-pressure, single-velocity stage impulse turbine. The principle of this type of turbine as contrasted with that of the simple-impulse type is illustrated in Fig. 140. In the simple-impulse turbine (at the left of Fig. 140), the entire pressure drop takes place in one nozzle or in a single set of nozzles. The pressure drop in the multi-pressure type is divided among several sets of nozzles (at the right of Fig. 140). *N* designates a nozzle. The relationship between pressure and velocity is illustrated for both the single- and multi-pressure types in diagrams (*a*) and (*b*), Fig. 140.



(a) (b)

FIG. 140.—Principle of simple-impulse and multi-pressure single-velocity stage

The Rateau turbine (Fig. 141) is an illustration of this type. This turbine consists of a number of stages, each stage including one row of moving blades and a set of stationary nozzles. The steam enters through the first set of stationary nozzles, in which it expands to a lower pressure with a corresponding increase in velocity, and strikes the first set of revolving blades. The steam next passes through the second set of stationary nozzles, which are of greater area than the first, because the volume of steam was

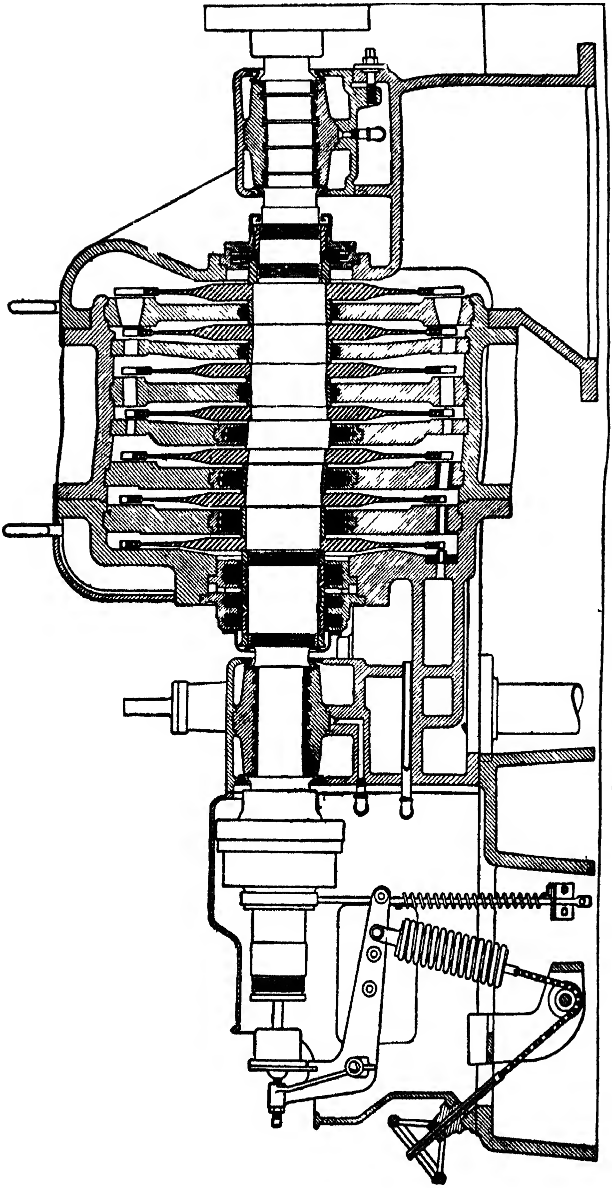


FIG 141 —Rateau-type steam turbine

increased by its expansion in the first set. Here the steam again expands and enters the second row of moving blades, and the process is repeated in succeeding stages until the steam reaches the exhaust outlet.

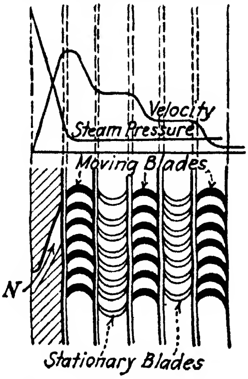


FIG. 142.—Principle of multi-velocity single-pressure impulse turbines.

Multi-velocity, Single-pressure Stage Impulse Turbines.—The principle of this type of turbine is illustrated in Fig. 142. Steam is expanded in one set of nozzles *N* and the speed is reduced by giving up the energy of the steam to several sets of moving blades, mounted on revolving wheels; the direction of the steam between the moving blades is changed by stationary blades.

The De Laval multiple-impulse turbine Fig. 143) is an illustration of multi-velocity, single-pressure tage principle. It consists of a series of blade wheels which revolve in independent chambers formed between diaphragms held in the casing of the turbine. Steam is admitted to the steam

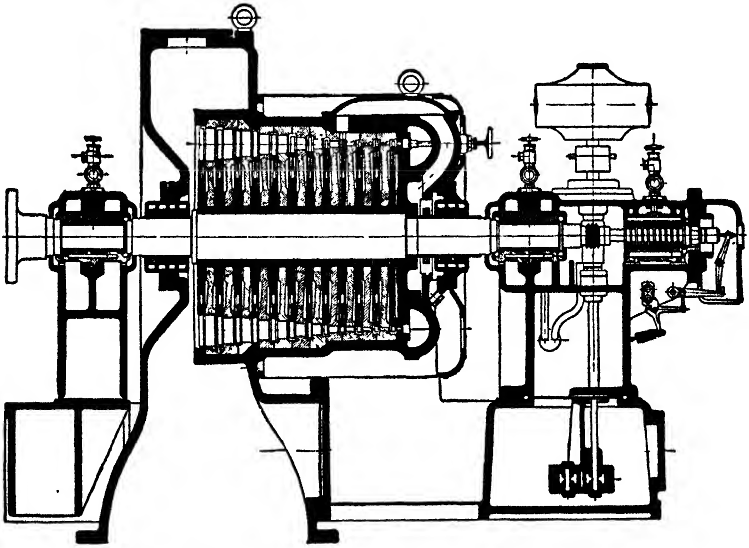


FIG. 143.—De Laval multiple-impulse steam turbine.

chest at the right-hand end of the turbine and is directed by means of nozzles upon the blades of the first revolving wheel. The steam leaving the first revolving wheel passes through guide blades, which are set around the entire periphery of the diaphragm separating the first and second stages, and strikes the blades of the second revolving wheel, and so on through the succeeding stationary and revolving blades.

The governing of the De Laval multiple-impulse turbine is accomplished by throttling the admission of the steam to the steam chest. An emergency governor is mounted in the end of the turbine shaft, entirely independent of the main speed governor, and can be adjusted to act at any predetermined speed.

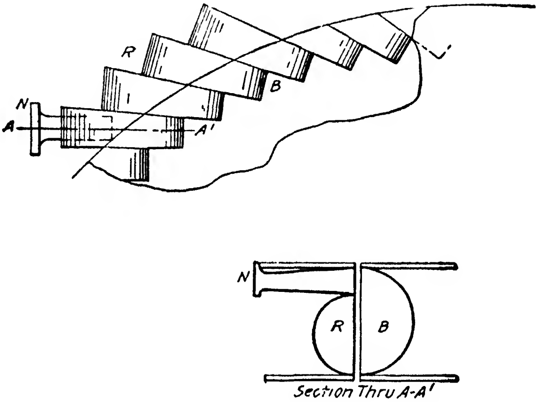


FIG. 144.—Principle of the re-entrant type of turbine.

In Figs. 144 and 145 is illustrated the application of the multivelocity, single-pressure stage principle to a single wheel of the re-entrant type. This type of turbine consists of one set of nozzles and one revolving wheel. The steam is expanded in the nozzle from approximately boiler pressure to exhaust pressure. The jet of steam issuing from the nozzle *N* (Fig. 144), at high velocity, strikes the side of the wheel blades, is reversed in direction 180 deg., and is guided into one of the stationary reversing blades *R*, by means of which the jet is redirected a second time on the buckets *B* of the wheel. This process is repeated several times until all the available energy of the steam has been abstracted by the revolving element.

Multi-velocity, Multi-pressure Stage Impulse Turbines.—The principle of this type of turbine is illustrated in Fig. 146. The expansion of the steam takes place in several stages, each stage being provided with nozzle *N* where the pressure drop takes place, and movable blades *M* and stationary blades *S*. The Curtis turbine is an example of this type. As indicated by the pressure and velocity diagrams (Fig. 142), the pressure drop takes place in several steps and the velocity developed is utilized in several stages.

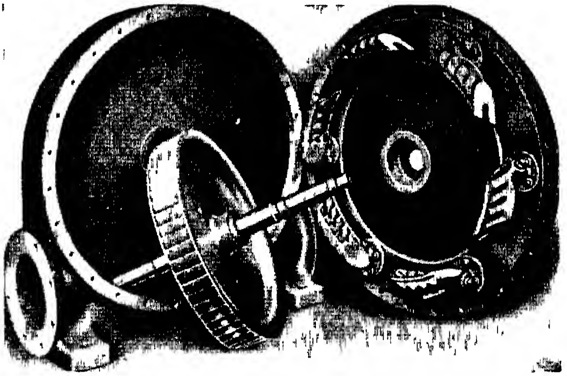


Fig. 145.—Parts of a re-entrant type turbine

In the Curtis steam turbine (Fig. 147), the expansion of the steam takes place in several stages and the velocity acquired in the nozzles of each stage is abstracted by one or two revolving wheels. The number of stages varies from one to fifteen or more, depending on the size of the machine and the range of steam conditions. In general, the higher initial pressures require a larger number of stages for condensing operation, while in noncondensing operation the back pressure plays an important part in fixing the number of stages in the turbine.

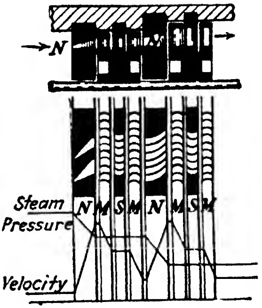


Fig. 146.—Principle of multi-velocity, multi-pressure stage impulse turbine.

The action of the Curtis turbine is illustrated by Fig. 147. Steam at boiler pressure enters through one or more admission valves *B* into the steam chest *C*. The steam from the steam chest enters the expanding nozzles *D*. The number of admission valves used is controlled by the governor in accordance with the load. The steam jet at high velocity issuing from the nozzle *D* strikes the moving blades *F*, giving up a portion of its energy. The direction of the steam is changed by the stationary or guide blades *G*, called intermediates, striking the second set of moving blades *H*. The steam issuing from the second set of moving blades enters the second stage, where it is further expanded by means of nozzles *K* and the energy developed is abstracted by moving blades *M*. The same operation is repeated in the third and in the subsequent stages.

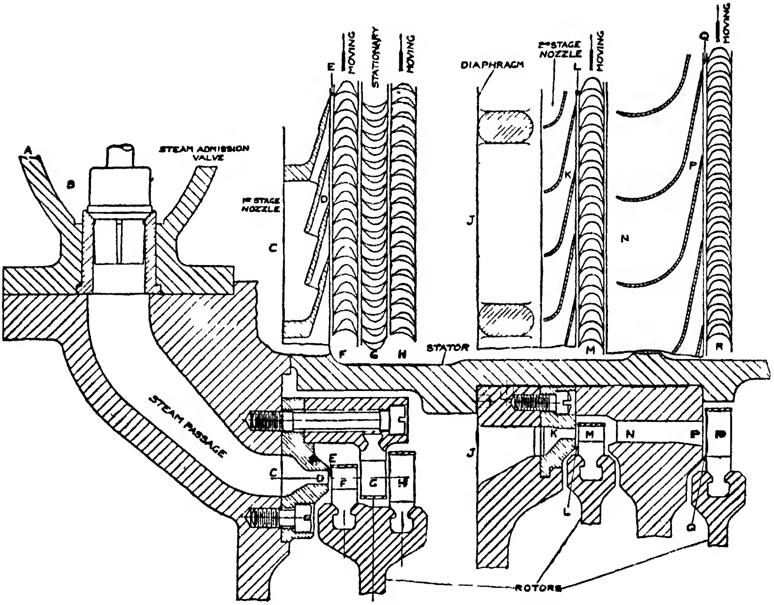


Fig. 147.—Arrangement of nozzles and blades in two-stage Curtis steam turbine.

The expanding nozzles of the first stage of a Curtis turbine are illustrated in Fig. 148. These extend around a relatively short arc of the periphery in the first stage, while in the low-pressure end they extend around the entire wheel.

The type of blade used in Curtis turbines is illustrated in Fig. 149.

The Curtis turbine is constructed as a horizontal machine (Fig 150). The vertical arrangement, used in some of the earlier designs, is now obsolete, but units of this type can still be found in operation in some power plants. In the vertical turbines, the shaft is supported by a step-bearing at the lower end Oil is pumped under this bearing at considerable pressure, thus floating the entire revolving element on an oil film.

Fig 148 First-stage nozzle plate for a Curtis turbine

Small Curtis turbines are controlled by means of a throttling governor. Large turbines are controlled by an indirect type of governor, which mechanically or through a pilot valve and a hydraulic cylinder opens or closes the admission valves, thus regulating, in accordance with the load, the number of nozzles which are open for the discharge of steam.

Curtis turbines are equipped with an automatic emergency governor, independent of the main governor, which through a trip operates the main throttle valve when the turbine speed exceeds a predetermined limit.

Fig. 149.—Blading of Curtis turbines.

The Moore turbine (Fig. 151) is similar to the Curtis (Fig. 150) and is also of the multi-velocity, multi-pressure stage impulse type.

The Reaction Turbine.—The reaction steam turbine is of the multi-pressure stage type and differs from the impulse turbines in that stationary blades are substituted for nozzles. The blades are shaped so that they can perform the functions of the nozzles

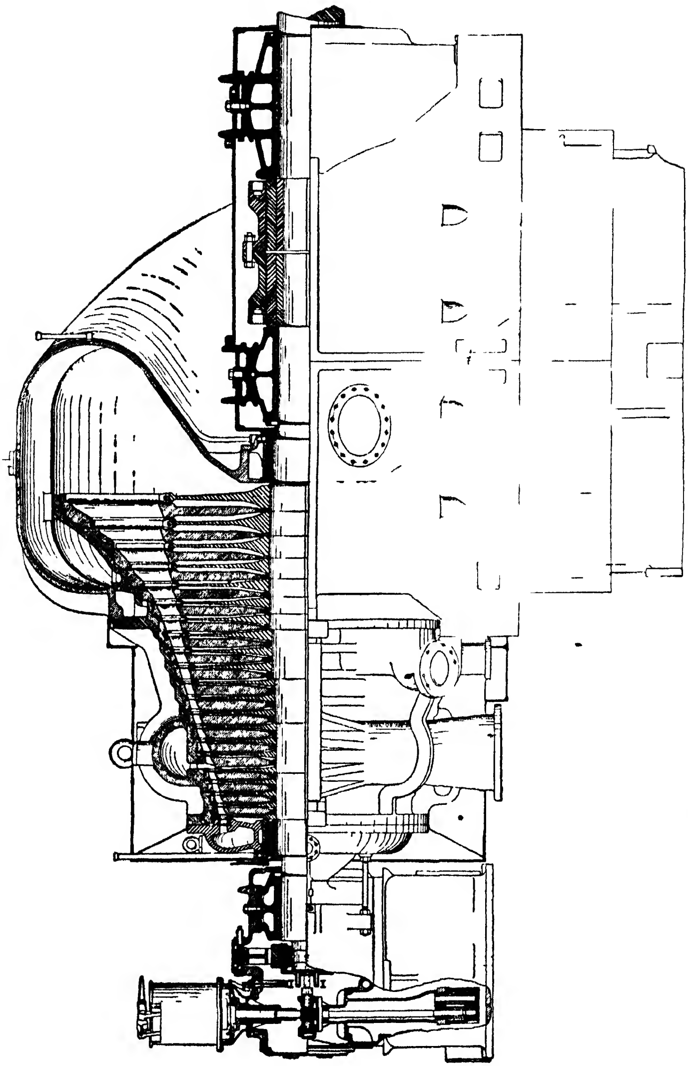


FIG 150 —Cross-section of a 45 000 kw 21 stage Curtis turbine

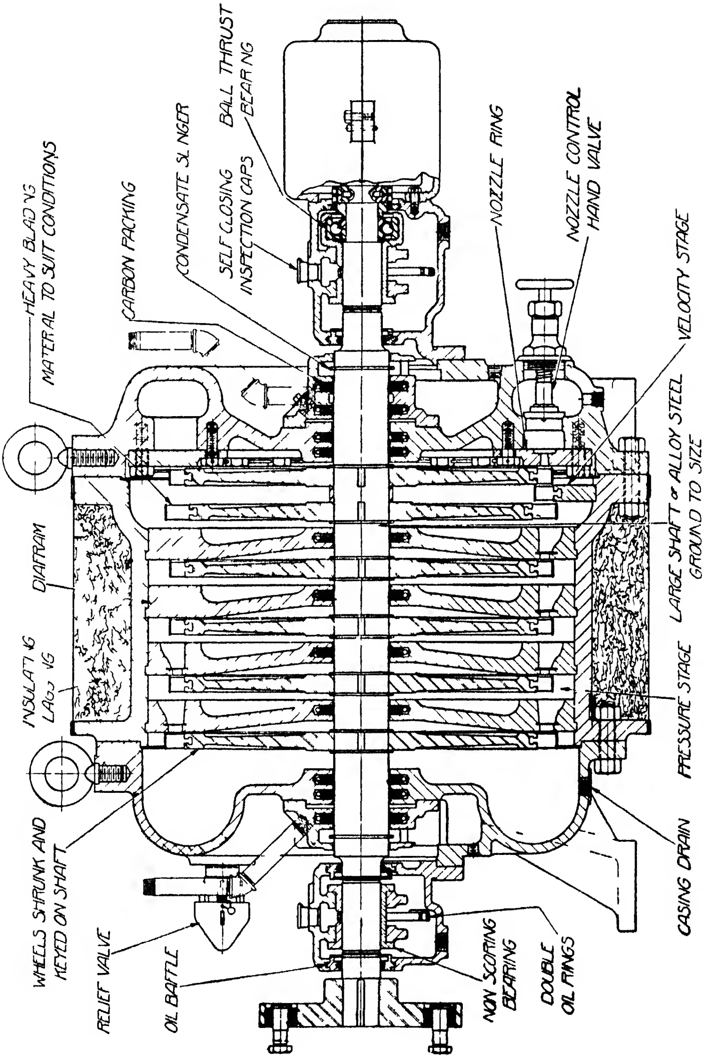


Fig 151 —Cross-section of a Moore five stage turbine and of the blades of impulse turbines. The reaction turbine has many stages, each stage consisting of a set of stationary and of rotating blades. Part of the expansion of the steam takes place in the stationary blades and part in the moving blades. In the impulse turbine, the pressure on both sides of the moving wheel is very nearly the same; in the reaction turbine, the pressure at the inlet to the wheel blade is greater than the pressure at the outlet.

The principle of the reaction type of steam turbine is illustrated in Fig. 152. Each stage is made up of one row of stationary blades *S* and one row of moving blades *M*. The pressure drop in each stage is divided into two parts, one being converted into kinetic energy in the stationary and the other in the moving blades. The stationary blades are attached to the outside casing, while the moving blades are fastened to the rotating element of the machine. The relationship between pressure and velocity changes is indicated in Fig. 152.

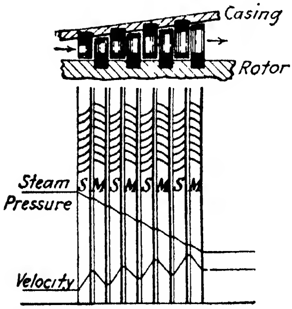


Fig. 152.—Principle of the reaction steam turbine.

The principle of the single-flow Parsons reaction turbine is illustrated in Fig. 153.

The steam enters a governor valve, reaches the chamber *I* and passes out to the right through the turbine blades, eventually arriving at the exhaust chamber *E*. The areas of the passages increase progressively in volume, corresponding with the expansion of the steam.

The rotating part of the turbine consists of a long drum upon which are mounted the moving blades. The stationary or guide blades are fitted in rings fastened to the turbine casing.

On the left of the steam inlet are shown the revolving balancing pistons, one corresponding to each cylinder or section of the turbine. The steam at *I* presses against the turbine and goes through doing work. It also presses in the reverse direction, but cannot pass the piston, thus equalizing the pressure and reducing end-thrust on the shaft. In most designs of Parsons turbines, all the balancing pistons are at the pressure end of the turbine. At *T* is shown a thrust bearing which serves to maintain the correct adjustment of the balancing pistons. *Q* is a pipe connecting the back of the balancing piston at *S* with the exhaust chamber *E'*, to insure that the pressure at this point should be the same as that of the exhaust. The governor gear and oil pumps generally receive their motion by means of a worm wheel, gearing into a worm cut on the outside of the coupling. An oil reservoir is provided into which drains all the oil from the bearings. From there it flows to a pump to be pumped to a chamber, where it forms a static head which gives a continuous pressure of oil to the bearings. A by-pass valve is provided, this valve admitting high-pressure steam to the lower stages. By opening this valve, the turbine can carry considerable overload or operate non-condensing at nearly full load.

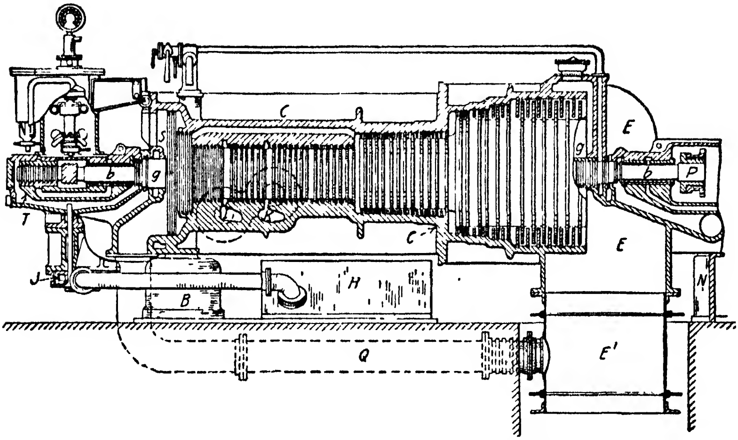


FIG. 153.—Sectional view of an early type of Parsons turbine.

In the Allis-Chalmers-Parsons turbine, of the reaction type, the largest balancing piston is placed at the low-pressure end of the rotating element behind the last row of blades.

Reaction turbines are controlled by an indirect type of governor, which causes the main steam admission valve to remain open for longer or shorter periods of time, depending upon the load carried by the machine.

Figure 154 illustrates reaction-turbine blading.

The Impulse-reaction Turbine.—A cross-section through a Westinghouse combined impulse and reaction turbine is shown in Fig. 155. The impulse element is similar to the first stage of a Curtis turbine, and consists of one set of nozzles, an impulse wheel with two rows of revolving blades, and a set of stationary blades. Steam first enters the turbine nozzles, is partly expanded, and impinges upon the impulse blades. The remaining energy of the steam after leaving the impulse blades is utilized in the reaction element of the turbine

Figure 156 illustrates a section through an Allis-Chalmers 35,000-kw., 3,600-r p.m , tandem-compound, impulse-reaction, condensing steam turbine, which has an initial steam pressure of 1,290 lb. gage, a steam temperature of 925°F , and exhausts at 29 in. vacuum referred to a 30-in. barometer.

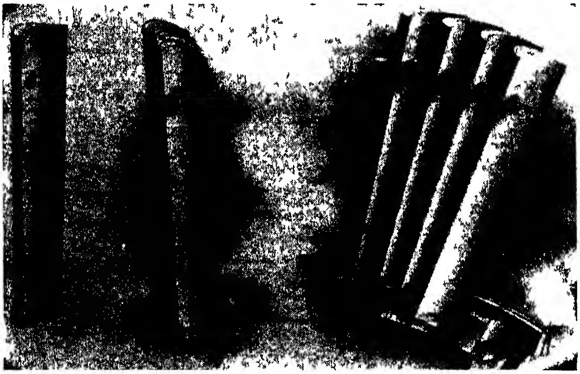


FIG 154 —Blading of Westinghouse-Parsons turbines.

The impulse-reaction turbine occupies less space than the pure-reaction machine. It is constructed either as a single-flow or as a double-flow machine. In the single-flow the reaction elements are on one side of the impulse stage, while in the double-flow the reaction elements are on both sides of the impulse wheel.

Multi-cylinder Steam Turbines.—Where operating conditions require the use of steam at high pressures and temperatures, it is found practical to allow the steam to pass in sequence through two or more turbines. Such installations are called multi-cylinder or compound steam turbines. The several turbines are mounted on one shaft or on separate shafts referred to as tandem-compound, and cross-compound, respectively The multi-cylinder arrangement is advantageous in that the steam may be

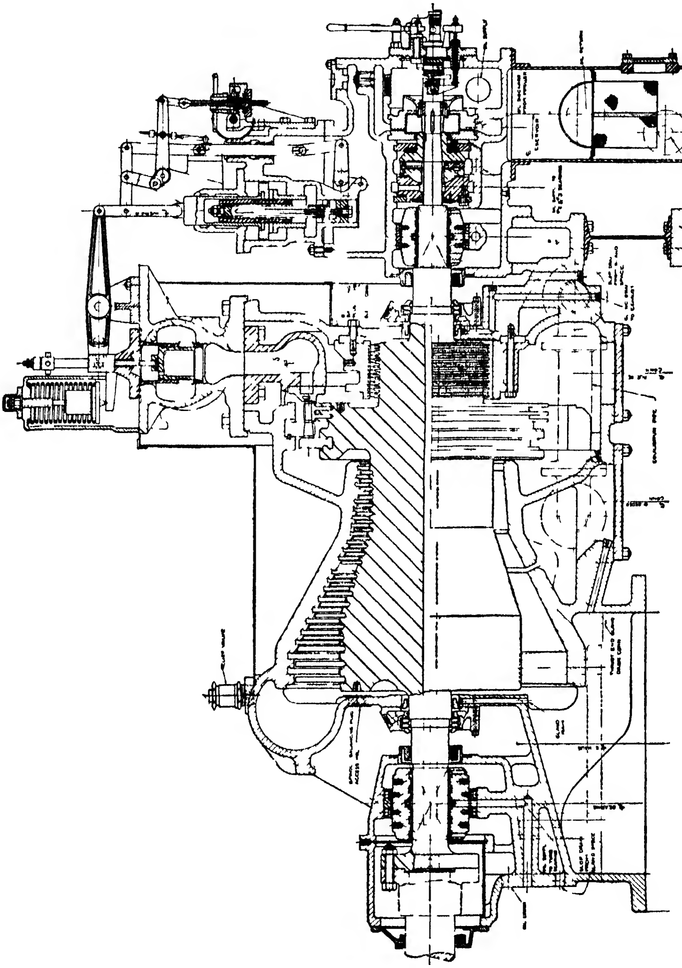


FIG. 155.—Cross-section of a Westinghouse combined impulse and reaction turbine

reheated very easily on its way between cylinders; also, the temperature range is less in each cylinder, thus reducing stresses in the casing and rotating element.

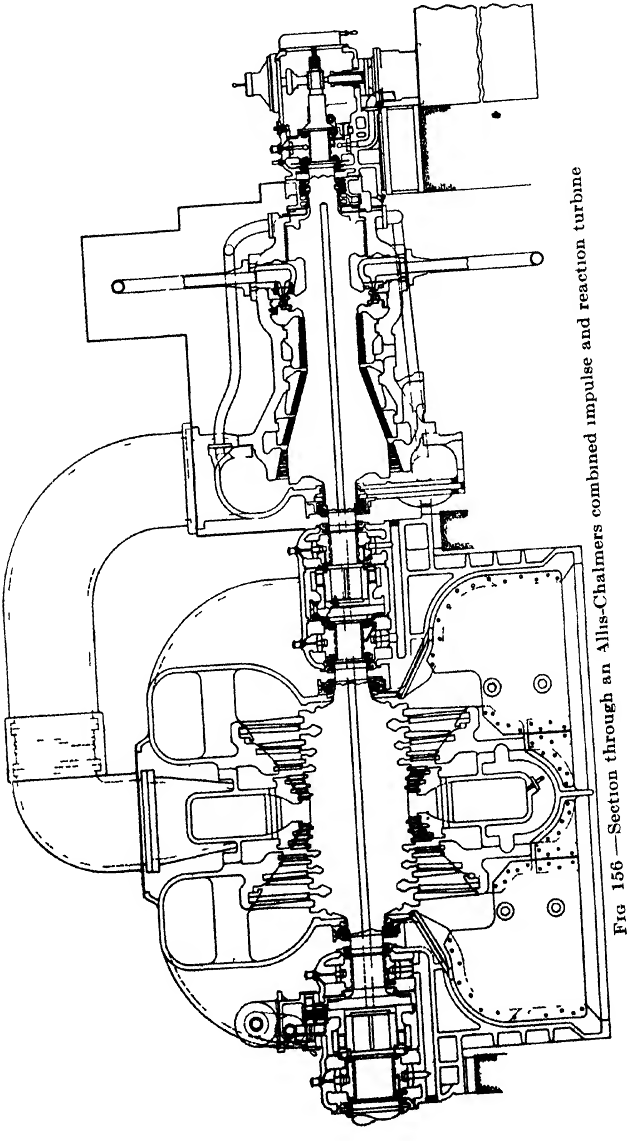


Fig 156 —Section through an Allis-Chalmers combined impulse and reaction turbine

The Illinois-Indiana State Line generating plant of the Commonwealth Edison Company has a three-cylinder, 208,000-kw. steam turbine. The high-pressure cylinder has a capacity of 76,000 kw. and receives steam at 600 lb. pressure and 730°F. After leaving this cylinder, the steam is reheated to 500°F. and delivered to two low-pressure cylinders rated at 66,000 kw. each.

Exhaust and Mixed-pressure Steam Turbines.—A steam turbine, installed between the exhaust of a reciprocating engine and a condenser, is called an exhaust steam turbine. The reciprocating steam engine does not show so high an economy at high vacuum as does the steam turbine. The capacity and economy of reciprocating engine steam power plants have been increased by the addition of a low-pressure turbine. Exhaust steam turbines may be operated as straight low-pressure turbines using only exhaust steam from engines, or as mixed-pressure turbines which operate on high- and low-pressure steam at the same time. Ordinarily, combined reciprocating engines and low-pressure turbines would not be selected for a new installation, as the cost of the combined units is much greater than that of the high-pressure steam turbine. The field of the low-pressure steam turbine is in connection with the large non-condensing reciprocating engine power plant.

Mixed-pressure turbines are designed to operate on both high- and low-pressure steam at the same time. This type is suitable for installations where the variation in the supply of low-pressure steam is such that an exhaust or low-pressure turbine cannot carry its load at all times. One type of mixed-pressure turbine utilizes the combined impulse-reaction principle, the impulse element for the high pressure and the reaction blading for the low pressure. The valves, under the control of the governor, admit steam to the high-pressure element only when the supply of low-pressure steam is not sufficient to enable the low-pressure element to maintain its speed at the required load.

Bleeder and Extraction Turbines.—The bleeder and extraction types of steam turbines are a modification of the multi-stage turbine. They are designed to take steam at boiler pressure exhausting part of this steam to a condenser or to the atmosphere, as in other types of turbines, while the other part is bled or extracted at some pressure above that of the main exhaust. In many industrial plants, there is need for steam at a pressure intermediate between the initial and exhaust pressure, and the bleeder or extraction type of turbine is designed to meet this condition. The larger the number of stages, the greater will be the range of steam pressures at which steam can be extracted. Bleeder turbines are used where there is a demand for low-pressure steam either for process work or for heating; a bleeder turbine has only one bleeder line. In power plants, steam is extracted from turbines at two to five points for use in feed-water evaporators and heaters. In industrial plants, steam is usually extracted at one point and above atmospheric pressure.

The Moore bleeder or extraction turbine is illustrated in Fig. 157. In this type, there is a bleeder chamber *A* between the velocity-stage wheel or wheels and the first single pressure-stage wheel. A cylindrical valve, as shown, allows the steam to enter the chamber *B*, from which point it flows through the single pressure-stage wheels. The steam bled is controlled automatically to maintain constant pressure at the bleeder outlet.

Applications of the Steam Turbine.—The steam turbine is applicable to work which requires a high and constant rotative speed, where a high starting effort is not required and where there is no need of reversing the direction of motion. These conditions exist in electric generating stations. For service in which the speed is low and variable, where a reversal of direction is necessary, or where the starting torque is high, the turbine is unsuited, and the reciprocating engine is better adapted. Speed-reduction and reversing gears have been employed in connection with turbines, but these have only a limited application.

The steam turbine is very seldom operated non-condensing; in power plants where the exhaust steam is used for heating or for manufacturing purposes, a bleeder turbine or a reciprocating engine should be selected.

Steam turbines are also used for the driving of power plant auxiliaries, such as boiler-feed pumps, hot-well pumps, and circulating pumps; also high-pressure fans and blowers.

Steam turbines are employed to an increasing extent for the propulsion of ships. The steam turbine has less weight and requires less space than the reciprocating engine of the same size.

Vessels propelled by steam turbines are more stable on account of the lower center of gravity of the machinery. The steam turbines are either connected to the propellers by means of gears, or drive electric generators, and the propellers are driven by electric motors, which receive their current from the generators of the turbines.

Steam Turbine Economy.—The economy of steam turbines is usually expressed in pounds of steam or in B.t.u. per kilowatt-hour, as the greatest field of the turbine is for the driving of electric generators. Steam turbines in sizes of 1,000 to 10,000 kw., when operated at 150 to 200 lb. gage pressure, with superheats of 100 to 200°F. and with a vacuum of 28 to 29 in., will ordinarily develop a kilowatt on 12 to 15 lb. of steam per hour. Better economies are secured as the size of the unit increases; also as higher pressures and temperatures are used. The smaller condensing steam turbines, when operated with saturated steam, will consume 18 to 30 lb. of steam per kilowatt per hour. Steam turbines when operated non-condensing will consume 50 to 75 lb. of steam per kilowatt per hour.

Steam turbines under ordinary operating conditions will show a gain of about 8 per cent for each 100° superheat. The presence of moisture will decrease the economy or increase the steam consumption by about 2 per cent for 1 per cent of moisture in the steam. Increasing the vacuum from 27 to 28 in. will increase the turbine economy from 3 to 5 per cent. Increasing the steam pressure from 150 to 200 lb. will increase the economy about 3 per cent.

Installation and Care of Steam Turbines.—The general rules given in Chap. VIII concerning the installation and care of reciprocating steam engines apply also to steam turbines.

The steam turbine should be located so that it will be accessible from all sides for inspection and repair. Proper crane and hoist facilities should be available for all parts which are too heavy to be handled by hand.

The foundation should be sufficiently heavy to afford a permanent support and rigid enough to prevent springing or warping any part of the turbine. To prevent vibrations from being conducted to the building, a space should always be left between the turbine foundation and the walls or floors; this space should

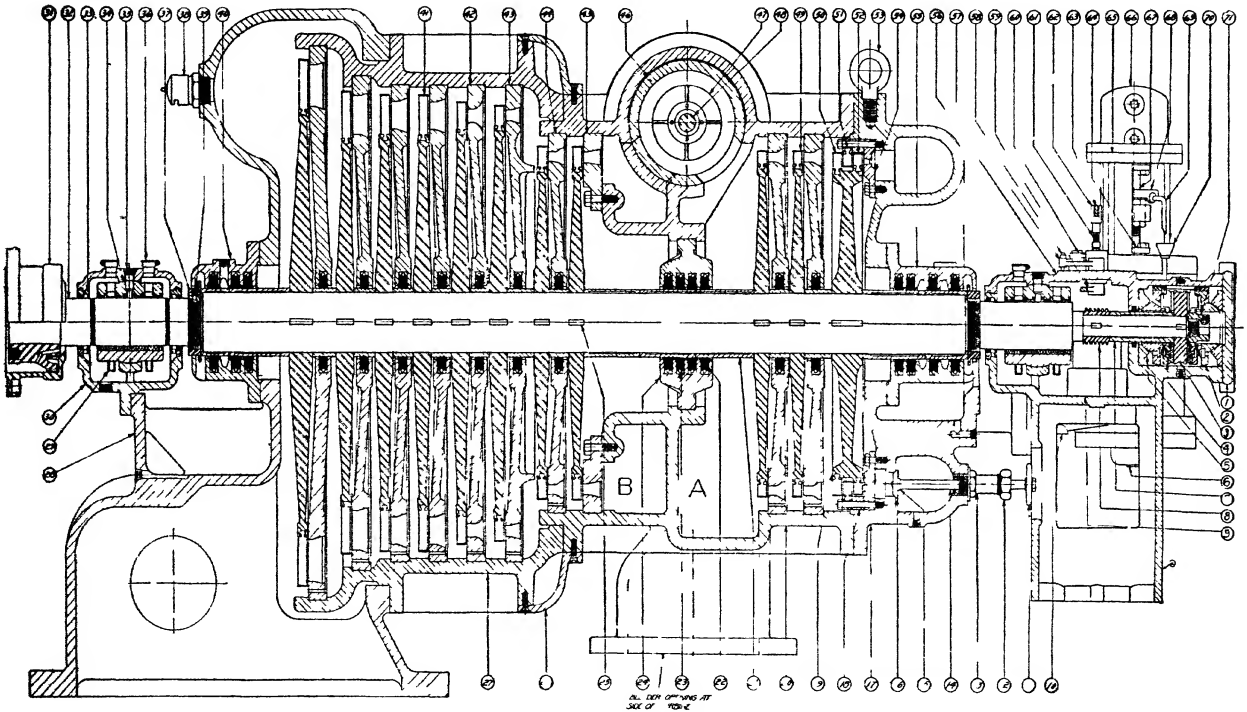
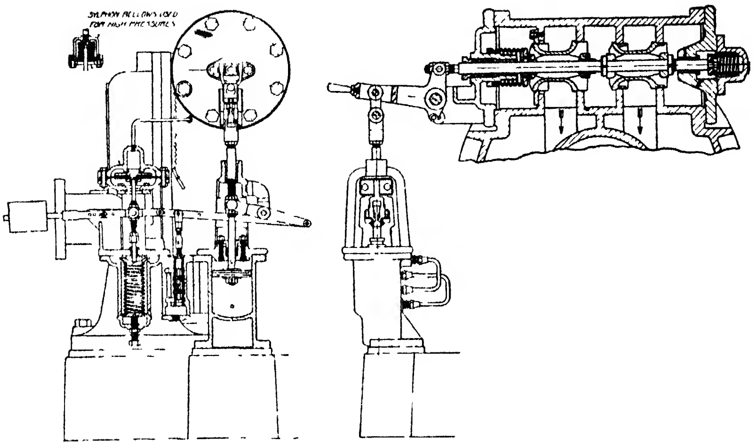


FIG. 157.—Cross section of bleeder turbine showing valve and pressure control mechanism.



1	A-806	Bearing case end cover
2	A-2449	Thrust bearing base ring
3	A-800	Thrust collar
4	A-801	Thrust bearing shoe
5	A-803	Thrust bearing seat
6	A-2828	Steam chest bottom cover
7	A 802	Shaft sleeve
8	A-279	Worm
9	C-2954	Steam end bearing case
10	C-3440	Steam chest
11	A-3036	Hand wheel
12	V-3898	Packing nut
13	A-3938	Control valve bonnet
14	V-3899	Control valve stem
15	V-3896	Valve stem collar
16	V-3897	Control valve disk
17	C-2817	Steam end
18	A-2538	Spacer block
19	B-2800	Curtis wheel
20	C-3399	Diaphragm cover T2B2
21	A-2814	Shaft sleeve
22	A-2766	Carbon rings
23	A-2769	Packing ring springs
24	B-3372	Blank diaphragm
25		Woodruff keys
26	B-2825	Lagging ring
27	C-3398	Diaphragm cover V5X
28	C-3400	Exhaust end
29	A-291-9	Oil rings
30	B-3401	Exhaust end bearing case
31	#4-Std	Fast coupling
32	B-3397	Turbine shaft
33	A-2260	Oil baffles (felt rings)
34	C-2249	Bearings
35	B-2258	Exn. end bearing case cap
36		Gits bearing oil cap
37	A-2816	Shaft nut
38		Relief valve 2″ size
39	A-1542-2	Stop pin
40	B-2772	Exhaust end packing case
41	B-2802	Turbine wheel
42	C-2786	Diaphragm
43	C-2780	Diaphragm
44	C-2776	Diaphragm
45	B-3379	Diaphragm
46	B-3370	Bleeder valve bushing
47	A-3369	Secondary valve
48	B-3364	Bleeder valve stem
49	B-2801	Turbine wheel
50	A-874-14	Buckets 2'nd row
51	B-2812	Guide blading ring
52	A-1148-3	Buckets 1'st row
53		William's eye bolt 1¼″
54	C-2270	Nozzle ring
55	B-2771	Steam end packing case
56	C-2953	St. end bearing case cap
57	A-356-2	Adjusting lever
58	A-451-2	Trip connection pins
59	A-356-1	Trip lever
60	A-451-1	Relay valve trip lever
61	B-302	Relay valve
62	A-415	Relay valve connection
63	A-2878	Governor lever
64	A-2181	Oil cylinder bracket gland
65	B-2834	Oil cylinder bracket
66	A-316	Oil cylinder
67	B-2868	Valve stem
68	A-1198	Valve stem oil pan
69		Drip pipe
70	A-1199	Pipe fitting
71	A-804	Shaft nut

FIG. 157.—(*Continued.*)

be filled with some soft material. After the foundation is properly set, care must be taken to obtain proper adjustment of the turbine. Small steam turbines are usually placed on concrete floors without foundations.

The piping must be so designed and installed that no strain will be thrown on the turbine due to expansion and contraction, or on account of the piping being improperly supported. Water pockets in the piping should be avoided.

Before starting a steam turbine for the first time, care must be taken to blow out the steam and oil from the piping in order to remove scale and dirt. The oiling system should then be put in operation and the turbine should be warmed up and started slowly, listening for any clicking or rubbing sounds, which may require investigation. While the turbine is turning over slowly, the oiling system and the auxiliaries should be examined. Heating of the bearings may be due to grit or to poor alignment. After ascertaining that everything is in good working order, the turbine should gradually be brought up to speed. As the turbine approaches full speed, the action of the governor should be observed. If the governor is working properly, the turbine is ready for the load.

In starting a condensing turbine, the condenser auxiliaries are started first, and after the vacuum has been obtained, the turbine is started.

Problems

1. To gain a conception of the enormous amount of power a 208,000-kw. turbine develops, calculate the following:
   (*a*) If all the energy of a 208,000-kw. turbine is used to supply light, calculate the number of candlepower it will supply by means of Tungsten lamps.
   (*b*) If a 208,000-kw. turbine develops a kilowatt on 1⅓ lb. of coal per hour, calculate the amount of fuel required to keep such a turbine in operation at full load for 10 hr.
2. Show by means of clear sketches the details of governors used in connection with:
   (*a*) Simple-impulse turbines,
   (*b*) Curtis turbines,
   (*c*) Parsons turbines.
3. Explain how vessels propelled by steam turbines are reversed.
4. Why can a steam turbine operate and take advantage of higher vacua than a reciprocating engine?

5. Why cannot a steam engine equipped with slide valves operate on highly superheated steam as well as a steam turbine?
6. What major factors delayed the development and utilization of the steam turbine?
7. What are the major differences between impulse and reaction turbines?
8. Under which conditions is the reciprocating engine preferable to the steam turbine?
9. A condensing turbine has an economy of 13.2 lb. of steam per kilowatt-hour when operated with steam superheated 200°, pressure 185 lb. gage and 28 in. of vacuum. If the superheat fails and the turbine has to be operated with steam which has a quality of 95.5 per cent, how much will the steam consumption of the turbine be increased?
10. A steam turbine designed to operate with steam at 200 lb. gage, 200° superheated and vacuum of 28 in. has to be operated with steam at a pressure of 160 lb. gage, dry and saturated and 28 in. of vacuum. If the economy of the turbine is 16.5 lb. per kilowatt-hour at the 200-lb. condition, what will be the economy at the 160-lb. condition?
11. Using Figs. 140, 142, 146, and 152 compare changes in pressure and velocity in different types of steam turbines.
12. What are the major differences between the three types of multi-stage impulse and the reaction turbines?

CHAPTER X

ENGINE AND TURBINE AUXILIARIES

Many of the auxiliaries which properly belong to the engine and turbine have been described in Chaps. V, VI, VII, VIII, and IX. This chapter will deal mainly with condensers and condenser auxiliaries, but will include other apparatus which may be considered auxiliaries or accessories to an engine or turbine.

CONDENSERS

The Principle of the Condenser. The advantage gained by operating a steam engine condensing is due to the reduction in the back pressure against which the engine exhausts. In the case of the steam turbine, the available energy in the steam can be more than doubled by carrying high vacua, as compared with non-condensing operation.

The gain in economy which can be expected by increasing the vacuum depends to some extent upon the size of engine or turbine, and also upon the type of machine. The theoretical gain for a perfect steam motor per inch of vacuum will vary from about 3.0 per cent at 25 in. vacuum to about 5.0 per cent at 28 in. vacuum. A well-designed steam turbine will very nearly realize the theoretical gains for any given vacuum. A high vacuum means low-temperature condensed steam, and this may necessitate the heating of condensed steam before it is used as boiler feed water.

If an engine or turbine is provided with some vessel into which the steam is exhausted, vacuum could be maintained by simply removing the uncondensed exhaust steam as fast as it enters. Such a method, however, would not be economical, as the equipment utilized in maintaining the vacuum would have to handle practically the entire volume of exhaust steam leaving the engine. If this were the case, very little gain would result, for as much work would have to be done by the condenser pump in maintaining the lower back pressure as would be gained by the engine.

Steam, however, may easily be condensed, and in the form of water occupies a very much smaller volume. Advantage of this fact is taken in the operation of condensers. Thus, if the exhaust steam from the engine is admitted into a vessel and condensed before being discharged, the work required to maintain the vacuum is greatly reduced, because the work of the condenser pump is only that due to the removal of a comparatively small volume of water.

In a system composed entirely of steam, or one in which the exhaust steam was not mixed with air or with other gases which have entered the system, the vacuum to be maintained is dependent upon the temperature of the condensed steam. By reference to the steam tables (Table 6), it will be found that water at a temperature of 126.08°F. boils at a pressure of 2 lb. absolute. A condenser in which the condensed steam is at that temperature would be limited to that pressure. Any attempt to lower the vacuum would cause an evaporation of the condensed steam.

In the actual operation of condensers, the temperature of the condensed steam must be below that corresponding to the vacuum to be carried. The condenser is never free from air, and the temperature of the condensed steam is several degrees below that corresponding to the vacuum carried. Air enters with the boiler feed water and also leaks in the condenser through piping and valves. The air mixed with the steam not only tends to destroy the vacuum and raise the pressure in the condenser above that theoretically required, but must also be continuously removed, if the vacuum is to be maintained.

The Measurement of Vacuum.—The pressure maintained in a condensing system may be measured by a mercury manometer or by a special gage. The pressure is below that of the atmosphere, hence the term vacuum is applied.

The measurement of pressure above that of the atmosphere is expressed in pounds per square inch gage. In the measurement of pressures below atmosphere, the unit of pressure is usually stated in inches of mercury and expresses the amount of pressure below that of the atmosphere. To convert pressure above atmospheric to absolute pressure, the gage pressure is added to the atmospheric pressure, corresponding to the barometric reading. When vacuum readings have to be converted into absolute pressures, the pressure corresponding to the vacuum must be deducted from the atmospheric pressure.

Illustration.—A condensing engine receives steam at 100 lb. per square inch gage and exhausts into a condenser whose gage reads 26 in. of mercury. The barometric pressure is 29 in. of mercury.

A column of mercury 1 in. high is equivalent to a pressure of 0.491 (roughly $\frac{1}{2}$) lb. per square inch, or the equivalent pressure of the atmosphere is then

$$29 \times 0.491 = 14.24 \text{ lb. per square inch.}$$

The absolute pressure of the entering steam is

$$100 + 14.24 = 114.24 \text{ lb. per square inch.}$$

Since the vacuum in the condenser is measured in units below atmospheric pressure, the absolute pressure within the condenser is

$$29 - 26 = 3 \text{ in. of mercury,}$$

which is equivalent to

$$3 \times 0.491 = 1.47 \text{ lb. per square inch absolute.}$$

Types of Condensers.—Condensers are either of the jet or of the surface type. The jet condensers produce condensation by the direct mingling of the exhaust steam and circulating water, and the resulting mixture of condensed steam and water leaves the condenser at the same temperature. In the surface condenser, the exhaust steam and the circulating water are separated by tubes, the heat transfer between the steam and circulating water taking place by conduction through the tubes. The surface condenser is more commonly used in large power plants.

The jet condenser is much simpler than the surface condenser and its first cost is lower, but in most cases it is restricted in its application to plants where the injection water is good. The surface condenser has the advantage in that its cooling water does not come in direct contact with the steam to be condensed. For this reason surface condensers are used where the condensed steam is returned to the boiler, and where the cooling water is salty, muddy, or otherwise unfit for steam making. While the surface condenser is particularly well suited for plants where the circulating water is poor, it must not be inferred that it would be practical to use water so filthy that it would foul the tubes.

Low-level Jet Condensers.—Figure 158 illustrates the construction of one of the simpler types of jet condensers. This type is called a low-level jet condenser, as the condensing chamber is at a low elevation and the condensate is removed by a pump *G*. Exhaust steam enters at *A*. Injection water enters at *B*, and is divided into a fine spray by the adjustable valve *D*. The steam is condensed by contact with the finely sprayed water, and the mixture accumulates in chamber *F*, from which it passes to the pump *G* and is discharged at *J*. The pump *G* in this type of condenser must remove both the air and the condensed steam. It is called a wet-air pump. The pump cylinder in order to handle the air and the condensed steam must be designed larger than would be required for the removal of the water alone.

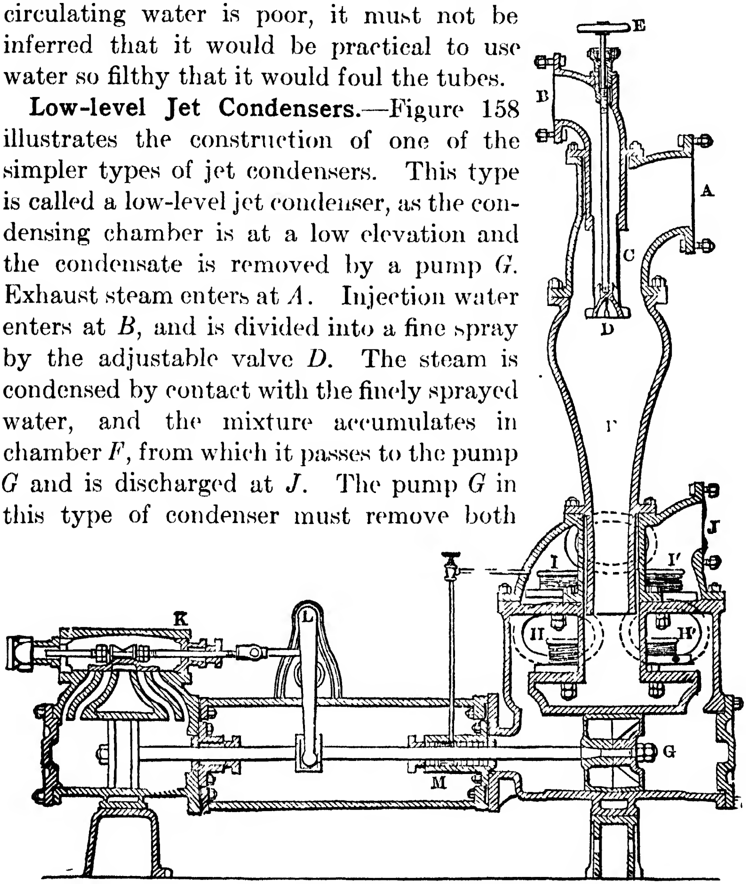


Fig. 158.—Jet condenser.

Injection water under pressure is not necessary with this type of condenser, as the water will be drawn into the condensing chamber by the vacuum produced, although the pumping head in such cases is limited to about 15 ft. With such an arrangement, means must be provided for creating a vacuum when starting the condenser. This is usually accomplished by starting the pump or by providing the condenser with an auxiliary supply of injection water under pressure, which will produce sufficient vacuum by condensing the first steam admitted

Condensers are usually provided with some means for automatically breaking the vacuum The atmospheric relief valve, illustrated in Fig. 159, is placed in a branch taken from the main exhaust line between the condenser and the engine, and leading to the atmosphere. The atmospheric exhaust valve is held closed by the atmospheric pressure when the vacuum is maintained, but should the vacuum be lost, the pressure of the exhaust steam operates the valve, permitting a free outlet of steam to the atmosphere. When the vacuum is restored, the the valve will close automatically.

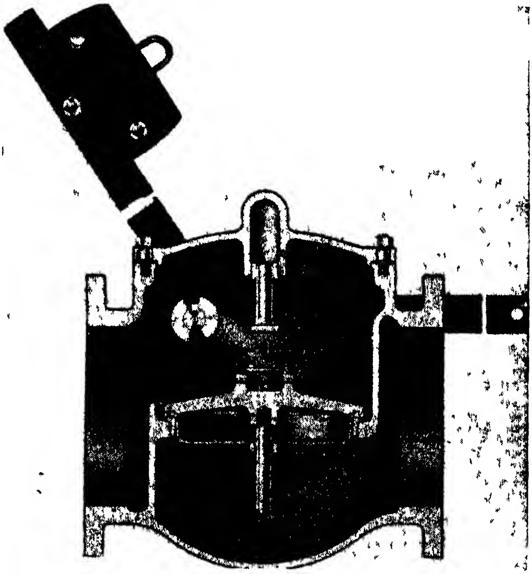


Fig. 159—Atmospheric relief valve.

Barometric Condensers.—Figure 160 illustrates the barometric type of jet condenser. The condensing chamber is supported upon a water-sealed tail pipe, 34 ft. above the surface of the water in the hot well. Atmospheric pressure at sea level will

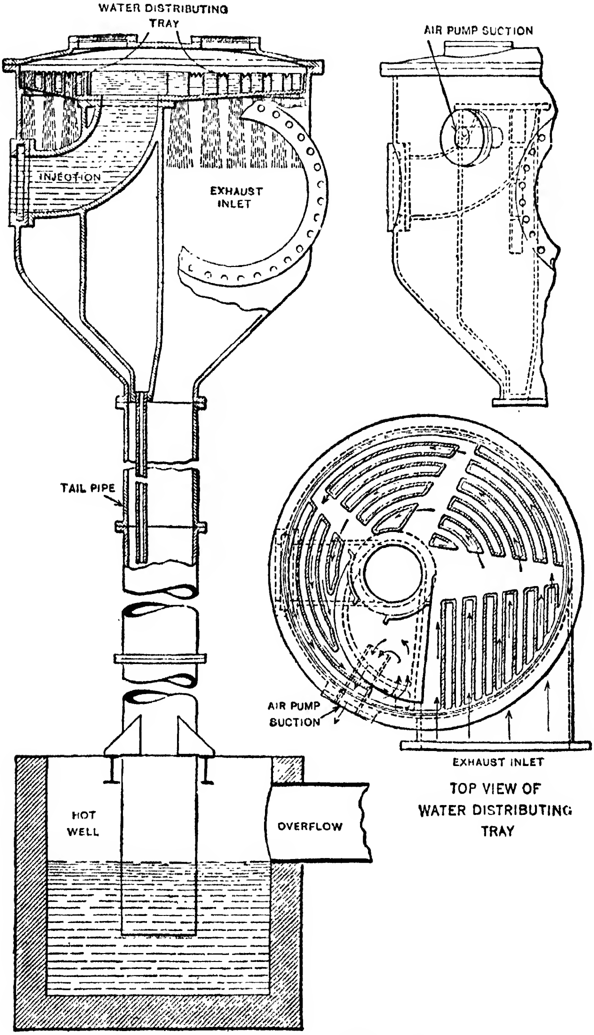


Fig. 160.—Sectional views of a barometric condenser.

support a column of water 34 ft. high, consequently the accumulation of condensed steam in the tail pipe which would tend to rise above this height, will displace an equal quantity of water from the bottom of the tail pipe. No pump is required for the removal of the condensed steam from the barometric condenser, but, in most cases, the use of a pump for the injection water is necessary. If the cold-water supply is within a vertical distance of 20 ft. from the injection opening to the condenser, the use of a pump for the injection water may be dispensed with, as the vacuum will lift the water to that extent.

Air is removed from the barometric type of condenser by a separate pump. Since this pump removes air alone, it is called a dry-air pump to distinguish it from wet-air pumps which remove both the condensed steam and air.

Ejector Condensers.—The ejector, eductor, and siphon types of jet condensers depend upon the high momentum of the condensed steam and cooling water to discharge the condensate against atmospheric pressure. No circulating, or air pump, or barometric tube is needed. Figure 161 illustrates two different types of such condensers. Exhaust steam enters the eductor condenser at *E*, completely fills the annular chamber *A*, and passes through the small nozzles. The cooling water is continuously drawn in through the nozzle *C* and meets the condensed steam in the tube *T*. Condensation takes place and sufficient velocity is developed to remove the condensed steam, the cooling water, and the air.

High-vacuum Jet Condenser.—The maintaining of a high vacuum in a condensing system requires the removal of a large volume of air. Figure 162 illustrates an assembly of the Leblanc multi-jet type of high-vacuum condenser. Steam enters the condenser and meets the cooling water. The condensed steam and circulating water are removed by a centrifugal pump. The centrifugal air pump depends for its operation upon the ejector action of water moving at a high velocity. Referring to Fig. 162, sealing water is introduced to the central chamber of the pump from which it passes through the distributors 21. The water is caught by the blades of the air-pump runner 16 and ejected into the collector cone 23, entrapping the air which enters, and discharging both the air and sealing water to the atmosphere through the diffuser 25. The temperature of the sealing water does not increase to any appreciable extent in passing through the system and is used over and over again.

Surface Condensers.—A sectional elevation through a surface condenser is shown in Fig. 163. It consists of a cylindrical, rectangular or heart-shaped cast-iron shell closed at the two ends by suitable heads. Attached to the inner surface of the condenser shell are two tube plates, which are joined by numerous seamless drawn-brass tubes.

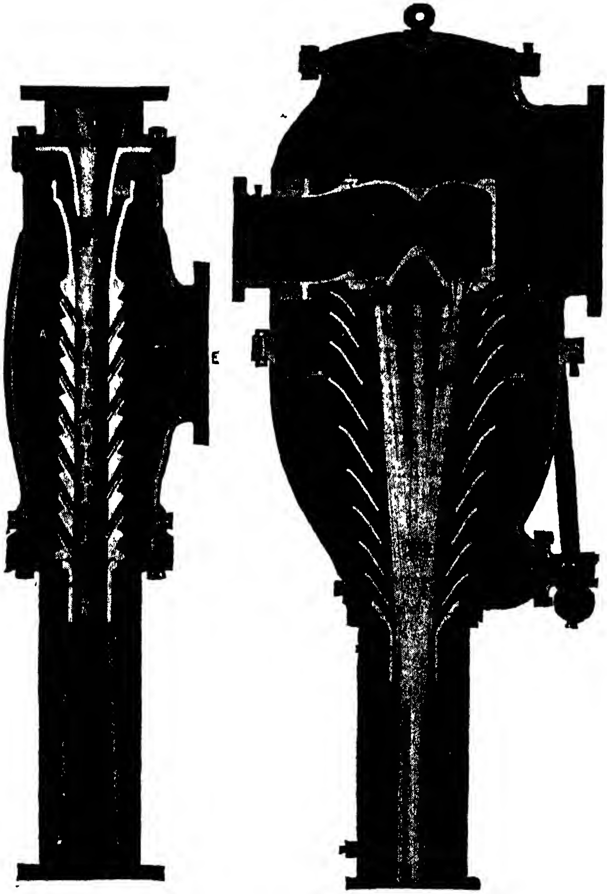


Fig. 161.—Ejector condensers.

Exhaust steam enters the top of the condenser and strikes a baffle plate which protects the upper rows of tubes and distributes the steam to all parts of the condenser. Circulating

	Name		Name
1	Inlet chamber	27	Pump bearing bracket (O.B.)
2	Injection nozzle	28	Pump bearing bracket (I.B.)
3	Condenser body	29	Pump gland
4	Vacuum breaker chamber	30	Pump gland spacer
5	Vacuum breaker chamber weight arm	31	Pump gland packing
6	Vacuum breaker cover	32	Pump bearing (O B.)
7	Vacuum breaker rod clevise	33	Pump bearing cover
8	Vacuum breaker valve	34	Pump bearing end cap
9	Vacuum breaker valve seat	35	Pump bearing oiling ring
10	Vacuum breaker float	36	Pump bearing oil guard
11	Vacuum breaker strainer plate	37	Pump bearing thrust collar (inner)
12	Pump body	38	Pump bearing thrust collar (outer)
13	Pump runner	39	Pump bearing thrust collar nut
14	Pump body liner	40	Pump bearing cover oil guard (inner)
15	Air pump body	41	Pump bearing cover oil guard filler
16	Air pump body runner	42	Pump bearing cover end cap
17	Air pump runner disc	43	Pump shaft
18	Air pump runner disc nut	44	Pump shaft sleeve (I.B.)
19	Air pump water chamber	45	Pump shaft sleeve packing ring
20	Air pump water chamber packing ring	46	Pump shaft sleeve (center)
21	Air pump distributor	47	Pump shaft sleeve packing (O.B.)
22	Air pump body liner	48	Pump shaft sleeve nut packing ring
23	Air pump collector cone	49	Pump bed plate
24	Air pump steam cone	50	Pump distance piece
25	Air pump diffuser	51	Pump shaft sleeve (O.B)
26	Expansion joint (complete)	52	Pump bearing (I.B.)

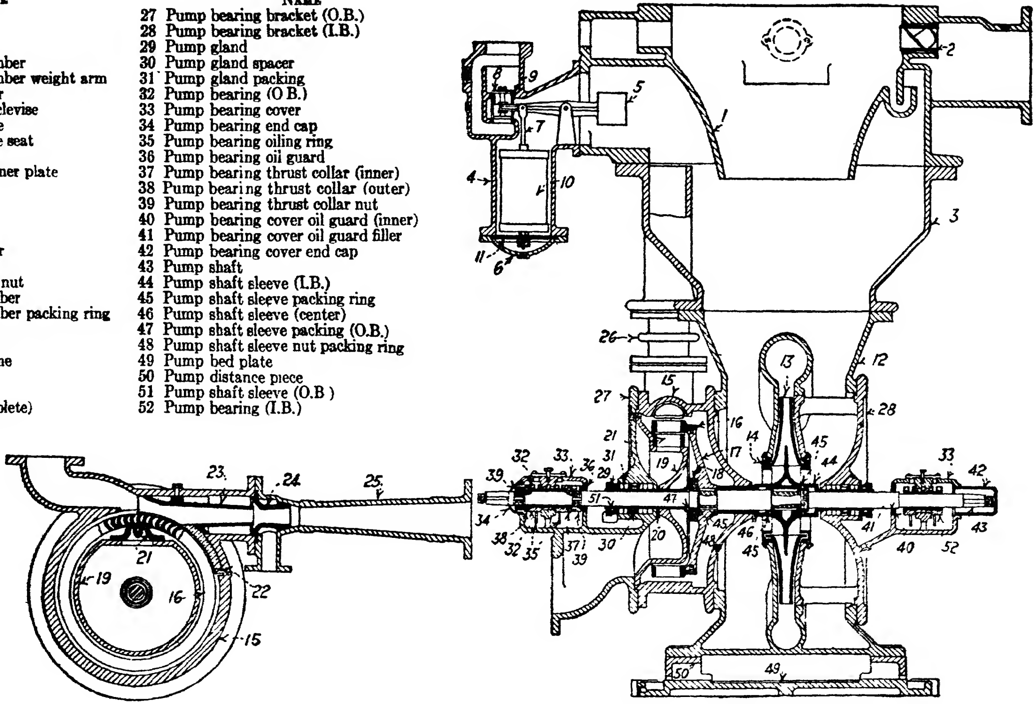


FIG. 162.—High-vacuum jet condenser.

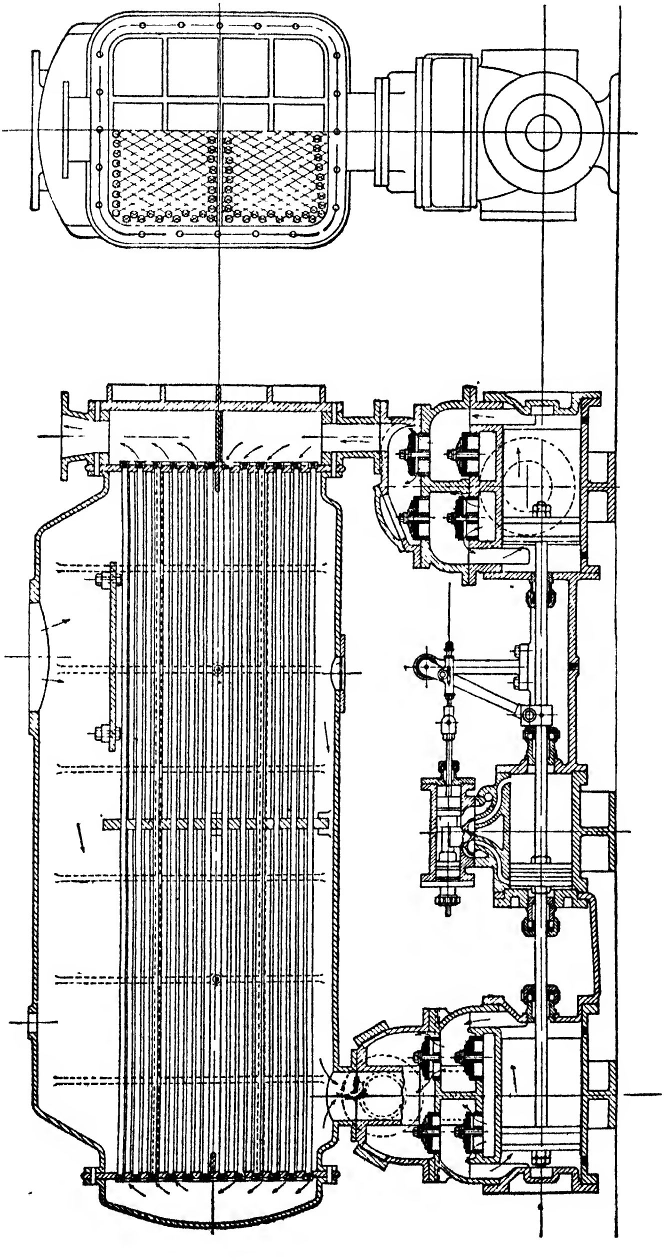


FIG. 163.—Surface condenser.

water enters at the ends of the condenser, and passes through the various banks of tubes as shown by the arrows The steam flows around the tubes and is condensed by coming in contact with the cool surfaces.

In the condenser illustrated, the circulating and wet-air pump form the base upon which the condenser rests, although this arrangement is not always adhered to The pumps (Fig 163) are connected by a common piston rod which is operated by the central steam cylinder.

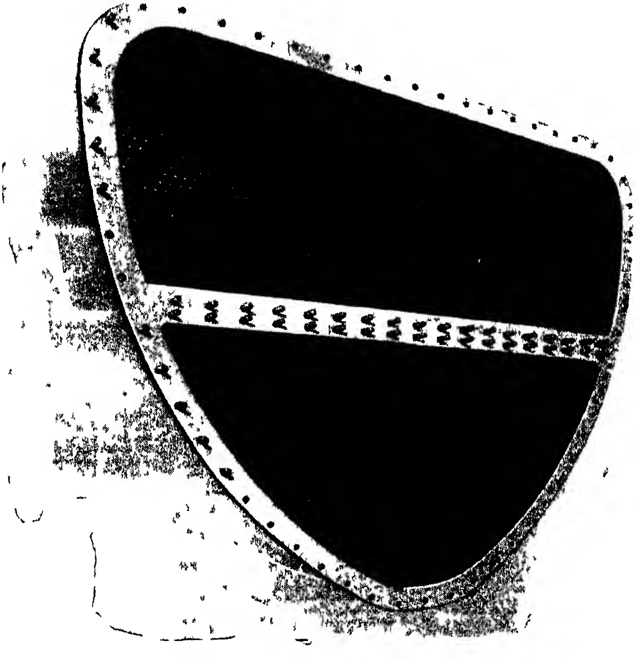


Fig 164 —Ingersoll-Rand single-pass surface condenser

The condenser, illustrated in Fig. 163, is of the two-pass construction; that is, the heads are divided into two compartments so that the cooling water passes through the lower bank of tubes and returns through the second or upper bank of tubes. In the single-pass condenser (Fig. 164) there is but one chamber between the tube sheets and the condenser headers. In large condensers, the tube bank is divided into three sections. The Ingersoll-Rand condenser (Fig. 164) has a heart-shaped shell in place of the circular or rectangular construction (Fig. 163). The tubes are arranged in stages and the areas are in the reverse order from that of a steam turbine. At the top the spacing is very wide both between the tubes and the rows of tubes. The tube spacing is arranged on smaller centers as the volume of the steam decreases

Surface condensers are built in large sizes and are usually used in modern central electric generating stations. Large surface condensers are built so that one-half of the tubes may be cleaned while the remaining tubes are in operation.

VACUUM PUMPS

In connection with a condenser installation, a wet-air pump and a circulating pump are required. To maintain a high vacuum, a dry-air pump is used in addition to a hot-well pump and a water-circulating pump. The power consumed by the condenser auxiliaries is about 2 per cent of the total output of the unit the condenser serves. Wet-air pumps are used to remove the condensed steam, the non-condensable vapors, and the cooling water. Dry-air pumps remove only the non-condensable vapors, and are used in steam-turbine installations where a high vacuum must be maintained. Hot-well or condensate pumps are those that remove the condensate from surface condensers; circulating pumps force the cooling water through the condenser.

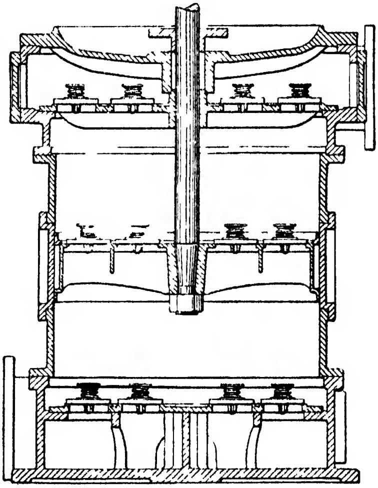


Fig. 165.—Wet-air pump.

Wet-air Pumps.—A type of wet-air pump commonly used in connection with jet condensers is illustrated in Fig. 165. These pumps are of the reciprocating type. On the upward stroke of the piston, a lower pressure than that maintained in the condenser is created below the piston, causing the cooling water and condensate, together with the air, to be drawn into the cylinder. The downward stroke of the piston causes the foot valves to close and the entrapped water and air to pass through valves in the piston. When the piston next moves upward, the mixture is compressed by the closure of the valves in the piston and is discharged through the valves at the top of the cylinder.

Figure 166 illustrates a type of wet-air pump designed for use with surface condensers. Pumps that depend upon foot valves for the entrapping of the air and water in the pump cylinder require an appreciable difference in pressure to insure the opening of the valves. The Edwards air pump (Fig. 166), by the elimination of these valves, is capable of maintaining a vacuum from ½ to 1 in. lower than would be possible with pumps of the valve-operated type.

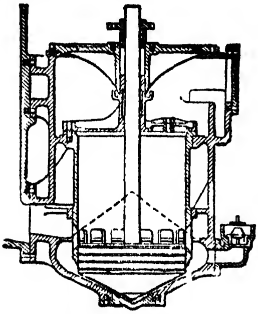


Fig. 166.—Edwards air pump.

The condensed steam flows by gravity from the condenser to the pump, where it collects in the base. Upon the descent of the conical-shaped pistons or bucket, the water is projected at high velocity through the ports into the working barrel of the pump, drawing with it considerable air and other non-condensable vapors. On the upward stroke, the ports are closed by the piston, and the water and entrapped air are discharged through the valve at the top of the cylinder.

Dry-air Pumps.—For high vacua, it is more desirable to discharge the air and condensate from the condenser separately. This arrangement necessitates the use of two pumps, a dry-air pump and a wet-air pump.

Figure 167 illustrates a sectional view of an Alberger dry-air pump. The suction valve is positively actuated by an eccentric on the crankshaft. This valve is provided with an equalizing port, which eliminates the detrimental influence of the air in the clearance space.

When the piston reaches the end of the stroke, the space between it and the cylinder head is filled with air at atmospheric pressure that has not been discharged through the outlet valve. If the piston were to make the return stroke while this air was under pressure, a considerable part of the stroke would be traversed by the piston before this air had expanded to the suction pressure. As a result, the drawing in of a fresh charge of air from the condenser would be confined to a small portion of the stroke. To increase the effectiveness of the pump, the valve is moved into its equalizing position before the piston begins its return stroke. The air under pressure is then transferred to the other side of the piston, where it is compressed and is discharged through the valves at the top of the cylinder. By this means, the suction side of the piston is effective throughout its entire stroke.

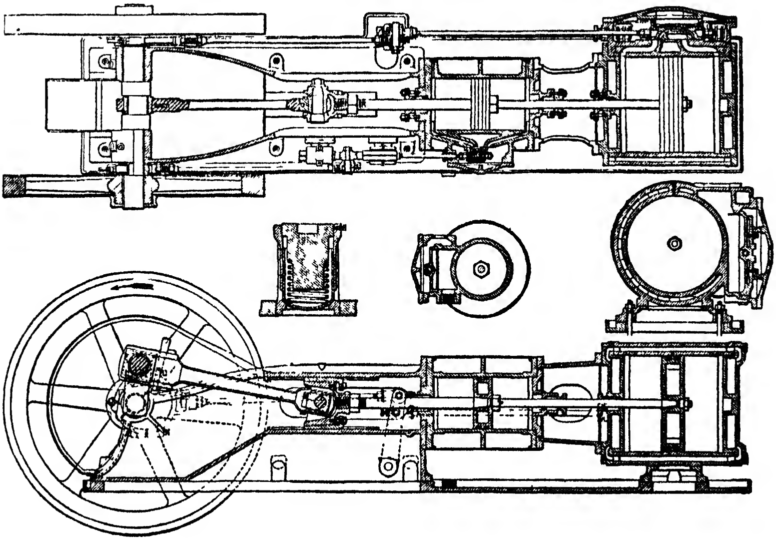


FIG. 167.—Dry-air pump.

The hydraulic type of dry-air pump similar to that discussed in connection with the Leblanc condenser (Fig. 162) is also used.

Ejector Pumps.—The steam type of air ejector, often called a steam-jet pump, is being used to an increasing extent in place of reciprocating, rotary or hydraulic types of air pumps. This type of pump is illustrated in Figs. 168 and 169. Figure 168 illustrates a Westinghouse two-stage non-condensing air-ejector pump. Figure 169 is a cross-section of a two-stage air-ejector pump with a jet condenser between the stages. In the non-condensing ejector pump (Fig. 168) the second stage handles both air and steam, while in the condensing type (Fig. 169) the condenser removes the steam from the first stage, and the second stage handles only air. Some condensing types of ejector pumps are equipped with surface condensers.

A condensing multi-jet ejector type of vacuum pump, manufactured by the Schutte & Koerting Company, is illustrated in Fig. 170. This is a pump suitable for handling large volumes of air and for creating high vacua.

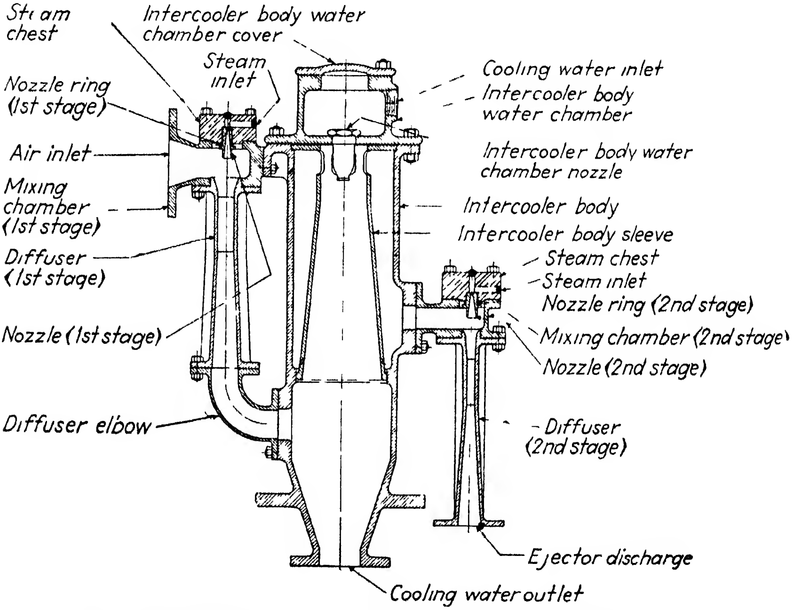
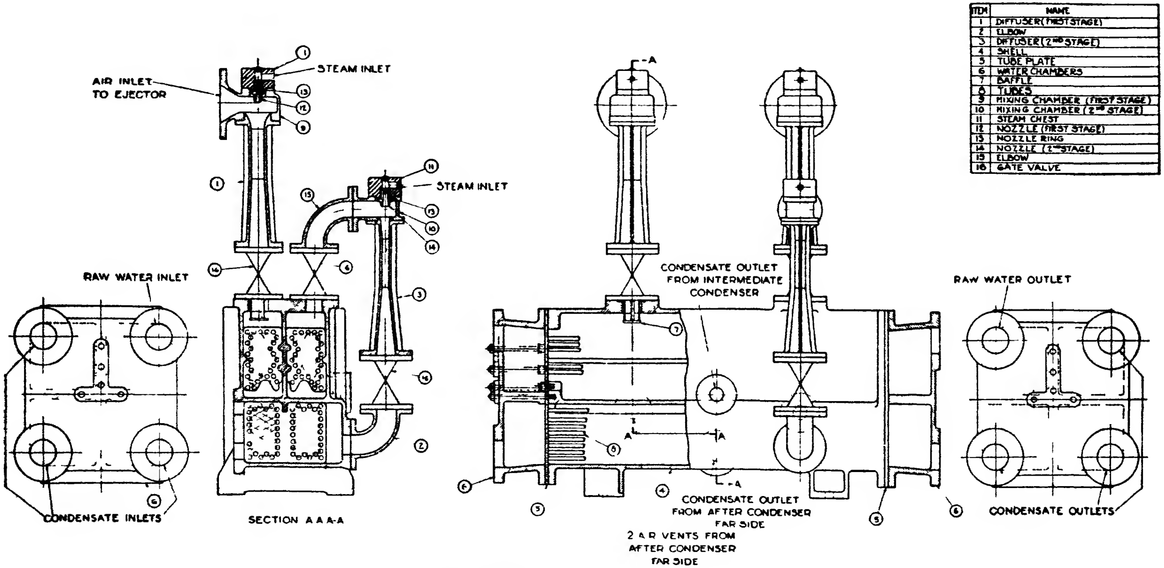


Fig. 168.—Westinghouse two-stage non-condensing air-ejector pump.

The ejector or jet pump is simple, has no moving parts, requires no lubrication, and is efficient.

Circulating Pumps.—While reciprocating pumps are used to a very large extent in condenser operation as dry- and as wet-air pumps, centrifugal pumps are generally used as circulating pumps supplying cooling water to surface condensers. Centrifugal pumps are also used as hot-well pumps.

Figure 171 illustrates a section through a single-stage centrifugal pump. It consists of a rotary impeller, into which the



ITEM	NAME
1	DIFFUSER (FIRST STAGE)
2	ELBOW
3	DIFFUSER (2ND STAGE)
4	SHELL
5	TUBE PLATE
6	WATER CHAMBERS
7	BAFFLE
8	TUBES
9	MIXING CHAMBER (FIRST STAGE)
10	MIXING CHAMBER (2ND STAGE)
11	STEAM CHEST
12	NOZZLE (FIRST STAGE)
13	NOZZLE RING
14	NOZZLE (2ND STAGE)
15	ELBOW
16	GATE VALVE

FIG. 169 —Westinghouse condensing air-ejector pump.

water is drawn and, because of the centrifugal force, leaves the tips of the rotor at high velocity. The casing of the pump guides the water from the propeller to the discharge outlet. No valves are required in this type of pump.

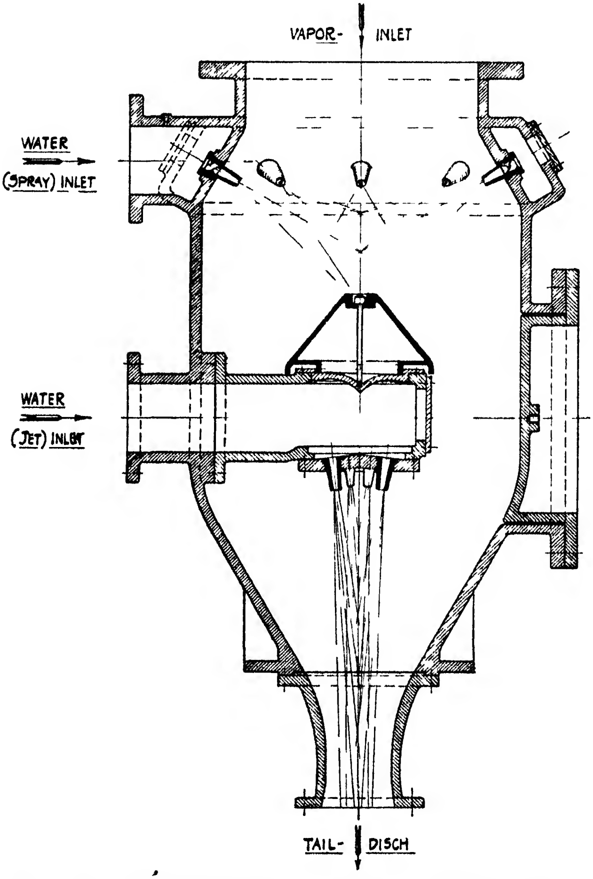


FIG. 170.—Schutte and Koerting multi-jet air-ejector pump.

The single-stage pump is limited in its application to comparatively low heads or pressures. For high heads, a greater number of stages is used. In these, the water is discharged from one rotor to the next, each rotor acting as a booster. Condenser operation, however, requires comparatively low heads and the single-stage pump will be found sufficient for most installations.

Condensing Water Required.—The quantity of cooling water required for condensing operation depends theoretically upon the type of condenser. In the jet condenser, the cooling water and steam to be condensed mingle and the two leave the condenser at the same temperature. In the surface condenser, the cooling water and steam are kept separate, and the cooling water leaves the condenser at a temperature several degrees lower than the condensed steam

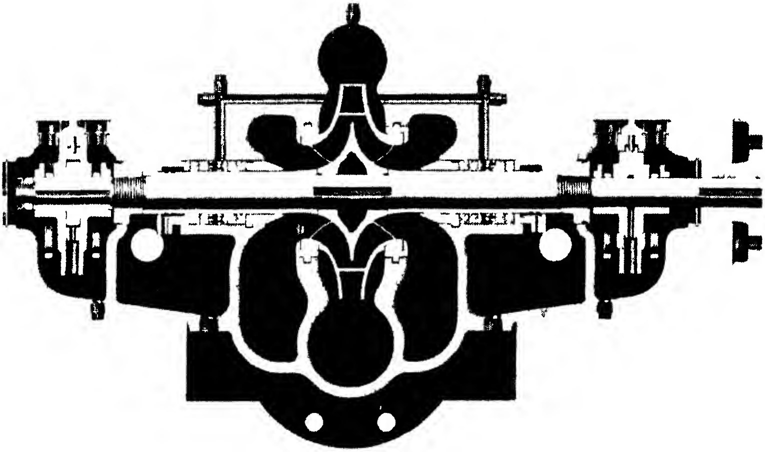


Fig. 171 — Single-stage Allis-Chalmers centrifugal pump

In the case of either the jet or surface condenser, the quantity of cooling water is calculated in the same manner. Neglecting radiation and leakage, the heat absorbed by the cooling water equals that given up by the condensation of the steam. This principle may be expressed:

Heat given up per pound of steam
= heat absorbed by cooling water.

If

w = weight of cooling water required to condense 1 lb. of steam.

h_{g_1} = enthalpy of 1 lb. of the steam entering condenser.

h_{g_2} = enthalpy of 1 lb. of the condensed steam leaving the condenser.
h_{f_1} = enthalpy of 1 lb. of the cooling water leaving the condenser.
h_{f_2} = enthalpy of 1 lb. of the cooling water entering the condenser,

then

$$w(h_{f_1} - h_{f_2}) = h_{g_1} - h_{g_2}; \therefore w = \frac{h_{g_1} - h_{g_2}}{h_{f_1} - h_{f_2}}. \qquad (57)$$

In the jet condenser:

$$h_{g_2} = h_{f_1}$$

In the surface condenser:

$$h_{g_2} > h_{f_1}$$

Illustration.—Dry and saturated steam enters a jet condenser at a pressure of 2 lb. per square inch absolute. The cooling water enters the condenser at 70°F., while the condensate is discharged at a temperature of 110°F. How many pounds of cooling water are required to condense 1 lb. of the steam?
From steam tables,

$$\begin{aligned} h_{g_1} &= 1{,}116.2. \\ h_{g_2} &= 110 - 32 = 78. \\ h_{f_1} &= h_0 = 78. \\ h_{f_2} &= 70 - 32 = 38. \end{aligned}$$

Then,

$$w = \frac{1{,}116.2 - 78}{78 - 38} = 25.9 \text{ lb.}$$

COOLING PONDS AND COOLING TOWERS

Reclaiming Cooling Water.—The quantity of cooling water required to condense steam varies from 30 to 70 lb. for each pound of steam condensed. In many plants this water, after passing through the condenser, is wasted; hence, a continuous supply of fresh water is required. In localities where water is plentiful and its cost is low, this practice may be correct, but many plants are handicapped on account of the scarcity or high cost of water. In such cases, the saving of cooling water is an important problem. Several methods have been developed to cool the condenser circulating water so that it can be used repeatedly.

The means for reclaiming the water usually adopted at the present time depends upon the cooling effect derived from the evaporation of water. Air has the property of evaporating and absorbing water. The amount of water absorbed depends upon the condition of the air, while the rate of evaporation depends upon the velocity and degree of contact between the air and water. As an illustration, air at a temperature of 90°F. and 50 per cent humidity, which signifies that the air is only one-half saturated, would be theoretically capable of cooling condenser circulating water to 75°F., or 15° below the temperature of the atmosphere. On the other hand, on a wet, rainy day, when the air is saturated with moisture, little or no cooling effect could be produced by evaporation, for the air contains nearly as much water as it will absorb.

The following three systems are used for reclaiming condenser circulating water: cooling ponds, spray ponds, and cooling towers.

When reclaiming circulating water by any of the above methods, an allowance of 2 to 8 per cent should be made for evaporation.

Cooling Ponds.—Cooling ponds or tanks depend for their cooling effect upon the exposure of a comparatively large area of water to the air. In these, the water is cooled partly by radiation, but principally by evaporation. The cooling is dependent upon the surface exposed and consequently cooling ponds are usually shallow, but spread over a considerable area. The hot water from the condenser enters the pond at one point, and is cooled by surface evaporation when it reaches the intake point to the condenser.

Cooling ponds are very simple, but are open to the objection that the evaporation is slow. Furthermore, they may freeze in winter, and thus cut off the supply of condensing water.

Spray Ponds.—In this system, the hot water from the condenser is cooled by spraying it into the air so that it falls in a thin mist into the basin or pond below. The spray brings the air and water into intimate contact, exposes a large amount of water surface to the air, and consequently produces a large cooling effect in a comparatively small space. The water is pumped from the condenser and is forced through the spray nozzles under pressure. Sufficient cooling is effected by the fine spray so that the water may be immediately returned to the condenser.

When compared with the cooling pond, the spray pond occupies less space. A pond depending upon natural evaporation would be approximately fifty times as large as a spray pond for the same cooling capacity. In cases where the cooling effect is not sufficient in a single spraying, the water may be forced through the nozzles a second time, thus securing a double-cooling effect.

Cooling Towers.—A cooling tower consists of a wooden, sheet-iron, or concrete chamber that is filled with mats made of steel wire, wooden slats, or tile. Hot water from the condenser is elevated to the top of the tower and is distributed evenly over the top surface. The water in descending is retarded and broken up by the mats, and is thus brought in intimate contact with the air that ascends through the tower.

The method of supplying the air to cooling towers gives rise to three classifications: open towers or atmospheric coolers; natural-draft towers; forced-draft towers.

The open tower is the simplest, although it requires larger ground space. The mats are supported on a tower of open grill work, so arranged that the descending water will be subjected to the slighest wind. This type of tower has proved successful in localities where the climate is dry and where winds prevail.

The natural-draft or flue tower depends for its cooling upon the flow of air, which results when the air within the tower and that without are at different densities. The air within the tower will always be the lighter, because of its higher temperature and because of the greater amount of moisture it contains. The necessary velocity of air through the tower can be made as desired by proportioning the height of the tower. The natural-draft tower is entirely enclosed, except at top and bottom. The condenser water is distributed at the top, while the air becoming heated is displaced by the colder air which enters at the base of the tower. These towers are suitable for locations where space requirements would prohibit the open or atmospheric tower

The forced-draft tower lends itself to practically all locations and conditions. Figure 172 illustrates a forced-draft tower. This type of tower is operated in the same manner as other cooling towers, but a fan is used to create the flow of air through the descending water.

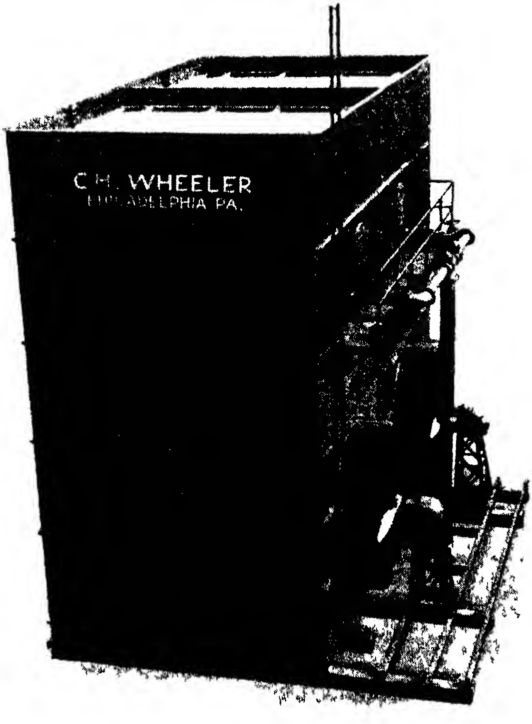


Fig. 172 - Forced-draft cooling tower

These towers are light and compact, requiring about one-fifth the space occupied by a tower of the natural-draft type. They are entirely independent of the natural circulation of the air, and are consequently more reliable. The power required to operate a forced-draft cooling tower will vary from 2½ to 4 per cent of the total power generated by the main units.

SEPARATORS

Steam Separators.—The function of a steam separator is to protect engines and turbines from the dangerous results that might occur if large quantities of water or grit enter them. When the boiler is improperly proportioned or when it is forced above its rating, there is a possibility of large amounts of water being carried over with the steam. The condensation that occurs in long pipe lines adds to the water in the steam. The steam separator automatically separates the water from the steam, thus protecting the cylinder, and at the same time promotes lubrication by preventing the washing action that results when wet steam is used in the engine cylinder.

Figure 173 illustrates one type of steam separator. The flow of the steam in passing through the separator is interrupted by corrugated plates. The momentum of the heavier particles of water causes them to be thrown out, and they adhere to the surface of the baffle. The separated water then flows by gravity to the trap or receiver below, from which it is drained.

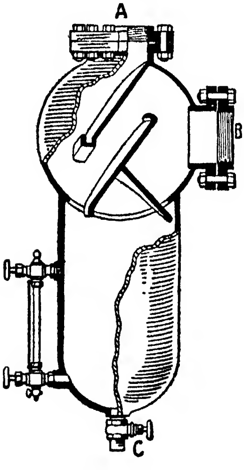


FIG. 173.—Steam separator.

Separators are made in various sizes, depending upon the size of the pipe to which they are to be attached. They may be used on vertical, horizontal, or angle pipes. Special separators, known as the receiver type, with an extra large water-storing capacity are made and are usually installed in plants having long pipe systems, where there is a possibility of large quantities of water suddenly passing through with the steam.

The separator should be placed as close to the steam chest of the engine as possible. The receiver type of separator is preferable, if the engine load is intermittent or fluctuates rapidly.

Exhaust-steam and Oil Separators.—Exhaust-steam separators are constructed on the same principles as steam separators, but their function is to remove oil that may be contained in the exhaust steam. The use of a good oil separator between the engine and the condenser will eliminate the oil from the condensate, thus making it satisfactory as boiler feed water. In the case of surface condensers, oil separators prevent the fouling of the condenser tubes by the oil which would lower the efficiency of the condenser if allowed to accumulate.

In exhaust-steam heating, the oil separator is used to remove the oil from the steam before it enters the heating system. Oil in the steam would coat the inner surface of radiators with a thin layer of grease which would soon impair the amount of heat transmitted through them.

In the use of feed-water heaters, the oil separator may be entirely independent and separately installed, but in most cases, it is made a part of the heater itself.

In plants where low-pressure turbines are utilized, an oil separator is placed between the engine and the turbine. The moisture and oil are thus removed from the exhaust steam before it enters the turbine.

Exhaust Heads.—Figure 174 illustrates a section through an exhaust head. This device is used to prevent the deposit of any moisture or oil upon roofs and side walks when the exhaust from an engine is allowed to escape to the atmosphere. Exhaust heads are attached in a vertical position at the end of the atmospheric exhaust pipe. Their principle of operation, like that of the separator, depends upon the changing of the course of the steam. The moisture and oil thrown out by centrifugal force collect at the bottom of the head and are drained to waste.

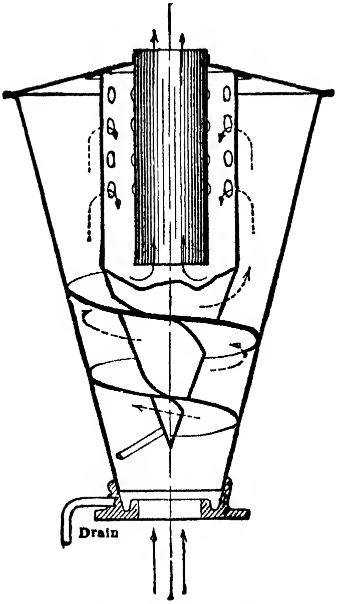


FIG. 174.—Exhaust head.

Problems

1. Compare the volumes of steam and of water at atmospheric pressure.
2. Compare the volume of 1 lb. of steam at atmospheric pressure with the volumes at 26 in. vacuum, 28 in. vacuum, and 29 in. vacuum.

3. A condenser gage registers 28.5 in. of mercury. The barometer registers 29.35 in. of mercury. What is the absolute pressure of the air in pounds per square inch? What is the absolute pressure in the condenser in pounds per square inch?
4. Make a sketch of the exhaust piping between an engine and a condenser showing the location of the atmospheric relief valve.
5. What factors govern the choice of the type of condenser?
6. Determine the amount of cooling water required to condense 1 lb. of steam in a jet condenser operating under the following conditions; vacuum in condenser 26 in. referred to a 29.6 in. barometer, temperature of water entering condenser 80°F., temperature of condensate and water leaving condenser 105°F., steam entering condenser is dry and saturated.
7. Determine the amount of cooling water required to condense 1 lb. of steam in a surface condenser. The vacuum in the condenser is 29 in. referred to a 30-in. barometer; the temperature of the condensed steam is 98°F.; the cooling water enters the condenser at 70°F. and is discharged at a temperature of 110°F.
8. An electrical generating station has a maximum capacity of 120,000 kw. and is equipped with surface condensers. The generating units use 12 lb. of steam per kilowatt-hour when the vacuum is 28.5 in referred to a 30-in. barometer. The cooling water enters the condenser at a temperature of 75°F., and is discharged at a temperature of 81.5°F The temperature of the condensed steam leaving the condenser is 85°F. If the condensing water is obtained from a stream that is 2 ft. deep and flows at a velocity of 5 miles per hour, what would be the width of such a stream to supply the quantity of water required?
9. Compare the designs of surface condensers illustrated in Figs 163 and 164.
10. Describe the working of the ejector pumps in Figs. 168, 169, and 170.

CHAPTER XI

STEAM POWER PLANT TESTING

Power Plant Instruments. To maintain a power plant at high efficiency, it must be equipped with suitable instruments to record plant performance. Modern power plants are usually equipped with the following instruments:

Steam-pressure gages on boilers, headers, and near engine or turbine throttle valve; thermometers for measuring the temperatures of feed water, flue gases, and steam if superheated steam is used; means for measuring weight of feed water; means for metering amount of steam generated by boilers; steam calorimeters to determine the quality of saturated steam; draft gages; CO_2 recorders or other instruments for analyzing flue gases; electrical instruments; also special instruments to suit local conditions.

General Rules.—The chief object in the testing of power plant equipment is to secure data from which the cost of operation may be calculated. Tests are also carried on for the purpose of comparing actual with guaranteed results as to capacity and efficiency of the complete power plant or of the separate parts. The effect of different conditions of operation or of changes in design can also be determined by test.

The test of a power plant is essentially a test of each of the various main parts; it is a combined test of the steam boiler, of the steam engine or turbine, and of the other power plant equipment.

The testing of a power plant includes the measurement of certain conditions which are important economically in the operation of the plant. This may be done by the reading of various appliances at specified intervals when the test is in progress or by the use of special instruments of the recording type. The recording instrument gives a continuous record which is often desirable in studying the daily operation of the plant. In reality, with recording instruments, the plant is continuously under test and any variation that may occur from day to day is indicated graphically. The economy test consists, in general, in the measurement of the amount of heat supplied and the amount of energy that has been transformed into useful work.

In testing a boiler, the amount of coal fired would give a direct measure of the heat supplied. To find the amount of energy transformed, the weight of the water evaporated, the quality of the steam generated, the pressure in the boiler, and the temperature of the entering feed water must be measured. To assist in determining the extent of the losses in a boiler plant, such readings as the temperature of the flue gases, the draft at various points in the boiler, and the analysis of the flue gases are usually taken.

The testing of the engine or turbine consists in measuring the weight of the steam supplied together with its quality and pressure at the throttle as well as the pressure of the exhaust; from these data, the heat supplied to the motor may be calculated The delivered power is measured by a Prony brake, an electrical generator, or some other form of dynamometer. As in the case of the boiler, many other readings are taken during the test These consist of such data as indicator cards, in the case of reciprocating steam engines; the amount of condensing water, and various temperatures at the condenser.

Preparing for the Test.—A thorough examination should be made of the physical condition of all parts of the plant including boilers, furnaces, settings, engine cylinders, piping, valves, etc. Prior to the test, any defects that may make the results of the test unfavorable should first be remedied. In boilers, for example, any abnormal leakage found at the tubes, rivets, or metal joints should be repaired. All leakage from blow-offs, drips, etc., or through any steam or water connections which might affect the results should be prevented. In preparing for the test, the dimensions of the principal parts of apparatus to be tested should be taken and recorded. Before the test is started, it is important that the apparatus to be tested has been in operation a sufficient length of time to attain proper operating conditions.

Starting and Stopping the Test.—In a plant operating continuously day and night, the time for starting and stopping the test of a boiler should follow the regular period of cleaning the fires. The fires should be quickly cleaned and then burned low. When this condition has been reached, the time should be noted as the starting time, and the thickness of the coal bed, the water level in the boiler, and the steam pressure should be noted. At the close of the test following a regular cleaning, the fires should again be burned low, and when this condition has become the same as that observed at the beginning, the water level and steam pressure also being the same, the time is noted and the test is stopped.

Weighing the Fuel.—The approved method of weighing the fuel burned in a specified interval of time is by the use of ordinary platform scales. If accurate results are to be secured, it is not recommended to weigh the fuel in a wheelbarrow or similar conveyance full of coal and assume that all other loads brought into the plant weigh the same; it is also inaccurate to base the weight of the fuel upon the number of strokes of the plunger in certain types of stokers. Even in the use of scales, care must be taken to test their reliability by calibrating them with standard weights. In case the use of scales is impracticable, sacks or bags containing a known weight of coal, as measured by a platform scale, may be used to good advantage.

Large plants in which coal-handling machinery has been installed use weighing hoppers to measure the coal fed to the boilers. As usually installed, the weighing hopper is placed between the main storage bunker in the loft of the plant and the stoker hoppers below. Coal from the main bunker passes first to the weighing hopper. After being weighed, the coal is distributed to the stoker hoppers. The weighing hopper travels upon a special overhead track which makes it possible for one weighing hopper to serve several boilers. The scale beams and levers extend downward so that the poise on the weighing beam is read from the boiler-room floor.

Weighing the Feed Water.—The most satisfactory method for weighing the feed water, which is the weight of the water evaporated by the boiler, consists in the use of one or more tanks each placed upon platform scales. These are elevated a sufficient distance above the floor to empty into a receiving tank, which is in turn connected to the boiler feed pump. When only one tank is available, the receiving tank should be of sufficient size to afford a reserve supply to the pump while the weighing tank is filling.

A great many types of water meters are sold commercially and are often used in measuring the feed water. To insure a fair degree of accuracy, the meter should be calibrated before and after the test under the identical conditions it is required to operate.

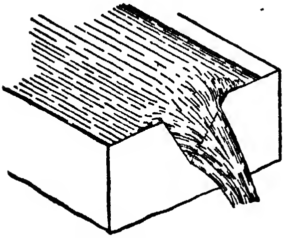


Fig. 175.—Triangular weir.

The measurement of large quantities of hot water is usually accomplished by the use of special types of water meters, weirs, orifices, or automatic water weighers.

Figure 175 illustrates a weir with a triangular notch, although many other forms of notches may be used. The amount of water discharged is dependent upon the distance or head above the bottom of the weir.

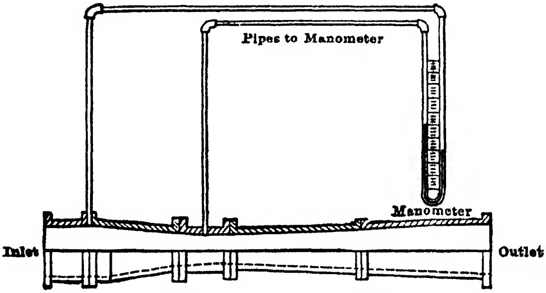


Fig. 176.—Venturi meter.

The Venturi meter is an arrangement of piping in which there is a gradual narrowing of the section followed by a gradual enlargement. Figure 176 illustrates this type of meter. Tubes entering the meter at the sections shown and attached to the manometer are used in measuring the quantity of water delivered.

Draft Gages.—The simplest form of draft gage is the U-tube or manometer, illustrated in Fig. 177. For the measurement of draft the tube is filled with water and is connected at *A* by means of tubing to the point where the pressure is to be measured. The amount of pressure will be indicated by the difference in the level of the liquid and may be measured in inches of water.

For the measurement of slight pressures an inclined tube, as illustrated in Fig. 178, may be used. The bottle *B* to which the inclined tube *CD* is attached is filled with water. The outer end of the inclined tube is attached to the chamber in which the pressure is to be measured. The pressure is measured as with the U-tube (Fig. 179), but by use of the inclined tube the movement of 1 in. in a vertical scale is magnified.

Fig. 177.—U-tube or manometer.

Compound- and triple-draft gages are used to determine the draft at different points of a boiler setting.

Temperature Measurement.—Temperatures are usually measured by means of one of the following types of thermometers: mercurial thermometers, electrical-resistance thermometers; mechanical pyrometers; thermoelectric pyrometers.

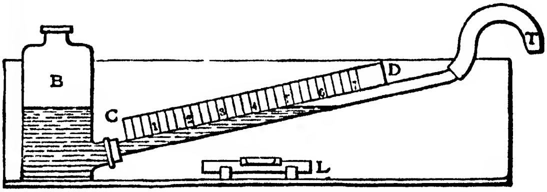


Fig. 178.—Inclined tube manometer.

The ordinary mercury-in-glass thermometer is commonly used for temperatures less than 500°F.; above 500° special nitrogen-filled glass thermometers must be used.

Electrical-resistance thermometers are based upon the principle that the resistance of certain metals changes with change of temperature. The thermometer element is constructed of some metal, like platinum, and the variation of resistance measured by a Wheatstone bridge.

Mechanical pyrometers consist of two metal rods whose rates of expansion differ. The rods are connected through gears and

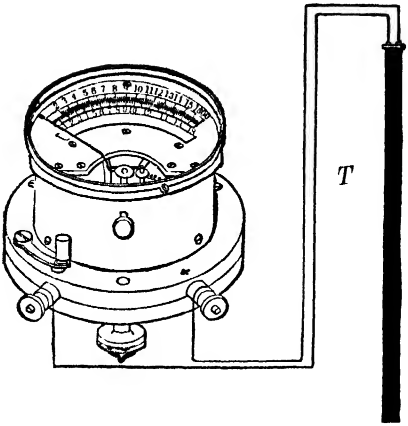


FIG. 179.—Diagram of the thermoelectric method of temperature measurement.

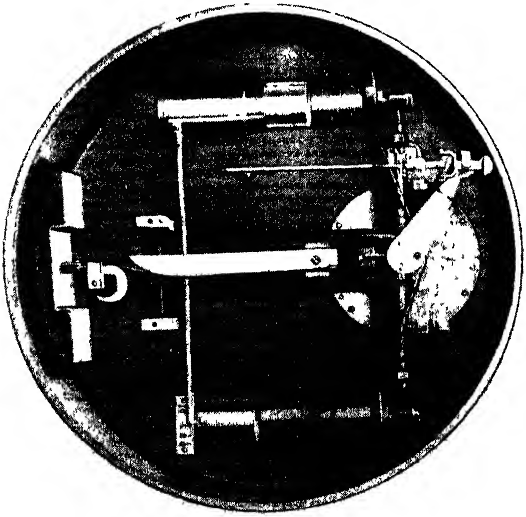


FIG. 180.—Cochrane steam-flow meter.

levers to a pointer which rotates over the dial graduated in degrees of temperature.

Thermoelectric pyrometers are based upon the principle that an electromotive force is produced when two wires of different metals are joined and heated. Figure 179 illustrates a thermoelectric pyrometer. *T* is a porcelain tube which holds the two dissimilar metal wires and which is placed at the point where the temperature is to be read. There is also a meter for measuring the impressed voltage; it is provided with a scale calibrated in degrees.

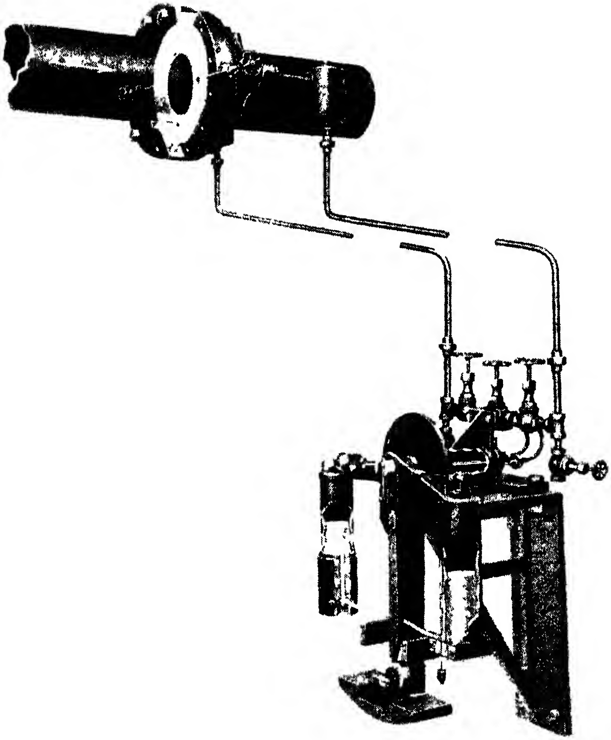


FIG. 181.—Details of Cochrane steam-flow meter.

Measuring the Weight of Steam.—The most satisfactory method of weighing the amount of steam consumed by the engines or turbines is by the use of platform scales and surface condensers. This method utilizes two scales and two tanks which are alternately filled with condensed steam from the condenser, weighed, and emptied.

Various forms of steam meters may be employed for measuring the steam, provided such meters are properly calibrated under the conditions to which they will be subjected when in use.

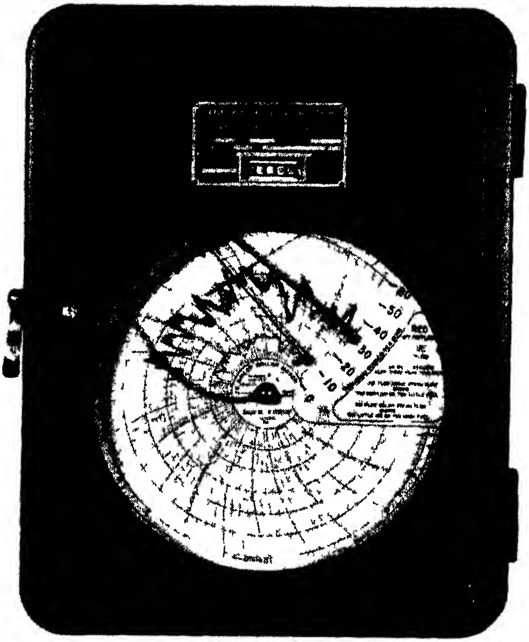


Fig. 182.—The Bailey boiler meter.

Figure 180 illustrates the interior of the Cochrane steam-flow meter. The details are further illustrated in Fig. 181.

Another type of meter, illustrated in Figs. 182 and 183, records the amount of steam the boiler is making (steam flow), the amount of air used to burn the fuel (air flow), the fire-box draft, and the flue-gas temperature. This meter is called the Bailey boiler meter. When the air-flow pen is above the steam-flow pen, it shows that too much air is passing through the fire for the amount of steam generated. When the air-flow pen is below the steam-flow pen, there is an insufficient supply of air for economical combustion. Different colors of ink are used to record the steam flow, air flow and flue-gas temperature.

Measurement of Power.—One of the simplest means of measuring the power delivered by a small motor is by the application of a

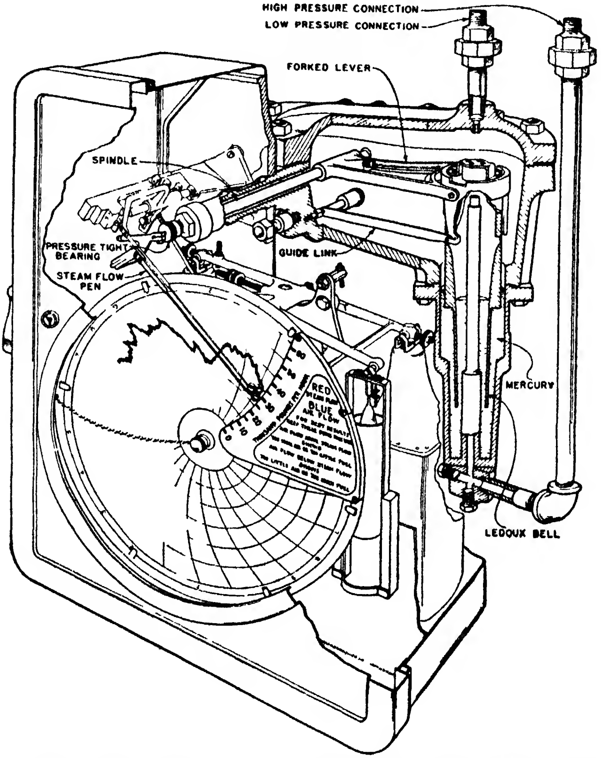


Fig. 183.—Steam- and air-flow mechanism of Bailey boiler meter.

Prony brake to the rim of the wheel as explained in Chap. VIII For motors of large capacity or operating at high speeds, some other type of dynamometer or an electrical generator must be used.

Another type of brake for absorbing and measuring power is some form of water friction brake. Figure 184 illustrates one type of water brake. It consists of a disc *A* which is connected

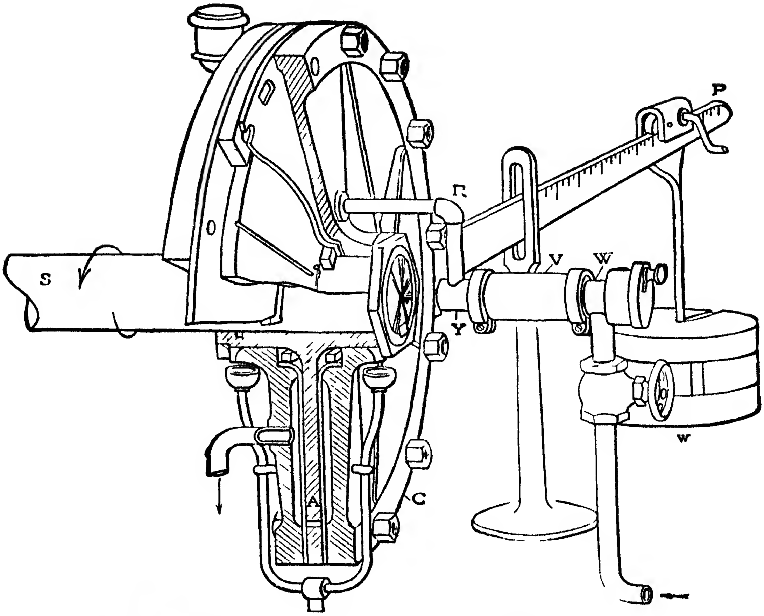
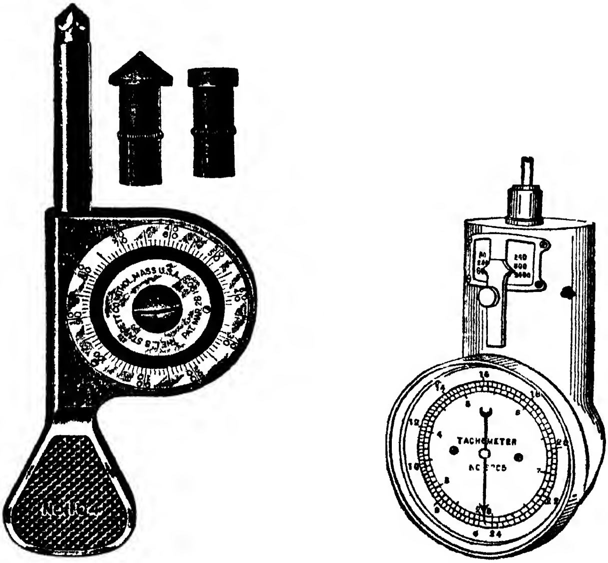


FIG. 184.—The Alden water brake.



Speed counter

Tachometer

FIG. 185.—Speed-measuring devices.

to the shaft *S* transmitting the power. The disc revolves in a copper chamber filled with oil, while cooling is effected by the circulation of water around the outer surface of the copper chamber. The friction of the oil producing the braking effect is transmitted to the arm *P* where it is measured as in the Prony brake.

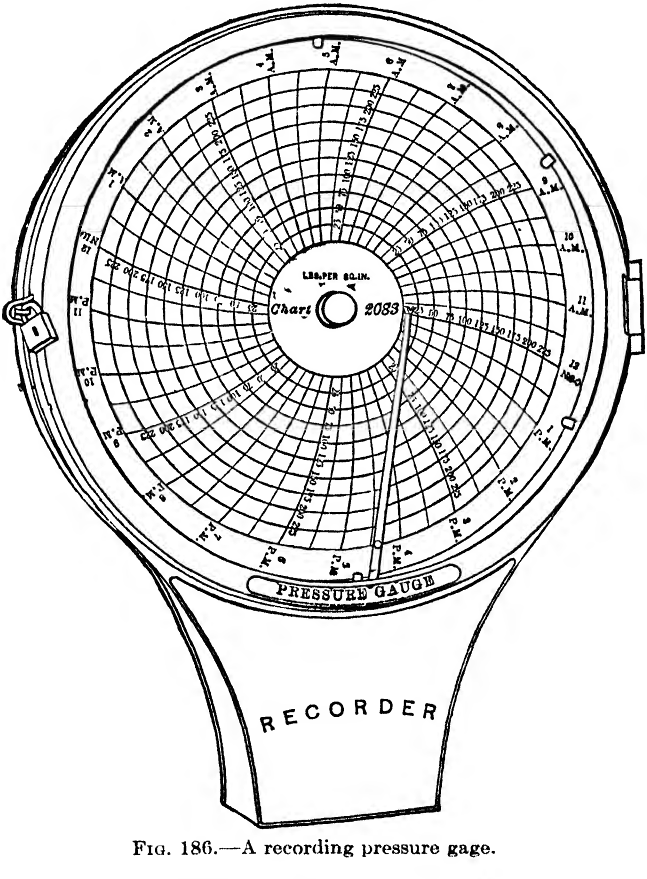


FIG. 186.—A recording pressure gage.

Measurement of Speed.—For determining the speed of an engine shaft in revolutions per minute a speed counter and watch. or a tachometer (Fig. 185) is used. The tachometer is more convenient, as it indicates on the dial the revolutions per minute.

Indicator and Calorimeters.—Steam-pressure gages, steam-engine indicators, steam calorimeters, coal calorimeters, apparatus for analyzing flue gas, and other important instruments used in power plant testing were explained in previous chapters

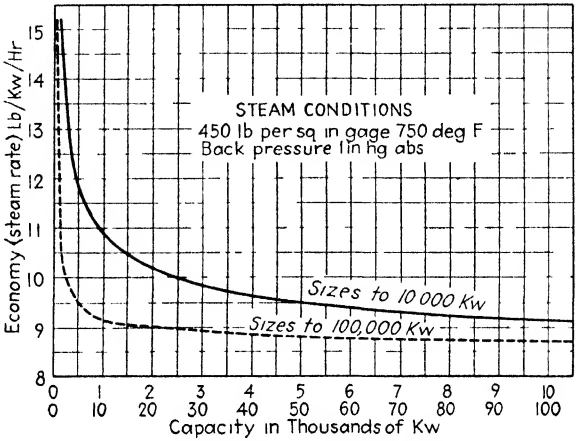


FIG 187 —Economy of steam turbines

Recording Instruments.—In modern power plants recording instruments are used to give a graphic record on a chart A recording pressure gage is illustrated in Fig 186.

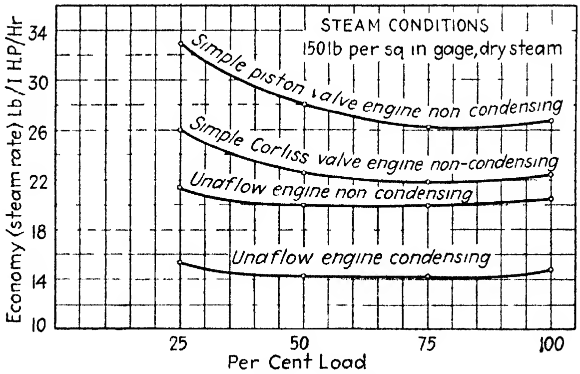


FIG 188.—Economy of steam engines

A. S. M. E. Code.—Complete and more detailed instructions concerning the testing of steam power plants and power plant equipment will be found in the *Rules for Conducting Performance*

Tests of Power Plant Apparatus, published by the American Society of Mechanical Engineers.

Turbine and Engine Performance.—In Fig. 187 are given steam rates for turbines. The upper full line is for steam turbines up to 10,000 kw. capacity. The dotted line indicates approximate economies of sizes up to 100,000 kw., with steam conditions as indicated.

Figure 188 illustrates what economies in steam rates per indicated horsepower may be expected from piston valve, Corliss valve, and uniflow types of reciprocating steam engines.

Problems

1. Examine some water meter and explain, using clear sketches, how the meter works
2. Explain the principles upon which the construction of recording instruments are built
3. From the A. S. M. E Power Plant Code compile a table showing the principal data to be taken of a test on a non-condensing steam power plant.
4. What are the objectives of the A. S. M. E. Power Codes and for which types of equipment are these codes used?
5. What draft pressures are maintained in power plants under the fuel bed, above the fuel bed, and at the entrance of the stack?
6. At what temperature should the fuel bed be maintained?
7. What is the ordinary temperature of flue gas?
8. Would a 1-hr. boiler test give results which are reliable? Give reasons for your answer.
9. Why take draft readings at more than one place?
10. Why are recording instruments of value?

CHAPTER XII

INTERNAL-COMBUSTION ENGINES

The internal-combustion engine, commonly called a gas engine differs from the steam engine, which is an external-combustion motor, in that the transformation of the heat energy of the fuel into work takes place within the engine cylinder.

History.—The earliest internal-combustion engine was the gunpowder engine invented by Huyghens in 1680. In the Huyghens engine, a charge of gunpowder was introduced into a vertical cylinder filled with air and exploded; the products of combustion were driven out of the cylinder through valves, and the piston, which was at the end of the stroke, was forced down by the atmospheric pressure into the vacuum thus formed.

The first attempt to produce power from an inflammable gas, manufactured by the distillation of coal or oil, was made by Barber in 1791. The Barber motor included an air pump and a compressor which forced the inflammable gas and air into a vessel, where the mixture was ignited; the burning mixture issuing from the vessel impinged against the vanes of a paddle wheel and produced the rotation of a shaft connected to the machinery to be driven. The first reciprocating engine using an inflammable gas was invented by Street in 1794.

Lebon, in 1801, first suggested the compression of the mixture of gas and air before ignition. This was applied by Barnet in 1838.

From 1801 to 1860, many efforts were made to produce a practical internal-combustion engine. Several types of free-piston engines were developed during this period in which the explosion of a mixture of gas and air was utilized in moving upward in a vertical cylinder a piston which was free from the connecting rod. The work was done on the return stroke by the pressure of the atmosphere forcing the piston down, the piston rod on its downward stroke producing rotary motion through a rack meshing with a spur pinion and connected by a ratchet and pawl to the driving shaft.

The Lenoir engine, which was invented about 1860, was the first internal-combustion engine to be used commercially to any extent for producing power. The Lenoir engine was a horizontal double-acting reciprocating motor. The mixture of the fuel and air was drawn into one end of the engine cylinder during the first part of the stroke, the inlet valve being closed at about one-half of the stroke, when the mixture was ignited. The explosion (rapid combustion) of the mixture forced the piston to the end of the stroke. Near the end of the stroke the exhaust valve opened, and the products of combustion were expelled during the return stroke. The same operation took place at both ends of the cylinder, the energy stored in the flywheel driving the piston forward during the suction part of its stroke. The Lenoir engine, similar to the steam engine, had two working strokes during each revolution, but on account of its poor economy it was superseded by engines working on the Otto or Diesel cycles, which have only one working stroke for every two revolutions of the crankshaft.

The Otto Internal-combustion Engine Cycle.—The majority of modern commercial internal-combustion engines operate upon the Otto internal-combustion engine cycle, which was suggested by Beau de Rochas in 1862, and which was made a practical success by Nicholas A. Otto in 1878. The term "engine cycle" is applied to the series of events which are essential for carrying out the transformation of heat into work. The Otto internal-combustion engine cycle requires four strokes of the piston and comprises five events, which are: suction, compression, ignition, expansion, and exhaust.

The action of an internal-combustion engine working on the four-stroke Otto cycle is illustrated in Fig. 189.

1. Suction of the mixture of air and gas through the inlet valve takes place during the complete outward stroke of the piston, the exhaust valve being closed. This stroke of the piston is called the suction stroke.

2. On the return of the piston, both the inlet and exhaust valves remain closed, and the mixture is compressed between the piston and the closed end of the cylinder. This is called the

compression stroke. Just before the compression stroke of the piston is completed, the compressed mixture is ignited by a spark and rapid combustion or explosion takes place.

3. The increased pressure within the cylinder due to the rapid combustion of the mixture drives the piston on its second forward stroke, which is the power stroke. This power stroke, or working stroke, is the only stroke in the cycle during which power is generated. Both valves remain closed until the end of the power stroke, when the exhaust valve opens and provides communication between the cylinder and the atmosphere.

4. The exhaust valve remains open during the fourth stroke called the exhaust stroke (Fig. 189), during which the burned gases are driven out from the cylinder by the return of the piston.

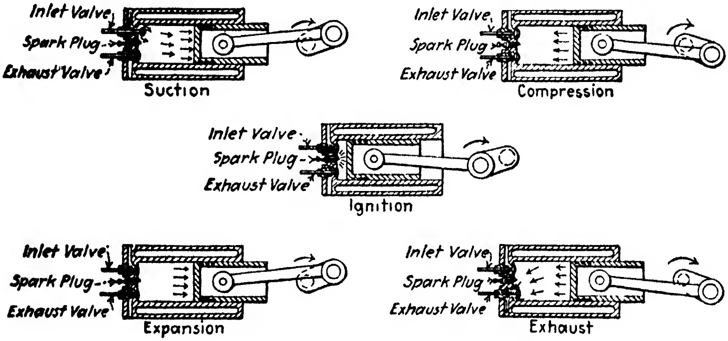


FIG. 189.—The events in the Otto cycle.

The simplest type of internal-combustion engine operating on the Otto four-stroke cycle is the gasoline engine which is illustrated in Fig. 190. The fuel from the liquid fuel tank *T* is supplied to the mixing valve or carburetor through the fuel regulating valve *G*. The air, through the air pipe *A*, enters the same carburetor and is thoroughly mixed with the fuel. The mixture of air and vaporized fuel enters the engine cylinder *C* through the inlet valve *V* as the piston *P* moves on the suction stroke. The mixture is then compressed, and ignited by an electric spark produced at the spark plug *Z*, by current furnished from the battery *B*. The ignition of the mixture is followed by the power stroke. The reciprocating motion of the piston *P* is communicated, through the connecting rod *R* to the crank *N*, and is changed into rotary motion at the crankshaft *S*. The crankshaft *S*, while driving the machinery to which it is connected, also turns the valve-gear shaft, sometimes called the two-to-one shaft, through the gears *X* and *Y*. The gear *Y* turns once for every two revolutions of the crank, and near the end of the power stroke opens the exhaust valve *E* through the rod *D* pivoted at *O*.

In larger engines, the valve-gear shaft also opens and closes the admission valve *V* and operates the fuel pump and ignition system. As the temperature resulting from the ignition of the explosive mixture is usually over 2000°F., some method of cooling the walls of the cylinder must be used in order to facilitate lubrication, to prevent the moving parts from being twisted out of shape, and to avoid the ignition of the explosive mixture at the wrong time of the cycle. One method of cooling gas engines is to jacket the cylinder *J*, that is, to construct a double-walled cylinder and circulate water between the two walls, through the jacket space. The base *U* supports the various parts of the engine; the flywheel *W* carries the engine through the idle strokes. Besides the above details, every gas engine is usually provided with lubricators *L* for the cylinder and bearings, and with a governor for keeping the speed constant at variable loads.

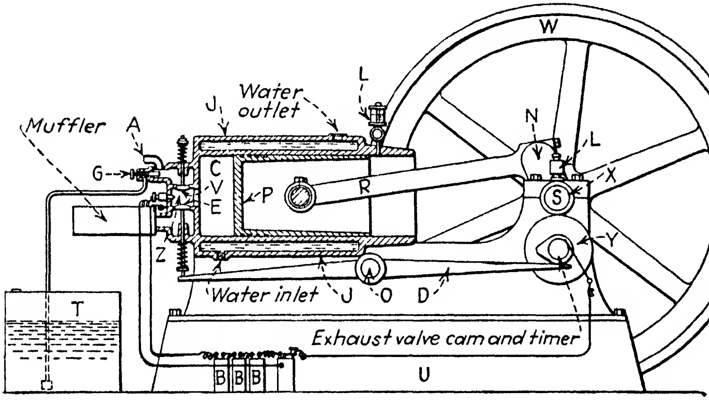


FIG. 190.—Parts of a gasoline engine.

An indicator diagram, taken from a four-stroke cycle internal-combustion engine, using gasoline as fuel, is illustrated in Fig. 191. *IB* is the suction stroke, *BC* the compression stroke, *CD* shows the ignition event, *DE* the power stroke, and *EI* is the exhaust stroke. The direction of motion of the piston during every stroke is illustrated in each case by arrows. Lines *AF* and *AG* were added to the indicator diagram; *AF* is the atmospheric line, while *AG* is the line of pressures. From Fig. 191 it will be noticed that part of the suction stroke occurs at a pressure lower than atmospheric. The reason for this is that a slight vacuum is created in the cylinder by the piston moving away from the cylinder head. The vacuum helps to draw the mixture of fuel and air into the cylinder.

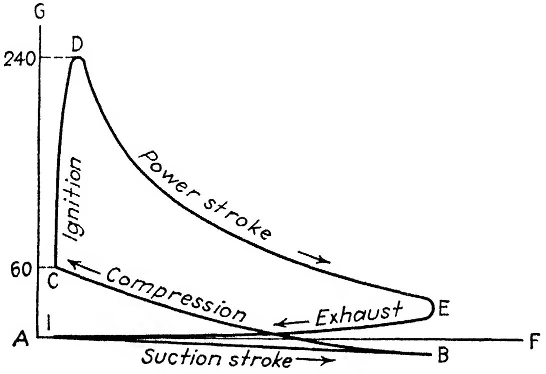


FIG. 191.—Gas-engine indicator card.

Modern internal-combustion engines, operating on the Otto four-stroke cycle, will convert 14 to 30 per cent of the heat available in the fuel into work. The Lenoir engines, in which the mixture was not compressed previous to ignition, converted only about 4 per cent of the heat available in the fuel into work.

The Ideal Otto Cycle.—The ideal diagram for the Otto cycle is illustrated in Fig. 192, the operations being as follows:

A mixture of gas and air is drawn in during the complete forward stroke of the piston, as shown by *a'a*. The return of the piston compresses the mixture along the adiabatic curve *ab*. Explosion of the compressed charge takes place at *b*, with the consequent combustion at constant volume to *c*; *cd* is the adiabatic expansion producing the second forward stroke. The exhaust valve opens at *d*, cooling the gases to the exhaust pressure *a*, and rejecting them to the atmosphere.

Calling P, V, T the absolute pressure in pounds per square foot, the specific volume in cubic feet per pound of mixture, and the absolute temperature in degrees Fahrenheit, respectively; also using subscripts *a*, *b*, *c*, and *d* to designate the events in Fig. 192, the following expressions will be obtained: The heat added during the combustion from *b* to *c* is

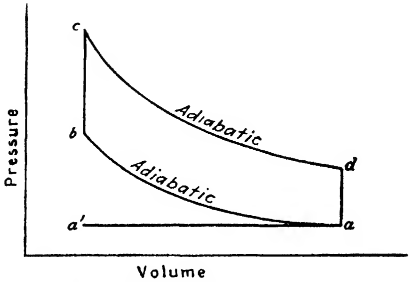


FIG. 192.—Ideal Otto cycle.

$$Q_1 = wC_v(T_c - T_b). \tag{58}$$

The heat rejected from *d* to *a* is

$$Q_2 = wC_v(T_d - T_a). \tag{59}$$

The cycle efficiency is

$$\begin{aligned} e &= \frac{Q_1 - Q_2}{Q_1} = \frac{wC_v(T_c - T_b) - wC_v(T_d - T_a)}{wC_v(T_c - T_b)} \\ &= 1 - \frac{T_d - T_a}{T_c - T_b}. \end{aligned} \tag{60}$$

Since the expansion and compression are adiabatic, the following relations will hold:

$$T_aV_a^{k-1} = T_bV_b^{k-1}, \text{ and } T_cV_c^{k-1} = T_dV_d^{k-1}.$$

Since

$$V_c = V_b \text{ and } V_a = V_d,$$

$$\frac{T_d}{T_a} = \frac{T_c}{T_b}; \text{ also } \frac{T_d - T_a}{T_c - T_b} = \frac{T_a}{T_b}.$$

Since

$$\frac{T_a}{T_b} = \left(\frac{V_b}{V_a}\right)^{k-1} = \left(\frac{P_a}{P_b}\right)^{\frac{k-1}{k}},$$

equation (60) may be expressed as

$$e = 1 - \frac{T_a}{T_b} = 1 - \left(\frac{V_b}{V_a}\right)^{k-1} = 1 - \left(\frac{P_a}{P_b}\right)^{\frac{k-1}{k}}. \qquad (61)$$

Equation (61) shows that the efficiency of engines operating on the Otto cycle depends upon the pressure to which the mixture of fuel and air is compressed before ignition. Theoretically, the greater the compression pressure, the better is the economy. Practical considerations and the danger of preignition limit the compression pressures for various fuels to the following values in pounds per square inch; gasoline, 60 to 90 lb.; kerosene, 50 to 80 lb.; alcohol, 120 to 180 lb.; natural gas, 80 to 120 lb., producer gas, 120 to 160 lb.; blast-furnace gas, 120 to 190 lb.

From the above values of practical compression pressures, it is evident that with fuels high in hydrocarbons lower compression pressures should be employed than with fuels which are low in these constituents.

The Two-stroke Cycle Engine.—The internal-combustion engine working on the four-stroke cycle requires two complete revolutions of the crankshaft, or four strokes of the piston to produce one power stroke. The other three are only idle strokes, but power is required to move the piston through these strokes, and this has to be furnished by storing extra momentum in heavy flywheels. The Otto cycle can be modified so that the five events can be carried out during only two strokes of the piston by precompressing the mixture of fuel and air in a separate chamber, and by having the events of expansion, exhaust, and admission occur during the same stroke of the piston. In large two-stroke cycle engines, the air and fuel for the mixture are compressed and delivered separately by auxiliary pumps driven from the main engine shaft. The precompression of the mixture in the case of small two-stroke cycle engines is accomplished by having a tightly closed crankcase, or by closing the crank end of the cylinder and by providing a stuffing box for the piston rod.

The main features of the two-stroke cycle internal-combustion engine are illustrated in Fig. 193. On the upward stroke of the piston *P*, a partial vacuum is created in the crankcase *C*, and the explosive mixture of fuel and air is drawn in through a valve at *A*. At the same time, a mixture previously taken into the upper end of the cylinder *W* is compressed. Near the end of the compression stroke, the mixture is fired from a spark produced at the spark plug *S*. The explosion of the mixture drives the piston on its downward or working stroke. The piston descending compresses the mixture in the crankcase to about 6 or 8 lb. above atmospheric, the admission valve at *A* being closed as soon as the pressure in the crankcase exceeds atmospheric. When the piston is very near the end of its downward stroke, it uncovers the exhaust port at *E* and allows the burned gases to escape into the atmosphere. The piston continuing on its downward stroke next uncovers the port at *I*, allowing the slightly compressed mixture in the crankcase *C* to rush into the working part of the cylinder *W*. Thus, two full strokes of the piston complete one cycle.

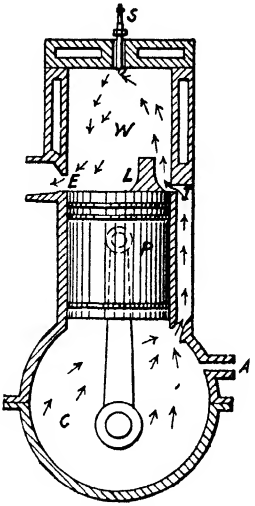


FIG. 193.—Small two-stroke cycle engine.

The distinctive feature of the two-stroke cycle engine is the absence of valves. The transfer port *I* from the crankcase *C* to the working part of the cylinder *W*, as well as the exhaust port *E*, is opened and closed by the piston.

Large two-stroke cycle engines are often made double acting and have the same number of power impulses per revolution as the single-cylinder steam engine. The proper amounts of gas and air are delivered to each end of the piston at the correct time by auxiliary pumps. An admission valve is provided at each end of the cylinder. The exhaust takes place through ports near the middle of the cylinder, which are uncovered by the piston at the end of each working stroke.

To offset the advantages resulting from fewer valves, less weight, and greater frequency in working strokes, the two-stroke cycle engine is usually less economical in fuel consumption and is not so reliable as is the four-stroke cycle engine. As the inlet port *I* (Fig. 193) is opened, while the exhaust of the gases takes place at *E*, there is always some chance that part of the fresh mixture will pass out through the exhaust port. Closing the exhaust port too soon will cause a decrease in power and efficiency, on account of the mixing of the inert burned gases with the fresh mixture. By carefully proportioning the size and location of the ports, and by providing the piston with a lip at *L* (Fig. 193) to direct the incoming mixture toward the cylinder head, the above losses may be decreased. In large two-stroke cycle engines, an effort is made to eliminate the above loss by forcing a current of air through the cylinder by the air pump, while the exhaust port remains open. In any case, the scavenging of the cylinder of the waste gases is not so thorough in the two-stroke cycle as in the four-stroke cycle engine, where one complete stroke of the piston is allowed for the removal of the exhaust gases. The four-stroke cycle engine has also the advantage of wider use and longer period of development.

The Diesel Internal-combustion Engine Cycle.—The Diesel engine cycle is applied only to oil engines. This cycle, similar to the Otto, comprises five events: suction, compression, ignition, expansion, and exhaust. In the Otto internal-combustion engine cycle, air is mixed with the fuel in definite proportions and the combustible mixture is subjected to the process of compression. In the Diesel engine cycle, *only air* is admitted to the cylinder during the suction stroke, so that compression pressures as high as desired are permitted without the danger from pre-ignition. The compression pressures used with Diesel engines vary from 450 to 500 lb. per square inch. The higher compression pressure limit in this case is not dependent upon the composition of the mixture within the cylinder, but upon construction details. At the end of the compression stroke of the Diesel engine piston, oil fuel is injected into the cylinder. The oil enters the cylinder in the form of a fine spray, mixes with the highly compressed air, which is at a temperature of about 1000°F., is ignited and burns at nearly constant pressure. The duration of the oil injection is governed by the load upon the engine. This period of oil injection, as well as the compression pressure, influences the fuel economy of a Diesel engine.

An indicator diagram taken from a Diesel oil engine is shown in Fig. 194. Air is drawn into the cylinder during the suction stroke *AB*. The return of the piston compresses the air to a pressure of about 470 lb. per square inch during the stroke *BC*. The fuel oil is then gradually introduced by means of an oil pump, to an amount depending upon the load, and burns during *CD*, the first part of the third stroke. This is followed by the expansion of the gases within the cylinder to the end of the third stroke along *DE*. At *E*, the exhaust valve opens and the burned gases are exhausted from the cylinder during the fourth stroke *EA*.

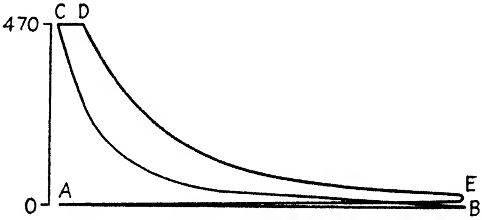


FIG. 194.—Indicator card from a Diesel oil engine.

The Ideal Diesel Cycle.—The ideal cycle of operations for the Diesel cycle is represented in Fig. 195. The equations representing the heats involved and the efficiency of the cycle may be expressed as follows:

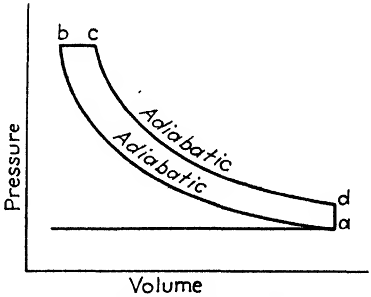


FIG. 195.—The ideal Diesel engine cycle.

The heat added during the combustion of the fuel from *b* to *c* is

$$Q_1 = wC_p(T_c - T_b). \tag{62}$$

The heat rejected from the cycle from *d* to *a* is

$$Q_2 = wC_v(T_d - T_a). \tag{63}$$

The efficiency is then

$$e = \frac{Q_1 - Q_2}{Q_1} = \frac{wC_p(T_c - T_b) - wC_v(T_d - T_a)}{wC_p(T_c - T_b)}$$

$$= 1 - \frac{C_v}{C_p}\left(\frac{T_d - T_c}{T_c - T_b}\right) = 1 - \frac{1}{k}\left(\frac{T_d - T_c}{T_c - T_b}\right). \qquad (64)$$

Details of Internal-combustion Engines.—The fundamental details of an internal-combustion engine are:

1. *The Fuel System.*—This includes fuel storage, piping from the storage to the engine, and a device for preparing the mixture of air and fuel. In order to form an explosive mixture, air must be mixed in certain definite proportions with the fuel, and this can be accomplished only when the fuel is in the gaseous state, or is a mist of liquid fuel easily vaporized at ordinary temperatures. Thus, the essential difference between internal-combustion engines using the various fuels is in the construction of the device for preparing the fuel before it enters the engine cylinder. If the fuel is initially a gas, only a mixing valve is necessary to control the proportions of fuel and air. Fuels which are in the liquid state must be vaporized and mixed with air to form an explosive charge. The devices required for preparing liquid fuels depend on the character of the fuel, a heavy fuel requiring heat, while a volatile fuel, such as gasoline, is easily vaporized at ordinary temperatures by being broken up into fine mist. When an engine uses a volatile liquid fuel, like gasoline, the fuel is vaporized and mixed with the correct proportion of air in a device called a carburetor. Various types of carburetors will be illustrated and explained in Chap. XIV.

2. *A Jacketed Cylinder and Piston.*—In small engines, only the cylinder and cylinder head must be cooled. In large engines, it becomes necessary to cool also the piston and the exhaust valve to prevent overheating of the metal. The methods used in cooling gas-engine cylinders are illustrated in Figs. 196 and 197.

An air-cooled cylinder is illustrated in Fig. 196. This cylinder is cast with webs, and air is circulated by means of a fan driven by the engine. The air-cooling system has not been found practical for stationary engines above 5 hp., as there is no positive temperature control with this system. This lack of temperature control results in the decomposition of the cylinder oil and in carbon deposits on the piston and cylinder walls. Considerable success has been attained with air-cooled motors for automobiles, airplanes and motorcycles.

The cooling of engine cylinder walls by means of water is the most common method. In this case, the cylinder barrel or the cylinder barrel and cylinder head are jacketed; that is, they are built with double walls and water is circulated through the space between the walls. The cylinder wall or barrel is cast separate from the jacket, except in small engines, where the cylinder barrel and jacket walls are cast together. In order definitely to control the temperature of the water jacket, the forced system

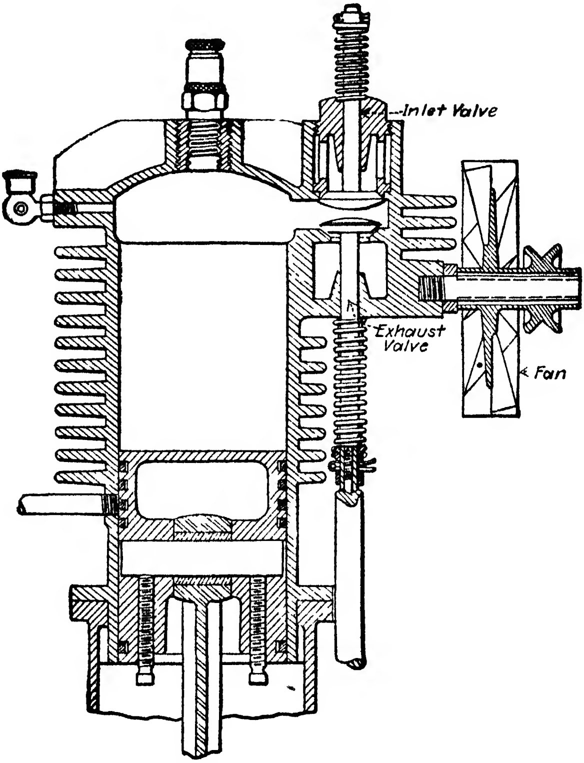


FIG. 196.—Air-cooled cylinder.

of water circulation (Fig. 197) is generally used for stationary engines.

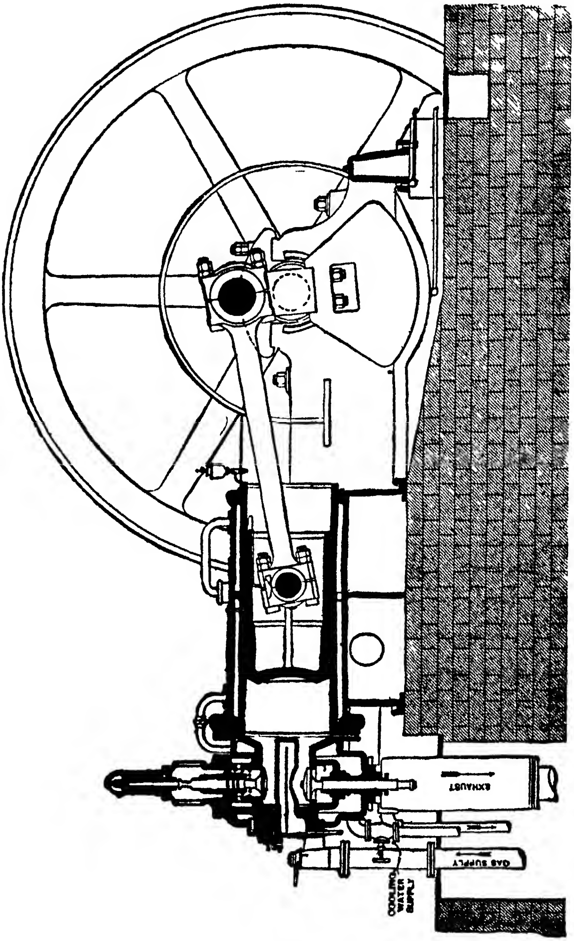


Fig. 197.—Water-cooled gas engine

Cylinders for internal-combustion engines are generally single acting, and are usually fastened to the frame at one end only, to allow for the free expansion of the metal.

The trunk type of piston (Fig. 197) is most commonly used, for it acts not only as a piston but also as a crosshead. The piston is usually provided with three or more rings, as it is very important that leakage past the piston be eliminated.

3. *Inlet and Exhaust Valves.*—With the exception of some automobile motors, which are equipped with sleeve valves, valves for internal-combustion engines are generally of the poppet or mushroom type, with conical seats (Fig. 197).

The inlet valves are not jacketed, as they are cooled by the incoming mixture during the suction stroke. Exhaust valves must be cooled in all except very small engines, as these valves are in contact with very hot gases for a considerable period of time.

Small engines are sometimes provided with inlet valves, which are automatically operated by the suction of the piston, being held to their seats by weak springs. Automatically operated valves are uncertain in their action, and are seldom used. Mechanically operated valves are positively controlled, and are generally used both for inlet and for exhaust valves.

The valves are operated by means of cams or eccentrics from an auxiliary shaft, which is driven by means of gears from the main engine shaft. In the four-stroke cycle engine, the auxiliary shaft is operated at one-half the speed of the main shaft. In small engines, the valves are actuated by cams, but in large engines, eccentrics are employed for this purpose.

4. *Connecting Rod and Crank.*—A mechanism for changing the reciprocating motion of the piston into rotation at the crankshaft. This change is accomplished by means of a connecting rod and crank.

5. *Ignition System.*—Ignition of the mixture in modern internal-combustion engine is accomplished either by a spark, or automatically by the high compression to which either the air or the mixture is subjected in the engine cylinder. The subject of ignition will be treated in detail in Chap. XIV.

6. *Governor.*—A governor for keeping the speed constant as the power developed by the engine varies. The governing mechanism is operated by the speed variations of the engine and the speed control is accomplished either by the hit-or-miss, or by the throttling method as will be explained later.

7. *Flywheel.*—A flywheel for carrying the engine through the idle strokes.

8. *Engine Frame.*—Engine frame and bearings for supporting the various parts of the engine.

9. *Foundation.*—Foundations for the engine and auxiliaries.

10. *Lubricating System.*—Lubricating system which includes grease cups, sight-feed oilers, and positive force-feed oilers. For high-speed motors, the forced-flooded system of lubrication is commonly employed. In this system, a pump forces oil to the various bearings, keeping them flooded with oil at all times.

Low-pressure Oil Engines.—The first successful low-pressure oil engines were gasoline engines, as gasoline is the lightest of all commercial hydrocarbons and is easily vaporized at ordinary atmospheric temperatures. Gasoline engines consume $\frac{1}{8}$ to $\frac{1}{10}$ gal. gasoline per brake horsepower per hour. Gasoline is the most important fuel for small stationary and portable engines; also for light-weight high-speed engines, such as are used on automobiles and airplanes.

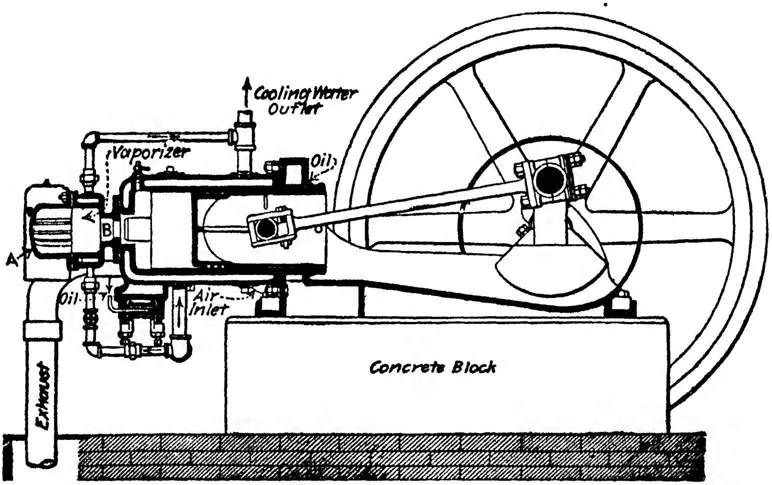


FIG. 198.—Hot-bulb oil engine.

The ordinary gasoline engines (Fig. 190) which employ electric ignition cannot operate satisfactorily on heavy petroleum fuels. The type of hot-surface ignition, formerly called hot-bulb engine, illustrated in Fig. 198, has been used to some extent for petroleum oils as heavy as 30°Bé. (see Table 8, Chap. XIII). This engine is provided with an unjacketed vaporizer *A*, which communicates with the cylinder by means of the small opening *B* (Fig. 198). The vaporizer is raised to a red heat before starting, by means of a torch, and is kept hot by repeated explosions when the engine is running. This engine works on the regular four-stroke Otto gas-engine cycle. During the suction stroke of the piston, air only is drawn into the cylinder, and the charge of oil fuel is injected into the vaporizer by a pump. On the return stroke, the air is compressed, forced into the vaporizer, mixed with the fuel, and automatically ignited. This is followed by the expansion and exhaust strokes, as in other internal-combustion engines.

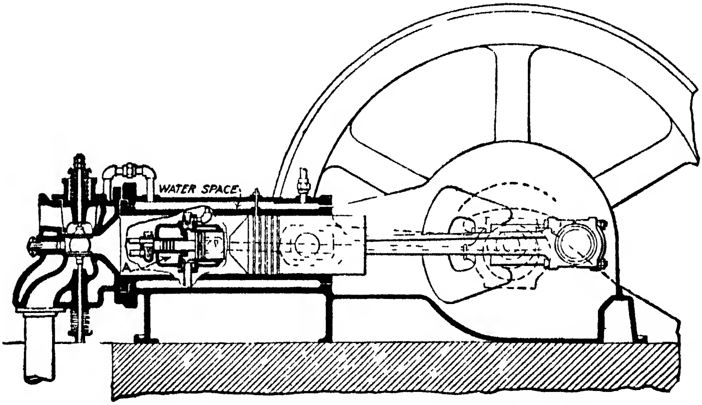


FIG. 199.—Medium-pressure, hot-surface oil engine.

In another type of low-pressure oil engine, a lip at the inner end of a vaporizer is raised to a high temperature by a torch before the engine is started. A pump injects a small stream of fuel oil at every stroke and drops it from a pipe on the heated lip. The lip being kept at a high temperature, vaporizes the fuel and ignites the mixture when the compression is high enough, thus eliminating the necessity for an electric ignition system.

Medium-pressure Oil Engines.—A modification of the hot-bulb type of low-pressure oil engine is the so-called medium-pressure type of oil engine, which can be operated on the lowest grades of petroleum fuels. One type of medium-pressure engine is illustrated in Fig. 199. Like the Diesel, the medium-pressure engine compresses only air, but operates at a compression pressure of about 300 lb. per square inch, depending partly on a hot unjacketed combustion chamber to ignite the charge. During the suction stroke, a charge of air is drawn into the cylinder, which is compressed into the combustion space. At or near the end of the compression stroke, the fuel oil is admitted in a fine spray, is mixed with the air, and is ignited. The resulting expansion forces the piston on its working stroke. Near the end of the working stroke, the exhaust valve is opened and the piston on its return stroke expels the burnt charge. An indicator card from a medium-pressure oil engine is illustrated in Fig. 200.

The Hvid type of oil engine is also classed among medium-pressure engines. This type of engine operates on the principle that every oil, no matter how heavy it may be, contains some light hydrocarbons which will vaporize at fairly low temperatures.

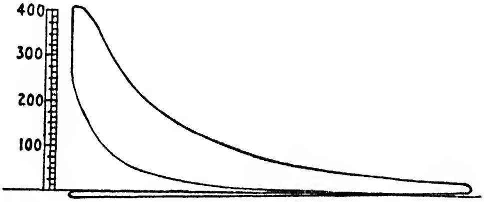


FIG. 200.—Indicator card from a medium-pressure oil engine.

The Diesel Oil Engine.—The Diesel cycle previously described (Fig. 195), is the most economical type of engine for low grades of fuel. While its high cost limits its field of application in small sizes, this is compensated by the higher fuel economy and by the ability of this type to operate on any liquid fuel without leaving an appreciable residue. Diesel engines are constructed to operate on either the two- or four-stroke cycle.

An end section and a side section of an Ingersoll Rand four-stroke-cycle Diesel engine are shown in Figs. 201 and 202. This type is built in sizes from 175 to 1,500 b.hp.

Figure 203 illustrates a double-acting, two-stroke-cycle Diesel engine.

Two systems of fuel injection are used in commercial Diesel engine practice. In one air is used to atomize and force the fuel into the cylinder. Such a system requires a source of compressed air at a pressure of about 1,000 lb. per square inch and an injection valve. In operation the oil is deposited at the base of the injection valve and subjected to the high pressure of the compressed air. At the proper time, the injection valve opens and the oil is forced into the cylinder. In the other system, known as the solid injection type, the oil is forced into the cylinder mechanically. Fuel pumps, operated by cams on the main shaft of the engine, deliver the fuel to the injection nozzle at the correct period in the cycle and force the fuel into the cylinders.

Internal-combustion engines operating on the Diesel cycle are more expensive to build and require better supervision than engines operating on the Otto cycle, but give better fuel economy and are capable of operating with the very cheapest liquid fuels. Under good conditions, Diesel engines will convert more than 30 per cent of the heat in the fuel into work, while oil engines operating on the Otto cycle will usually convert only about 20 per cent. Tests indicate that Diesel engines will consume about 0.45 lb. of low-grade oil per brake horsepower per hour.

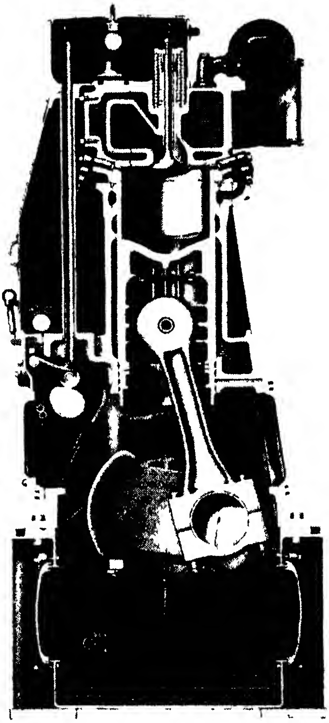


FIG 201.—End section of an Ingersoll Rand Diesel engine.

In Fig. 204 is shown a typical fuel-consumption curve of a Diesel engine. The characteristics of Diesel engine performance are given in Fig. 205.

The number of Diesel engines in use has mounted steadily, as refinements have improved fuel economy and have increased reliability. In 1906 the total production of oil engines was less than 100,000 hp. with the Diesel type only a small part of the total. Diesel engine sales have increased more than four times during the past ten years, and have more than doubled since 1934.

The Diesel engine ranks next to water power as a prime mover for stationary purposes. Light-weight Diesel-propelled trains have focused public attention upon this type of engine for transportation.

Combination Steam-internal-combustion Engine.—The heat from the exhaust gases of an internal-combustion engine is used in the Still engine to generate steam, which is supplied to the under side of the piston of the engine. This type of engine has gas pressure on one side of the piston and steam pressure on the other side, thus producing one gas-power stroke and one steam-power stroke per revolution.

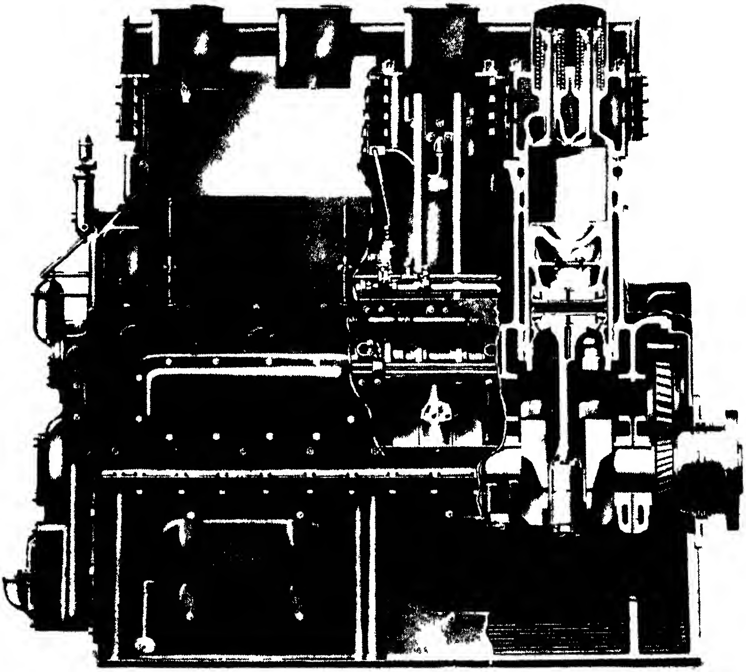


FIG. 202.—Side section of an Ingersoll Rand Diesel engine.

Losses in Internal-combustion Engines.—Internal-combustion engines convert 10 to 30 per cent of the heat energy supplied by the fuel into useful mechanical work. The two greatest

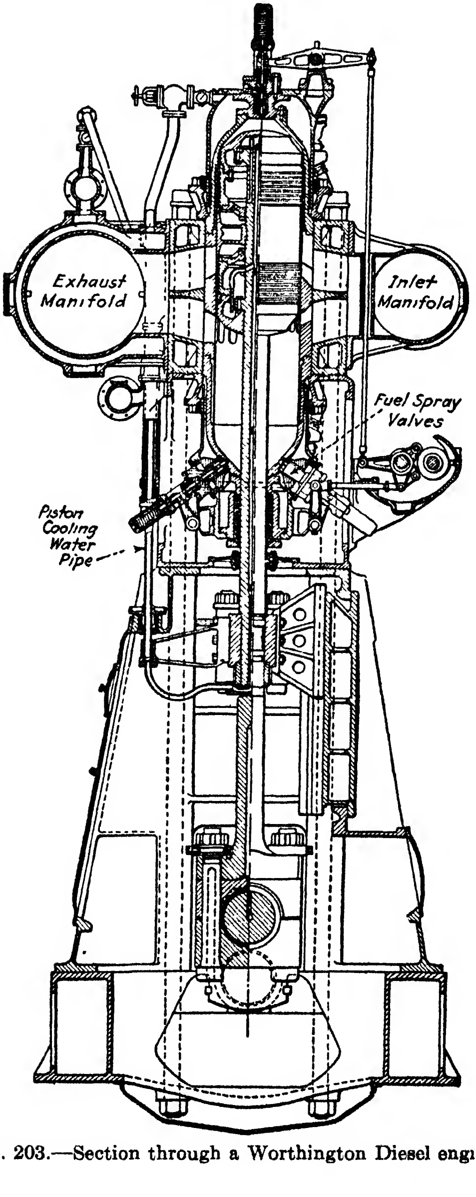


FIG. 203.—Section through a Worthington Diesel engine.

losses are those due to the heat carried away by the jacket water and by the exhaust gases. The loss in the jacket water will vary from 25 to 40 per cent of the heat supplied by the fuel. The loss of heat in the exhaust gases, owing to their high temperature.

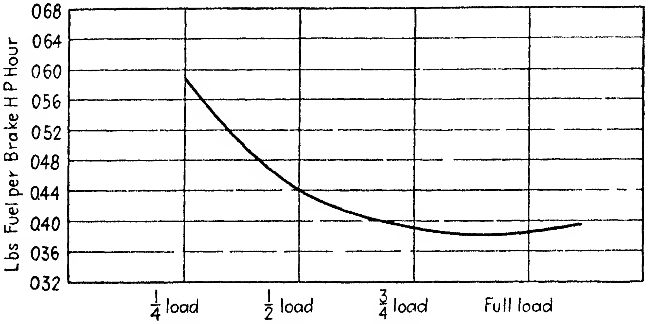


Fig. 204 —Diesel engine fuel economy.

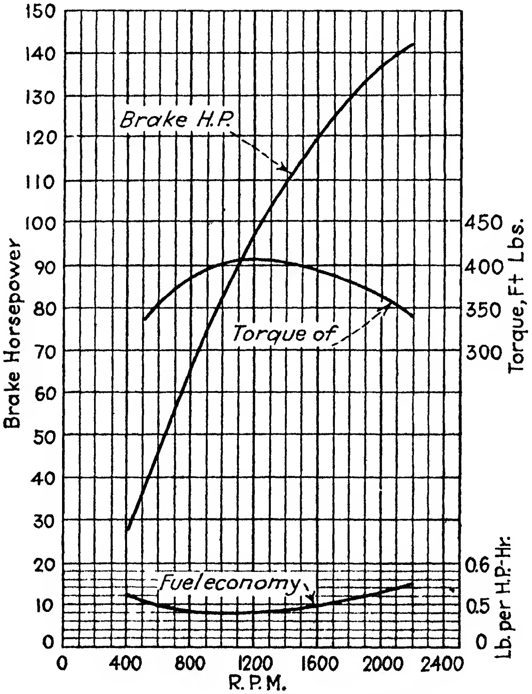


Fig. 205.—Diesel engine characteristics.

will vary from 25 to 50 per cent of the heat supplied, increasing as the jacket loss decreases.

The other main losses are those due to incomplete combustion of the fuel, heat radiated from the outer surfaces of the engine, and frictional losses in the mechanism of the engine.

Installation and Care of Internal-combustion Engines.—The general rules governing the installation of steam power plant equipment apply to internal-combustion engines. An engine should be installed in a well-lighted and ventilated room, which is free from dirt and dust. The engine room must be large enough so that there is sufficient space for easy access to any part of the engine so as to facilitate starting, oiling, inspection, and repair of all parts.

In installing oil engines, the fuel tank should be located outside the building and preferably underground. In any case, the tank should be lower than the pipe to which it is connected in the engine room.

As the mixture of fuel and air is ignited inside the engine cylinder, the resulting explosion produces a shock of considerable magnitude on the engine mechanism, which in turn is transmitted to the foundation. This necessitates very carefully built foundations, which should be separated from the walls of the building, so that vibrations caused by the engine will not affect the building or the surrounding structures.

The exhaust piping should be as straight and as short as possible and the exhaust gases should discharge out of doors. The air supply is preferably taken from the outside.

Before an engine is started for the first time, all the working parts should be carefully examined and placed in proper condition.

The gas engine is not self-starting, as is the steam engine when steam is turned on. The reason for this is that the explosive mixture of fuel and air must be taken into the cylinder and compressed before it can give up energy by explosion. It is, therefore, necessary to set the engine in motion by some external means not employed in regular operation, before it will pick up its normal cycle.

Small engines are started by hand. This is accomplished by turning the flywheel over by hand in the direction of normal rotation until the engine picks up, or by turning it in the opposite direction against compression and then snapping the igniter by hand. As it is difficult to pull over an engine by hand against compression throughout the whole cycle, some engines are provided with a starting cam, which can be shifted so as to engage the exhaust lever. This relieves the compression while cranking, as the exhaust port is open during the first part of the compression stroke. After the engine speeds up, the starting cam is disengaged. Most small engines and also all engines for automobiles, tractors, and trucks are provided with starting cranks. Starting cranks are arranged so that, when turned in the direction of rotation of the engine, they grip the shaft. The starting crank is released as soon as the engine shaft turns faster than the crank.

As the size of the engine increases, hand methods for starting cannot be used. Stationary gas and oil engines are usually started by compressed air. If the engine consists of two or more cylinders, this can be accomplished by shutting off the gas supply to one of the cylinders and running this cylinder with compressed air from a tank, in the same manner as a steam engine is operated with steam from a boiler. As soon as the other cylinders pick up their cycle of operations, the compressed air is shut off and a mixture of fuel and air is admitted to the cylinder used in starting. With large gas engines of only one cylinder, the compressed air is admitted long enough to start the engine revolving, when the compressed air is shut off and the mixture of fuel and air is admitted. The air supply for starting is kept in tanks which are charged to a pressure of 50 to 150 lb. by a small compressor, driven either from the engine shaft, or by means of an auxiliary motor.

In electric central stations, starting by electricity is the simplest. Electric starting systems are also used exclusively on modern automobiles as will be explained in Chap. XVI.

Before an internal-combustion engine is started, the fuel supply should be examined, the ignition system tested, the lubricating devices examined and placed in proper working condition, the load disconnected from the engine, and the spark mechanism retarded to the starting position. In starting an engine by hand cranking, the operator should always pull up on the crank. As soon as the engine starts, the spark should be advanced to the running position and the engine connected to its load.

To stop an engine, the fuel valve is closed, the switch controlling the ignition system is opened, the lubricators and oil cups are closed, and the jacket water is turned off. In cold weather, the water from the engine jackets should be drained to prevent freezing. Before leaving the engine, it should be cleaned, all parts examined and put in order ready for starting up.

The operation and the economy of an internal-combustion engine are greatly influenced by the proper timing of the valves and of the point of ignition. The exact setting of the valves and of the point of ignition depends upon the speed of the engine and upon the fuel used.

The exhaust valves should open before the end of the power stroke and generally from 25 to 40 deg. before the crank reaches the outer or crank-end dead center. This is necessary to prevent loss of power when the piston starts on the exhaust stroke. The time of opening of the exhaust valve must be earlier for high-speed than for slow-speed engines. The exhaust valve should remain open until the crank has turned 5 to 12 deg. beyond the completion of the exhaust stroke. The suction stroke follows the exhaust stroke, and, in order to prevent the mixing of the fresh charge with the burnt gases, the inlet valve should open about 3 deg. after the exhaust valve closes. The time of closing of the inlet valve should be after the crank has turned 10 to 25 deg. beyond the completion of the suction stroke. To ascertain if the valves of an engine are properly timed, the flywheel should be turned over slowly and the time of opening and closing of each valve noted. The proper setting of the valves can be accomplished by changing the length of the valve push rods or by changing the timing of the valve-gear shaft. If for any reason the gears are removed on the crankshaft or on the valve-gear shaft, care should be taken that they are properly replaced, as one tooth out of place will throw the valve mechanism out of time.

The exact point of ignition depends upon the system of ignition, the speed of the engine, the compression, and upon the fuel used. Proper ignition timing can best be determined by means of an indicator. Indicator cards showing early, late, and proper ignition are illustrated in Fig. 206.

If an engine runs well at no-load but will not carry its rated load, the fault may be due to: poor compression, poor fuel, defective ignition, poor timing of ignition, incorrect valve setting, incorrect mixture, leaky inlet or exhaust valves, too much friction at bearings, or to the engine being too small for the rated load.

Premature ignition, usually called preignition, is due to the deposition of carbon or soot on the walls of the cylinder, the compression being too high for the fuel used; by overheating of the piston, exhaust valve, or of some poorly jacketed part.

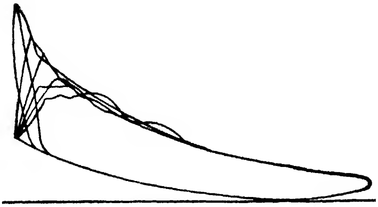


FIG. 206.—Indicator cards showing early, late, and proper ignition.

Best results will be secured if the operation of an engine is placed in charge of one man who is held responsible for the condition of the motor.

Problems

1. Can an economical internal-combustion engine be developed to operate upon a one-stroke cycle? Give reasons for your answer.
2. How does the combustion of the mixture in an Otto cycle engine compare with the explosion of gunpowder?
3. Under what conditions is the two-stroke cycle engine most practical?
4. Why are higher compression pressures more practical with blast-furnace gas than with natural gas?
5. Calculate the cycle efficiency of an engine which operates with gasoline fuel and compression pressures of 90 lb. per square inch.
6. At what temperature should the water in the jacket of a gas engine be maintained? Give reason for the temperature used.
7. Compare poppet and slide valves for internal-combustion engines.
8. Why will an automatically operated inlet valve decrease the power of a gas engine?
9. An oil engine is found to deliver 150 hp. when tested at sea level. Will this engine develop the same power at Denver, Colo.? Give reasons for your answer.
10. Explain the difference between preignition and back firing.
11. Failure of an internal-combustion engine to start is due to what causes? Explain in detail causes and remedies.
12. If an internal-combustion engine slows down and stops, apparently without cause, where would you look for trouble? Explain in detail.
13. Check and correct the valve setting of some internal-combustion engine.
14. Black smoke issues from the exhaust of a gas engine. What is this an indication of? What causes blue smoke at the exhaust?
15. What will cause the deposition of carbon on the cylinder walls?

16. Compare the low-pressure, the medium-pressure, and the Diesel oil engine.

17. What is meant by the term "dual cycle engine?"

18. Why has the combination steam-gas engine, such as the Still engine, found so little general approval?

19. What factors influence the application of the Diesel engine to automobiles and airplanes?

20. What is the future of the Diesel internal-combustion engine? Give reasons for your conclusions.

CHAPTER XIII

INTERNAL-COMBUSTION ENGINE FUELS AND GAS PRODUCERS

FUELS

Classification of Fuels.—Solid, liquid, and gaseous fuels are used in internal-combustion engines. The value of a fuel depends upon its heating value, upon its cost, upon the rapidity with which it burns, and upon the cost of preparing it for use in the gas-engine cylinder. The fuel must be capable of being transformed into a vapor or a gas before entering the engine cylinder, must readily combine with air to form an explosive mixture, and should leave no residue or ash after combustion.

Gaseous fuels are the simplest for use in internal-combustion engines. The fuel in the gaseous state requires simply a mixing valve to proportion the air and the fuel before the mixture enters the engine cylinder. For this reason, when a suitable gaseous fuel can be obtained at a low cost, it is generally preferred.

Solid fuels in their natural state cannot be used for internal-combustion engines. The chief difficulty experienced in their use is from the ash or residue which remains after combustion. Several attempts have been made to inject coal dust directly into the cylinder of an internal-combustion engine, but the resulting ash seriously interferes with the operation. Gunpowder as a fuel has also been attempted, but has not proved successful. The only successful method of utilizing the energy of solid fuels at the present time is to transform the fuel from the solid to the gaseous state. The gas producer, to be explained later, is one of the most practical means by which this transformation is accomplished. The use of solid fuel requires considerable extra equipment, but has proved practical in many instances.

Liquid fuels are comparatively inexpensive in certain localities, are easily transported, and large quantities of such fuels may be stored in a comparatively small space. Petroleum distillates are used most commonly in internal-combustion engines, although alcohol, tar, tar oil, shale oil, and phenoloid (liquid fuel from blast furnaces) are also employed to some extent.

Selection of a Fuel.—While the heating value of a fuel is an important index of its value, several other properties are usually considered.

The value of a solid fuel depends upon the percentage of water it contains, the amount of ash, the tar-forming ingredients, and whether it is of a coking or non-coking variety. Moisture simply dilutes the gas generated and, consequently, lowers its heating value per cubic foot. A high percentage of ash in the fuel requires more frequent cleaning of the producer and often causes a partial stoppage of the air supply. Coking fuels require constant breaking up of the charge with the consequent hindrance in the operation of the producer. The formation of tar, which results when bituminous or high-volatile coals are gasified, requires cleaning of the gas before it enters the gas-engine cylinder. Tar in the cylinder leaves a large deposit of soot, which interferes with the operation of the engine. Anthracite coal and coke are perhaps the ideal solid fuels for gas producers, because of the absence of tar, although other varieties of coal and lignite are used to a certain extent.

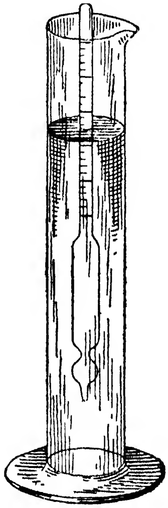


Fig. 207.—Baumé hydrometer.

The quality of a liquid fuel depends upon its specific gravity, flash point, water content, cold test, color, sulphur content, presence of acids, and residue.

By specific gravity is meant the relation existing between the weight of any substance and the weight of an equal volume or bulk of water. The Baumé hydrometer (Fig. 207) is generally used for this determination. This instrument carries an arbitrary scale and sinks to a depth corresponding to the density of the liquid in which it floats. Table 9 shows the relation existing between the Baumé hydrometer scale, the specific gravity, and the weight of liquid fuels in pounds per gallon. (Bé° means degrees by the Baumé hydrometer.) Formerly, liquid fuels were

TABLE 9.—SPECIFIC GRAVITY AND BAUMÉ SCALE

Specific gravity	Degrees, Baumé	Pounds per gallon	Specific gravity	Degrees, Baumé	Pounds per gallon
1.000	10	8.336	0.775	51	6.462
0.993	11	8.277	0.771	52	6.428
0.986	12	8.220	0.767	53	6.394
0.979	13	8.161	0.763	54	6.358
0.972	14	8.104	0.759	55	6.324
0.966	15	8.051	0.755	56	6.290
0.959	16	7.997	0.751	57	6.258
0.953	17	7.944	0.747	58	6.212
0.947	18	7.891	0.743	59	6.195
0.940	19	7.837	0.739	60	6.163
0.934	20	7.785	0.736	61	6.133
0.928	21	7.736	0.732	62	6.101
0.922	22	7.687	0.728	63	6.070
0.916	23	7.638	0.724	64	6.038
0.911	24	7.590	0.721	65	6.006
0.905	25	7.541	0.717	66	5.975
0.899	26	7.493	0.713	67	5.946
0.893	27	7.444	0.710	68	5.916
0.887	28	7.395	0.706	69	5.886
0.881	29	7.347	0.703	70	5.856
0.876	30	7.298	0.699	71	5.827
0.870	31	7.251	0.696	72	5.797
0.865	32	7.210	0.692	73	5.771
0.860	33	7.166	0.689	74	5.743
0.854	34	7.122	0.686	75	5.715
0.849	35	7.079	0.682	76	5.688
0.844	36	7.038	0.679	77	5.659
0.840	37	6.998	0.676	78	5.632
0.835	38	6.966	0.672	79	5.603
0.830	39	6.918	0.669	80	5.576
0.825	40	6.878	0.666	81	5.548
0.820	41	6.839	0.662	82	5.517
0.816	42	6.804	0.658	83	5.487
0.811	43	6.760	0.655	84	5.457
0.806	44	6.721	0.651	85	5.427
0.802	45	6.683	0.648	86	5.402
0.797	46	6.644	0.645	87	5.374
0.793	47	6.608	0.642	88	5.353
0.788	48	6.571	0.639	89	5.316
0.784	49	6.534	0.636	90	5.304
0.779	50	6.498			

judged mainly by their specific gravity. In the case of blended fuels, specific gravity is not an accurate indication of its quality.

The flash point of a liquid fuel is the lowest temperature at which the vapors arising therefrom will ignite when a small test flame is brought near its surface. The flash point is an index of the volatile constituents of a fuel.

The cold test is the lowest temperature at which a liquid fuel will pour. Upon this property depends the free circulation of liquid fuels through pipes.

Gaseous fuels to be suitable for internal-combustion engines must be free from dust, tar, sulphur vapors, and other impurities.

The Heating Value of a Fuel.—The heat content of a liquid or gaseous fuel is an important index of its value, as is the case of solid fuels discussed in Chap. III. This property is measured in much the same manner as is the heating value of coal. The fuel is burned in some form of calorimeter and the heat liberated is measured by the amount of heating absorbed by the water which surrounds the combustion vessel or chamber of the calorimeter. In Fig. 208 is illustrated a calorimeter for determining the heating value of gaseous fuels. This type of calorimeter with special equipment is also used for testing light liquid fuels.

The heating value of a liquid fuel may be calculated by equation (35). Another method is to determine the specific gravity in degrees Baumé (Bé°) and to calculate by the following formula:

$$\text{Heating value of fuel oil} = 18{,}650 + 40\,(\text{Bé}^\circ - 10). \quad (65)$$

The apparatus (Fig. 208) is designed for determining the number of heat units in a certain volume of gas, as a cubic foot or a cubic meter.

The gas enters the meter at *g* and passes thence through the pressure regulator to the calorimeter proper, where the gas burns at the burner shown in dotted outline.

The products of combustion rise to the top where they enter and pass down through a double row of pipes which are surrounded by circulating water and leave at the exit flue at the base.

The water entering at *a*, passes through the regulating cock *c*, thence around the tubes and issues at *c*, whence it flows into the measuring glass.

Thermometers register the temperatures of the gases and the water entering and leaving the calorimeter.

Knowing the volume of gas burned, the quantity of water collected, and the temperatures above noted, a simple calculation gives the heating value of the gas.

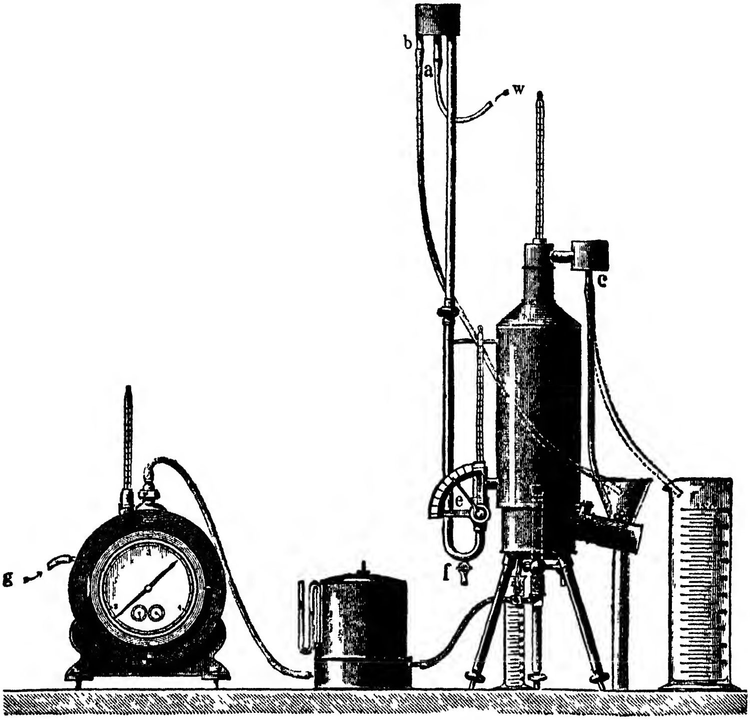


FIG. 208.—Gas calorimeter.

Distillates of Crude Petroleum.—The so-called distillates of crude petroleum are obtained by boiling or refining crude petroleum and condensing the vapors which are driven off at various temperatures. Crude petroleum is a mineral oil which is found in greatest quantities in the United States, Russia, Mexico, and Roumania. The exact composition of crude petroleum varies in different localities. It is made up mainly of carbon and of hydrogen, in the ratio of about two-thirds carbon to one-third hydrogen.

Crude petroleum in certain localities has a paraffin base; that is, it yields a solid paraffin residue. Other petroleums with an asphalt base yield an asphalt residue. The specific gravity of petroleum oils from different fields varies between 0.800 and 0.970.

The vapors which are condensed into gasoline are driven off at temperatures of 140 to 160°F. The various grades of kerosene are the condensed vapors, driven off at temperatures of 250 to 400°, and the heavy oils are driven off at still higher temperatures.

Gasoline.—Of all petroleum distillates, gasoline is the most important fuel for internal-combustion engines.

While kerosene and the heavier distillates are used as fuel in internal-combustion engines, especially designed for their use, the percentage used for this service is small as compared to that of gasoline. Gasoline finds its greatest use as a fuel for the automobile, tractor, truck, airplane, and small stationary internal-combustion engines.

Early refining processes resulted in a very small percentage yield of gasoline. Twenty-five years ago, a yield of 10 per cent of the original crude oil as gasoline was considered good practice. Today, the original crude oil produces an average yield somewhat greater than 40 per cent. The increase in yield of gasoline has resulted from the use of cracking stills, from better practice in blending of the various grades of gasoline, and from improvement in refining equipment and practices.

Gasolines may be classified as: (1) straight refinery, (2) cracked, (3) casing head.

The straight refinery method of manufacturing gasoline from crude petroleum is to heat the crude oil in a closed retort, called a still, then cooling and condensing the vapors given off. Destructive distillation, or cracking, is prevented by keeping down the temperature within the still either by placing the still under a partial vacuum or by allowing steam to bubble through the crude oil when distilling.

Cracked gasolines are obtained by subjecting petroleum oils of high boiling point to high temperatures and pressure; the heavy oil decomposes and cracked gasoline is recovered from the distillate.

Natural-gas gasoline is obtained from natural gas by either the compression or the absorption method. The compression process is usually applied to wet gas, called casing-head gas; that is, to gas which is produced from the same sands as petroleum oil. The absorption process can be used with ordinary natural gas. A gasoline similar to casing-head gasoline is also being manufactured in refineries by the compression process from the very light vapors which are driven off when the stills are first heated.

Commercial gasoline is usually a physical blend of these various grades. Its density varies from 57 to 85° Bé. (0.65 to 0.75 sp. gr.), depending upon its composition. The weight of gasoline varies from 5.4 to 6.2 lb. per gallon. Its heating value is about 19,000 B.t.u. per pound. The flash point of gasoline varies from 10 to 20°F. This means that gases are liberated which form an inflammable vapor at low temperatures provided a sufficient supply of air is present. For this reason, care must be taken in the handling of gasoline. A good storage tank free from leaks and placed underground contributes greatly to the safety as well as to the economical use of gasoline. When filling a gasoline storage tank or in handling gasoline, care must be taken not to have any unprotected flame nearby. In case of fire, it is best to extinguish the flame by means of wet sawdust or a special fire extinguisher.

Kerosene.—Kerosene ranks next to gasoline among the products of crude petroleum for use in oil engines. Its density varies from 41 to 49° Bé. (0.78 to 0.82 sp. gr.). Its flash point is 70 to 150°, depending upon the grade, and its heating value per pound is about 18,500 B.t.u. Kerosene is less volatile than gasoline, is safer to handle and store, does not evaporate so rapidly, but requires preheating to produce rapid evaporation. Kerosene is quite satisfactory as a fuel for engines operating under constant loads and speeds. Any gasoline engine can be operated with kerosene fuel provided it is started and run with gasoline until the cylinder walls become hot. Hot-bulb engines will start on kerosene.

Crude Oil.—Distillate and fuel oils are the heavier petroleum products which are used as fuels in Diesel or semi-Diesel types of internal-combustion engines. These fuels have a high flash point and a heating value of 18,000 to 20,000 B.t.u. per pound.

The qualities of these oils are based principally upon their heating value and to a certain extent upon their specific gravity.

Alcohol.—Alcohol as a fuel for gas-engine use has many advantages as compared with the petroleum distillates. It is less dangerous than gasoline, its products of combustion are odorless, and it lends itself to greater compression pressures than do the various petroleum fuels. Experiments show that an engine designed to stand the compression pressures before ignition most suitable for alcohol will develop about 30 per cent more power than a gasoline engine of the same size, stroke, and speed.

Several years ago, when the internal-revenue tax was removed from alcohol, so denatured as to destroy its character as a beverage, it was expected that denatured alcohol would become a very important fuel for use in gas engines. Its price up to this date, however, has been so much higher than that of gasoline, the most expensive of petroleum fuels, that the use of alcohol in gas engines is out of the question. It is possible that, as the cost of the petroleum distillates increases, and processes are developed for producing denatured alcohol at a low price, the alcohol engine will come into prominence as a motor.

The specific gravity of denatured alcohol is about 0.795 and its calorific value is about two-thirds that of petroleum fuels. Alcohol requires less air for combustion than do petroleum fuels. Theoretically, the calorific value of a cubic foot of explosive mixtures of alcohol and of gasoline is about the same. Actual tests show that the fuel economy per horsepower is about the same for both fuels, provided the compression pressures before ignition are best suited for the particular fuel used. In gasoline engines, compression pressures of about 75 lb. are used, while the alcohol engine gives best results, as far as economy and capacity are concerned, when the compression pressure before ignition is about 180 lb. per square inch.

Benzol.—Benzol is a liquid fuel derived from the distillation of coal. In the pure state, it has a density of about 29° Bé. (0.88 sp. gr.) and a heating value of about 17,200 B.t.u. per pound. When mixed with various proportions of gasoline or of alcohol, a desirable fuel results. A 50 per cent mixture of benzol and alcohol has been successfully used as a fuel. Commercial benzol contains about 90 per cent benzol, while the remaining constituents are other minor coal-tar derivatives.

Shale Oil.—Shale oil is obtained from the destructive distillation of shale in vertical retorts in which the shale is exposed to a temperature of about 900°F. The crude shale oil has a specific gravity of 0.86 to 0.89 and yields, by refining, oils which are suitable for use in internal-combustion engines of special design.

Fuel Gases.—The fuel gases suitable for internal-combustion engines are blast-furnace gas, coke-oven gas, natural gas, and producer gas. Internal-combustion engines can also be operated on manufactured gas, acetylene, and oil gas; but these fuel gases are usually too expensive.

Manufactured gas is made by the distillation of bituminous coal and has a heating value of about 600 B.t.u. per cubic foot.

Acetylene gas is formed when calcium carbide is decomposed by water and has a heating value of about 1,500 B.t.u. per cubic foot.

Oil gas is produced by vaporizing crude petroleum.

Blast-furnace Gas.—Blast-furnace gas is made by the combustion of coke during the production of pig iron. The gas, after leaving the top of blast furnaces, can be purified and used for operating internal-combustion engines. Blast-furnace gas has a heating value of only about 100 B.t.u. per cubic foot, but can be compressed to high pressures with the resulting high efficiency if used in internal-combustion engines operating on the Otto cycle. From 120,000 to 180,000 cu. ft. of blast-furnace gas are generated at the production of each ton of pig iron, and this is available for the generation of power as well as for the various heating processes required in the plant. Blast-furnace gas must be thoroughly cleaned of all fine dust and of metallic vapors before it is used in gas engines.

Coke-oven Gas.—Coke-oven gas has a heating value of about 600 B.t.u. per cubic foot and, when free from tar, is suitable as a fuel for internal-combustion engines. Modern coke-oven plants yield considerable gas for power purposes, as only about 60 per cent of the gas generated in the coke ovens is used as fuel for the coking process.

Natural Gas.—Natural gas is found near practically all oil fields and has been very successfully used as a gas-engine fuel. The heating value of natural gas varies ordinarily from 900 to 1,000 B.t.u. per cubic foot. On account of the high hydrogen content of natural gas, engines utilizing this fuel must operate at low-compression pressures in order to prevent preignition. Owing to the need of natural gas as a fuel for industrial and household use and to the uncertainty of a continued supply, its utilization for the generation of power is limited to very few localities.

Producer Gas.—Producer gas is manufactured from solid fuel in a brick-lined vessel, called a gas producer. The gas producer is blown continuously with a mixture of air and steam, in definite proportions, generating a combustible gas, which is suitable for use in internal-combustion engines or for heating. Producer gas can be manufactured from charcoal, coke, anthracite coal, bituminous coal, lignite, peat, or wood. Producers operating on anthracite coal or coke have been more satisfactory than those using bituminous coal or lignite, as anthracite coal producer gas contains very little tar and the plant does not have to be provided with elaborate scrubbing systems for cleaning the gas.

The amount of gas generated per pound of fuel depends upon the fuel used. Producers using lignite will usually generate less than 40 cu. ft. of gas per pound of fuel. With bituminous coal, the gas generated per pound of fuel will be about 65 cu. ft., with anthracite about 75 cu. ft., and with coke about 90 cu. ft. of gas will be produced.

Anthracite producer gas has an average heating value of about 130 B.t.u. per cubic foot and contains approximately: 9 per cent of hydrogen, 24 per cent of carbon monoxide, 5 per cent of carbon dioxide, 2 per cent of hydrocarbons, and about 60 per cent of nitrogen. Bituminous producer gas has a heat of combustion of about 140 B.t.u. and contains approximately: 12 per cent of hydrogen, 20 per cent of carbon monoxide, 8 per cent of carbon dioxide, 3 per cent of hydrocarbons, and about 57 per cent of nitrogen.

Internal-combustion engines using producer gas can be operated at a compression pressure before ignition of about 160 lb. per square inch and will produce a horsepower for about 75 cu. ft. of gas, which can be generated in a producer by the gasification of about 1 lb. of coal.

Producer gas is at present of minor importance as a fuel for power generation, but the principle of the gas producer has numerous applications in industry. Accordingly, some of the major types are included in this chapter.

GAS PRODUCERS

Details of Gas Producers.—A gas producer is a brick-lined, air-tight, steel-plate cylinder arranged with a grate to hold a thick bed of fuel, a hopper, and an ash pit to receive the fuel and the non-combustible material, respectively, means for supplying a mixture of air and steam to the fuel bed; a gas outlet, and gas-cleaning apparatus. Producers are usually provided with poke holes and shaking grates for breaking up and for maintaining the fuel bed in uniform condition.

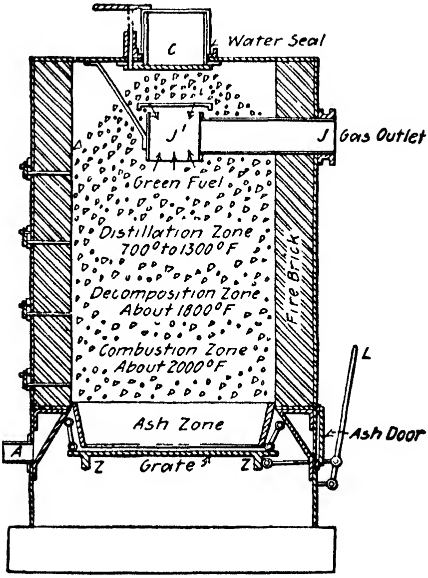


FIG. 209.—Gas producer generator.

Details of a typical producer generator are illustrated in Fig. 209. Fuel is charged into the retort *C* and is admitted to the shell of the generator by means of a quick-opening gate valve. The retort *C* is provided with a water-sealed cover, this arrangement enabling the operator to charge the producer while the plant is in operation, without the danger of admitting air or of allowing gas to escape. Coal entering the shell is distributed by means of the hood *J′*, the inside of which serves as a gas collector. The gas outlet is at *J*. A swinging grate *Z* supports the fuel bed and is suspended from the shell by chains. The shaking motion of the grate is produced by the hand lever *L*. Doors are provided at the bottom for the removal of ashes. The generator is provided with peep holes and poke holes for observing and maintaining the fuel bed in the proper condition. The mixture of steam and air enters at *A*. The temperatures of the various zones are approximately as indicated in Fig. 209.

Classification of Gas Producers.—Producers are classified by the manner in which the mixture of air and steam is caused to pass through the producer and gas-cleaning apparatus.

In the suction types of producers, the air is drawn through the producer and gas-cleaning apparatus by the suction formed in the engine cylinder. The rate of gas formation in this type is automatically controlled by the demand of the engine. This type of gas producer is inexpensive and is suitable only for small installations.

In the pressure types of producers, the mixture of air and steam is forced through the fuel bed of the producer by means of a fan. The amount of gas generated in this case is independent of the amount used by the engine.

In a third type, called combination producer, a fan is placed between the producer and the engine which delivers the gas to the engine or to a gas holder under pressure. The producer proper in this case operates as a suction producer, but the amount of gas generated is independent of the engine's demand.

Gas producers are also classified with reference to the fuel gasified. Anthracite producers are usually of the suction type, the draft being produced by the suction of the engine piston. Bituminous producers are of the pressure or of the combination types and are provided with special scrubbers and purifiers for removing tar and other impurities.

Suction Gas Producers.—A simple suction gas producer suitable for anthracite coal is illustrated in Fig. 210. The generator *A* of the producer is a cast-iron or steel shell with a grate below and a fuel hopper above. Steam for the blast is generated in a vaporizer, which is either arranged around the top of the producer or is independent of, but attached to, the producer proper. The mixture of air and steam enters at the bottom of the fuel bed, a valve regulating the proportion of air and steam. The gas leaving the producer is cooled and purified in a coke-filled, wet scrubber *S* and passes to the engine cylinder *C*.

In some suction producer plants the gas is cooled and cleaned of dust in a water-sprayed coke scrubber, after which it is allowed to pass through a dry scrubber on its way to the engine. The dry scrubber is filled with shavings, excelsior, and iron turnings and is intended to remove sulphurous fumes from the gas.

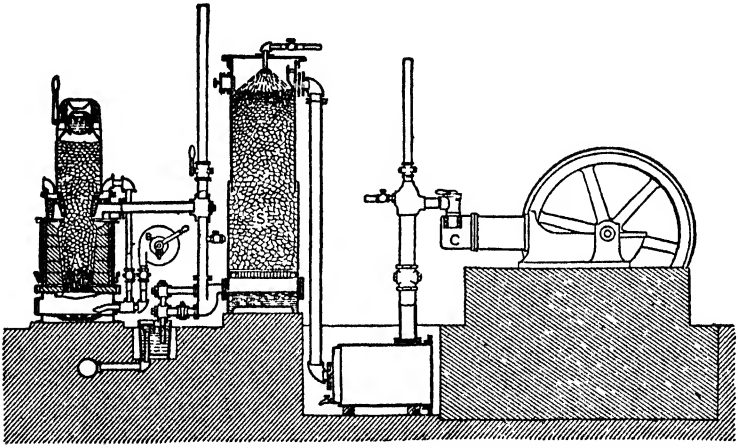


FIG. 210. —Suction producer plant.

The hand-operated fan *B* (Fig. 210) is used to furnish draft during the starting of the fires. When the engine is in operation the draft from the fan *B* is not necessary. A producer is also provided with a change valve, which is used to discharge the poor gases to the atmosphere when the fire is started up.

Pressure Gas Producers.—One type of pressure producer, called the water-bottom producer, is illustrated in Fig. 211. The grate in this case is dispensed with and the ashes drop into a water seal at the base of the producer. The blast is admitted to the center of the producer by a steam jet blower *B*. The fuel is discharged from the hopper *D* into the chamber *E*, from which it is distributed uniformly by the device *F*. Poke holes are provided at *G* and at *H* for breaking up the fuel bed. The gas leaving the producer at *C* enters scrubbers, tar extractors, and other purifiers on its way to the engine cylinder. The water-bottom type of producer is advantageous in that the ashes can be removed conveniently while the producer is in operation. Some water-bottom pressure producers are provided with an automatic fuel-feeding device.

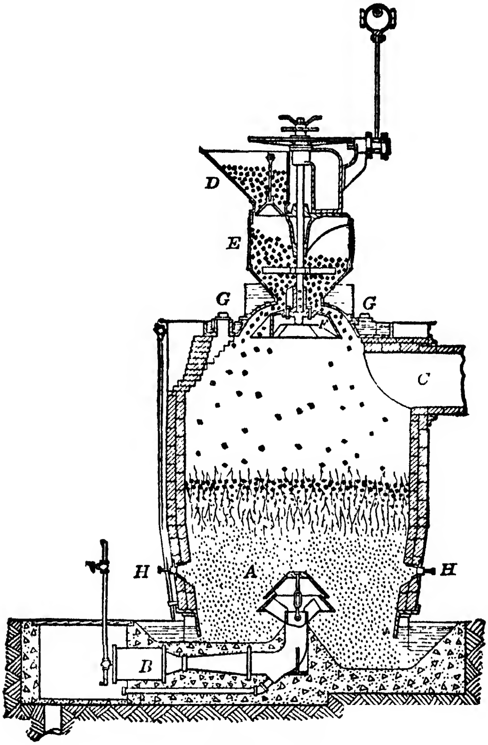


Fig. 211.—Pressure gas producer.

Combination Producers.—Combination producer plants have a blower placed between the producer and the engine cylinder. Some plants of this type are similar to the producers described and are equipped with elaborate scrubbers and purifiers when operated with low-grade fuels.

In the down-draft, double-furnace producer, illustrated in Fig. 212, the formation of tar is prevented by carrying the gases, which are distilled from the fresh fuel in the upper strata, through the hottest zone at the lower part of the producer. The cleaning apparatus used with this type of plant consists only of a wet and a dry scrubber.

In starting the down-draft, double-furnace producer, the fires are kindled with coke and wood in both generators and the blower is started, leaving open the top doors *H* and *I*, and valves *A*, *B*, *G*, and *C*. Valve *D* is closed. As soon as the fires are thoroughly kindled, steam is admitted to the top of the generators at *F* and *E*, and mingles with the air admitted through top doors *H* and *I*, which the operation of the blower draws down through the fresh charge of coal and then through the hot fuel bed beneath. The gas produced is then drawn down through the grates and ash pits of both generators, up through the vertical boiler, through the valve *G*, through the wet scrubber, and blower. When valve *C* is closed, and valve *D* is opened, the gas is pushed by the blower through the dry scrubber and to the gas holder. The gas from the gas holder is delivered to the engine cylinder.

Rating of Gas Producers.—The capacity of a gas producer is expressed by the number of pounds of fuel it can gasify per hour or in horsepower if the gas is generated for power purposes. The gasifying capacity of a producer depends upon its design and upon the quality of the fuel used. The rating in horsepower is incorrect, because no mechanical work is done by the producer and there is no definite relation between the capacity of a producer and the power developed by an internal-combustion engine. There is at present no standard method for rating gas producers.

Factors Influencing Producer Operation.—One of the most important factors to be considered in the selection of a gas-producer fuel is its volatile constituents. The fuel that produces tar and lampblack in large quantities will require complicated scrubbing systems, or producers of special design. This will in either case increase the first cost of the plant as well as the cost of the upkeep of engines and pipe lines. The amount of tar-forming gases is small with anthracite coal, but is considerable in the case of most bituminous coals and lower grades of solid fuels.

The kind of ash is also of importance. If the ash fuses or fluxes to a clinker, the proportion of steam to air in the blast must be increased to reduce the temperature of the fuel bed. This

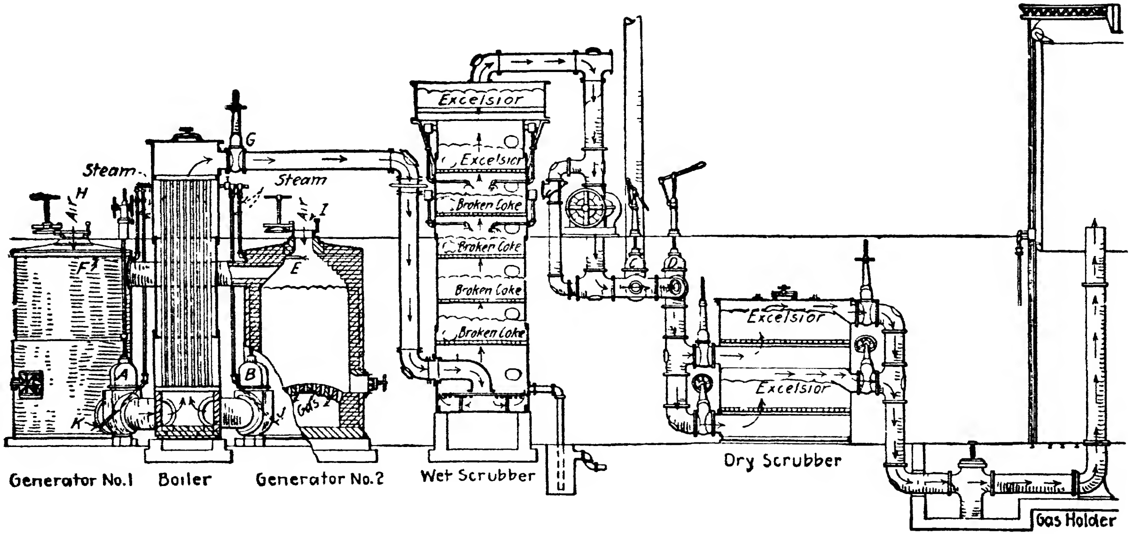


FIG. 212.—Down-draft double-furnace producer.

decrease in temperature reduces the percentage of combustible carbon monoxide formed in the producer. The use of too much steam in the producer results in the formation of a gas which has considerable hydrogen. This means that when used in internal-combustion engines the gas cannot be compressed to as high a pressure as producer gas which has little hydrogen.

Clinker formation is also serious, because it obstructs the gas passages, requiring increased blast pressure to allow the air to pass through the fuel bed. Uniform conditions during producer operation and careful poking will reduce the difficulties from clinker.

The size of coal used influences the capacity and efficiency of a gas producer. If the coal is too large, too little surface is offered for gasification and the producer efficiency is reduced. A nut-size of bituminous coal is best, while the pea-size anthracite will give good results. If the coal is too fine, the resistance through the fuel bed is increased, requiring greater blast pressure, and this reduces the capacity of the producer.

The grate area, the rate of gasification, and the depth of the fuel bed are affected by the character of the fuel, the lower-grade fuels requiring a larger grate area, slower rates of gasification, and deeper fuel beds.

Some form of gas calorimeter will prove very useful in the daily operation of gas producers.

Problems

1. An analysis of a gas by the gas calorimeter (Fig. 208) gave the following readings: gas passed through meter 3 cu. ft., water collected 85 lb., inlet temperature 65°F., outlet temperature 84°F. Calculate the heating value of the gas in British thermal units per cubic foot.
2. Compare the relative values of gasoline, kerosene, alcohol, and crude petroleum for use in internal-combustion engines.
3. Calculate the heating value of the fuels which have specific quantities in degrees Bé. 28 and 70, respectively.
4. At what price must the ordinary manufactured gas sell in order to compete with natural gas at 50 cts. per thousand cubic feet?
5. Under what condition is the gas producer plant most suitable for power generation?
6. Compare natural gas, blast-furnace gas, producer gas, and coke-oven gas as to their heating values.
7. What type of petroleum fuel is used in Diesel engines?
8. Discuss mixtures of alcohol and gasoline as automotive fuels.

CHAPTER XIV

AUXILIARIES FOR INTERNAL-COMBUSTION ENGINES

CARBURETORS

Principles of Carburetion.—When fuel in the gaseous state is used in an internal-combustion engine, a proper mixture of gas and air is easily secured. When a liquid fuel is used in an Otto cycle engine it must be atomized before it can be mixed with air in correct proportion for use in the engine cylinder. The function of a carburetor is to mix the liquid fuel with air in the correct proportions by weight for use in the engine cylinder at all loads and at all speeds of the engine.

A mixture too rich, that is, having too large a proportion of gasoline to air, will give a black, odorous exhaust, due to the fact that some of the gases are unburned. A mixture too lean, that is, having insufficient gasoline, is slow burning and, consequently, may result in back firing through the carburetor. A lean mixture is accompanied also by the heating of the motor and by a loss of power.

Practically all modern carburetors use some form of spray nozzle for atomizing the fuel. A throat, or Venturi tube, is usually made use of to increase the velocity of the air at the spray nozzle, thereby increasing the spray of gasoline from the nozzle. The mixing of fuel and air is carried on automatically, the operator controlling the speed and power by opening and closing the throttle valve.

Simple Carburetors or Mixer Valves.—The simpler forms of carburetors which were used on old makes of stationary and constant-speed engines are called mixer valves. Mixer valves are not suitable for variable-speed motors.

Float-feed Carburetors.—At present, some form of the float-feed type of carburetor is exclusively used on automobiles, trucks, and other variable-speed engines. Float-feed carburetors are of two types: first, the concentric, in which the float chamber surrounds the mixing chamber, or is concentric with it; second, the eccentric, which has the float chamber and mixing chamber side by side. The concentric type keeps the fuel at the predetermined level much better than the eccentric carburetor. In the conenetric type, the height of the fuel in the nozzle is not changed by road inclinations, whereas in the case of the eccentric type, the fuel level may become very low or may be high enough actually to flow from the nozzle. Many of the successful modern carburetors are of eccentric type, because other advantages or conveniences more than offset the disadvantages mentioned above. Only a few of the many different types of carbureters will be illustrated in this chapter.

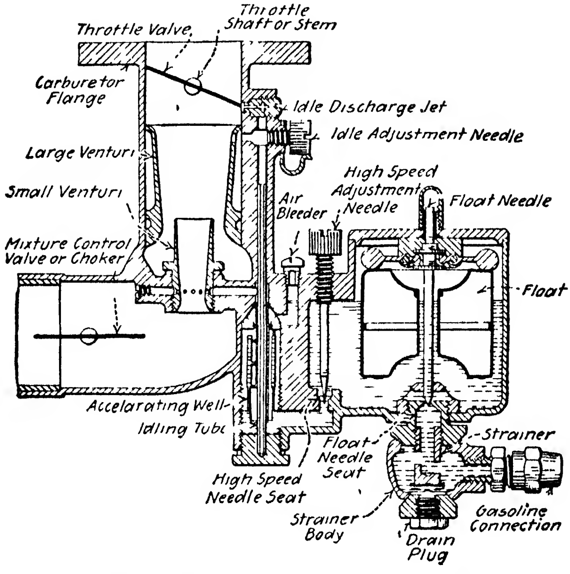


FIG. 213.—Stromberg plain-tube carburetor.

The Stromberg Carburetor.—Figure 213 represents the Stromberg plain-tube carburetor. A plain-tube carburetor is one in which both the air and the gasoline openings are fixed in size. In this carburetor the proper proportion of air to gasoline is maintained at all motor speeds by means of what the manufacturer calls an air-bled jet. Air is taken in through the air bleeder and discharges into the gasoline channel before the gasoline reaches the jet holes in the Venturi. The air enters the tube at right angles to the flow of gasoline, thereby breaking up the flow of gasoline and producing a finely divided spray. When this spray reaches the jet holes and is discharged into the high-velocity air stream, it is further broken up and enters as a very finely divided mist.

An accelerating well is made use of to facilitate sudden increases in the speed of the motor.

The air when the engine is idling is drawn from below the throttle and mixes with the gasoline before reaching the idling jet. Under certain conditions, the suction draws gasoline from both idling jet and small Venturi, but as the throttle is opened more, the gasoline comes only from the Venturi. The function of the large Venturi is to aid in more finely dividing the gasoline vapor and further to mix it in the correct proportion with air.

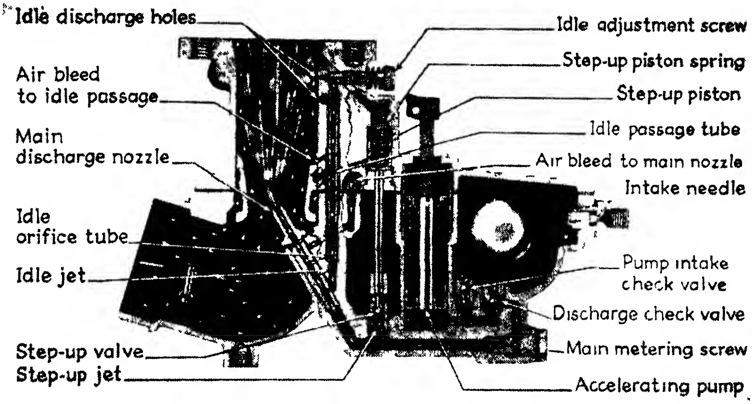


FIG. 214.—The Carter carburetor.

The plain-tube Stromberg carburetor has two adjustments, one for low and one for high speeds. The low-speed screw adjusts the amount of air, and the high-speed screw regulates the quantity of gasoline.

The Carter Carburetor.—Figure 214 illustrates this type of carburetor. The main nozzle discharges the fuel at an upward angle into the primary Venturi against the downward air stream.

A pneumatic-type accelerating pump is employed, operated automatically by the throttle.

The Marvel Carburetor.—This type, used on Buick cars, is shown in Fig. 215. This type is made up of two major units, a cast-iron double-throttle body, fuel bowl, and double mixing chamber combined, and a die-cast zinc-bowl cover and air inlet assembly combined. This carburetor is provided with two floats, two complete idle systems, two main nozzle systems, two metering pin and jet systems, two mixing chambers, and two throttle valves.

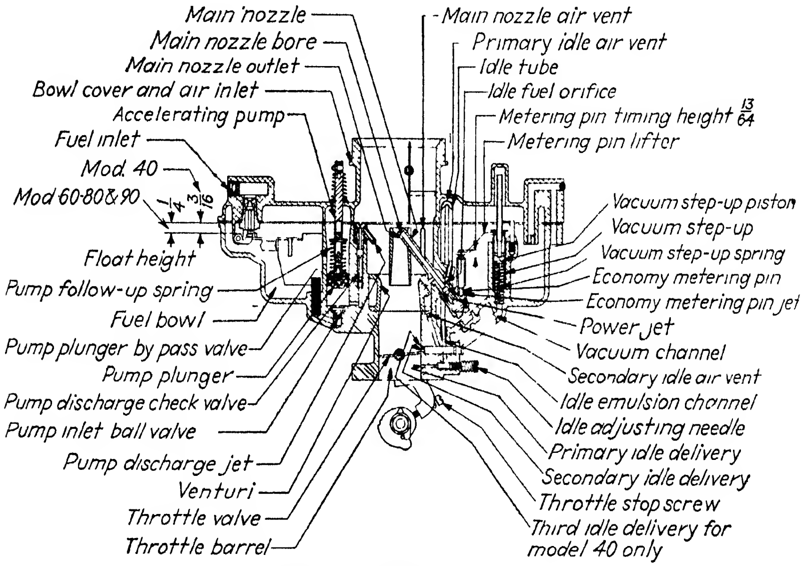


FIG. 215.—The Marvel carburetor.

Some models of the Marvel carburetors are provided with jacketed mixing chambers, through which hot gas from the exhaust manifold is passed, thereby aiding in the vaporization of the fuel. The heat supply is controlled by hand as well as automatically.

A form of carburetor for burning fairly heavy fuels is illustrated in Fig. 216. A connection from the exhaust pipe heats the bowl of the carburetor. This heat is necessary in order to vaporize the heavier fuels. Above the needle valve *J* is placed a set of stationary blades resembling the rotor of a windmill. The high-velocity air stream, laden with particles of unvaporized kerosene, strikes these blades and is given a whirling effect. This throws the particles of fuel, due to their inertia, against the sides of the heated bowl and vaporizes them so that they can be mixed properly with the air for use in the cylinder. This carburetor has two needle valves, two adjustments and also an auxiliary air valve.

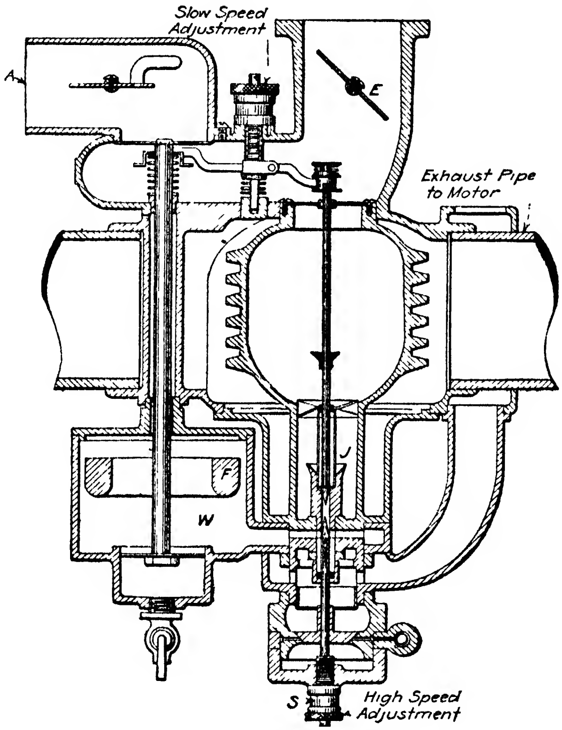


FIG. 216.—Kerosene carburetor.

IGNITION SYSTEMS

For igniting the fuel charge in an internal-combustion engine, two methods are employed: the electric spark, which is most commonly used, and the automatic ignition system, which is produced by the heat to which the air or the mixture of air and fuel in the cylinder is subjected.

In some of the older but now obsolete makes of engines, the hot-tube system is employed. The tube, open at one end and closed at the other, is made of porcelain or of some nickel alloy. The closed end of the tube is heated by a Bunsen burner. During the compression stroke, a portion of the mixture is forced into the tube and is ignited by the hot walls. The walls of the tube are then kept hot by heat caused from the explosions. Low first cost and low upkeep are the only points in favor of this system, but they are more than offset by the difficulty in regulating the time of ignition.

Electric Ignition Systems.—Two electric ignition systems are in use, the make-and-break and the jump-spark. In the case of the make-and-break system, the spark is similar to that produced when one electric wire connected to a battery is drawn across another, or to the spark produced by the opening of a switch. The spark in this system is produced by the contact and quick separation of metallic points located within the clearance space of the cylinder. In the jump-spark system, a current of high voltage is used which jumps across a small air gap within the clearance space of the cylinder.

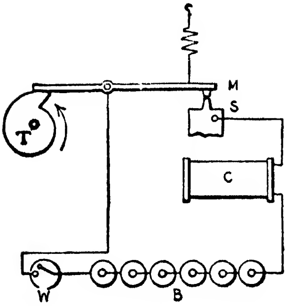


Fig. 217.—Make-and-break ignition system.

The Make-and-break System of Ignition.—The principle of the make-and-break system of ignition is illustrated in Fig. 217. *B* is the battery which supplies the electric current for ignition. *C* is an inductance spark coil, often called a kick coil. It consists of a bundle of soft iron wires, called the core, surrounded by many turns of insulated copper wire through which the current passes. On account of the inductive action of such a coil, the spark is greatly intensified, producing a strong arc from a battery of low voltage. *S* is a stationary electrode well insulated from the engine, and *M* a movable electrode not insulated from the engine. Both electrodes are set in the combustion space of the cylinder.

The contact points of the two electrodes are brought together by means of the cam *T* operated by the valve-gear shaft of the engine. When the switch *W* is closed, current will flow through the circuit as soon as the contact points of the electrodes are brought together by the cam *T*. A sudden breaking of the contact, aided by a spring, causes a spark to pass between the points which ignites the mixture. The more rapidly the electrodes are separated the better is the spark produced.

The contact between the two electrodes of the make-and-break system may also be made by sliding one contact point over the other. This type is known as the wipe-spark igniter and is illustrated in Fig. 218. *B* is the stationary insulated electrode and *A* is the movable electrode. *B* is made in the form of a spring and may be moved toward the electrode *A* by means of a screw. The wiping action of this igniter keeps the points clean at all times.

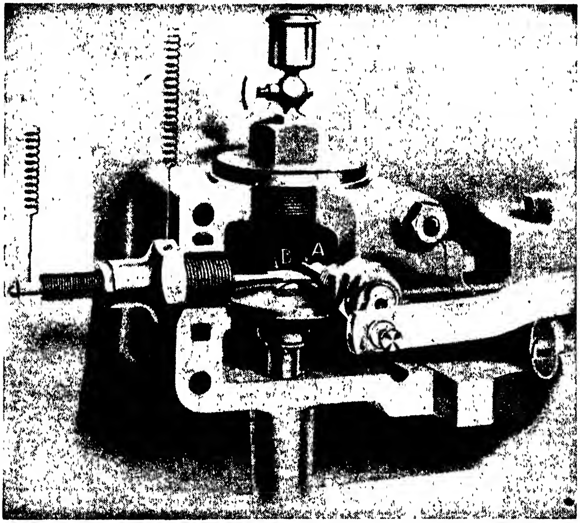


Fig. 218.—Wipe-spark igniter.

Figure 219 illustrates the hammer-break igniter. *M* is the movable and *S* the stationary insulated electrode. The points are rapidly separated by a sort of hammer blow furnished by the action of the springs on the end of the movable electrode. The hammer-break igniter is more commonly used than the wipe-spark on account of the easier adjustment and less wear of the contact points.

The Jump-spark System of Ignition.—The principle of the jump-spark system is illustrated in Fig. 220. *A* is a spark plug, the points *E* and *F* of which project into the cylinder. These points are stationary, are insulated from each other, and are separated by an air gap of about $\frac{1}{32}$ in. When the switch *W* is closed, the current from the battery *B* flows through the timer *T*, which completes the circuit at the proper time, through the induction coil *I*. The induced high-voltage current produces a spark at the gap of the spark plug, igniting the explosive mixture in the cylinder.

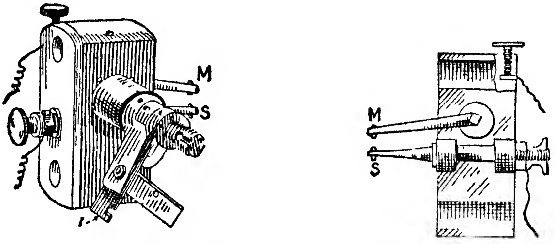


FIG. 219.—Hammer-break igniter.

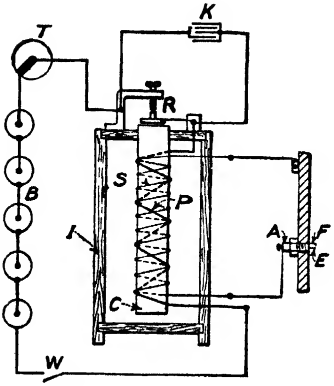


FIG. 220.—Jump-spark ignition system.

The induction coil *I* (Fig. 220) differs from the inductance coil used in connection with the make-and-break system of ignition (Fig 217), in that there are two layers of insulated copper wire wound around the soft wire core of the induction coil, whereas in the inductance coil there is only one winding, the primary. The winding immediately surrounding the core consists of several turns of fairly large insulated copper wire and is known as the primary winding. The outside winding is known as the secondary and consists of a large number of turns of very fine insulated wire. It is wound over the primary without any metallic connections. In some cases, a common end or terminal is used, in which case this terminal is grounded, thereby eliminating one ground wire.

The primary current must be broken or interrupted in order to induce a current in the secondary winding. In the common form of induction coil, this is done by means of a vibrator, sometimes called an interrupter. The function of the vibrator is to break the primary circuit with great rapidity, thereby inducing a high-voltage alternating current in the secondary winding. This results in a series of sparks at the air gap of the spark plug.

An electric condenser *K* is made use of to prevent the burning of the vibrator points. It consists of alternate layers of tin foil and some insulating material such as paraffined paper and is connected across the vibrator points. In addition to preventing sparking at the vibrator points, the condenser absorbs the excess current at the primary winding and again gives it up at the proper time to increase the intensity of the spark.

The induction coil, consisting of all the parts mentioned, is usually placed in one box and the space between the parts is filled with some insulating material such as wax or paraffin, in order to protect the parts from moisture.

In some cases, the primary circuit is broken by some mechanical means, thereby eliminating the vibrator. One vibrator, known as a master vibrator, is sometimes used to break the circuit for several coils. In either of the last two cases mentioned, the non-vibrator type of induction coil is used.

The current from the battery *B* (Fig. 220) enters the primary circuit *P* through the timer *T* and the vibrator *R*. The other end of the primary is connected through a ground with the other terminal of the battery, thereby completing this circuit. As the current flows, it magnetizes the soft iron core *C*. The magnetized core immediately attracts the steel spring of the vibrator and thereby breaks the primary circuit. The core *C*, being of soft wire, immediately loses its magnetism and the spring *R* is released ready again to complete the primary circuit. This vibrating action induces a high-voltage current in the secondary winding *S*, one end of which is connected to a ground and the other to the center post of the spark plug. The circuit is then complete with the exception of an air gap of approximately $\frac{1}{32}$ in.

at the spark-plug points, across which the current jumps producing a series of sparks which ignite the charge.

A spark plug, such as is illustrated in Fig. 221, is used with the jump-spark system. It consists of two well-insulated metallic points. The central point is connected to a binding post which receives the current from the secondary or high-tension winding of the induction coil. The other point is about $\frac{1}{32}$ in. distant from the first and is separated from it by an air gap. The second point is grounded through the thread of the plug to the engine frame. The insulating materials used in the spark plugs are mica, porcelain, and stone. The plugs are well insulated except at the air gap.

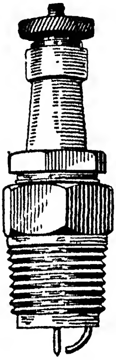


Fig. 221.—Spark plug

Comparison of the Two Systems of Electric Ignition.—The jump-spark system is much more simple mechanically, as it has no moving parts inside the cylinder. The make-and-break system is more simple electrically, requires less care in wiring, does not have to be insulated so carefully, and the spark is more certain. It is difficult to lubricate the many parts of the make-and-break system. The make-and-break system is usually used on stationary slow-speed engines and to some extent on tractors. The jump-spark system is better adapted for high-speed and multiple-cylinder engines than is the make-and-break, and is used on automobiles, tractors, trucks, small stationary engines, marine engines, and airplanes.

Source of Current for Make-and-break, and Jump-spark Systems.—The electric current for producing the spark in the make-and-break system may be obtained from a primary battery of dry or wet cells, from a storage battery, low-voltage dynamo, or from a low-tension magneto. The current for the jump-spark system may be obtained from any of the above sources or from a high-tension magneto. In the latter case, the induction coil is a part of the magneto.

Either system requires a source with about 6 volts pressure. In case of a battery, this may be obtained by connecting in series four to eight dry cells, or three to four storage battery cells.

Electric Batteries.—Batteries are of two types; one type called the primary battery generates electrical current by means of direct chemical action between certain substances; another type—called a secondary battery, or storage battery—requires charging with electricity from some outside electrical source before it will generate electrical energy. The active materials in the primary battery when once exhausted cannot be brought back to generate electricity and must be renewed, while in the storage battery the active materials can be used over and over again.

The term "battery" is applied to two or more cells, whether primary or storage types, when they are connected together to increase the total amount of electrical energy delivered to a circuit.

Primary Batteries.—A primary cell (Fig. 222) consists essentially of a vessel containing some acid called the electrolyte, in which are immersed two solid conductors of electricity, called electrodes, one of which is more easily attacked by the acid than the other. A simple cell consists of a weak solution of sulphuric acid, as an electrolyte, a plate of zinc, which is easily decomposed by the sulphuric acid, and a plate of some other solid like copper or carbon which resists the action of sulphuric acid. If the plates of zinc and of copper are put side by side in a vessel containing sulphuric acid, and the circuit is completed by joining the two plates with a wire, chemical action will be set up with the vessel or cell, and a current of electricity will be generated.

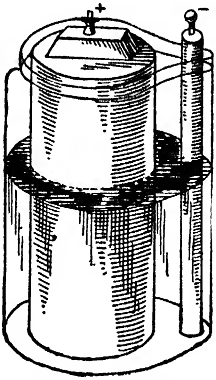


Fig. 222. Wet primary cell.

The dry cell, which is used extensively at the present time on account of its portability, is a modification of the cell illustrated in Fig. 222. It has zinc for the negative electrode, carbon for the positive electrode, sal ammoniac and zinc chloride as the electrolyte for decomposing the zinc, and some oxidizing agent like manganese dioxide to eliminate polarization. The solution in the dry cell evaporates slowly, so that it will become worthless after a time, even if not used. Generally, a dry cell in good condition will have a current strength of 15 to 25 amp. and should show a pressure of 1¼ to 1½ volts. A binding post is attached to the carbon and another one to the edge of the zinc cylinder.

Storage Batteries.—A storage battery consists of two sets of plates or electrodes known, respectively, as positive and negative, submerged in a liquid called the electrolyte. The plates are encased in a jar or container. This type of battery must be charged frequently with electricity, in order that it may continue to give out current to the external circuit. The storage battery does not store electricity. It stores energy in the form of chemical work. The electrical current produces chemical changes in the battery and these allow a current to flow in the opposite direction when the circuit is closed.

Storage batteries are used for gas-engine ignition and are preferred for this purpose to primary dry or wet batteries, on account of their greater capacity and more uniform voltage. Modern automobiles also employ storage batteries for starting, lighting, and ignition

The capacity of a storage battery is measured in ampere-hours, determined by multiplying the current rate of discharge by the number of hours of discharge of which the battery is capable at that rate. As an illustration, a battery that will deliver 10 amp. for 8 hr has a capacity of 80 amp.-hr. The ampere-hour capacity of a storage battery is dependent upon the rate of discharge. Most manufacturers specify the rate of discharge for their particular make of storage batteries. If the rate of discharge is greater than the specified amount, the capacity of the battery is reduced. As an illustration, if a storage battery has a capacity of 80 amp.-hr., at the 10-amp. rate, it will have a greater ampere-hour capacity if discharged at a 5-amp. rate; that is, it will deliver a current of 5 amp. for more than 16 hr. The normal rate of discharge is the 8-hr. period.

A storage battery can be charged from any direct-current circuit, provided the voltage of the charging circuit is greater than that of the storage battery when fully charged. Before a storage battery is connected to the charging circuit, its polarity should be carefully determined, and the positive and negative terminals of the battery connected to the positive and negative terminals, respectively, of the source. One good method of determining the polarity of the wires from the storage battery or source is to immerse them in salt water. Bubbles of gas will form more rapidly on the surface of the negative wire. Another test is that the negative wire will turn blue litmus paper red. Should the positive wire of the battery be connected to the negative wire of the source, the effect would be a discharge of the battery, and this being assisted by the incoming current, a reversal of action would take place. This is very injurious to the battery. It is not well to charge a battery at a too rapid rate, as this will raise its temperature and will cause buckling of the battery plates. It is well also to charge batteries at regular intervals.

Two types of storage batteries are used—the lead storage battery and the Edison. The Edison battery is also called the alkaline or nickel-iron battery.

The Lead Storage Battery.—The lead storage battery (Fig. 223) is the type used almost exclusively in connection with the modern motor propelled vehicles. In this battery, both the positive and the negative plates are built upon lead grids. The perforations in the positive grid are filled with a lead compound (PbO_2) which may be distinguished by its brown color. The perforations in the negative grid are filled with spongy metallic lead which has a dull-gray color. The positive plates are all united to a common positive terminal and the negative plates are all united to a common negative terminal.

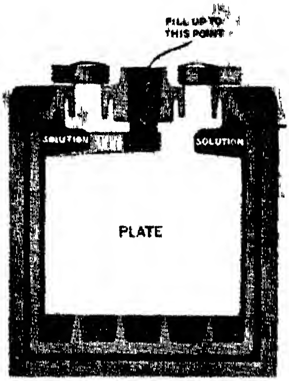


Fig. 223.—Cross-section through lead storage battery.

A lead storage cell, when fully charged, will show 2.2 to 2.5 volts on open circuit and about 2.15 volts when the circuit is closed. A lead storage battery should not be allowed to discharge to a voltage lower than 1.8 volts while giving its full rated current. For ignition purposes, 6- and 12-volt systems are employed.

For successful operation and long life, storage batteries should be tested frequently with a pocket voltmeter for voltage, and with a hydrometer for the specific gravity of the electrolyte. The specific gravity of the electrolyte of a stationary battery should be 1.17 to 1.22 when the battery is fully charged. A portable battery should have a greater specific gravity, from 1.275 to 1.300

when fully charged. Pure distilled water must be added occasionally to the electrolyte to make up for the evaporation. The electrolyte should be ¼ to ½ in. above the plates.

Ignition Dynamos.—An ignition dynamo is a miniature direct-current generator. It has electromagnets as field magnets and is usually of the iron-clad type. In using an ignition dynamo, the internal-combustion engine must be started on batteries, as the speed developed when turning the engine by hand is insufficient to produce a spark of sufficient intensity by the dynamo. As soon as the engine speeds up, the battery current is thrown off and the spark is supplied by the ignition dynamo. Most ignition dynamos will supply a spark of sufficient intensity for a make-and-break system of ignition without an inductance coil.

Magnetos.—The magneto differs from the ignition dynamo in that its magnetic fields are permanent magnets. For this reason, it is unnecessary to run the magneto for any length of time in order to build up its field. Magnetos can be run in any direction and at any speed. Magnetos can be classed under two general heads:

1. Low-tension magnetos which are used in place of batteries or of batteries and inductance coils.
2. High-tension magnetos which generate sufficient voltage to jump the gap of a spark plug.

Low-tension Magnetos.—The low-tension magneto may be of the direct-current type, in which case it differs from the ignition dynamo in that the magnetic field is a permanent magnet; or may be an alternating-current magneto. The alternating-current magnetos are generally used.

Figure 224 represents a simple type of alternating-current, low-frequency magneto. It is used chiefly for the make-and-break system of ignition and takes the place of the battery and inductance coil.

The magneto illustrated in Fig. 225 is also a low-tension, alternating-current magneto, differing from the preceding one in that it has a circuit breaker and a distributor. This magneto can be used for a jump-spark ignition system when used with a non-vibrating induction coil.

The distributor is made use of in case of multi-cylinder engines. The function of the distributor is to send the current to the right cylinder at the proper time. The circuit breaker, or interrupter, takes the place of the vibrator in the induction coil and mechanically breaks the primary circuit, thereby inducing a high-voltage current in the secondary circuit. The distributor is timed with the circuit breaker and the circuit breaker is timed with the engine, so that the hottest spark takes place at the time of ignition.

Inductor Type of Magneto.—In all of the magnetos previously mentioned, the armature carried the winding and has been the revolving or rotating part. In the inductor type of magneto, the winding and the field magnets are stationary, and the revolving part, which turns between the pole pieces, is made up of a steel shaft upon which are mounted laminated iron inductors. By laminated parts are meant those made up of punchings of sheet iron placed side by side.

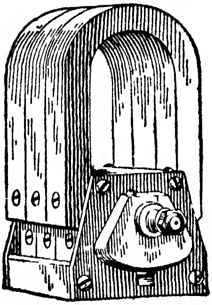


FIG. 224.—Low-tension magneto.

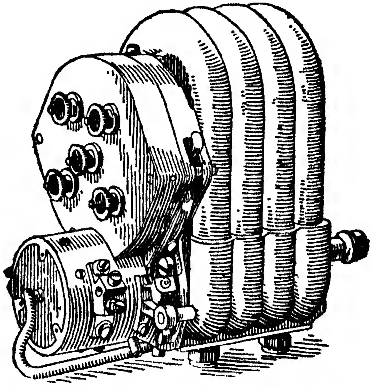


FIG. 225.—Low-tension magneto with circuit breaker and distributor.

In the inductor type of magneto, all moving wires, carbon brushes, and collector rings are eliminated. It is possible to have inductor type of magnetos in connection with any type of ignition on which magnetos are used. The oscillating magneto is one of the inductor type and is most commonly used with the make-and-break system of ignition. This magneto gets its name from the fact that the moving part does not revolve through a complete circle, but merely oscillates through a very few degrees. The rapid separation of the points is caused by strong springs attached to the arms situated near the end of the rotor shaft As the spring snaps the inductor back, the current is generated, and at the same time the igniter points within the cylinder are very quickly separated, producing the spark.

High-tension Magnetos.—A high-tension magneto differs from a low-tension magneto in that it can generate a high-voltage current without the aid of an induction coil. Figure 226 illustrates a high-tension magneto circuit diagram for a six-cylinder engine. Both the primary and secondary windings are wound on the same core. In the armature type, both windings are on the armature and revolve with it, while in the inductor type, both primary and secondary windings are on the stationary coil between the pole pieces.

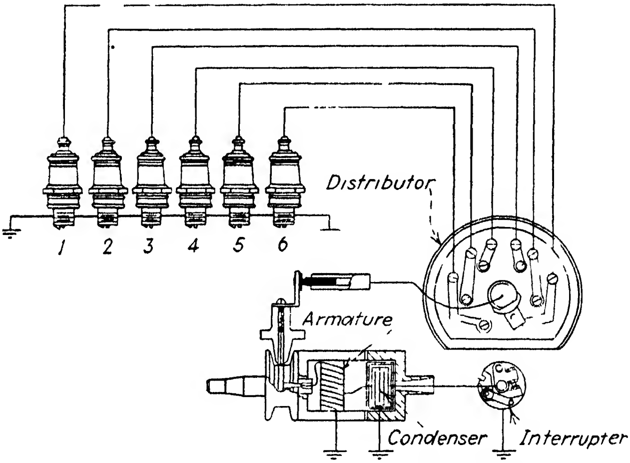


FIG. 226.—Circuit diagram of Bosch type magneto.

In the armature type, the armature carries a primary winding of a few turns of fairly large insulated copper wire and a large number of turns of very fine insulated copper wire. The condenser is also carried in the armature. The interrupter or circuit breaker of a high-tension magneto is usually mounted on the end of the armature shaft and revolves with it. The high-tension current is taken from the armature by a brush and collector ring. The interrupter also acts as a timer and breaks the primary circuit at the proper time. This breaking of the primary circuit induces a high-voltage current in the secondary exactly in the same manner as the vibrator did in the induction coil, previously discussed.

Due to the fact that the windings are revolving, there is a generative as well as an inductive effect. This generative effect prolongs the duration of the spark which would be of very short duration with the inductive effect alone. The cams must be so arranged that the primary is broken at approximately the time when the voltage is at a maximum, which is when the armature core is removed from the field.

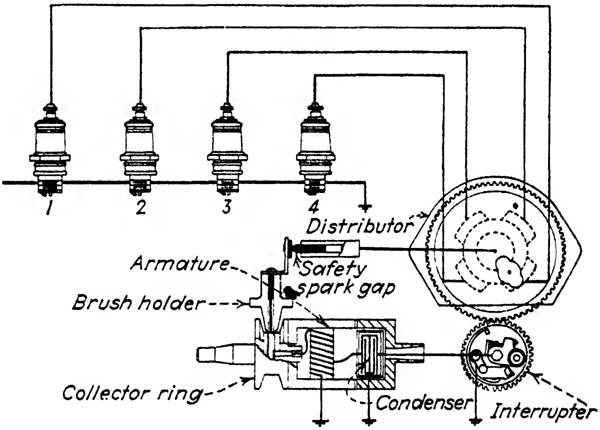


Fig. 227.—Circuit diagram for a high-tension magneto.

A safety gap is provided in high-tension magnetos to protect the secondary winding. This is simply an air gap across which the current may jump in case of a break in the secondary winding. Without the safety gap, the insulation of the secondary would be in danger of being punctured by the high-voltage current, in case of a break or loose connection.

If more than one cylinder is to be served, a high-tension magneto carries a distributor which distributes the current to the proper cylinder, as indicated in Fig. 226.

Figure 227 illustrates a circuit diagram of a high-tension magneto for a four-cylinder engine.

Timer and Distributor Systems.—With multiple-cylinder engines, a timer is often used in connection with vibrating induction coils. The function of the timer is to complete the primary circuit at the proper time for each cylinder, thereby causing the vibrator to function, resulting in a hot spark at the spark plug. One type of timer, illustrated in Fig. 228, is used on a four-cylinder engine. *E* represents the segments in the housing *S*. These segments are electrically insulated from each other with fiber or some other insulating material. *R* is the revolving arm for closing the circuit at the proper time.

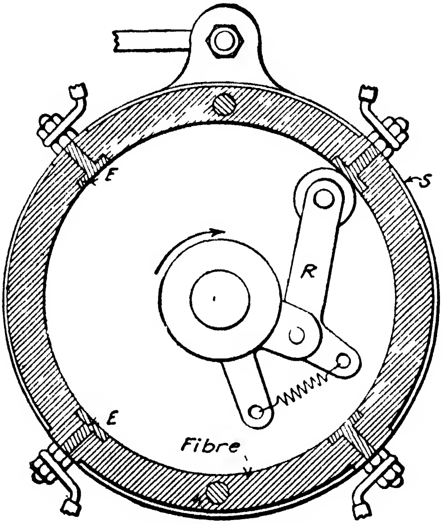


FIG. 228.—Timer.

The distributor system of ignition is very common practice on multiple-cylinder, high-speed engines. In this system, the distributor and circuit breaker are mounted on one shaft. This shaft has projections or in some cases indentations equally spaced and corresponding to the number of cylinders to be served. These projections or indentations act as cams for interrupting the primary circuit. A condenser is usually placed across the breaker points, to prevent sparking at the points. In connection with this system, a non-vibrating induction coil is usually used. One end of the secondary is usually grounded, while the other leads to the center post of the distributor. The distributor then conducts the secondary to the proper cylinder at the proper time.

Figure 229 represents a high-tension distributor system employing a timer and vibrating induction coil.

In most distributor systems, a circuit breaker takes the place of both timer and vibrator, so that a non-vibrating induction coil can be used.

GOVERNORS

Every internal-combustion engine must be provided with a governor, in order that its speed may be kept constant as the power developed by the engine varies. Stationary engines are usually mechanically regulated, the governor being operated by the speed variations of the engine. Motor vehicles are generally hand-governed, but are often equipped with a limit governor to prevent overspeeding. The speed regulation of internal-combustion engines is accomplished by one of the following methods: hit-and-miss system, varying the quality of the mixture, varying the quantity of the mixture, varying the time of ignition, and combination systems.

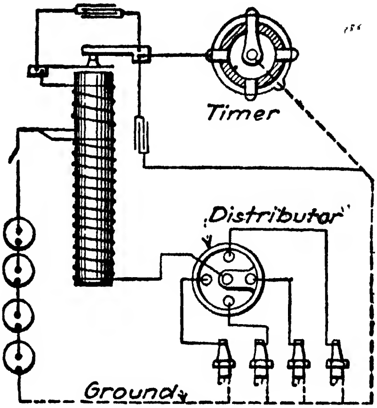


FIG 229.—High-tension distributor system

Hit-and-miss Governing.—In this system, the number of explosions is varied according to the load of the engine. When the engine is running at full load, the explosions follow each other in regular order until the speed has increased enough above the normal to cause the governor to act, preventing the drawing in of the next charge, thus missing an explosion. This is followed by the slowing down of the engine, which causes the explosions to recur.

The hit-and-miss system can be carried out in several ways, depending upon the valve gear of the engine.

In the case of small engines, where the inlet valve is operated automatically by the suction of the piston, the governor acts by keeping the exhaust valve open, thus preventing the spring-loaded inlet valve from opening.

When the inlet valve is mechanically operated from the valve-gear shaft, the governor acts directly on the inlet valve by withdrawing a trigger, called a pick blade, or a cam roller in the valve-actuating mechanism, thus preventing the admission of a new charge at light loads.

The hit-and-miss system can also be operated by keeping the fuel valve closed, so that the engine draws in only air at light loads.

The governor proper in connection with the hit-and-miss system is usually some form of fly-ball governor.

The hit-and-miss system of governing is very simple and gives good fuel economy at variable loads. As the explosions in the engine cylinder do not occur at regular intervals, this system of governing necessitates the use of very heavy flywheels in order to keep the speed fluctuations within practical limits. The hit-and-miss system is satisfactory for small engines where close speed regulation is not essential, but is not practical in connection with engines which must operate at nearly constant speed.

Quality Governing.—In this system, the number of explosions per minute and the quantity of the mixture admitted to the cylinder remain constant, but the quality of the mixture, that is, the ratio of fuel to air, is varied according to the load. This is accomplished either by the governor controlling a throttle or a cut-off valve in the gas supply pipe. The inlet valve which admits the mixture to the engine cylinder opens under all load conditions to its full lift, admitting to the cylinder a mixture of the same volume at different loads. The governor controls both the air and gas openings, increasing the air supply at light loads in the same proportion as the amount of gas is decreased.

This method of governing retains the same compression pressure at all loads, but the fuel economy decreases very rapidly as the load drops, as weak mixtures are difficult to ignite and are slow burning.

Quantity Governing.—In the quantity-governing system, the proportion of air to fuel remains constant, but the speed regulation is accomplished by altering the quantity of the charge admited to the cylinder at variable loads. This system of governing can be carried out by the use of a butterfly valve under the control of the governor, which throttles the charge in a manner similar to the throttling steam engine. By another method, called the cut-off method, the inlet valve is held open only during a portion of the suction stroke, and is suddenly closed at a point determined by the governor and suitable to the load. The cut-off method of quantity governing is similar in its action to the governor in connection with automatic cut-off steam engines, such as the Corliss.

Combination Systems.—A combination of the hit-and-miss and the throttling-regulating systems has been tried. The throttling constant quantity system is used for loads above one-half the rated load of the engine, whereas the hit-and-miss system is employed for loads below one-half. Another combination governor uses quality governing at heavy loads and quantity governing at light loads. These combination systems have been designed to utilize the advantages of the several systems, but are complicated and are used only in special cases.

MUFFLERS

An exhaust muffler is generally used to silence the noise incidental to the escape into the air of the exhaust gases from an internal-combustion engine. In some installations, mufflers are also used for the air intakes of large engines.

Exhaust mufflers vary greatly in design, but are intended to silence the exhaust noise by reducing the velocity of the exhaust gases to a minimum, without appreciably increasing the back pressure.

In some cases, the muffler is an enlarged exhaust pipe or a vessel of suitable volume to permit the gradual expansion of the exhaust gases. Some mufflers are provided with baffles and other obstructions to reduce the velocity of the exhaust gases. In other cases, sprays of water have been employed in connection with mufflers, to reduce the velocity of the gases by cooling. The use of water is effective, but should not be employed if the exhaust gases contain sulphur compounds.

A muffler should have sufficient volume in order to throw little back pressure on the engine, should be strong enough to stand the strain of an explosion, which may result from the presence of unburned gases in the exhaust, and should be constructed so that it can be readily taken apart for inspection, cleaning, and repair.

The exhaust gases from an internal-combustion engine should never be allowed to escape into a chimney or into a sewer, as an explosion due to the accumulation of unburned gases may occur at any time.

Problems

1. Examine some float-feed carburetor and hand in report showing how these carburetors differ from those described in the text. Clear sketches, showing fundamental details of construction, should accompany report.
2. Examine some magneto and hand in a report which will illustrate and explain its construction.
3. Show by means of clear sketches the details of a hit-and-miss governor and also of a governor of the throttling type.
4. Examine the lubricators in use on various stationary internal-combustion engines and report in which respects these differ from lubricators for steam engines.
5. Make clear sketches of mufflers suitable for small and for large stationary internal-combustion engines.
6. Give directions for determining whether a battery is fully charged.
7. To prevent a battery from being ruined by freezing what should it test for safety at 20° below zero, Fahrenheit?
8. Prepare an ignition diagram for some type of an eight-cylinder automobile engine.

CHAPTER XV

GAS POWER PLANT TESTING

The testing of internal-combustion engines operating upon gaseous or liquid fuels is similar to the testing of steam engines, at least in the more important details. The heat supplied to the engine by the fuel and the delivered power are the two main points to be investigated. Indicator cards may be used to determine the inner workings of the cylinder and in measuring the indicated horsepower. The amount of heat absorbed by the jacket water can be determined by weighing the amount of water passing through the jacket and taking the temperature of the inlet and outlet water.

Measurement of Fuel Used.—When the fuel used is in a gaseous state, the volume used is usually measured by some form of gas meter. Most commercial meters give a fair degree of accuracy, but they should be calibrated under the conditions to which they are subjected during the test. Venturi meters (Chap. XI) are used when the volume of the gas to be measured is large.

When liquid fuels are used, the amount supplied to the engine is best measured by means of small platform scales. One method consists in placing a supply tank or reservoir upon the scales, using a flexible connection from the tank to the carburetor. The difference in the weight of the fuel at the beginning and at the end of the test gives a direct measure of the quantity of fuel used. The flexible connection between the tank and engine is best made of flexible metallic tubing having no rubber insertions. Rubber tubing is acted upon by petroleum fuels and is soon destroyed.

Many internal-combustion engines are equipped with an overflow type of carburetor, in which a constant quantity of fuel is maintained in the carburetor by supplying a larger quantity of fuel than is necessary, while the excess is drained through an overflow pipe. ·In this case, the method of weighing the fuel is much the same as that just explained, with the exception that the fuel from the overflow is collected in a separate vessel and is either returned to the main fuel tank before the final weighing at the end of the test or is weighed separately and the amount deducted from the weight as determined from the main tank.

Instead of measuring the fuel by weighing, measurements by volume are sometimes used. In that case, a cylindrical vessel of small diameter is equipped with a gage glass. The vessel is calibrated by filling the tank to various heights and by determining the corresponding weight of fuel per inch of height. The fuel supplied to the engine during the test is then indirectly measured by noting the difference of the fuel level in inches and converting it into pounds from the calibration data. Such a method is not considered accurate, because of the change of volume of the fuel with the change of temperature. For accurate results, the method of direct weights should be used.

Heat Consumption of the Engine.—The heat consumption of the engine, or the heat supplied by the fuel, is found in the case of gaseous fuels by multiplying the heat of combustion of 1 cu. ft. of the fuel, as determined by calorimeter test (Fig. 208), by the volume of the gas consumed in cubic feet. For liquid fuels, the heat consumption is equal to British thermal units per pound of fuel multiplied by the weight of fuel used in pounds.

Brake Horsepower.—The brake horsepower, or the delivered horsepower, of an internal-combustion engine is usually measured by means of a Prony brake. Other types of dynamometers, as explained in the measurement of the delivered power of the steam engine (Chap. XI) could also be used.

When a Prony brake is used, the power is calculated by the formula:

$$\text{Brake horsepower} = \frac{2\pi lwn}{33{,}000} \qquad (66)$$

π = 3.1416.
l = length of brake arm in feet.
w = net weight of brake arm on the scale.
n = number of revolutions per minute.

Indicated Horsepower.—The indicated horsepower of an internal-combustion engine is measured in practically the same manner as in the case of steam engines, but with the following differences: Ordinary types of steam-engine indicators are not well adapted to the testing of gas engines. The pressures exerted in the gas-engine cylinder are usually higher than those common in steam engines and are more suddenly applied. In order to withstand these stresses, the steam-engine indicator would have to be equipped with a comparatively strong spring. The piston of the gas-engine indicator is usually made one-half the area of that of the steam-engine indicator piston and the springs are interchangeable. Thus, a 100-lb. steam indicator spring when used with a gas-engine indicator would produce a 1 in. vertical movement of the pencil for a pressure of 200 lb.

In calculating the indicated horsepower, it must be remembered that the complete cycle is not produced at every revolution, and it is the number of explosions rather than the number of revolutions that determines the horsepower.

The formula for calculating the indicated horsepower becomes:

$$\text{Indicated horsepower} = \frac{plae}{33{,}000} \tag{67}$$

in which p = mean effective pressure in pounds per square inch as determined from the indicator card.
l = length of the engine stroke in feet.
a = area of the piston in square inches.
e = number of explosions per minute.

The Measurement of the Heat Absorbed by the Jacket Water. The heat absorbed by the jacket water is calculated by the formula:

$$W(t_2 - t_1) \tag{68}$$

in which W = the weight of water passing through the jacket in a unit of time.
t_2 = the temperature of water discharged from the jacket.
t_1 = the temperature of the inlet water to the jacket.

The weight of the jacket water is best measured by the use of one or more tanks placed upon platform scales. During the test, these tanks are alternately filled, weighed, and emptied.

Duration of Test.—When the load upon a gas or oil engine is nearly constant, and can be maintained so for an appreciable period, the duration of the test need not be more than about one hour. When the load fluctuates, longer periods are necessary for accurate results.

Starting the Test.—Before starting a test upon a gas or oil engine, sufficient time should be allowed for conditions to become constant. The engine should be operated at the prescribed load until all parts are thoroughly heated. At a certain predetermined time the test is started and the regular measurements and observations are made until the test is closed.

Gas-producer Testing.—To ascertain the efficiency of a gas producer, the following data must be obtained: the quantity of fuel used, the amount of gas generated, the heat of combustion of the fuel, and the heat of combustion of the gas.

The heat of combustion of the fuel and of the gas can be determined by means of the calorimeters explained in Chaps. III and XIII, respectively.

To determine the amount of fuel used, the length of the test should be such that the total consumption of the fuel should be at least ten times the weight of fuel contained in the producer during normal operation. Producer tests of short duration are inaccurate. The fuel used is weighed on platform scales.

The amount of gas generated is determined by means of a Venturi meter, Pitot tube, or some other gas meter of special design.

In a complete test, the amount of power required for driving the fans and other auxiliaries is determined, as well as the amount of steam used and the final purity of the gas.

A. S. M. E. Code.—Complete and more detailed instruction concerning the testing of gas power plants will be found in the *Rules for Conducting Performance Tests of Power Plant Apparatus*, published by the American Society of Mechanical Engineers.

Problems

1. Prepare a table which will show the economies per brake horsepower per hour of gas engines using gasoline and oil as a fuel. If possible, add to this the economies of gas engines using blast-furnace, natural, and producer gas as a fuel.

2. Compare the heat consumption in British thermal units of the following engines per brake horsepower per hour:
  (*a*) Gasoline engine which delivers a brake horsepower per hour for $\frac{1}{10}$ gal. of gasoline.
  (*b*) Producer-gas plant which consumes $1\frac{1}{2}$ lb. of anthracite coal per brake horsepower per hour.
  (*c*) Diesel oil engine which consumes 0.47 lb. of crude oil per brake horsepower per hour.
  (*d*) Alcohol engine which consumes 1 lb. of alcohol per brake horsepower per hour.

3. Compile from the Power Test Code of the American Society of Mechanical Engineers a table suitable for taking data in connection with a complete test of a gasoline or gas engine.

4. Compile from the Power Test Code of the American Society of Mechanical Engineers a table suitable for taking data in connection with a complete test of a gas producer.

5. In which respects do engine indicators for high-speed internal-combustion motors differ from those for steam engines?

CHAPTER XVI

MECHANICAL POWER IN TRANSPORTATION

THE STEAM LOCOMOTIVE

During recent years statements have been made in the public press which lead to the belief that the modern steam locomotive, even if important, is rapidly losing its vitality, that it is inefficient, that it has reached a stage of development where further improvement cannot be made, and that this type of prime mover cannot meet practically and economically the traffic and speed conditions of today. The above statements are not borne out as indicated by the following facts:

Type of service	Number	Aggregate tractive effort, pounds
Freight locomotives	28,493	1,561,490,571
Passenger locomotives	8,238	301,428,625
Switch locomotives	8,448	336,395,866
Total	45,179	2,199,315,062

From 1904 to 1935 the weight of the best locomotives per indicated horsepower has been cut in two, or more accurately, the weight has been reduced per indicated horsepower from 187 to 93.4 lb. During the same period the thermal efficiency, or the percentage of the heat energy of the coal burned that reaches the drawbar of the locomotive tender in the form of useful work, has been more than doubled; the average thermal efficiency in 1904 was about 3 per cent and at the end of 1935 between 7 and 8 per cent. From 1910 to 1930 the coal consumption per drawbar horsepower was reduced by 40 per cent. The coal consumption in freight service in 1931 was 27 per cent better than in 1922; during the same period the fuel economy in passenger service was improved by 19 per cent.

The Association of American Railroads reports for February, 1936, a total of 45,179 locomotives for Class I railroads. This figure includes all types (steam, electric, and Diesel) and is made up of the classes shown in the table on page 322.

Included in the above classification are the following data about electric and Diesel locomotives:

Type of service	Electric		Diesel	
	Number	Aggregate tractive effort	Number	Aggregate tractive effort
Freight	295	20,459,656	3	112,750
Passenger	348	20,408,182	6	272,800
Switch	126	5,185,450	127	6,776,304
Total	769	46,053,288	136	7,161,854

The Locomotive Compared with the Stationary Steam Power Plant.—On account of requirements which must be met in each case, the locomotive and the stationary steam power plant differ in construction. The stationary power plant has practically unlimited space available. The locomotive is limited in width by the gage of the track, and by the clearance required for station platforms and passing trains; it is restricted in height by the clearance of bridges and tunnels; the sharpness of the curves limit its length, and its weight is practically fixed by the strength of bridges and by the type of roadbed. To develop the variable power demands to which locomotives are subjected, the boiler must contain ample heating surface and at the same time must occupy small space. The rate of combustion must be forced to the extreme, as the grate surface is limited in width by the allowable road clearance and in length by the distance a fireman can spread the coal. In stationary plants, 10 to 20 lb. of coal are ordinarily burned per square foot of grate surface when operated with natural draft; in locomotive practice, by the use of artificial draft, 150 lb. or more are usually burned per square foot of grate surface.

Space limitations on locomotives prohibit the use of fans or of high stacks for the production of draft, and an induced draft created by the exhaust steam must be used. This practice prevents the operation of the engine condensing and makes difficult the use of the exhaust steam in connection with feed-water heaters.

The Essential Parts of a Locomotive. The essential parts of a locomotive are illustrated in Fig. 230. The boiler (1) consists of a cylindrical shell, closed at its two ends by tube plates which are connected below the water level by numerous fire tubes (3).

The furnace, or fire box (2), is an extension of the boiler shell, the sides of which extend downward, forming a chamber surrounded at the top and at the bottom by water. The bottom of the fire box is fitted with a grate (24) upon which the fuel is burned. Below the grate is an ash pan (28), which retains the ash until such a time as it may be removed. An opening at the back of the fire box serves as a fire door (23).

The furnace gases pass through the fire tubes and enter the front end or smoke box (4). In entering the smoke box, the gases are deflected downward by the diaphragm or deflector plate, thence through the spark-arrester netting (15), after which they mingle with the exhaust steam entering the smoke box from the exhaust pipe (11), and pass out the stack (5). Accumulation of cinders is removed from the smoke box through the spark chute (12), cleaning tools being inserted through the spark-cleaning hole (13). Access to the smoke box is made through the door (17), or the entire smoke-box cover (16) may be removed.

Practically all front ends now in use are known as "self-cleaning." Most of the cinders pass out through the stack, leaving only a small amount below the door (17).

Steam from the boiler enters the steam dome (6) from which it passes to the engine cylinder. The throttle lever (8), which controls the valve in the throttle chamber (7), is used to regulate the quantity of steam entering the cylinder.

The steam after passing through the throttle valve enters the dry pipe (9), which passes through the steam space and absorbs a certain amount of heat from the steam with which it is in contact. Upon reaching the smoke box, the dry pipe terminates in a tee from which two steam pipes (10) are used to direct the steam into the two cylinders.

The two cylinders are on the opposite sides of the locomotive and the cranks are separated 90 deg. Considering only one cylinder, the steam enters through the valve (36) and after performing its function it passes through the exhaust pipe (11) and is further utilized in creating the draft. When the engine is running, the exhaust causes a constant movement of air through the furnace and tubes.

The reversing of the engine, as illustrated in Fig. 230, is accomplished by the use of the Walschaert valve gear (see Chap. VIII). The reversing lever (54) is located in the engine cab. The valve gear shown differs from that illustrated in Chap. VIII in that it has inside admission valves. The reach rod (55) connects the radius rod (49), thus giving a means for controlling the position of the link block with respect to the link (48) and thereby controlling the position of the valves and the direction of the engine. The motion of the link is obtained from the eccentric crank arm (46), and the additional motion from the lap and lead lever (50), as shown in Fig. 230.

The injector (105) admits water to the boiler. Sand stored in the box (91) is delivered to the rails through the sand pipes (92) when it is necessary to increase the adhesion of the drivers. Air pumps (83) deliver air to the braking system, while such parts as the bell (90), whistle (19), safety valve (22), and the headlight (86), need no explanation.

Early History of the Locomotive.—One of the earliest attempts in steam locomotion was made by a Frenchman, Nicolas Joseph Cugnot, in 1769. His machine operated on roads without rails at a speed of about 2¾ miles per hour and carried 4 persons. The Cugnot locomotive was propelled by two single-acting cylinders which developed about 5 hp. Cugnot's locomotive is still preserved in the conservatory of Arts and Sciences at Paris.

In 1803, William Trevethick, a Cornish miner, constructed the first tramway locomotive.

George Stephenson's first attempt at locomotion was in 1815, but, in the year 1825, George Stephenson is credited with the first successful locomotive. That locomotive called Locomotion or No. 1, operated at an average speed of 6 miles per hour and drew 38 vehicles upon which were 450 passengers and about 90 tons of merchandise.

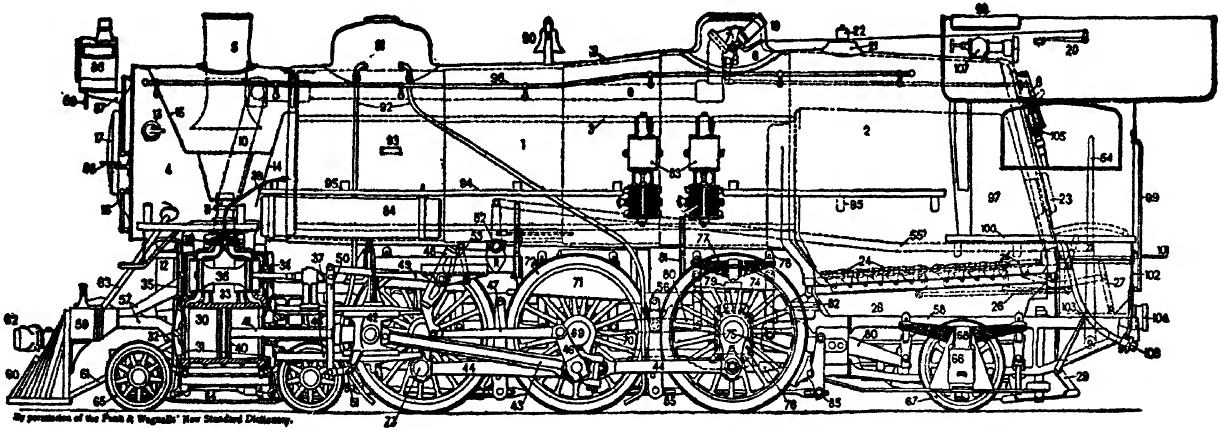


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FIG. 230.—Parts of a locomotive.

Guide for Parts of Locomotive in Fig. 230

1. Boiler
2. Fire box
3. Fire tube
4. Smoke box
5. Smoke stack
6. Dome
7. Throttle chamber
8. Throttle lever
9. Dry pipe
10. Steam pipe
11. Exhaust pipe
12. Spark chute
13. Spark-cleaning hole cap
14. Diaphragm or deflector plate
15. Spark-arrester netting
16. Smoke-box front
17. Smoke-box door
18. Boiler lagging jacket
19. Whistle
20. Whistle lever
21. Safety-valve dome
22. Safety valve
23. Fire door
24. Shaking grates
25. Drop grates
26. Shaking-grate rod
27. Drop-grate lever
28. Ash pan
29. Ash-pan dump bell crank
30. Cylinder
31. Cylinder heads
32. Cylinder-head casing
33. Valve chamber
34. Valve-chamber head
35. Valve-chamber head casing
36. Valve (piston)
37. Valve stem
38. By-pass valve
39. Oil pipe
40. Piston
41. Piston rod
42. Crosshead
43. Main rod
44. Side rod
45. Guides
46. Eccentric crank arm
47. Eccentric rod
48. Link
49. Radius rod
50. Lap-and-lead lever
51. Lap-and-lead lever connector
52. Lift shaft
53. Radius rod hanger
54. Reverse lever
55. Reach rod
56. Main frame
57. Front frames
58. Rear frame
59. Front bumper
60. Pilot
61. Pilot brace
62. Coupler
63. Smoke-box bumper brace
64. Front truck pedestal tie bar
65. Truck wheel
66. Trailer-truck oil box
67. Trailer wheel
68. Trailer-truck spring
69. Driving axle
70. Driving-wheel center
71. Driving-wheel counterbalance
72. Driving-wheel tire
73. Crankpin
74. Driving box
75. Driving-box shoes
76. Frame pedestal brace
77. Driving spring
78. Driving-spring hanger
79. Driving-spring saddle
80. Driver equalizer
81. Expansion plate
82. Fire-box expansion brace
83. Air pumps
84. Main reservoir
85. Driver brakes
86. Headlight
87. Headlight bracket
88. Step
89. Number plate
90. Bell
91. Sand box
92. Sand pipes
93. Step
94. Running board
95. Running-board bracket
96. Hand rail
97. Cab
98. Cab ventilator
99. Cab handhold
100. Cab floor
101. Apron
102. Cab bracket
103. Deck plate
104. Back chafing plate
105. Injector
106. Supply pipe
107. Steam turret

Stephenson's Rocket was built in 1829, and was improved in 1830. This locomotive had cylinders 8 by 16½ in., weight about 4 ton, and was capable of making about 30 miles per hour.

The first locomotive in the United States, called the America, was built in England, and was brought to this Continent by the Delaware and Hudson Canal Company in January, 1829.

The first locomotive of American design was built by Peter Cooper of New York in 1830. It hauled about 4½ tons at a speed of 12 miles per hour.

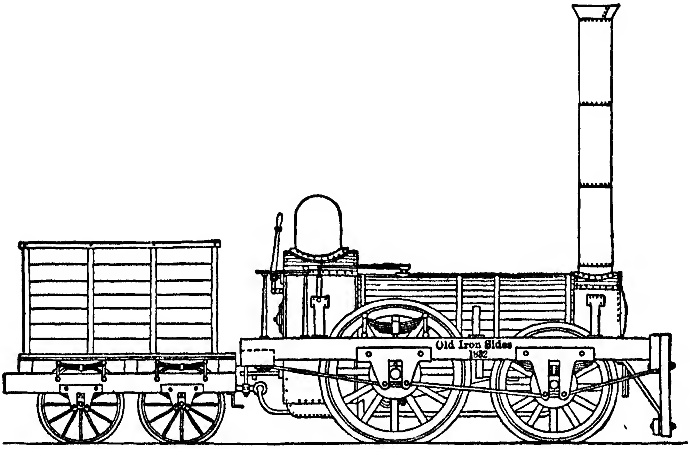


FIG. 231.—The locomotive of 1832.

The West Point Foundry Shops of New York City built the "DeWitt Clinton" locomotive, in 1831, for the Mohawk and Hudson River Railroad. This engine weighed about 3½ tons and operated at a speed of about 30 miles per hour.

The "John Bull," built by George Stephenson in England in 1831, was the first in use in the State of New Jersey, and is on exhibit in the Smithsonian Institute at Washington, D. C.

M. W. Baldwin, the founder of the Baldwin Locomotive Works built, in 1832, the "Old Ironsides," illustrated in Fig. 231. This was a four-wheeled engine, diameter of drivers 54 in. The cylinders were 9½ in. in diameter by 18 in. stroke. The boiler was 32 in. in diameter and had 32 tubes 7 ft. long. It weighed about 5 tons and operated at a speed of about 30 miles per hour.

The following historic locomotives are being preserved in the engineering laboratories of Purdue University at Lafayette, Ind.:

A full-size model of the Tornado which was in service on the Seaboard Air Line in 1840.

The original Daniel Nason Locomotive which was operated by the Boston and Providence Railroad in 1845.

The Rueben Wells which was built in the shops of the Jeffersonville, Madison, and Indianapolis Railway Company in July, 1858, and was in service for 38 years.

The Winan's "Camel Back" locomotive which was built in the Baltimore and Ohio Shops in 1868.

The C. and N. American type which was built in 1873.

The "Marmosa" or Eddy locomotive which was built in the shops of Boston and Albany Railroad in 1876.

The modern locomotive is a development of the above types. Its improvements paralleled the practice in steam power engineering.

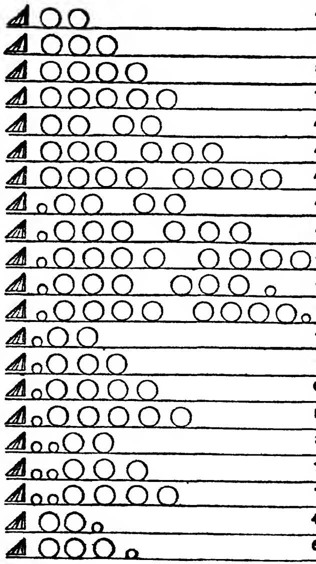
Classification of the Locomotive.—Several methods for the classification of locomotives are in general use. One method quite commonly used is based upon the wheel arrangement. This system indicates the number of truck, driving, and trailer wheels. Thus, a 262 type would signify a machine having a two-wheeled front truck, six drivers, and a two-wheeled trailing truck. Table 10 gives the wheel arrangement, the designating name, and the numerical symbol of the various types of locomotives.

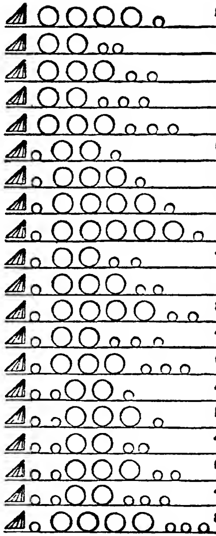
Locomotive Types.—The development of the locomotive to its present state has resulted from the demands for machines of larger haulage capacity. The greatest difficulty found was in securing the larger boiler and grate areas which were necessary. The method by which these features were met is best illustrated by considering those types of locomotives which were especially designed for passenger traffic.

The American type, or the eight-wheel 440, was once considered the standard locomotive for passenger service, while at the present time its use is confined to light service.

The Atlantic type, 442, was developed from the American type, and in general the difference between the two types is the addition of a trailing truck. By this design, the boiler-heating surface could be enlarged, while the use of the trailing truck

TABLE 10.—CLASSIFICATION OF LOCOMOTIVES





040	4 WHEEL SWITCHER
060	6 WHEEL SWITCHER
080	8 WHEEL SWITCHER
0100	10 WHEEL SWITCHER
0440	ARTICULATED
0660	ARTICULATED
0880	ARTICULATED
2440	ARTICULATED
2660	ARTICULATED
2880	ARTICULATED
2662	ARTICULATED
2882	ARTICULATED
240	4 COUPLED
260	MOGUL
280	CONSOLIDATION
2100	DECAPOD
440	8 WHEEL
460	10 WHEEL
480	12 WHEEL
042	4 COUPLED & TRAILING
062	6 COUPLED & TRAILING
082	8 COUPLED & TRAILING
044	FORNEY 4 COUPLED
064	FORNEY 6 COUPLED
046	FORNEY 4 COUPLED
066	FORNEY 6 COUPLED
242	COLUMBIA
262	PRAIRIE
282	MIKADO
2102	10 COUPLED
244	4 COUPLED
264	6 COUPLED
284	8 COUPLED
246	4 COUPLED
266	6 COUPLED
442	ATLANTIC
462	PACIFIC
444	4 COUPLED DOUBLE ENDER
464	6 COUPLED DOUBLE ENDER
446	4 COUPLED DOUBLE ENDER
286	8 COUPLED DOUBLE ENDER

rather than another set of drivers made space for the necessary additional fire-box capacity.

The Pacific type, 462, is the development of the Atlantic type, using the same general design. The insertion of an additional driver is to distribute the weight by not having it concentrated upon two drivers, thereby increasing the rail contact and the amount of adhesion.

The Mountain type, 482, is one of the later developments for heavy passenger service. By using an extra pair of driving wheels this type is well adapted for heavy passenger service as well as for fast freight work.

The need for larger powered locomotives and the limiting conditions to which the locomotive in its construction is subjected leaves practically but one course to follow if any increase in capacity is to be made and that is by increasing the number of drivers or the length of the engine. To increase the length and maintain a rigid type was out of the question on account of the difficulties and dangers in rounding curves.

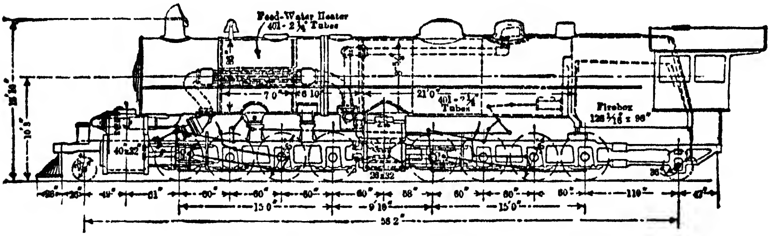


FIG. 232.— Articulated compound locomotive.

The articulated compound locomotive, illustrated in Fig. 232, has been designed to meet the above conditions. This type consists of two sets of engines under one boiler. The rear set is fixed rigidly to the boiler, while the front set supports the overhanging end of the boiler and is capable of adjusting itself to the alignment of the road. The two sets of engines are hinged together and exhaust pipes from one set of cylinders to the other are made flexible by ball-and-socket joints. The steam from the boiler enters the high-pressure cylinders and exhausts into the low-pressure cylinders, which are located on the front engine, from which the steam exhausts as is the case in other types.

The most powerful locomotives are of the articulated type. While little used at the present time in passenger service, they have been very satisfactory in heavy freight service, especially on roads having heavy gradients combined with sharp curves.

Locomotive types most generally used for freight service are the following: Consolidation, or 280; Mikado, or 282; and the Santa Fe, or 2102. The above types are arranged in the order of increasing weight and capacity.

Locomotive Superheaters.—Two types of superheaters are used in locomotive practice: one receives its heat wholly from the gases in the smoke box, the other receives part of its heat from the smoke box, but the greater amount of heat is derived from superheater elements extending into the tubes.

The smoke-box type is constructed wholly within the smoke box, requiring little or no change in the usual boiler arrangement, but has the disadvantage of being limited to low degrees of superheat. It consists of two small cast-steel drums connected to each of the steam pipes, while numerous small tubes complete the path of the steam. The steam entering the upper drum passes through the tubes and absorbs heat from the flue gases which surround them.

The smoke-box type of superheater has been almost wholly replaced by the fire-tube type.

One type of locomotive superheater is illustrated in Fig. 233. As usually constructed, this superheater consists of a box or header *A* located in the smoke box to which are attached numerous superheating elements. These elements are constructed of seamless steel tubing and return bends, and are located in large fire tubes *C* through which the furnace gases pass. The steam is thus made to pass through a superheating element before entering the cylinder. The flow of gases over the superheater surface is controlled by a damper *D* which is operated by the cylinder *E*. When the engine throttle is closed, the damper is similarly closed, thus protecting the superheater tube. When the throttle is opened and steam is passing through the superheater, the damper is automatically opened.

Locomotive Stokers.—Many different designs of stokers have been applied to locomotives. The chief advantage in the use of a mechanical stoker lies in the facility for the burning of a greater amount of coal and in the possibility of using cheaper fuels than is possible with hand firing. Stokers also permit the utilization of more of the reserve capacity of a locomotive than is possible under conditions of hand firing.

Figure 234 illustrates one type of locomotive stoker.

Coal from the tender passes first through regulating screens, thence by a screw conveyor to the engine cab, and is finally delivered to the distributing nozzles from which it is fed to the furnace by means of a steam blast. Of the three distributing nozzles shown the central one utilizes the fine coal and feeds the center of the furnace. The remaining two are supplied with coarser coal and feed the two sides of the furnace.

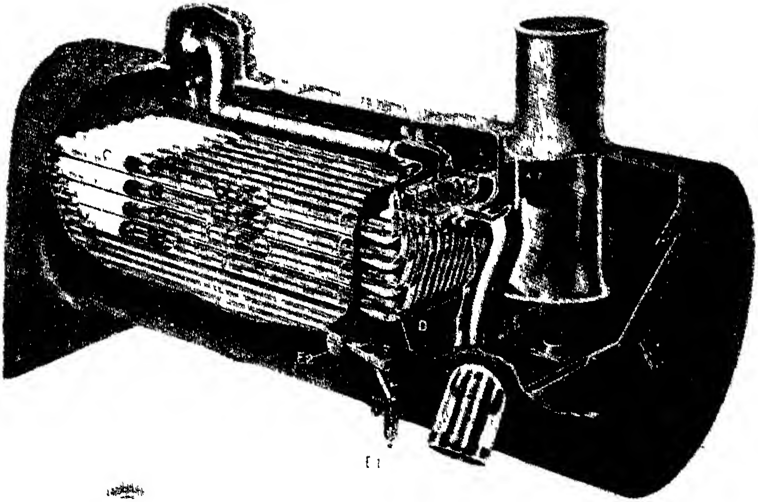


FIG. 233.—Locomotive superheater.

Draft Appliances.—A typical front end is illustrated in Fig. 235. The exhaust steam from the cylinders passes through the exhaust ports into the exhaust pipe *E*, which terminates in a restricted area or exhaust tip. This arrangement regulates the velocity of the exhaust and the intensity of the draft. A small opening creates an intense draft, but at the same time raises the back pressure in the cylinder. The nozzle is arranged so that sufficient draft is obtained and the back pressure in the cylinders is as low as possible.

The stack extension or "petticoat pipe" *P* is used when the exhaust nozzle is low. This is used as an additional channel to conduct the steam which, if not used, would fill the smoke box, thus destroying the draft. The diaphragm *D* begins above the top row of tubes and terminates in a movable slide *S*, which may be raised or lowered to meet varying conditions The diaphragm acts first to deflect the solid particles in the gases downward, and, second, as a draft-regulating device. Without the diaphragm the upper rows of tubes would be greatly affected by the exhaust. This would produce uneven burning of the fuel over the surface of the grate. By regulating the diaphragm, the draft can be made uniform over the entire grate surface.

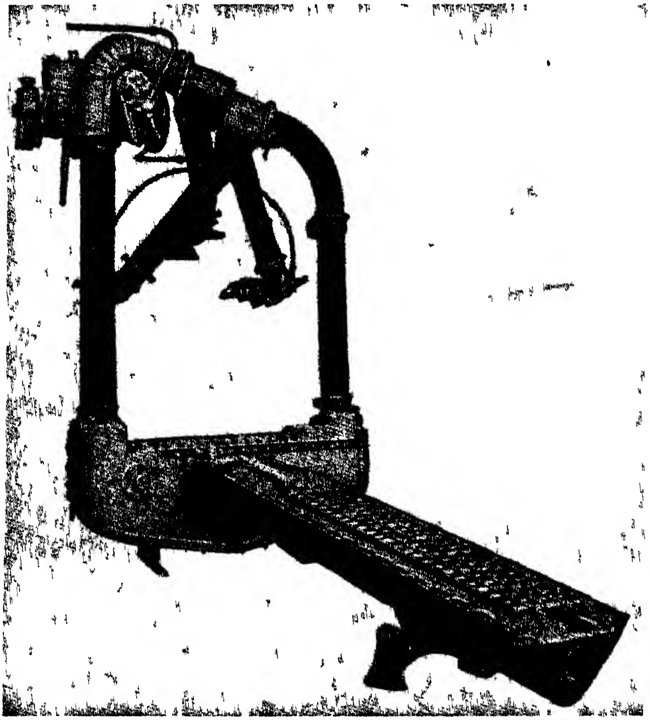


Fig 234—Locomotive stoker

Injectors.—The injector as a means of introducing feed water into a boiler is seldom used in stationary power plant practice, but is generally used in American locomotive practice. It is the general impression that the injector is not so reliable as the reciprocating pump and in addition cannot pump hot water. Its chief advantage is due to the small space it occupies, and this fact makes it practical for use on locomotives, where space economy is important. To overcome the possibilities of failure to operate, locomotives are equipped with two injectors. If one injector becomes inoperative, the other may be relied upon.

Air Brakes.—One of the first types of air-braking systems was what was generally known as the straight air brake. This consisted of a steam-driven air pump located on the engine, a reservoir in which compressed air was stored, a pipe line extending throughout the length of the train, each car being connected by flexible hose couplings, and a brake cylinder on each car the piston of which was directly connected to the brake levers. The engineer's valve could admit air to the piping and thence to the cylinder causing the brakes to act, or could discharge the air from the braking system or train line, thus releasing the brakes.

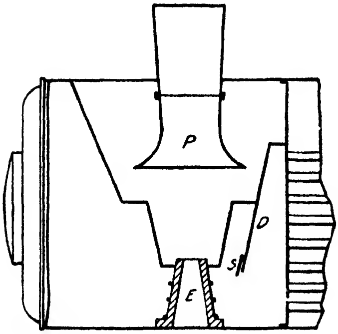


FIG. 235.—Locomotive front end.

Experience has demonstrated that the use of the straight air-brake system is dangerous, when used on trains. The hose connection between cars often broke, resulting in the loss of the braking effect throughout the entire train. When the train would break apart, the rear part often overtook that of the front with the possibility of a serious collision and damage. It was found necessary to have an automatic system, and this led to the introduction of the indirect or automatic system which is still used.

The automatic system operates by decreasing the air pressure in the train line, rather than by increasing it as in the case of the direct-air system. A diagrammatic layout of an automatic system is illustrated in Fig. 236. A compressor delivers air to a main reservoir, which is connected through the engineer's valve to the train line. Under each car is another reservoir, termed the

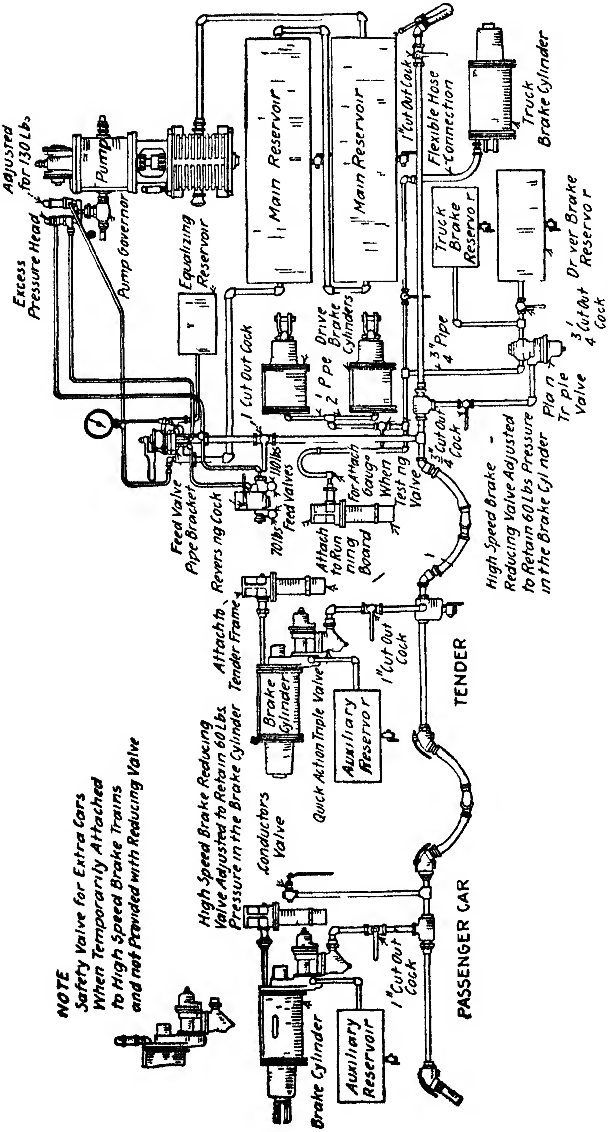


FIG 236 — Automatic air-brake system

auxiliary reservoir, a brake cylinder and triple valve controlling air to and from the brake cylinder.

When the engine is coupled to the train, air is admitted to the train line, passes through the triple valve, and enters the auxiliary reservoir. When air is released from the train line, the lowering in pressure causes the triple valve to operate permitting the air in the auxiliary reservoir to be transferred.to the brake cylinder; thus the brakes are applied. In this system, if a coupling hose should burst or the train part, the brakes would be set because of the lowering of the pressure in the train line.

AUTOMOBILES

Types of Automobiles. - Automobiles are generally propelled by internal-combustion engines. Some of the early makes used steam engines, or electric motors with current secured from storage batteries.

At the present time, nearly all automobiles are driven by internal-combustion engines, using gasoline as fuel. The gasoline automobiles possess the following advantages: they are manufactured in many different types and designs, can be secured at a wide range of prices, are more economical than other types, and are usually provided with a fuel storage of sufficient capacity to propel the car several hundred miles. The disadvantages of the gasoline automobile are that it is not self-starting, lacks overload capacity, and must be built with a complicated system of gears for speed changing and for reversing.

The automobile propelled by a steam engine is very flexible, is easily controlled, and has a very large range of power. To offset these advantages, the steam automobile requires considerable time to start after a long stop, as steam must be generated in the automobile boiler before the engine will start. This fault is being greatly remedied in some of the recent designs of steam automobiles, but all steam automobiles require considerable skill in operation, as constant attention must be given to the fuel and water supply.

The electric automobile is also very flexible, operates more quietly than other types, is clean, and is easy to start and to control. The greatest disadvantage of the electric car is that it can run only for short distances without recharging its storage batteries. The use of the electric automobile is limited mainly to cities, where facilities are available for charging storage batteries. Electric cars are also expensive to operate and are seldom used at present.

As steam and electric automobiles are not used, this chapter will deal only with the gasoline automobile.

Essential Parts of a Gasoline Automobile.—The essential parts of a gasoline automobile are:

1. A power plant, which consists of an internal-combustion engine and its auxiliaries, such as the fuel system, carburetor, ignition system, and cooling and lubricating systems. In nearly all cars this also includes the starting equipment.
2. Friction clutch, for disengaging the engine from the propelling mechanism.
3. Transmission mechanism for speed changing and reversing.
4. Differential gear, the purpose of which is to allow one drive wheel to revolve independently of the other, this being necessary when turning corners.
5. Front and rear axles.
6. The frame for supporting the power plant, the transmission system, and the body of the car. Interposed between the body and the axles are the springs, which are built up from a number of leaves.
7. Brakes on two or four wheels.
8. Control system, which includes the steering mechanism, hand levers and foot pedals, means for controlling the spark position, the carburetor throttle, the clutch, the transmission gearing, and the brakes.
9. Wheels, tires, lights, alarm, body, top, fenders, dash, running board, wind shield, and speedometer.
10. Body.

The term chassis is applied to the car with the body and accessories removed.

Automobile Engines.—Figure 237 illustrates a sectional view of a Chrysler automobile engine. Modern automobiles use four-, six-, eight-, or twelve-cylinder engines. The engines are all of the vertical or semi-vertical type and operate on the Otto four-stroke cycle. The engine is mounted in the front end of the car for accessibility, and also for the purpose of more evenly distributing the weight of the car. Multi-cylinder engines permit of easier starting, operate more smoothly, run with less vibration, and have a wider range of power. Four- and six-cylinder engines have all cylinders in one row and located on one side of the crankshaft. Eight-cylinder engines have their cylinders in a row or they are arranged V-type in two rows with the rows set at an angle of 90 deg. Twelve-cylinder engines are usually of the V-type, and have two rows of cylinders set at an angle of 60 deg.

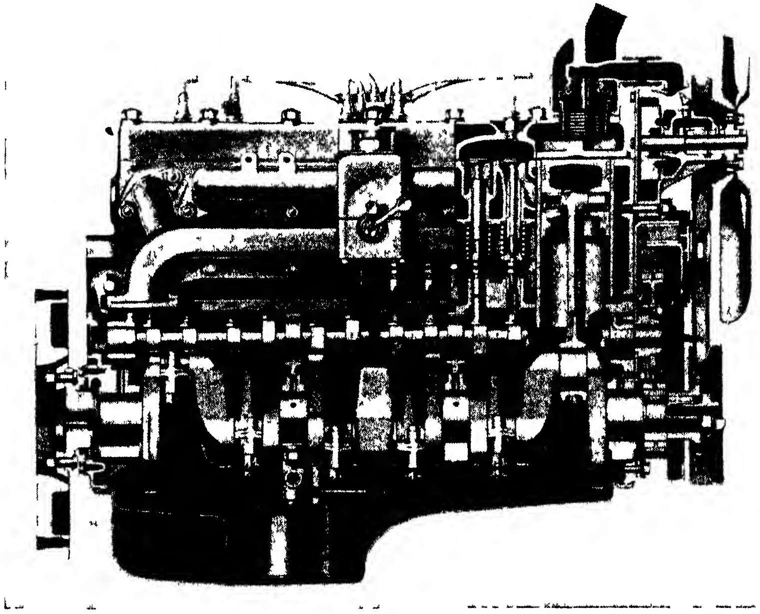


FIG. 237.—Sectional view of an automobile engine.

The cylinders may be cast singly or en bloc; the en bloc construction means that several cylinders are cast in one piece. The single-cylinder casting is light in weight and is easily replaced. The en bloc motor is more rigid, occupies less space, and is the more commonly used.

Cooling of Automobile Engines.—Automobile engines are generally water cooled and are provided with radiators for the purpose of cooling the water after it has absorbed heat from the cylinder walls. Either the thermosyphon or the forced-water circulation system is used.

The thermosyphon system (Fig. 238) depends upon the fact that water rises when heated. This system does not require a pump to circulate the water. The water enters the cylinder jackets at *A* (Fig. 238). Upon becoming heated by the explosions going on within the cylinder of the engine, the water rises to the tops of the cylinder jackets, entering the pipe *B* and passing into the radiator at *C* where it is brought into contact with the radiator cooling surfaces. On being cooled, the water becomes heavier and sinks to the bottom of the cooling system, to enter the cylinder once more and to repeat its circulation. The cooling action of the radiator is increased by the fan *F* which draws air through the radiator spaces.

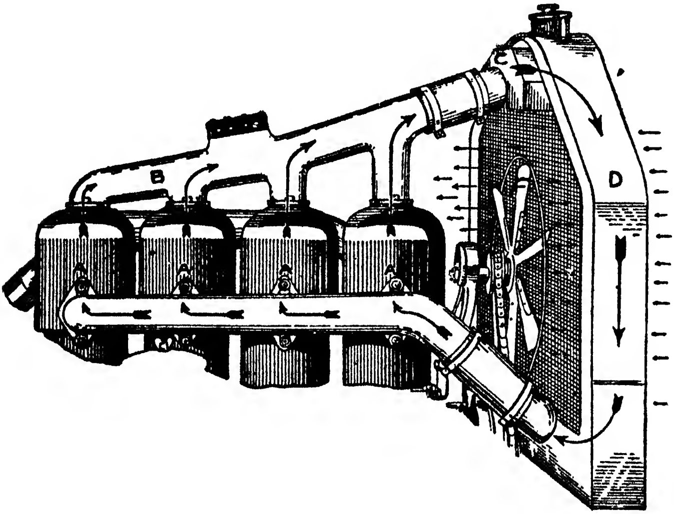


Fig. 238 —Thermosyphon water-circulation system.

The forced-circulation cooling system differs from the thermosyphon system in that it has a circulating pump to aid in the circulation. The pump which is usually of the centrifugal type makes the circulation more positive. The course taken by the circulating water is exactly the same in both systems. Figure 239 illustrates the application of the forced-circulation system.

Some air-cooled automobile engines have proven very satisfactory. The cylinders of air-cooled engines are ribbed to increase the radiating surface and the circulation of the air is produced by means of a fan located in the motor flywheel.

Lubrication.—Five methods are used for lubricating automobile engines:

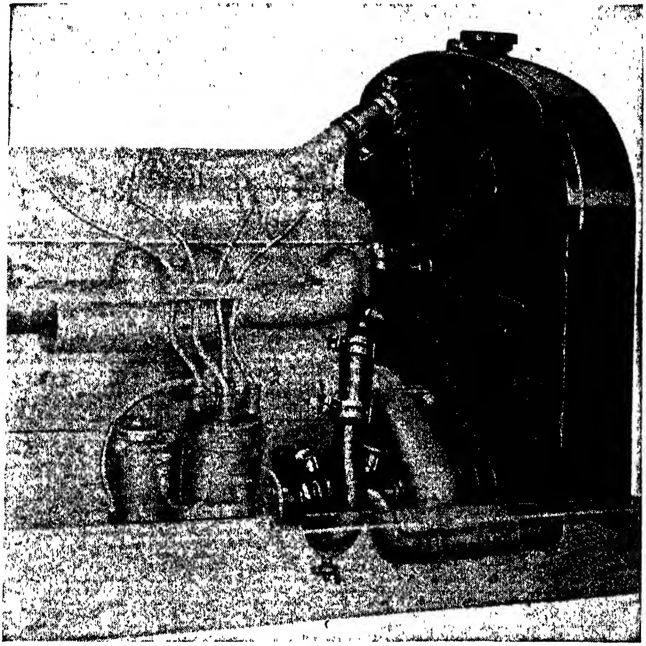


FIG. 239.—Forced-circulation cooling system.

1. *The Splash System.*—This system depends entirely upon dippers on the connecting rods to splash the oil to the various parts of the engine.

2. *The Circulating Splash System.*—This differs from the straight splash method in that a pump at a low point in the crankcase delivers the oil to troughs under the connecting rods. From these troughs the dippers splash the oil in the same manner as in the straight splash system.

3. *The Forced-splash System.*—This system uses a pump to force the oil to the main bearings and to the troughs previously mentioned. Dippers on the connecting rods then splash the oil in

the same manner as mentioned before. This system differs from the circulating splash in that the oil is forced to the main bearings.

4. *The Forced System.*—This system has a hollow or drilled crankshaft through which the oil is forced from the main bearings to the connecting-rod bearings and is then splashed to the wristpins and cylinder walls.

5. *The Full Forced System.*—This system has tubes leading up along the connecting rods to the wristpins. The oil is forced by the pump to the main bearings, thence through the crankshaft to the connecting-rod bearings, thence through the tubes to the wristpins, and through the hollow wristpins to the cylinder walls. With a full forced system, a relief valve is provided to prevent the oil pressure from becoming excessive.

The parts of the automobile engine which require lubrication are the main shaft bearings, crankpin bearings, wristpin bearings, camshaft bearings, timing gears, cams, cam-lifter guides, cylinder walls, and other moving parts, such as yokes and ends of rods.

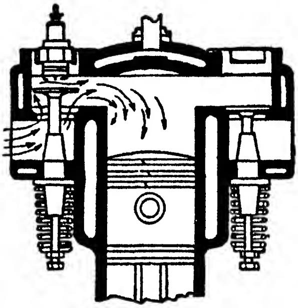


FIG. 240.—Motor with poppet valves.

Automobile Valves.—The poppet type of valve, (Fig. 240) is generally used on automobile engines. The sleeve-valve type of engine (Fig. 241) is used on certain designs of automobiles.

Poppet-valve engines are built in several forms according to location of valves.

1. The valve-in-the-head or I-head engine (Fig. 242) has both intake and exhaust valves in the cylinder head.

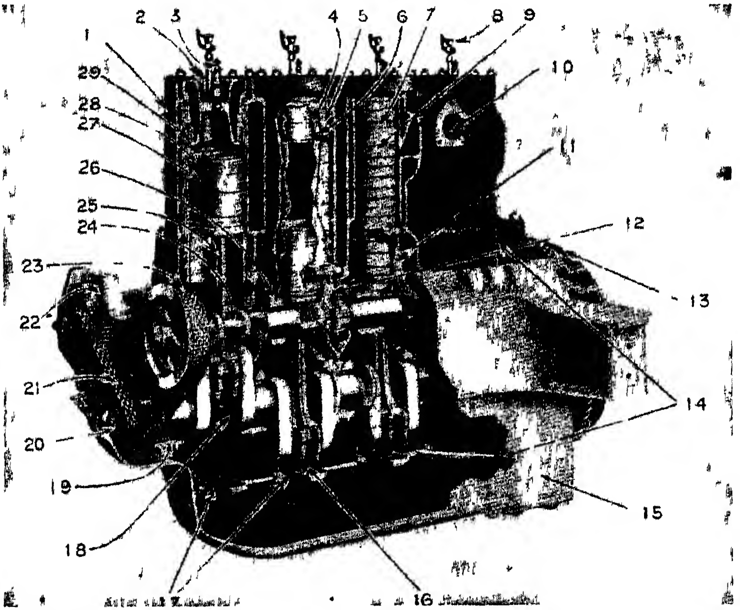
2. The ell-head motor (Fig. 243) has both the intake and exhaust valves on one side of the cylinder.

3. The tee-head motor (Fig. 244) has the exhaust valves on one side of the cylinder and the intake valves on the other.

4. The combination ell-head and valve-in-head, sometimes known as F-head, has the intake valve in the head and the exhaust valve on the side of the head.

Clutches.—The clutch is a device used for connecting the engine to, and disconnecting it from, the propelling gear of the car Clutches depend upon the frictional adhesion between surfaces

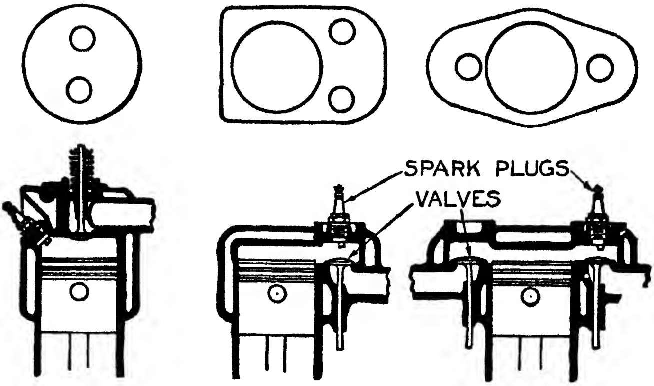
The disc or plate clutch is most commonly used The disc clutch is of either the dry or wet type, depending upon whether or not it runs in an oil bath



1 Cylinder
2 Water jacketed cylinder head
3 Spark plug
4 Inner sleeve
5 Outer sleeve
6 7 Port openings in sleeves
8 Priming cup
9 Oiling grooves in sleeves
10 Port opening in cylinder
11 Connecting rod operating outer sleeve
12 Connecting rod operating inner sleeve
13 Flywheel
14 Oil trough adjusting lever connected to throttle
15 Lower part of crank case containing oil pump strainer and piping
16 Oil scoop
17 Adjustable oil troughs
18 Crankshaft
19 Crankshaft bearing
20 Starting clutch
21 Silent chain drive for magneto shaft
22 Silent chain driving sprocket for electric generator (on 4 cylinder models)
23 Silent chain drive for eccentric shaft
24 Eccentric shaft
25 Connecting rod
26 Bearing for eccentric shaft
27 Piston
28 Piston rings
29 Cylinder-head ring (junk ring)

FIG 241 Sectional view of Sterns-Knight four-cylinder motor

The multiple-disc clutch (Fig 245) depends for its action upon the friction between discs Alternate discs are fastened to the driving and driven parts The discs marked *A* are fastened to the engine shaft and those marked *B* connect with the



I-Head. L-Head. T-Head.

Figs. 242, 243 and 244.—Arrangement of valves and spark plugs in various types of engines.

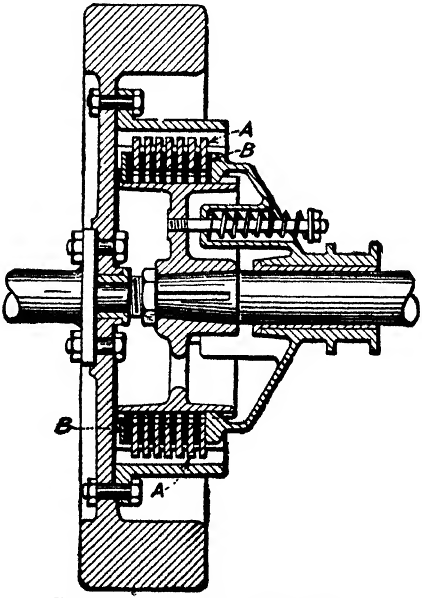


Fig. 245.—Multiple-disc clutch.

mechanism to be driven. If the clutch runs in a bath of oil, it is called a wet-disc clutch. A spring is employed to hold the discs in contact when the clutch is in action.

The driving discs *A* have lugs or projections on their outside rims, which fit into slots cut in the inside edge of the flywheel rim. The driven discs *B* have slots on their inside rims, which fit the lugs on the surfaces of the clutch drum.

In normal position, the discs *A* are kept in close contact with the discs *B* by means of springs and the power of the motor is transmitted to the propelling mechanism of the car. A clutch pedal, when depressed by the driver's foot, disengages the two sets of discs.

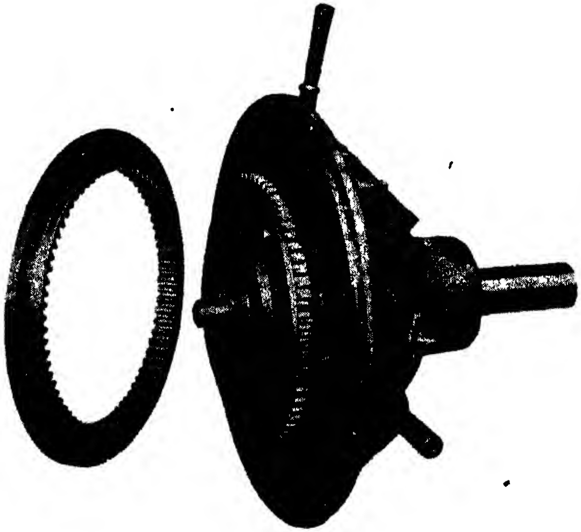


FIG. 246.—Twin-disc clutch. (*Twin Disc Clutch Co., Racine, Wis.*)

The detailed construction of a twin-disc clutch is shown in Fig. 246.

Figure 247 illustrates a single-plate clutch and its relation to the flywheel and shaft.

Transmissions.—The speed of an internal-combustion engine and its direction of rotation cannot be varied to meet the requirements of an automobile. This necessitates the introduction of some form of mechanism for speed changing and also for reversing, in order that different speed ratios and reversal of direction can be secured between the engine and the drive axle. The mechanism, which is used in speed changing and in reversing, is known as the transmission. The transmission is so constructed that the propelling ability of the motor is increased at the expense of the speed of the automobile. That is, the motor through the gear ratios of the transmission is able to pull a larger load at a lower speed than it could by direct drive.

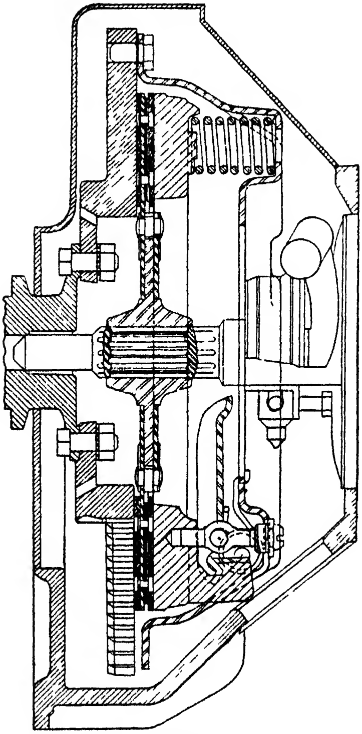


FIG. 247.—Single-plate clutch.

Only one type of transmission, namely, the selective-sliding type, is now extensively used. The progressive-sliding type, the planetary type, as well as the friction drive are practically out of date.

Figure 248 illustrates the principle of the selective-sliding gear-transmission system. The desired gear ratio can be obtained by means of this type of transmission without shifting through other positions. This system is most generally used.

In Fig. 248, *A* is the driving shaft, *B* the driven shaft. *S* and *L* are slides carrying yokes that move on the wheels *D* and *K*. All the wheels on the counter-shaft are fastened to the shaft. A lever is arranged for shifting either *S* or *L* and for allowing the various gears on the shaft *B* to mesh with those on the counter-shaft. This system is usually arranged for three speeds forward and one speed reverse, but can be modified for any number of speeds forward and for reversing. For reversing, an idler gear is provided between the driver and driven gears. High-speed forward is usually direct drive. Some cars have transmissions which permit of a higher speed than the direct drive.

In the planetary-transmission system, speed changes do not depend upon the shifting of gears, but clutches or brakes are applied to hold certain wheels in position. The drive is positive and the gears are always in mesh. For high speeds this system is very well adapted, as the entire system is clamped solidly and revolves with the motor crankshaft as a single mass. As no gears are turning idly, the entire system by its weight serves to steady the rotation of the motor at high speeds. The planetary system provides only two speeds forward and one reverse. It is inefficient in low speed and reverse, as much power is absorbed by friction in the gears and clutches. The use of the planetary system is obsolete.

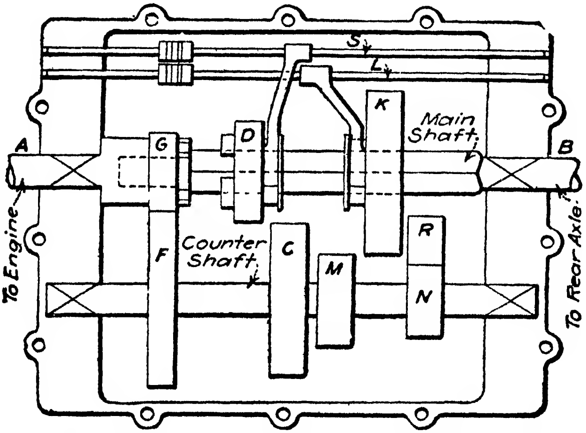


FIG. 248.—The selective-sliding gear-transmission system.

Differentials for Automobiles.—Differential gears, sometimes called compensating gears, are provided to permit one wheel to turn faster than the other on turning corners or when meeting obstructions. The outside wheel in turning a corner has a greater distance to travel than has the inside wheel in the same length of time. In automobiles, the differential is a part of the rear axle assembly. If two drive wheels were rigidly connected without a differential, it would be necessary for one wheel to skid or slip when turning a corner or when going over an obstruction, thereby throwing great strain on the parts and producing excessive wear on the tires.

The bevel-gear differential (Fig. 249) illustrates the principle of a differential. The rear axle *S* (Fig. 249) is divided into two halves. Each half of the rear axle carries a drive wheel at its outer end and a bevel gear *C* or *D* at its inner end. The bevel gears *C* and *D* are connected by, from two to four, differential or compensating pinions *B*, *B*, *B* which are placed at equal distances apart around the circle. These bevel pinions *B*, *B*, *B* are

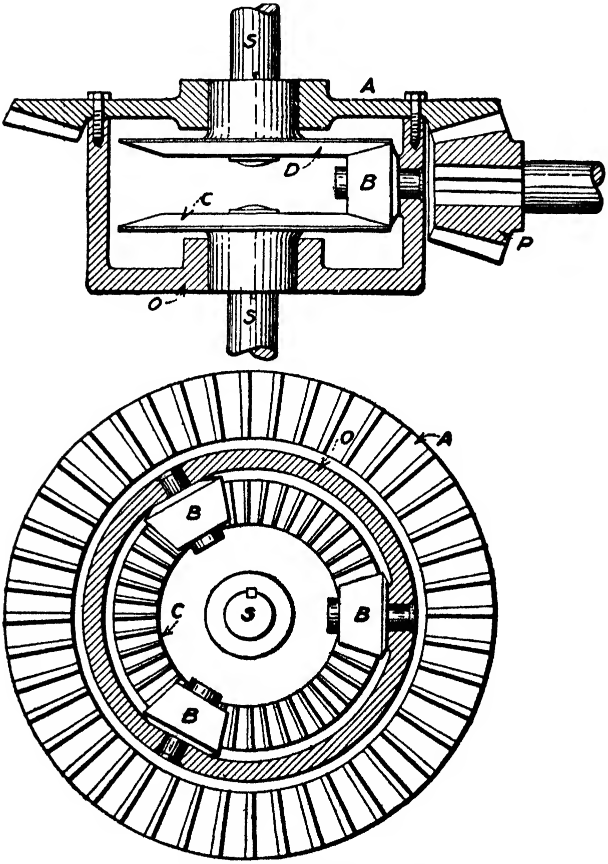


FIG. 249.—Bevel-gear differential.

capable of rotating loosely on radial studs, which are fastened at their outer ends to the casing or housing *O*. The gear *A* is made to turn loosely upon the hubs of the bevel gears *C* and *D*, but is made fast to the housing *O* by means of bolts or rivets. The power from the engine is transmitted to the housing *O* through the bevel-gear pinion *P*, which meshes with gear *A*. The housing transmits this power through the small bevel pinions *B*, *B*, *B* to the bevel gears *C* and *D*, which are connected to the rear or drive wheels. On a level road, with both drive wheels rotating at the same speed, the housing *O*, with all the gears and pinions will revolve as one mass, and the small pinions *B*, *B*, *B* will remain stationary. The wheel which turns the more easily is always the one to turn. In turning a corner, in meeting an obstruction, in case one of the wheels slips, or if the drive wheel attached to the bevel gear *C* must turn slower than that attached to gear *D*, the differential pinions *B*, *B*, *B* will revolve on their axes. The bevel pinions *B*, *B*, *B* divide the torque between the two bevel gears *C*, *D*, thereby permitting the two drive wheels to run at different speeds.

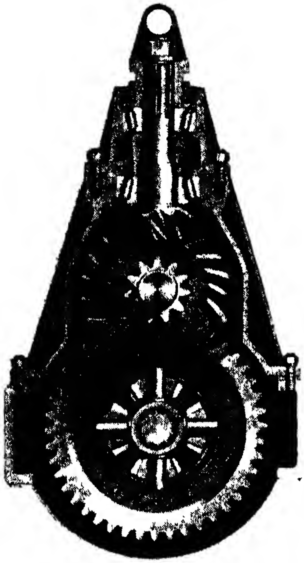


Fig. 250.—Timken-Wisconsin differential.

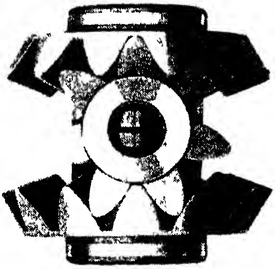


Fig. 251.—Gear details of Timken differential.

Figures 250 and 251 show the differential in a Timken-Wisconsin front-mounting double-reduction-drive unit. Figure 250 illustrates two differential drive gears and one differential pinion in their proper relation with each other. Figure 251 illustrates gear details

Universal Joint.—Since the engine and the gearing are mounted on the frame of the automobile, while the driving wheels are connected to the frame by springs, automobiles must be provided with one or more flexible joints. The flexible joint is known as a universal joint and consists of two forked arms at the ends of shafts. These forked arms are joined by pins through their ends to a center member and are arranged so that the pin of one forked arm lies in the same plane, but at right angles to the pin of the other. This permits the lower end of the propeller shaft to move independently of the motion of the rear axle.

Front and Rear Axles.—The front axles are of a construction which permits the wheels to pivot near the hub. This reduces the tendency of the wheel to swing when striking an obstruction in the road. The steering knuckles are the part of the front axle assembly on which the wheels revolve. Steering arms are inserted in the knuckles and are connected together with an adjustable tie rod so that both knuckles turn simultaneously. A third arm, usually on the left-hand knuckle, is connected to the steering gear by means of the steering connecting rod. Automobile front axles are drop forged with I-beam cross-sections.

Rear axles for automobiles are live axles; that is, they turn with the wheels. They are divided into three types: the semi-floating, the three-quarter ·floating, and the full-floating. In the semi-floating type, the entire load is carried on the axle. The bearing in a three-quarter floating is on the housing and the wheel is keyed to the axle; with this type, it is not possible to remove the axle without also removing the wheel. When a full-floating axle is used, the bearing is also on the axle housing and the entire weight is supported on the housing. With the full-floating type of rear axle, the only strain on the axle is the torque in turning the wheel; as the axle is not fastened rigidly at either end, it can be taken out without disturbing the wheel, by removing the hub flange.

Steering and Control Systems.—Automobiles are steered by means of a hand wheel, which is located on top of the steering column. The steering gear operates on the front axle, through the steering connecting rod, and turns the knuckles and the front wheels. The steering column, besides the steering mechanism, usually contains several concentric tubes with connections to the alarm, the throttle control, and the spark control.

Modern cars are provided with two methods of throttle control, the hand-throttle control and a foot control, known as the accelerator.

The foot accelerator and the hand-throttle control are so connected that the hand accelerator also works the foot accelerator, but the operation of the foot accelerator does not change the position of the hand control.

The control system includes a pedal for operating the friction clutch, one for operating the service brake, a lever for operating the emergency brake, and a lever for operating the speed changing and reversing gears of the transmission. In some makes of cars, the service brake is operated by the clutch pedal and the emergency by the other foot pedal.

Brakes.—Automobile tires being made of rubber, the brakes are not applied to the wheel tires, but to metal drums which are fastened to the rear wheels. Two sets of brakes are employed. One brake, called the service brake, is operated by means of a foot pedal. The other brake, called the emergency brake, is usually operated by a hand lever, and is intended for use only for parking purposes and in case the service brake fails or when a very strong braking action is required. The braking effect can be produced by expanding the brake band or shoe within the brake drum or by contracting the brake shoe around the outside of the brake drum. Brakes for automobiles are of either the external-contracting or internal-expanding type. The energy of the brake pedal is transmitted to the brake mechanism on the wheels either mechanically or hydraulically. The mechanically operated braking system uses rods and cables which are controlled by the foot pedal or hand lever. In the hydraulically operated braking system, the brake mechanism is operated by hydraulic pressure from a master cylinder under control of the brake pedal.

At the present time, four-wheel brakes are being applied to most makes of automobiles. In these, the braking action is applied to both the front and rear wheels. The braking action is thereby increased as compared with two-wheel brakes.

The brake bands are usually covered on the rubbing side with an asbestos preparation, which can be replaced when worn out.

Carburetors.—Automobile carburetors have been illustrated and described in Chap. XIV.

Ignition.—The jump-spark electric ignition system is employed Most modern automobiles employ a high-tension distributor system of ignition, using batteries as the source of current

In Fig 252 is illustrated a wiring diagram of a simple type automobile ignition system. This system works on the open circuit principle and consists of a nonvibrator type of induction coil of the unisparker type, a contact maker, a high-tension distributor and a governor which automatically advances the spark within certain limits as the speed increases.

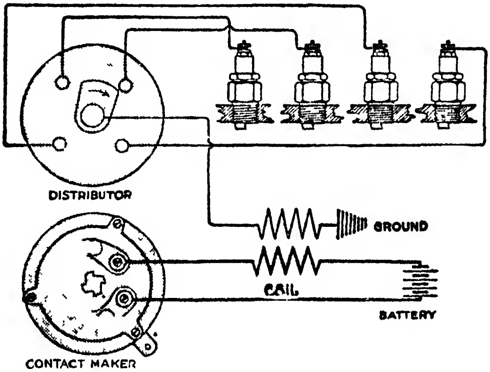


Fig 252 —Wiring diagram of the Atwater-Kent system

Figure 253 illustrates the Delco-Remy circuit diagram showing location of circuit breaker (current limit relay), ignition, starting, and lighting system and wiring details. A motor-generator set performs the function of cranking the engine and of supplying electrical current for ignition, lighting, sounding the horn, and charging the storage battery. The ignition apparatus is incorporated in the forward end of the motor generator. A combination switch is used for the purpose of controlling the lights, the ignition, and the circuit between the electrical generator and the storage battery.

Automobile Starting Systems.—Automobile motors are started by some electric starting device. Before the motor is cranked, the carburetor throttle lever on the steering wheel should be moved to a position where the throttle is slightly open. The gears should be placed into neutral position.

In cranking by hand, the crank should be pushed in as far as possible and turned in the clockwise direction until it catches. In cranking an engine, always set the crank so as to pull up. One should not bear down on the crank.

Electric starting devices are always employed in modern automobiles. An electric self-starter consists of an electric generator for furnishing electricity, a storage battery, and an electric motor to crank the engine. The electric starting system is also supplied with switches for the purpose of controlling the supply of current; with protective devices, such as fuses or circuit breakers to prevent the discharging of the storage battery or damage to the coils, motor, or lamps; with an electric regulator to maintain constant voltage for the various speeds of the engine; and with electric meters for the purpose of showing the amount of current supplied by the generator to the storage battery and for indicating how much current is being supplied by the battery for ignition and lighting.

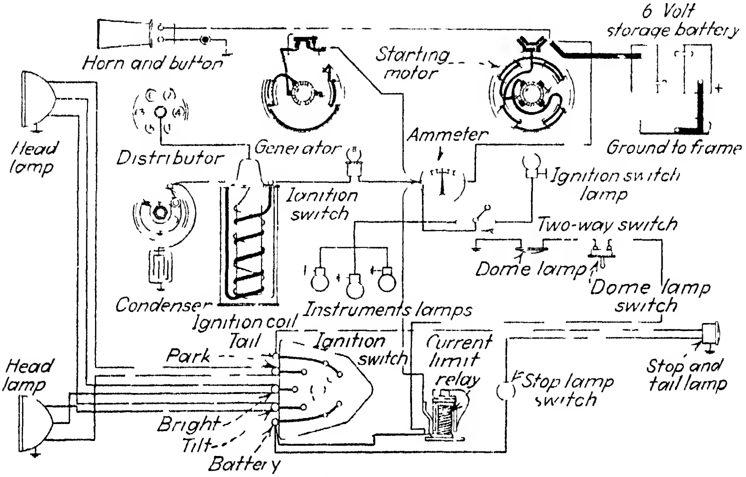


FIG. 253. —Circuit diagram of the Delco-Remy system.

Electric starters are built in the single-unit, the two-unit, or the three-unit system. In the single-unit system, the generator and motor are in one unit and this motor generator is used for cranking the engine, for charging the storage battery, and for furnishing current to be used for operating the engine ignition system and for the automobile lights. In the two-unit system, a separate motor, which receives its current supply from the storage battery, is used for cranking the engine. The electric generator supplies current for charging the storage battery and also for ignition and lighting. In the three-unit system, a magneto furnishes current for the engine ignition system; a separate direct-current motor, supplied with current from a storage battery, is used for cranking; while the electric generator is used only for charging the storage battery and for operating the lights.

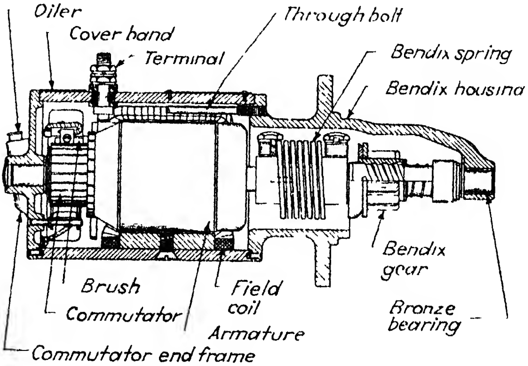


FIG. 254.—Starting motor

One type of starting motor is illustrated in Fig. 254. This type utilizes the Bendix drive for the engagement and disengagement of the motor pinion with the engine flywheel.

Automobile Lighting.—Electric lights are used exclusively on modern automobiles. The electricity for illumination is secured from a storage battery. In the cars with electric starters, the storage battery is recharged from the generator; in other cases, the battery is recharged from an outside source. In some automobiles alternating-current magnetos furnish lighting current while the car is in motion.

A car lighted with a battery charged from an outside source is equipped with a storage battery of 80- to 100-amp.-hr. capacity which supplies current for illumination and for blowing the horn. This lighting storage battery is usually not used for engine ignition, unless the car is equipped with a dynamo to recharge the battery. When the storage battery is used for lighting, ignition, and starting, its capacity should be at least 90 amp.-hr.

Management of Automobiles.—Before an attempt is made to start an automobile, the operator should be certain that the fuel tank has sufficient gasoline, that the gasoline valve from the tank to the carburetor is open, that the lubricating system is in good working order, that the radiator is filled with clean water, and that the engine ignition system is working properly. The transmission system should be thrown into neutral position and the carburetor throttle should be partly opened before the engine is cranked. The rules given in the discussion of starting systems should be followed in starting an automobile by hand cranking. With electric self-starters, the starting pedal is pushed forward or down as far as it will go and held until the engine starts. As soon as the engine starts, the foot should be removed from the starter pedal.

When the engine starts, the spark lever should be advanced. To start the car, the emergency brake is released, the clutch is disengaged, while the transmission gears are thrown into low gear forward, and the foot accelerator and the spark lever are operated to take care of the increased load on the car. In changing from low to intermediate and to high speed, the clutch is thrown out, the gears are shifted, the clutch is thrown in mesh, and the throttle, or foot accelerator is adjusted for proper operation.

To stop an automobile, the motor is slowed down by removing the foot from the accelerator, the clutch is disengaged, the service brake is operated so that the car comes to a gradual stop, and the transmission gears are shifted into neutral position.

To stop quickly, the operator presses on both pedals, releasing the clutch and applying the service brake, while applying also the hand emergency brake.

To reverse, the car is stopped, the reverse gear is shifted, and the clutch is thrown in slowly.

Details concerning the care of a car are given in manufacturers' instruction books and will not be repeated here.

An automobile engine will smoke if too much lubricating oil is used, if the lubricating oil is of poor quality, if the piston rings are worn or broken, or if the mixture of air and fuel is incorrect.

Engine hissing may be produced by loose or broken spark plugs, by leaving priming or relief cocks open, by having exhaust pipe loosely connected, or by leaky gaskets or intake manifolds.

Irregular action of the automobile engine may be due to incorrect fuel mixture, poor wiring such as defective insulation or defective connections, carbon deposits, poor fuel or defects in carburetor, magnetos, spark plugs, or mechanism.

Misfiring is often due to carbon deposits on the spark plug. Overheating of the engine may be due to incorrect valve or spark timing, defective water circulation, clogged radiator, or a lack of proper lubrication. Engine knocks are due to rich mixture, too much spark advance, carbon deposits in the cylinder, loose or worn bearings, loose flywheel, or lack of lubrication.

TRUCKS

Most of the essential parts of a truck are similar to those of an automobile, but are usually heavier to stand the greater strains imposed by the conditions under which a truck operates.

Power Plants for Trucks.—The truck power plant is usually a four-cylinder vertical poppet-valve type of internal-combustion engine, which operates on the Otto four-stroke cycle. Six-cylinder engines are employed to a limited extent in trucks.

A standard type of float-feed carburetor is used. Generally some trucks are equipped with special carburetors.

Truck motors are cooled with the forced-water circulation system and are usually provided with tubular radiators, in which the upper and lower tanks are connected by a series of tubes through which the water passes. Some of the lighter trucks are equipped with cellular radiators, similar to those used on automobiles.

The jump-spark system of ignition is employed. In some makes of trucks, batteries are used for furnishing current when starting and magnetos supply electricity for ignition after the motor has attained normal speed. This is called the dual system. Most trucks are equipped with a high-tension magneto.

In some cases, trucks are provided with two independent ignition systems, including a high-tension magneto and a distributor.

Power Transmission Systems for Trucks.—The power transmission systems of trucks and of automobiles include the same elements.

Some trucks employ a dry multiple-disc clutch and others use a wet multiple-disc clutch. Dry or wet single-plate clutches are also used for trucks. The friction plate is independent of the flywheel and of the housing, and a spring holds the friction surfaces in contact. The friction surfaces are separated by depressing a foot pedal.

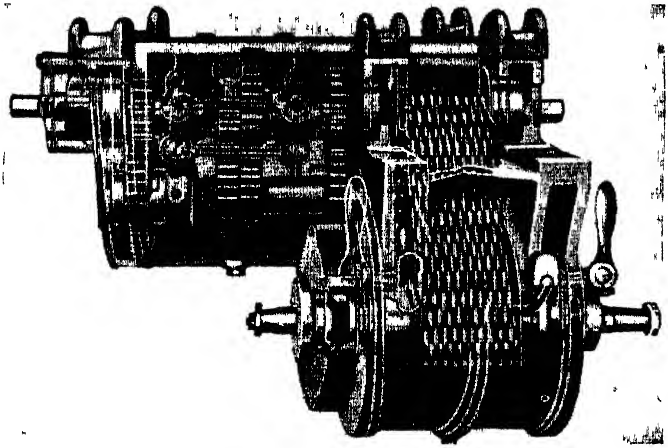


FIG. 255 —Truck transmission.

The transmission of a truck is usually of the selective type and includes three speeds forward and one reverse. Some trucks employ a four-speed transmission system. Such trucks have direct drive on the fourth speed and three lower gear ratios. To reduce the danger of stripping the gear teeth, the gears of the counter-shaft and main shaft of the transmissions for heavy trucks are placed permanently in mesh, the drive being obtained by the use of shifting forks or clutches. A transmission for a heavy truck is shown in Fig. 255.

The propeller shaft carries the power from the transmission through the universal joints to the rear axles. The power from the propeller shaft to the rear axle is transmitted either by shaft or by chain drive.

The shaft drive is the most common for trucks, as well as for automobiles. The shaft drive transmits the power to the differential, which is placed on the rear axle through bevel, helical, or worm gears. The bevel-gear drive is seldom employed for trucks. The helical or spiral bevel-gear drive is more satisfactory, as two or more teeth are in mesh at one time, reducing irregularity in wear. The worm-gear drive is particularly well suited for trucks, on account of the large gear reduction which this drive makes possible. A large differential-gear reduction decreases the torque required to drive the rear wheels.

For heavy trucks, chains are often used for the final drive in order to obtain the greatest possible speed reduction. In such trucks, the differential is not placed on the rear axle, but is contained in the same housing with the transmission. From the differential, the power is transmitted to jack shafts, which drive the rear wheels by means of chains.

Some trucks are constructed so that they drive and steer with four wheels. In such cases, the power from the transmission is transmitted to two differentials. One differential serves to transmit the power to the front wheels and the other to the rear wheels.

The differential of the truck has the same function as that of the automobile, and permits the drive wheels to revolve at different speeds without interfering with the operation of the truck.

TRACTORS

Essential Parts of a Tractor.—A tractor consists of the following essential parts:

1. *Power Plant.*—This, in the case of a steam tractor, includes a steam engine, a boiler, a pump or injector, steam and feed-water piping, fuel hopper, water storage, and the ordinary steam power plant accessories. Gas tractors employ an internal-combustion engine burning gasoline, kerosene, or some heavier oil.

2. *Speed Reduction Gears.*—A train of gears must be interposed between the motor and the drive wheels, in order that the tractor may be propelled at a very low speed.

3. *Reversing Mechanism.*—A steam tractor is reversed by a Stephenson link motion similar to that used for reversing locomotives or by some form of single eccentric radial valve gear. Gas tractors employ a train of gears.

4. *Steering Mechanism.*—Steering is usually accomplished by turning the front axle.

5. *Friction Clutch.*—A friction clutch is necessary for the purpose of disengaging the motor from the propelling gear. The expanding cone and the expanding shoe clutches are used in addition to those explained. Figure 256 illustrates an expanding shoe clutch. The type illustrated in Fig. 246 is also used.

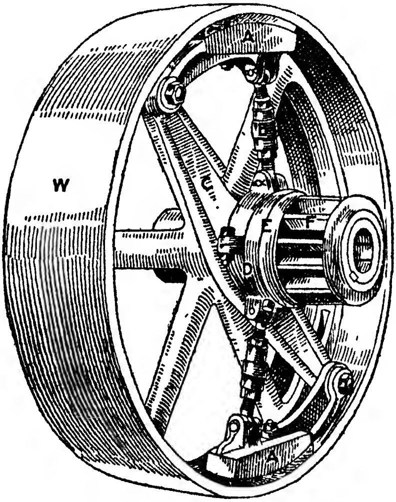


Fig. 256—Tractor clutch.

6. *Differential.*—The differential (Fig. 257) is similar to that used on some makes of trucks, and its function is to allow one drive wheel to revolve independently of the other.

7. *Tractor Frame.*—The frame supports the various parts and keeps them in proper alignment.

8. *Drive Wheels and Steering Wheels.*—Usually, the two rear wheels are the drive wheels and the two front wheels are used for steering. Some tractors employ a drum for driving. Several makes are constructed so that the front wheels are the driving wheels, and in other makes all four wheels drive. Tractors

are also built on the "caterpillar" principle and employ a crawler instead of a wheel or drum.

Steam Tractors.—The steam tractor, or traction engine, is usually equipped with an internally fired boiler. Some builders use the return-flue type, others the direct-flue or locomotive type.

Coal, lignite, wood, straw, or crude oil are used as fuels for steam tractors.

The feed water is delivered to the boiler by an injector, a direct-acting steam pump, a crosshead pump, or a gear-driven pump. Some tractors employ two independent methods for feeding water to the boiler.

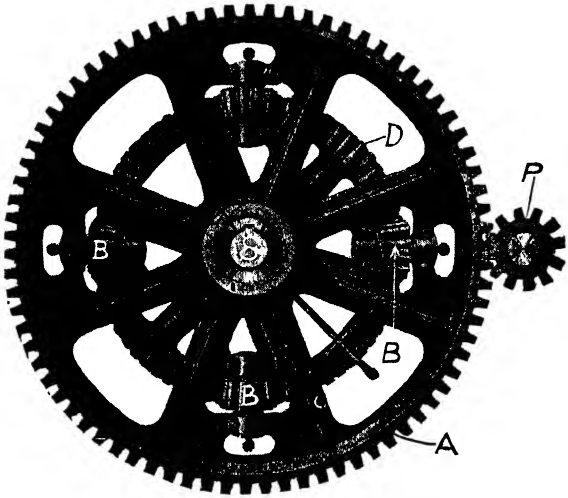


Fig. 257.—Tractor differential.

Feed-water heaters are used in connection with the better types of steam traction engines.

A simple type of slide-valve engine is employed. Some tractors are provided with double-cylinder engines. Compound engines are also used to some extent.

Oil Tractors.—The use of the oil tractor has been increasing much more rapidly than that of the steam tractor. Oil tractors are made in many different sizes, prices, and special designs suitable for various uses. An oil tractor can be started much more quickly than one propelled by a steam engine, and requires less attention.

The motors of oil tractors operate on either the Otto- or Diesel-engine cycles. Figure 258 is an end section of a Waukesha gasoline tractor engine, which operates on the Otto cycle. A side view of the same type of engine is illustrated in Fig. 259. A Diesel type engine, applied to the caterpillar tractor, is illustrated in Fig. 260.

Rating of Tractors.—Two ratings are usually given to tractors. One is in brake or belt horsepower. This indicates the power developed at the shaft of the engine, which can be used for driving various machines by means of belt drive. The other rating is the tractive or draw-bar horsepower. The tractive horsepower is usually one-half to two-thirds of the brake horsepower, depending upon the transmission gearing and on the character of the ground over which the tractor must be propelled.

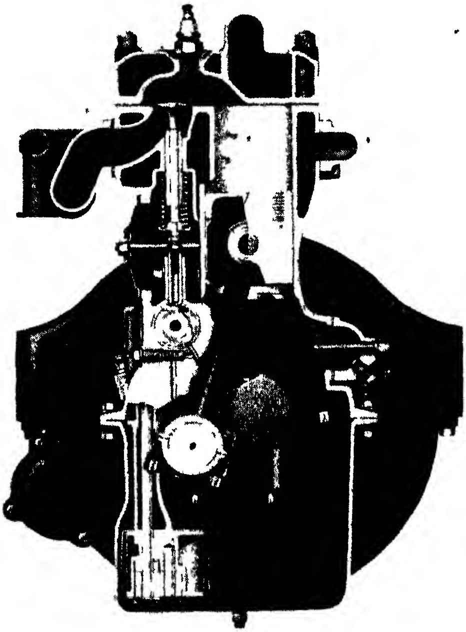


Fig. 258.—End section of a Waukesha tractor engine.

Care of Trucks and Tractors.—The general directions given concerning the care of an automobile apply to the truck and

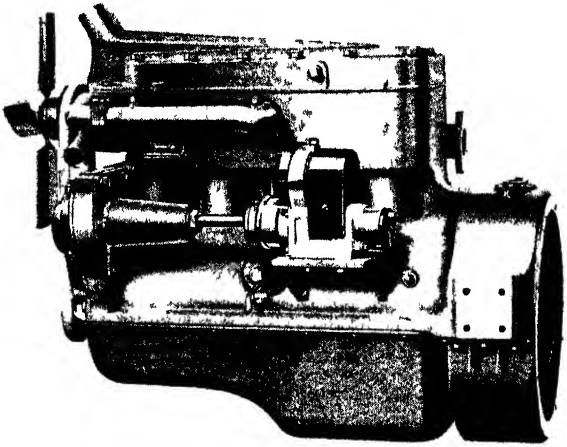


FIG 259 —Side view of a Waukesha tractor engine

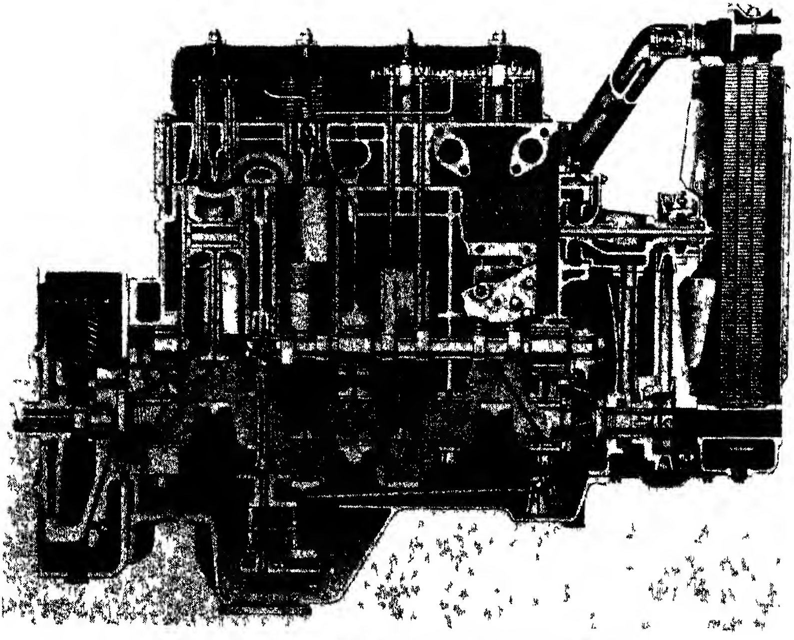


FIG 260 —Diesel engine of a caterpillar tractor.

tractor. Wearing surfaces must be kept well lubricated and lost motion in bearings must be avoided.

The steering mechanism of the tractor is less sensitive than that of the automobile or even of the truck on account of its slower speed and the lower gear ratio of the steering wheel.

Overloading a truck or a tractor is a serious mistake. The life and usefulness of any piece of machinery are increased by proper housing and systematic upkeep. The lubricating system of the motor should be examined daily. Frequent inspection should be made to determine the condition of the spark plugs, the alignment of the wheels, condition of the brakes, clutch, springs, rods, cylinders, and bearings. Valves should seat properly and should be correctly timed.

AIRPLANES

Types of Airplanes. Airplanes may be classified (1) as to their use: as pursuit plane, bombing plane, observation plane, mail plane, training plane, and passenger plane; (2) as to number of wing sections: as monoplane, sesquiplane, biplane, and triplane; (3) as to the application of the power: as pusher, tractor, helicopter, and ornithopter type; (4) as to the material used: as all metal, or wood and fabric; (5) as to the number of engines used: as single, twin, or trimotored; (6) as to type of landing gear: as seaplane, land-plane type, or amphibian which is capable of landing and taking off on either land or water.

Essential Parts of an Airplane. –The essential parts of an airplane are:

1. The power plant, which consists of an internal-combustion engine and its auxiliaries, together with the propeller which produces the tractive effort required to bring the plane to its desired speed.
2. The wings, which provide the lifting force to keep the plane and its load suspended in the air.
3. The control surfaces consisting of the ailerons, the stabilizers, the elevators, the fins, and the rudder, which give the operator control of the plane in all directions.
4. The fuselage, which forms the body of the plane and in which the load and operator are carried.

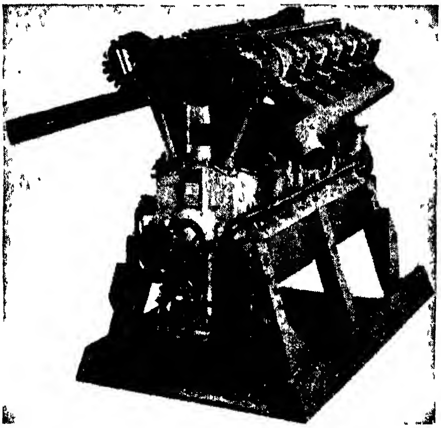


FIG. 261.—Liberty, 12-cylinder, airplane engine.

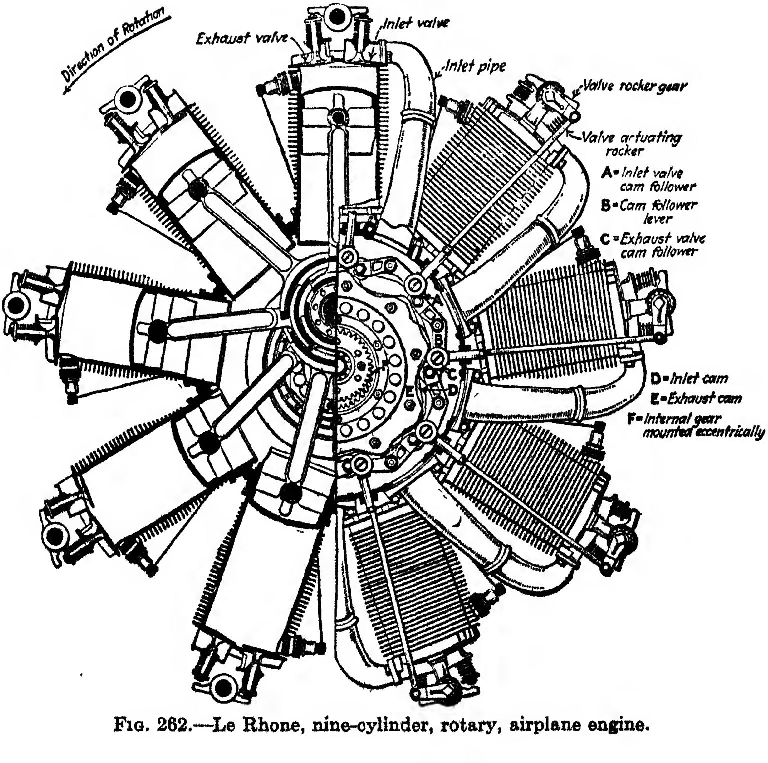


FIG. 262.—Le Rhone, nine-cylinder, rotary, airplane engine.

5. The landing gear, which supports the machine while on the ground.

6. Instruments to guide the aviator.

Airplane Engines.—Airplane engines differ from those in automobiles, tractors, and trucks largely because of the special requirements they must meet. An engine satisfactory for airplane use (1) must develop the necessary power with the least possible weight; (2) must be able to operate continuously at high speeds; (3) must be economical in the use of fuel; (4) must be reliable, flexible, and unfailing in operation; and (5) must be without excessive vibration.

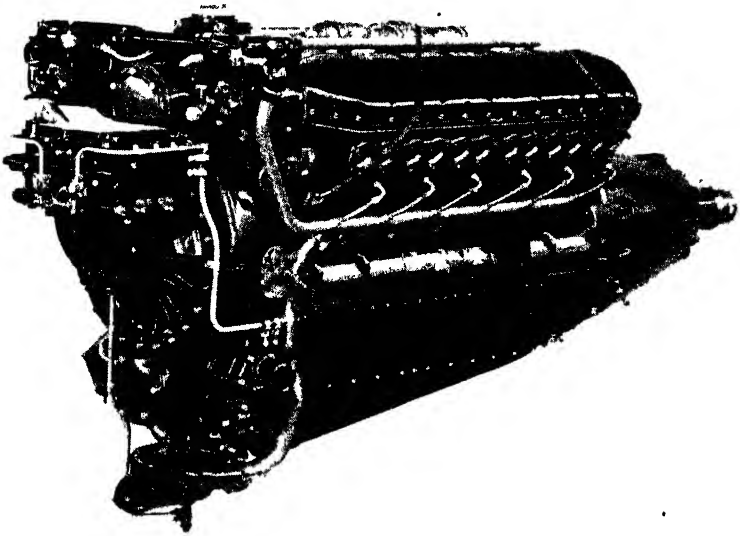


FIG 263 —Allison airplane engine.

Modern airplane engines have been the result of a great deal of experimenting and experience.

A large number of cylinders is current practice, largely because of reliability of continued operation in case one cylinder failed and because of less vibration.

Figure 261 illustrates the Liberty twelve-cylinder airplane engine developed during the World War. These engines were water-cooled, developed approximately 450 hp at a speed of 1,800 r p m and weighed about 850 lb. dry

Another popular type of engine during the World War was the Le Rhone radial rotary engine illustrated in Fig 262 In this machine the cylinders rotate with the propeller while the crank is held stationary, and the cylinders are thus cooled by air. Difficulties in balancing the rotary type of engine as well as the unfavorable gyroscopic effect of the rotating cylinders caused this type to be superseded by the radial air-cooled engine with fixed cylinders.

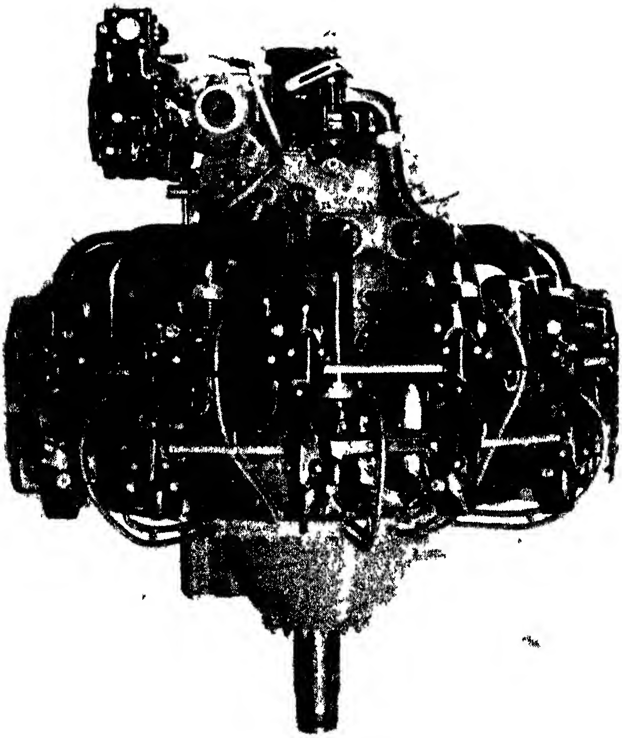


FIG. 264 —Pratt and Whitney radial engine

Both air-cooled and liquid-cooled airplane engines have continued in use since the close of the World War in 1918, but water has largely been replaced by glycol as a coolant.

Figure 263 illustrates the Allison liquid-cooled engine, which develops about 1,000 hp at 2,600 r p m at the crankshaft. Figures 264 and 265 show a Pratt and Whitney 14-cylinder radial air-cooled engine manufactured by the United Aircraft Corporation.

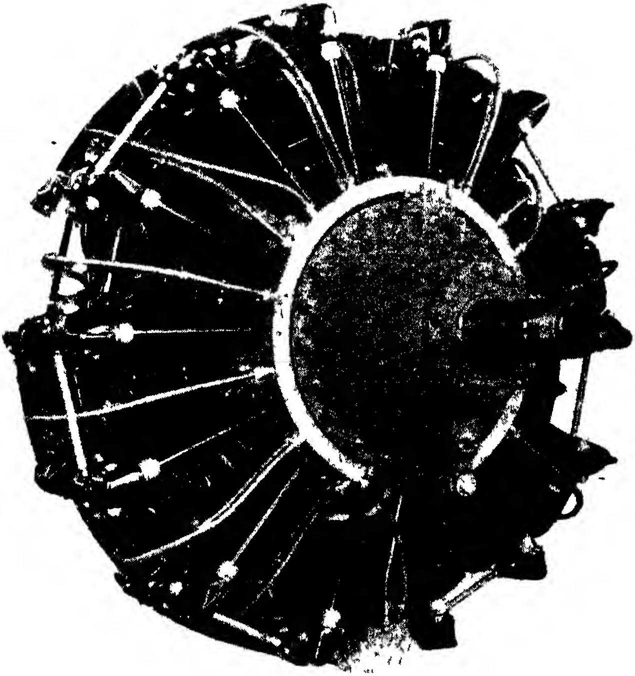


FIG. 265 —Pratt and Whitney 14-cylinder engine

The airplane engines, illustrated in Figs. 263, 264, and 265 have reduction gears of 3:2 or 2:1 to secure efficient operating speeds at the propellers Each engine weighs about 1.3 lb. per horsepower dry. The liquid-cooled engine, when installed in an airplane, will weigh somewhat more than the air-cooled, but the liquid-cooled installation may cause less aerodynamic resistance in an airplane wing, and this may more than compensate for the additional weight.

Problems

1. In which respects does the locomotive power plant differ from the ordinary stationary steam power plant?

2. Ascertain what reversing mechanism is used on the locomotives passing through your city.

3. Compare the air-brake system used on electric street cars in your city with the automatic air brakes as used on locomotives.

4. What provisions are made in modern locomotives to reduce danger from locomotive sparks?

5. What steam pressures are usually carried on American locomotives?

6. Prepare a chart to show the relative tractive efforts of steam, Diesel, and electric locomotives.

7. Make clear sketches showing the mechanism of an automobile steering gear.

8. Make a clear sketch of a universal joint.

9. Prepare a table showing the important differences in the specifications of automobiles and of trucks.

10. Compare the advantages and disadvantages of two- and four-wheel brakes.

11. Are trucks and tractors equipped with governors? If so, how does a governor of a truck function?

12. Prepare wiring diagrams for an eight-cylinder automobile motor.

13. What are the advantages of the Diesel-type engine for airplane use?

14. Prepare a table to show the economies in miles per gallon of fuel of four-, six-, eight-, and twelve-cylinder automobiles.

15. Why has a steam automobile not been commercially successful?

16. Has the electric automobile any practical value? Give reasons for your reply.

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