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HEAVY-OIL ENGINES
OF AKROYD TYPE

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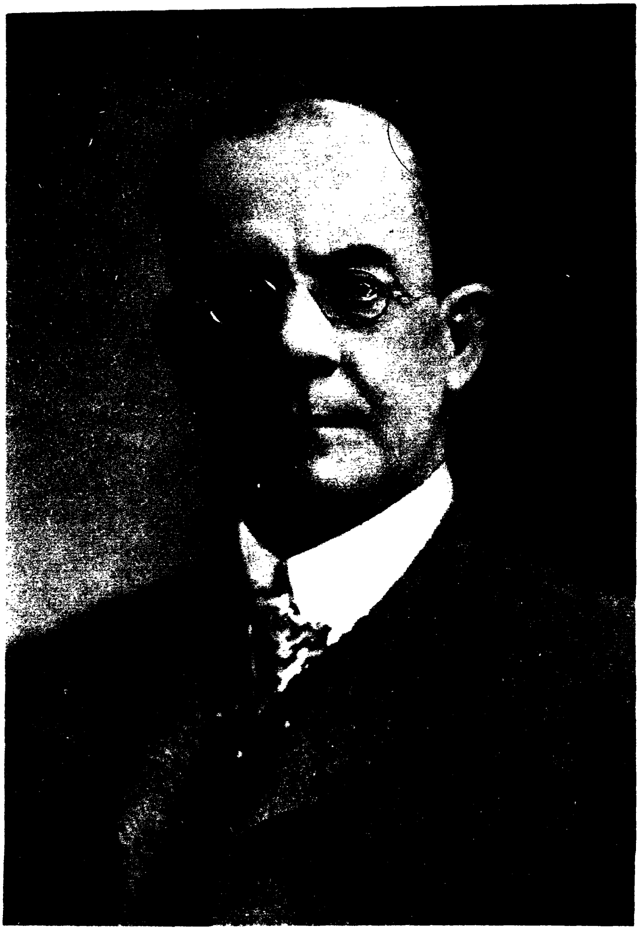

Herbert-Akroyd Stuart

HEAVY-OIL ENGINES OF AKROYD TYPE

Being Developments of Compression-ignition Oil Engines, including Modern Applications to Land Purposes, Marine and Airship Propulsion, and Railway Traction

BY

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PREFACE

In the following pages an attempt is made to furnish the reader with an account of the origin and development of the modern compression-ignition heavy-oil engine.

The Priestman may be regarded as the first successful, safe, and reliable engine in which ordinary paraffin oil was sprayed by air pressure through a nozzle into a vaporizer heated by the exhaust gases. But the compressed mixture of oil vapour and air in the cylinder was fired by the electric spark.

The author had the privilege of being in close touch with the late Herbert Akroyd Stuart in the early stages of his pioneer work, when he originated the compression-ignition type of heavy-oil engine which has produced such remarkable effects in the promotion of this great branch of engineering industry, and has influenced the practice of oil-engine design right up to the present time. It will be generally agreed that, unlike some inventors, he did not receive anything like due acknowledgment or recognition for the ingenious oil engines he invented.

His first simple yet far-reaching discovery was that by the compression of an excess charge of air in the engine cylinder, and by the injection of heavy-oil spray into the hot compressed air at the end of the compression stroke, the oil charge was ignited, giving rapid combustion or explosion at practically constant volume. This method of ignition is the characteristic of Akroyd engines and is common to most modern oil engines.

Later developments, founded on his original work, have been carried out by other British inventors, who deserve recognition for the recent successes achieved.

As pointed out by the late Captain H. Riall Sankey, C.B., R.E., when President of the Institution of Mechanical Engineers, " it might very well be agreed, that an oil engine compressing pure air and injecting oil at the end of the compression stroke should be called an Akroyd engine, and not a Diesel engine ".

The Diesel engine, evolved at Augsburg, Germany, seven years later than the Akroyd, used injection of oil fuel by very high-pressure air and *gradual combustion* at constant pressure, and is now rarely found except in large-power units. Whereas the Akroyd type uses quick airless-injection, by means of a pump and spraying nozzle, and *rapid combustion* at constant volume, yet the name " Diesel " is now applied to both types, and credit given to Diesel.

The second important discovery of Akroyd Stuart was a " foolproof " oil engine with a two-cell combustion chamber connected by a conduit of reduced area or a narrow neck which gives a well-defined stratified charge and imparts forced turbulence with all that follows from it. So much has his work been obscured that continental engineers now use airless injection and even the Akroyd two-cell combustion chamber, the latter as a new device, without reference to its origin.

There are several similar instances of the credit of British inventions being claimed for foreigners, so obscuring the work of British engineers, who are apparently too modest or magnanimous to seek publicity for their own achievements.

Under these conditions, the author, having no pecuniary interest whatsoever in the sale or manufacture of any oil engine, could not resist the request to give a brief record of the development of the heavy-oil engine, including only a few typical compression-ignition oil engines using airless injection and the constant-volume Akroyd cycle; taking examples of their applications to land purposes in electric generating stations, marine and airship propulsion, also for traction on road and railway.

Many other heavy-oil engines using the Akroyd cycle might be mentioned, but it is hoped those given will suffice to indicate the trend of invention. Heavy-oil high-compression ignition engines are now practically all coming to use the airless-injection constant-volume Akroyd cycle, that is, leaving Diesel practice of air-blast injection, with the complication of multi-stage air compressor, and the constant-pressure type, and returning to that of Akroyd Stuart.

The Akroyd cycle engine is more particularly exemplified to-day by heavy-oil engines of the quicker running type. The British multi-cylinder, quick-running, high-compression heavy-oil engines of light weight-to-power ratio, have proved most economical of fuel, and efficient in service for railway traction, and in British airships. Rapid progress has been made in these applications since airless injection and combustion at constant volume have been returned to, both in four-stroke and two-stroke cycles.

The author's grateful acknowledgments are due to the engineers and manufacturing firms who have favoured him with information, data, and drawings used in this book; to the Councils of the Institutions of Civil and Mechanical Engineers and to the other Institutions for the loan of blocks, for which acknowledgment is made in the footnotes; also to the publishers of *The Engineer* and *Engineering* for illustrations that appeared in their journals, and to Sir Isaac Pitman & Son, Ltd., for the loan of several blocks from his book on *Applied Thermodynamics*.

WILLIAM ROBINSON.

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Length.—One foot = one-third standard yard = 0·3048 metre.
One metre = 39·3702 inches, or 1 inch = 2·54 centimetres = 25·4 mm.

Weight.—lb. = pound's weight, and 1 kilogramme = 2·20462 lb.

Pressure.—lb. per sq. in. = pounds per square inch.
1 kilog. per sq. cm. = 14·223 lb. per sq. in.
b.h.p. = brake horse-power.
ind.h.p. = indicated horse-power.
r.p.m. = revolutions per minute.

Temperature.—(Centigrade) C.° = $\frac{5}{9}$ (F°−32), and Fahr.° = 1·8 C.° + 32.
T = absolute temperature = temp. C.° + 273 = temp. F.° + 460(approx.)

Volume.—1 British Standard gallon (8 pints) contains 10 lb. pure water at 62° F. and has a volume of 277·27 c. in.
1 American gallon of pure water weighs 8·331 lb. water at 62° F.
Thus 6 American gallons = 5 British gallons (nearly).

Energy.—1 B.Th.U. = one British thermal unit = 778 ft.-lb.
1 h.p. hour = one horse-power hour = 33,000 × 60 ft.-lb. = 2545 B.Th.U.
1 kilowatt-hour = 1000 watt-hours = Board of Trade unit of electrical energy.

Power.—1 Watt = 1 ampere × 1 volt = 0·7372 ft.-lb. per second.
1 Kilowatt = 1·3405 h.p.
1 British H.P. = 550 ft.-lb. per second = 746 watts.
1 Metric H.P. = 75 kilog. metres per second = 736 watts
= 0·9863 British H.P.

HEAVY-OIL ENGINES

CHAPTER I

Introduction

In the development of the modern internal-combustion engine, there are three outstanding dates or stages, curiously enough each fourteen years apart from the other, leading to the origin of the heavy-oil compression-ignition engine, namely, the years 1862, 1876, and 1890.

In the year 1862 a French engineer, Beau de Rochas, took out a patent and published a pamphlet in which, with wonderful insight, he laid down, on a sound scientific basis, the four chief conditions necessary to obtain, with greatest economy, power from the combustion of gaseous fuel in the internal-combustion engine; and further described the now well-known four-stroke cycle of operations in a motor cylinder to realize these results.

Fourteen years later, in 1876, this cycle was adopted and made a practical success by a German, Dr. N. A. Otto, in the common type of gas engine, introduced and developed in this country by Messrs. Crossley Bros., Manchester, and subsequently by many others.

The operations of the Beau de Rochas or Otto cycle, in one end of a single cylinder, are: first, outstroke of the piston, *charging* or *induction* of the explosive mixture of gaseous fuel and air; second, during the return stroke, *compression* of that mixture; third, *ignition*, *explosion*, and *expansion* during the power stroke; and fourth, *exhaust* of the burnt products during the next return stroke. These four piston strokes are repeated in the same order, giving one explosion or power stroke in two revolutions of the crank-shaft, and allowing time for cooling the cylinder.

In order to obtain greater power output and more uniform turning effort, 2, 4, 6, 8, or 12 cylinders have been combined to drive one crank-shaft in the multi-cylinder engine.

Beau de Rochas' conditions for best economy of fuel or highest thermal efficiency are: first, in order to reduce the loss of heat, the cooling surface of the combustion chamber in contact with the hot burning gases must be reduced to a minimum, that is, the combustion space has to be compact in shape, without recesses or pockets, and as nearly spherical as possible, say by dome-shaped cylinder cover and slightly concave piston head. Incidentally, this construction gives turbulence and good admixture of the charge, and reduces the tendency to detonation even with a flat piston head.

Second, high piston speed in order to convert the heat energy generated by the explosion into useful work quickly, and to reduce the time for loss of heat to the cylinder wall, by cooling.

Third, long range of expansion, namely, a large volume swept by the piston compared with the volume of the charge at ignition. In a sense, it is this expansion ratio, and not the compression ratio alone, that determines the thermal efficiency, as in the Atkinson cycle engine.

Fourth, the highest practical compression of the charge before ignition. Compression, by raising the temperature and bringing the particles of the gaseous mixture intimately into contact, tends to give rapid combustion, and is only limited by pre-ignition of the charge and the strength of the cylinder to withstand the increased initial pressure of the explosion.

Very soon other inventors: James Robson of North Shields, in Patent No. 2334 of 1877, and No. 4501 of 1879, performed all the operations of charging, compression, combustion, and exhaust in a *single cylinder* having a single piston, and in one revolution of the crank-shaft or two strokes of the piston. One end of the piston was used as a pump for drawing in and compressing the mixture of gas and air, into a reservoir, and the other end of the piston for explosion and exhaust, giving an impulse every revolution of the crank-shaft. The Robson *two-stroke cycle* gas engine was modified and built by Messrs. Tangye of Birmingham.

Sir Dugald Clerk, from 1878 to 1881, also developed the two-stroke compression cycle, giving an impulse or explosion in a single cylinder every revolution of the crank-shaft, in order to obtain greater uniformity in torque or turning effort, although the economy of fuel was not quite so good in small engines. In the engine of 1881, Clerk used an auxiliary cylinder with pump piston to draw in a measured charge of gas and air, and to deliver it into the power cylinder. Exhaust took place near the end of the explosion stroke, followed by charging and compression on the return stroke, when the power piston overran the exhaust ports.

Prior to 1890, the *combustible mixture*, after compression in the cylinder of gas and oil engines, was ignited by the electric spark, or by various devices of flame, heated platinum coil, and tubes kept red-hot by external burners. All these methods of ignition were dispensed with in the Akroyd **automatic compression-ignition** heavy-oil engine cycle of which Herbert Akroyd Stuart was the originator in the year 1890.

Paraffin oil or kerosene had been used in early oil engines, but petroleum spirit (petrol) or naphtha was regarded as dangerous owing to ignition of the petrol in cases of accidents at that time, and the British public had little confidence in any kind of oil engine.

Priestman Oil Engine.—To Messrs. Priestman Bros. of Hull is due the credit of producing a *safe* and reliable petroleum-oil engine—a self-contained and successful prime motor. Its fuel was ordinary paraffin oil of specific gravity 0·79 to 0·81 and flash point 76° F. to 150° F. The Priestman oil engine was first exhibited in 1888 at the Royal Agricultural Show at Nottingham. In 1891 it was improved to run on Russolene of specific gravity 0·82, but it worked best with Lighthouse oil and Royal Daylight.

In *tests* made by Professor Unwin,* the rate of consumption, at full load, was 0·842 lb. of Royal Daylight oil per brake h.p. per hour; and in two full-load trials the consumption of Russolene oil was 0·988 lb. and 0·946 lb. per brake h.p. hour.

The characteristic features of this engine are the methods of spraying the oil by compressed air, mixing each charge of oil spray and air in proper proportions, heating this mixture in a vaporizer by the exhaust gases, and automatically regulating the varying strength of the charge by a centrifugal governor to keep the speed constant for all loads. This adjustment was the chief difficulty in the manufacture, and could only be an approximation for different oils. In a single cylinder there is an explosion every second revolution, and no complete cut-off.

The *spray-maker*, K (fig. 1), consists of two concentric conical

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* *Proc. Inst. C. E.*, Vol. 109, p. 1.

mouthpieces. The compressed-air mouthpiece is re-entrant and turns the air flow in the outer annular space, JJ, through more than a right angle, to converge and meet the oil jet issuing from the bottle-neck central passage and tapering hole in the oil plug H. The compressed air flows from the top of the oil in the tank to the spraying nozzle, and the oil, by another pipe from the bottom of the tank, is forced by the air pressure to the V-shaped notch and taper hole through the oil plug H. The latter may be slightly turned by the governor acting on the lever S, to vary the opening in H for the oil flow. The oil jet issuing from the mouthpiece KK is broken up into fine spray or mist by the air-blast from JJ, and is held in suspension by the air in the heated vaporizer. A throttle-valve G, on the prolongation of the oil plug SH, and fitted in the auxiliary air passage F, is regulated at the same time as the oil by the governor, and carefully adjusted to give the correct proportion of air to oil. The suction stroke of the piston opens an automatic inlet valve L, when a large auxiliary supply of fresh air is admitted and sucked past the throttle valve G, enters the vaporizer by small holes *ab*, and sweeps the vaporized charge into the cylinder.

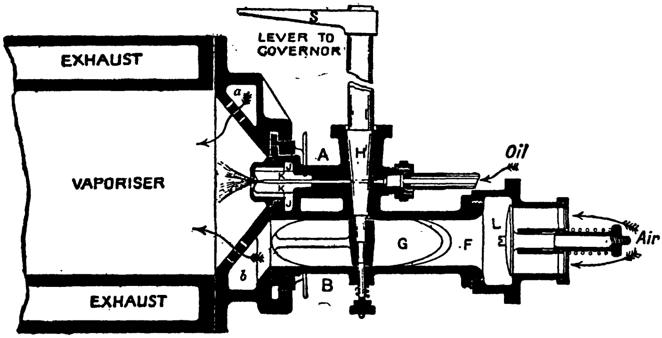

Fig. 1.—Priestman Spray-maker (Sectional Plan)

An eccentric rod, geared to half speed of the crank-shaft, has three functions: First, it works the pump which compresses air into the oil tank to force the oil and air through the spraying nozzle; second, it opens the exhaust valve at the correct moment and allows the hot exhaust gases to escape through the vaporizer jacket; and third, a knob or adjustable finger on the eccentric rod is brought between two spring contacts to close the battery circuit at the end of the compression stroke, to excite the induction coil and cause the electric spark to pass between the two platinum points of the ignition plug, which fires the charge. Unskilled handling of the induction coil was likely to give the attendant a shock.

The engine works on the four-stroke cycle. The explosive mixture of oil vapour and air, drawn into the cylinder during the suction stroke, is compressed on the return stroke, and fired at the end of the compression stroke, giving explosion and expansion in the power stroke. The next return stroke drives out the burnt products through the exhaust valve and vaporizer jacket to heat and vaporize the next incoming charge. Incidentally, even with low compression a small portion of the heavier hydrocarbon constituents in the oil vapour is condensed on the cylinder liner during compression, and lubricates the piston. Although about three times the quantity of air necessary for complete combustion of the oil is taken, the compression is kept low to avoid this condensation and the danger of pre-ignition after prolonged running at full load. It was found that the steadiness in running at full load was improved by a few drops of water admitted into the combustion chamber during the suction or charging stroke. The steam formed reduces the hard metallic knocks or blows of sudden explosions, increases the compression slightly without danger of pre-ignition, reduces the highest explosion pressure, and gives a higher mean effective pressure during expansion.

In 1891–2 this self-contained oil engine was adopted to work air compressors for fog signalling at lighthouses by the Northern Lighthouse Board, and Trinity House Brethren, by the Irish Lighthouse Board, and by the Norwegian Government. It was also used for pumping and rock-drilling in various mines, driving dynamos for private electric light installations in the country, and for agricultural purposes. The twin-cylinder vertical high-speed type was applied to the propulsion of barges, launches, and fishing smacks.

The engine was built up to 100 h.p.; but the cost of manufacture told against it in competition with heavy-oil engines of simpler design.

A single-cylinder Priestman oil engine of 8·5 brake h.p., in charge of the Author, after seven years' service, was tested in 1900, during a run of two hours at ordinary working load on the brake at 160 revolutions per minute. The consumption was 1·05 lb. of Royal Daylight of specific gravity 0·792 at 60° F. and flash point (closed) 83° F., gross calorific value, 20,000 B.Th.U., and net value 18,800 B.Th.U. per lb.

Oil Supply.—Since 1918 the world's annual output of crude oil has been practically doubled, from 68 to about 135 million tons, while the demand for petrol has increased still more rapidly with the further steady increase in the number of motor cars, buses, and lorries in use. The successful application of the compression-ignition heavy-oil engine to marine propulsion has also advanced rapidly on account of its high thermal efficiency. The gross tonnage of motor-ships by Lloyd's Register during the year has increased from 75,934 to 812,437 tons since the year 1918; while the proportion of motor tonnage to the total during each year has increased from 2 per cent to 43·3 per cent. Many vessels are fitted for oil burning because of its convenience and economy; the arduous manual operation of coaling being replaced by the simple oil fuelling and use; but some steam-boiler furnaces are fitted to burn coal when the price makes it more economical. The effect on the trade may be realized when the consumption of one gigantic transatlantic liner is about 1000 tons of fuel oil per day.

In this country, near the coal-fields and far from oil wells, the price per ton of fuel oil in bulk (70 shillings per ton) is four times that of coal, and curiously the fluctuations keep nearly proportional whilst varying with the demand; but this relative cost depends also on transport charges, and consequently, varies greatly in different countries.

The cost of production of crude petroleum is small compared with that of coal or shale oil. Crude oil is taken through pipes from the wells to reservoirs or tanks, and so to the refineries. In comparison, the capital and cost of working at collieries and the freights for haulage of coal by rail are heavy.

It is not yet possible to estimate the petroleum oil supply available; though the output of some oil-fields in our chief source, America, has been reduced, deeper drilling in those apparently exhausted is giving a new supply. California has produced more oil than the total estimated as available a dozen years ago, and is still going strong. There may be vast underground pools yet untapped elsewhere. However, the oil companies are evidently confident as regards the oil supply and have laid down oil-storage tanks and plant in ports throughout the world.

Enormous deposits of oil-bearing shale have already been explored in many countries, that would yield an oil supply far greater than the reserve in the oil wells, and will be available when petroleum oil becomes more limited or too costly. In Scotland the average yield of a ton of Broxburn shale by distillation is only 20 gallons of crude oil, with sulphate of ammonia and other by-products. American bituminous shales yield about a barrel (42 American gallons) of oil per ton; and the yield of some Russian shales is nearly double this quantity of oil. The Esthonia bituminous oil shale, by distillation in the Kohtla retorts at 550° C., yields 74 gallons of crude oil per ton. This crude shale oil by distillation gives Diesel oil of specific gravity 0·93 to 0·95 at 15° C., flash point (Pensky-Martens) over 60° C., and calorific value 17,460 to 18,000 B.Th.U. per lb. The Davidson rotary retort is also being used in Esthonia. Whether from petroleum or shale, it is highly probable that sufficient oil supply is assured for many future generations.

Fuel Oil.—*Crude petroleum oil* issuing from oil wells is nearly like *crude shale oil* obtained by the distillation of bituminous shale heated in retorts at 900° F., while superheated steam is passed through the retort to carry over the paraffin-oil vapours and ammonia without dissociation. Each crude oil consists of a complex mixture of various solid, liquid, and gaseous hydrocarbons in solution. These are separated by fractional distillation into:

First Fraction.—Gasoline, a mixture of paraffins and olefines of specific gravity 0·725. Motor spirit or petrol has flash point (close test) 0° to 32° F.

Second Fraction.—Kerosenes or paraffin oils of specific gravity 0·795 to 0·83, and flash point (close) 82° F. and upwards. The heavy paraffins, when distilled under pressure at a temperature higher than their normal boiling-points, are decomposed or *cracked* into lighter paraffins of lower boiling-points, and olefines, while gas is evolved and a little solid carbon deposited. By this *cracking process* distillers obtain a larger yield of the lighter oils, both gasoline and kerosene, than the crude oils would yield by ordinary fractional distillation. The yields of these fractions from different crude oils vary greatly in refinery practice. By the large demand and higher price of gasoline, refiners are naturally induced to crack the greatest possible amount of petrol out of the heavier oils, leaving only the residual fuel oil.

Third Fraction.—Solar or gas oils of specific gravity 0·84 to 0·88 are suitable fuel for internal-combustion engines. When the viscosity does not exceed 40 seconds at 100° F., these oils are readily broken up into fine spray. Excess of air, with the residual burnt products in the clearance space of the engine cylinder, hold in suspension the heavier hydrocarbon vapours of the sprayed oil, like a cloud, which is ignited by the hot compressed air. Although the heavier paraffins have higher flash points than motor spirit, they are most easily ignited when thoroughly pulverized.

Fuel oils for heavy-oil engines are of specific gravity 0·85 and upwards at 15° C. (59° F.); the usual range is to 0·95. These fuel oils are never purely refined distillates, but are either "topped" crude oils, of low asphalt content, from which gasoline and kerosenes have been distilled; or mixtures of gas oil and heavy residuals—the latter known as " boiler fuel " of specific gravity 0·95. Thick sluggish oils of great viscosity and high ignition temperature, like tar-oils, of specific gravity 1·019, have also been used satisfactorily in airless-injection compression-ignition oil engines, with a lighter fuel oil for pilot ignition (see pp. 26, 61). The fuel oils in common use in heavy-oil engines are hydrocarbon oils of petroleum or shale origin, and must be free from mineral acid, and care taken to get rid of water, sand and other solid *impurities* by heating in settling tanks, and by being passed through high-speed centrifugal separators and effective filters or strainers. This treatment does not remove ash and hard asphaltum, or substances in solution in fuel oils, which tend to produce deposits in the engine cylinder and by their abrasive action cause undue wear of the cylinder liner and piston rings. It is found desirable that the total *ash* content should not exceed 0·05 per cent, *water* not to exceed 1 per cent, and *hard asphaltum* not more than 4 per cent, though in some " boiler fuel " the limit is 12 per cent.

Hard asphaltum in petroleum oils increases the viscosity, reduces the calorific value, and is not always completely burned in high-speed heavy-oil engines, but forms a very hard coke deposit.

In order to indicate the limits of the deleterious matter in these oils, the British Engineering Standards Association decided upon four standard specifications (Pamphlet No. 209 * of 1924) of fuel oils suitable for heavy-oil engines. Limits are given of

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* This pamphlet can be obtained from the Secretary of the Association, 28 Victoria Street, Westminster, London, S.W. 1.

certain physical properties of petroleum or shale oils supplied to specifications of the four grades, and the percentages allowed, and the appropriate tests for the deleterious constituents—hard asphalt, water, and ash; also the various determinations to be made according to the Standard methods of testing petroleum and its products published by the Institution of Petroleum Technologists: The *flash point*, by Pensky-Martens closed tester not to be less than 150° F. The Admiralty demands not less than 175° F. for all fuel oils. *Viscosity* by the Redwood No. 1 Viscometer, and the result is expressed as the time in seconds for the flow of 50 c. c. at 100° F. The *pour point* (cold test) is defined as " the lowest temperature at which the oil will pour or flow, when it is heated and then chilled, without disturbance, under certain definite specified conditions ". Or the " pour point " is the temperature 5° F. (2·9° C.) above the solid point or temperature at which all constituent hydrocarbons in the oil are frozen solid and cease to flow. In the four grades specified, the oil is to remain liquid at 20° F., 35° F., 40° F., and 45° F., respectively. Fuel oils purchased to these specifications will have a *gross calorific value* of not less than the following: B.S. fuel oil No. 1:—19,000 B.Th.U. per lb.; No. 2:—19,000 B.Th.U. per lb.; No. 3:—18,750 B.Th.U. per lb.; and No. 4:—18,500 B.Th.U. per lb.

CHAPTER II

Akroyd Compression-ignition Heavy-oil Engines

Herbert Akroyd Stuart was born in Yorkshire, on 28th January, 1864. He was educated at Newbury Grammar School in Berks, and at the City and Guilds of London Technical College, Finsbury. He received his early practical training in the engineering works of his father, Charles Stuart, at Fenny Stratford; and upon the death of his father he took over the management of the works. He died on 19th February, 1927, at his residence " Akroydon ", Claremont, Western Australia.

The experimental work of Herbert Akroyd Stuart on oil engines began in the year 1886, and was carried out in his Iron-works at Bletchley, Bucks. His attention was directed to this branch of engineering by an accident in 1885, when experimenting with machinery for coating iron and steel sheets with tin at Llanelly, Carmarthenshire, South Wales. The " dross " or " scum " that accumulates on the surface of the molten metal must be cleaned off occasionally, and to do so the " flux " or " grease " (used in this process) about 12 to 15 in. deep had to be removed. At one of these " cleanings " the " dross " had just been removed, and while Akroyd Stuart was looking down into the " tinning pot " to inspect the molten tin, with a lighted malleable-iron wick-type of paraffin lamp, some of the oil was spilled on the molten metal. The vapour mixed with the heated air quickly rose to the lamp, and burst into flame. Somehow, his face escaped from being badly burned. Upon recovering from the shock, he decided to repeat the experiment and observe what really would happen. Care was taken to suspend the lighted lamp a little way down the tinning pot into the hot air. Then a small quantity of paraffin oil was poured down on the molten metal. Again the mixture of oil vapour and heated air was ignited. This was repeated with a similar result. Thereupon, he was led to think out a scheme to make use of the experience he had gained, i.e. to design an engine to work on oil vapour.

Being a young man with ambition, he visualized not only an oil engine but a self-contained and combined oil engine, air compressor, or force pump to do useful work in pumping water, &c. This combination is illustrated in his first patent specification No. 9866 of 31st July, 1886. At that date oil-engine design was to him an entirely new departure in engineering, although he was familiar with the Crossley gas engine. So, in order to gain some rudimentary experience of oil-engine behaviour, his idea was to build an experimental engine with plenty of moving parts.

He discarded the water pump parts, and soon decided he had, first of all, to build an oil engine that would work. The method of working adopted was to start the engine with benzoline, regulating the sight-feed fuel drip by hand, and heat "something" by the explosions—layers of gauze or a bunch of small tubes, fitted within the combustion chamber or clearance space of the engine cylinder. Ignition with a lamp constantly burning, and many kinds of rotary valves were tried with but little success. A reciprocating slide valve was substituted, for timing the ignition, actuated by the piston through a lever arrangement. Eventually this was discarded for electric ignition by battery and induction coil. But he intended to use a similar lever motion to work the plunger of the oil pump for a two-stroke cycle engine. That novel method would give a very simple reversible oil engine.

In every case a *thorough admixture of the oil vapour and air* was considered absolutely essential before compression in order to obtain complete combustion, as in the gas engine. In the year 1888 a vertical type (Patent No. 14076) was built of 2 h.p., but air draughts caused trouble with the lamp. An air chamber was used to measure and inject the oil fuel by a simple, novel kind of air pump: air injection at 20 to 30 lb. per sq. in. This air-chamber pump was sluggish in action, and was discarded because the combustion was incomplete, leaving carbon deposit.

His iron foundry had been a costly concern, and he decided in future to have the iron castings made elsewhere. Messrs. George Wailes, Ltd., Euston Road, London, made the castings and built some of the 1890 type of Akroyd engines to his instructions. In the Akroyd patent No. 14868 of 1889, the exhaust valve is actuated by an eccentric rod and rocking lever. A similar method has been adopted in some modern engines to actuate the injection oil pumps, suction valves, and exhaust valves, and is a simple serviceable arrangement for modern marine oil engines.

He also designed and made a special plunger pump to measure more accurately and inject *quickly* the charge of oil fuel. This gave great promise of success. The engines started readily and worked well, but when running under full load pre-ignition of the combustible mixture occurred frequently. What was the cause of this continual trouble? He concluded that overheating of the internal vaporizer ignited the mixture of heavy-oil vapour and air during the compression stroke. The next step was to take out the internal part of the vaporizer, and cover the crown and sides of the vaporizer with an asbestos-cloth hood. Thus fitted, the vaporizer could be kept hot by the constant-burning lamp and the explosions, but still pre-ignition of the mixed working charge occurred. The next endeavour was, if possible, to do without the burning lamp, which had given trouble throughout these experiments.

At that time there was controversy as regards *stratification* of the working charge of gas and air in the Otto gas-engine cylinder, and opinions differed on the subject. Whether stratification occurs or does not in a *gas* engine, Akroyd Stuart was satisfied from his own experiments that in a *liquid fuel* engine the charge should be stratified, i.e. a lean mixture of pure air only next the piston head which would help to keep the piston clean and the piston rings free.

During these experiments, in order to avoid the risk of pre-ignition and other troubles, Akroyd Stuart conceived the novel and brilliant idea of **changing the cycle** by first filling the engine cylinder with ordinary air alone during the suction stroke, then heating the excess charge of air by compression in the vaporizer or combustion chamber, and experiment proved that *heavy-oil spray could be ignited by rapid injection, by means of a pump and spraying nozzle, into the hot compressed air in the combustion chamber when the piston was at or near the end of the compression stroke, without any external source of ignition; and the explosion was at practically constant volume.*

This most important discovery of *automatic ignition by hot compressed air, or compression-ignition*, makes possible the use of higher compression pressures and of much heavier oil fuel with

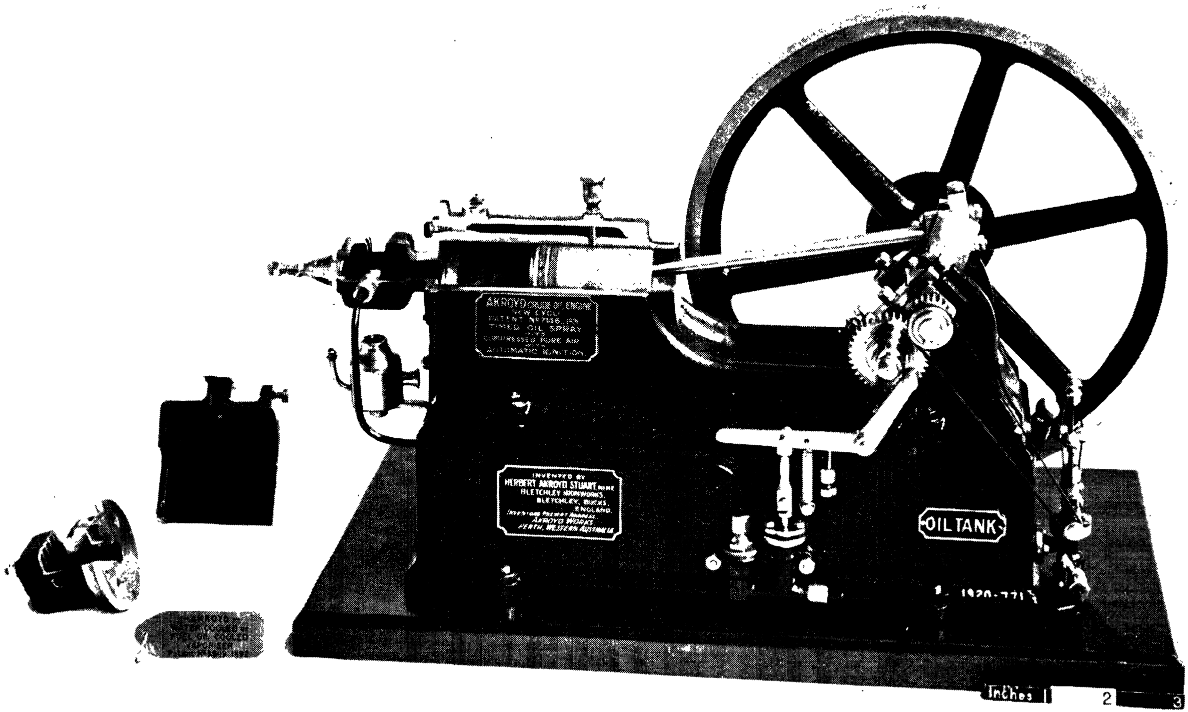

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Fig. 2.—AKROYD HEAVY-OIL ENGINE—NEW CYCLE (8th May, 1890)

advantage, and marks the beginning of a **new period**—the *origin of the modern compression-ignition heavy-oil engine.*

The principle of ignition by hot compressed air, with combustion at practically constant volume, is the characteristic of Akroyd engines, and this is adopted in the common class of heavy-oil engine met with nowadays.

The **Akroyd cycle** is different from that of Beau de Rochas or Otto, because in the latter the combustible charge was first thoroughly mixed before compression, and the methods of ignition were different. Further, in the Akroyd engine of the year 1890, when air is compressed to be hot enough, the ignition is under control by *timing the injection* of the oil spray near the end of the compression stroke.

Akroyd Stuart had been laboratory Assistant at the City and Guilds of London Technical College, Finsbury, in the early days of the Mechanical Engineering Department. He kept the Author in touch with his experiments at Bletchley, and this discovery was made known to him at once. At first it seemed too good to be true or practical, but the Author advised him to take out Patent protection immediately, to be completed later on, if the automatic ignition of the oil spray injected into compressed air without external heating proved reliable for continuous running of the engine at different loads and steady speed.

The construction of the Akroyd compression-ignition oil engine (fig. 2)* was remarkable for its simplicity.

In the most important and far-reaching patent specification No. 7146 of 8th May, 1890, Akroyd Stuart described this new type of heavy-oil engine of remarkably simple construction, with practically no cylinder clearance space. A vaporizer or combustion chamber at the rear end of the power cylinder (figs. 2 and 3) has internal webs BB, parallel to the axis, giving a large heating surface, and is open by a neck or throat to the motor cylinder, and the air inlet valve at the other end. When starting, the vaporizer is heated by an oil lamp until the temperature obtained is sufficient to ignite a few charges by compression of the air and set the engine going. Then the *starting lamp is removed,* and the *combustion chamber is maintained at a high enough temperature by the heat retained from the previous explosions, together with the heat of compression of the air to ensure regular automatic ignition.* In fact,

* A model of this engine is exhibited in the Science Museum, South Kensington, London.

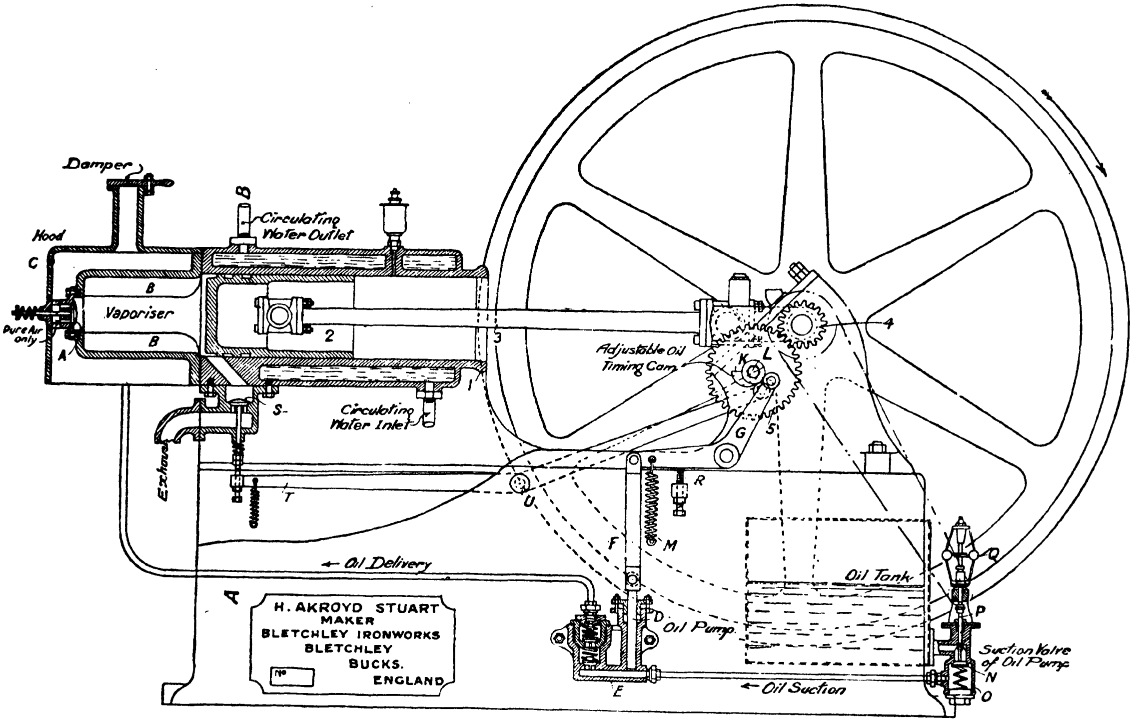

Fig. 3.—Akroyd Heavy-oil Engine: New Cycle (8th May, 1890)

the spring on the air inlet valve at the end of the combustion chamber became overheated, and its position was soon changed to the exhaust valve box underneath the small clearance space (fig. 4), where some of the exhaust heat warmed the incoming excess air during the suction stroke.

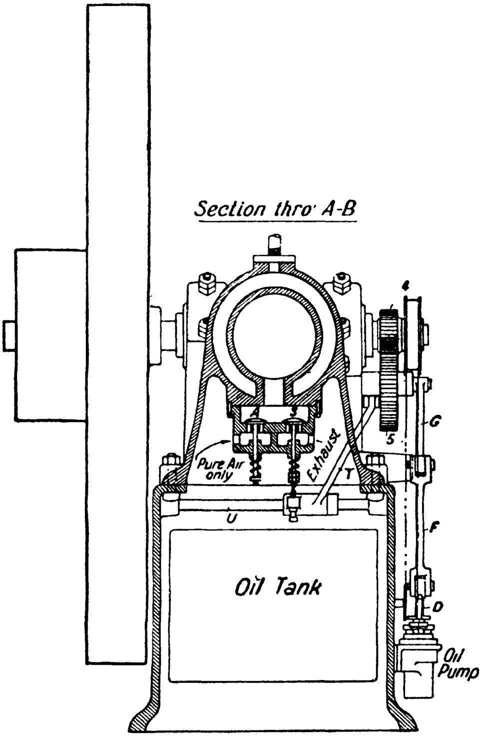

Fig. 4.—Akroyd Heavy-oil Engine (Section through AB)

The essential working parts, found more or less modified in modern oil engines running at ordinary speed, are: A *steep cam* K (fig. 3), on the half-speed shaft, by a thrust works the oil-pump plunger D through a bell-crank lever G, and the stiff spring M returns the bell crank *quickly* when released by the cam, and thereby delivers the charge of oil *quickly* through the spraying nozzle into the hot compressed air, near the end of the air-compression stroke. This cam K (fig. 3) is adjustable in order to *time the injection correctly*. Every charge of oil is drawn from the tank by the pump plunger, forced along the delivery pipe, and injected quickly through the spraying nozzle into the combustion chamber at the correct moment for ignition. A set-screw R adjusts the travel of the pump plunger to vary the supply of oil to the cylinder to suit the load on the engine.

The centrifugal governor (figs. 5 and 6), driven from the crankshaft, controls the speed by regulating the oil supply. When the engine runs slightly above its normal speed the governor spindle presses down upon, and partially opens, the suction valve, and allows the pump to force all or part of the oil charge back into the tank or by an overflow (fig. 6).

Fig. 5 shows the 1890 type of Akroyd centrifugal governor for regulating the speed by operating the suction valve of the oil-fuel pump. The balls R, R, R revolve round the plunger P, which is made square at the lower end to prevent it rotating. The spindle P is kept up to the collar on stop P′, and clear of the suction valve N, with the spring S, until the plunger P is moved down, when the balls R, R, R diverge under centrifugal action and thus partly open the valve N, to allow a portion of the oil charge to be returned into the oil tank instead of to the vaporizer. The light spring T returns the suction valve N to its normal position. The speed of the engine may be varied by adjusting the set screw X.

Fig. 6 shows the overflow type of governor.

In this way the pump is always worked, and the pipes kept full of oil, to avoid air lock. The exhaust valve S (fig. 3) is opened by a cam on the half-speed shaft L, through the lever T, and closed by a stiff spring when released by the cam.

When the vaporizer is warmed up, the operation of the engine is as follows. During the outward stroke of the piston the charge of excess air is drawn through the inlet valve A (fig. 3), and compressed on the return stroke into the vaporizer or combustion chamber BB. In the meantime the pump D has drawn a charge of oil from the tank, and forced it with great velocity through the spraying nozzle into the highly heated compressed air in the combustion chamber, near the end of the compression stroke. The finely-divided oil spray or mist is ignited automatically by the hot compressed air, giving rapid explosion at constant volume, and expansion, driving the piston on the power stroke. On the next return stroke the exhaust valve S is opened, and the piston drives the products of combustion out of the cylinder. The same cycle of operations (fig. 7) is repeated, and the temperature of the combustion chamber is kept high enough by the explosions and compression of the excess air to ignite each charge. With heavy hydrocarbon oils the compression is increased, depending upon the ignition point of the oil, so that much heavier oil fuels may be used than heretofore.

In his pioneer experiments Akroyd Stuart observed that his engines, with the combustion chamber having a large trumpet-shape mouth open to the motor cylinder (fig. 3), would work

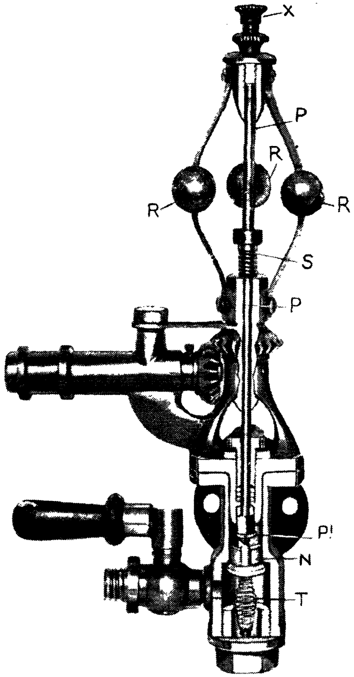

Fig. 5.—AKROYD GOVERNOR

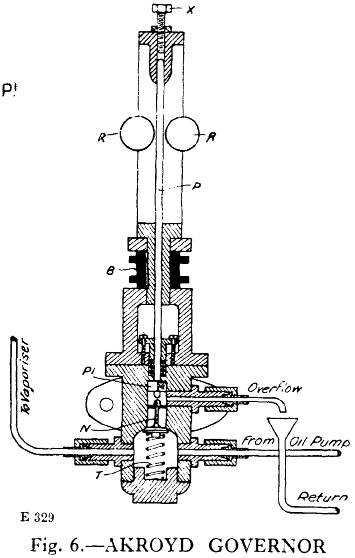

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Fig. 6.—AKROYD GOVERNOR

without pre-ignitions occurring *only when* the oil spray was injected at or near the end of the compression stroke, as described in the patent specification No. 7146 of May, 1890. Hence he designed another vaporizer having a contracted conduit or bottle-neck opening to the cylinder, and of much less sectional area than that of the vaporizer or cylinder. During experiments with this vaporizer having the narrow passage to the cylinder, he found that the oil-spray injection could be timed to occur not only at firing-time, but during any portion of the suction or compression stroke, without risk of pre-ignition.

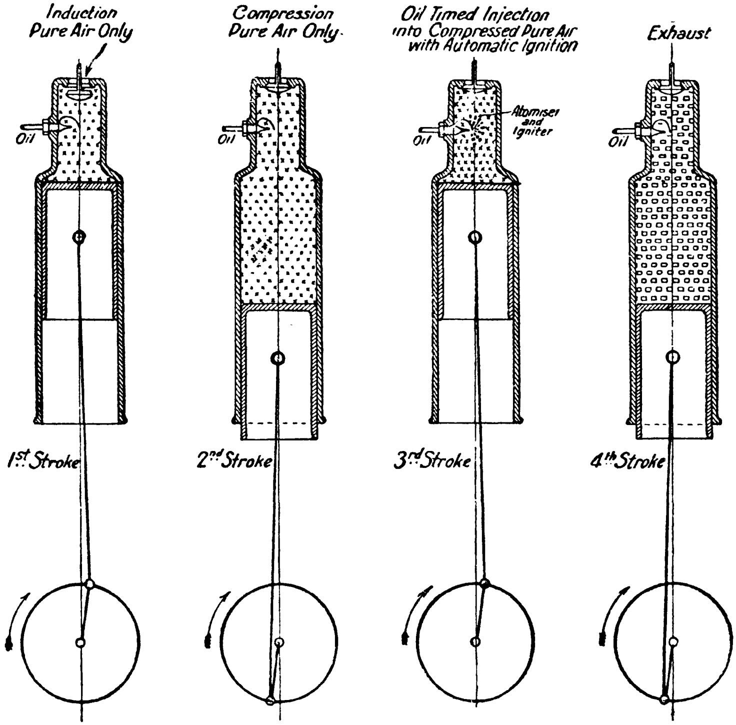

Fig. 7.—Akroyd Heavy-oil Engine: Cycle of Operations (May, 1890)

This type of Akroyd oil engine (fig. 8), with the narrow neck *A′* or conduit between the vaporizer and the clearance in the motor cylinder, and its method of working, were described in the patent No. 15994 of 8th October, 1890. The vaporizer or explosion

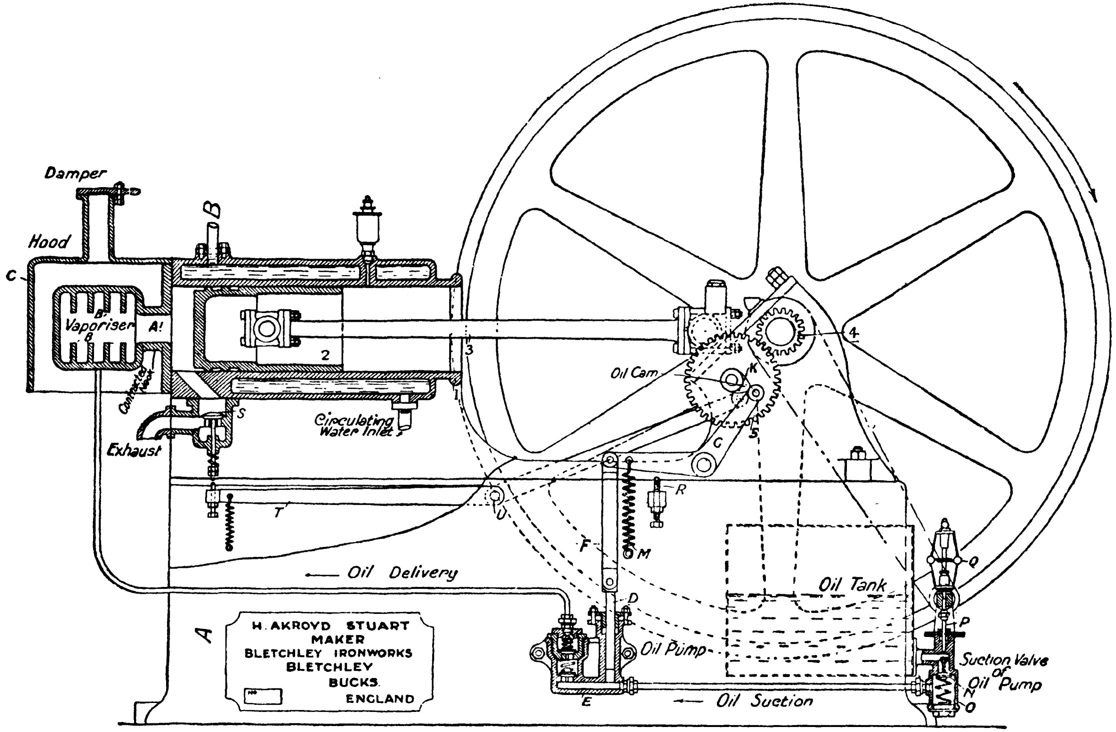

Fig. 8.—Akroyd Heavy-oil Engine (Contracted Neck Type, October, 1890)

chamber BB is made of sufficient capacity to contain the combustible charge of oil vapour and air, when the latter is compressed to the ignition point of the oil fuel.

A *large clearance* of about a quarter of the cylinder diameter, left between the piston and the end of the cylinder, is filled with relatively pure compressed air to prevent contact of the unburnt or partially burnt products during combustion with the piston and cylinder walls, as well as to supply "*an excess of oxygen to complete the combustion originated in the explosion chamber and thereby burn up the carbon which might otherwise form deposit*". This design of a **precombustion chamber,** connected by a conduit of reduced area to the combustion chamber in the cylinder, provides another method of keeping the air apart from the oil vapour, by which a well-defined **stratified charge** is formed, and pre-ignition is avoided; also thereby a simple method is provided of imparting **turbulence** to the charge greater than is obtained by normal means, and without throttling the induction at ordinary speed of engine.

The inlet valve (fig. 4) admits air into the large clearance during the suction stroke, and pre-ignition is prevented because air can only enter the explosion chamber from the motor cylinder through the contracted passage gradually during the compression stroke, and so mix with the oil vapour until an explosive mixture is formed, giving automatic ignition and explosion. Then the products of combustion are projected with violent *turbulence into the excess of compressed air* in the motor cylinder, and by adiabatic compression raise the temperature and complete the combustion of the oil. The volumes of the motor cylinder and explosion chamber are so proportioned that the mixture in the precombustion chamber or vaporizer is rendered explosive during compression just in time to ensure ignition at or near the end of the compression stroke. This two-stage combustion was considered by Akroyd Stuart to be the pioneer of *dual combustion.*

The cam K can be readily adjusted to time the oil-spray injection, and deliver it quickly into the vaporizer by the pump D, at any desired point of the suction or compression stroke to ensure the best conditions of working, and prevent overheating of the vaporizer, besides allowing time for the vaporization of the oil spray. By this simple method both the time for oil-spray injection and automatic ignition are under control. Fig. 9 indicates the cycle of operations in this type of Akroyd oil engine.

After four years of hard experimental work, worry, and great expenditure, Akroyd Stuart had automatic or compression-ignition heavy-oil engines built and working as described in the two master patents of the year 1890, both of which are fundamentals of modern oil-engine practice. Only provisional protection had been applied for, and before drafting the final specifications it was suggested by his patent agents, Redfern & Co., London, that the opinion of an expert engineer should be obtained. Mr. Fletcher Moulton, Q.C. (the late Lord Moulton), was engaged. The whole of the Akroyd patents and drawings from 1886 were examined. The two provisional specifications of 1890, were taken separately and together. These experts, Moulton and Redfern, agreed that the Akroyd automatic compression-ignition cycle, as described in the specification No. 7146, of 8th May, 1890, was very clear and covered all working compression pressures, say from 5 lb. per

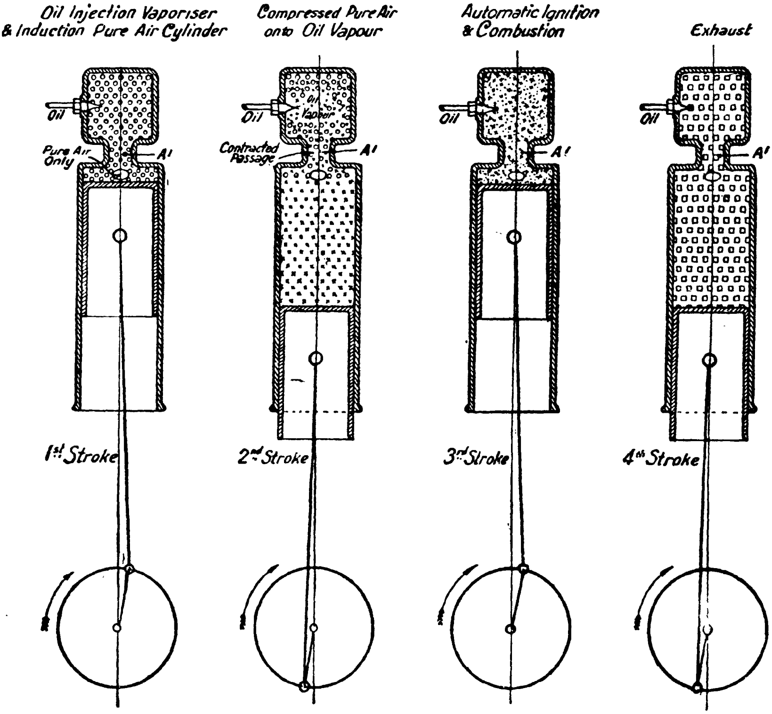

Fig. 9.—Akroyd Oil-engine Cycle (October, 1890)

square inch up to 5000 lb. per square inch or even higher, to whatever practical experience in working indicated. Further, as regards the merits of the invention, from the standpoint of practical engineers, these experts considered automatic compression-ignition of the working charge in an oil engine cylinder was almost an impossible proposition, but they held that if the results shown to them could be obtained in Akroyd engines of greater horsepower units, then this automatic ignition cycle would revolutionize internal-combustion engine practice to very nearly a miracle.

It was agreed that the best thing to do, without further delay, was to complete the final specification for Patent No. 7146 of 1890, and in the drawings illustrate a vaporizer with a contracted passage or bottle-neck, and then disclaim that construction for use with this patent, in order to reclaim it in the patent No. 15994 of 1890. The disclaimer is made in the complete specification No. 7146, 8th May, 1890, page 3, lines 25, 26, and 27: " As, however, this construction of vaporizer forms part of the subject-matter of my application for Letters patent No. 15994, dated 8th October, 1890, no claim thereto is made in this specification." "Nevertheless, in the future if you desire to do so, you are at liberty to use that or any other construction of combustion chamber or vaporizer with Akroyd engines, working according to your Patent No. 7146, of 1890. The engine cycle is your own invention, and we point out this for your guidance. This method of procedure will protect your patent rights."

Before the end of the year 1890, when the patent was only seven months old, Akroyd Stuart had a dozen of these automatic-ignition heavy-oil engines ready for delivery; four were sold and working very satisfactorily, and others sent out on approval. There were four engines, each of 2 h.p., in his show-rooms and offices, 11 Eldon Street, Finsbury Pavement, London, E.C., where Akroyd oil engines could be inspected, and a 1-h.p. kept running light in the shop window from 9 a.m. to 5 p.m. consumed only one gallon of oil daily. Four of the 2-h.p. Akroyd safety automatic-ignition heavy-oil engines were exhibited in 1890 at the Christmas Cattle Show in the Agricultural Hall, Islington, London, N.

In order to gain experience of their behaviour under varying conditions, half a dozen of these oil engines of sizes from 1 up to 6 h.p. were working at Bletchley Iron Works, Bletchley, Buckinghamshire. Such was the progress made at that early date in the construction of these heavy-oil engines. The object was to bring them prominently to the notice of the public, and form an Akroyd Oil Engine Limited Liability Company. However, Akroyd Stuart was informed by his patent agents, Redfern & Co., that their clients, Messrs. Richard Hornsby & Sons, Grantham, were looking for an oil engine to manufacture on a royalty payment basis, and perhaps that would be a better proposition than the limited liability company. A meeting was arranged with Mr. Southwell, the general manager of Hornsby & Sons, who suggested that their chief engineer, Mr. R. Edwards, should go to Bletchley and spend a day inspecting and testing Akroyd oil engines. On his visit in January, 1891, there were five engines of different sizes of the two types ready to start for inspection. Mr. Edwards was chiefly interested in the 6-h.p. engine working according to the patent No. 7146 of 8th May, 1890, that was driving the shafting and about a dozen workshop machine tools. During the day Mr. Edwards observed the regular speed of that 6-h.p. engine under varying loads, and remarked to Akroyd Stuart that the Akroyd oil engine was the best he had seen, although he had been all over the Continent to find one which he could recommend to his firm for manufacture. He did not fancy the oil engines working according to the other patent, No. 15994, of October, 1890, except for small powers. About a week afterwards Mr. Southwell arranged a visit to Bletchley on a similar errand, and was shown four Akroyd engines working on full load and running light. He was very pleased with the performance of the engines, especially the 6-h.p. on the early Akroyd cycle: induction and compression of air only, with *timed* oil-spray injection into the heated air near the end of the compression stroke, and automatic ignition, which he held was something " novel " and of great promise for the future with cheap and safe heavy oils. He expressed the same opinion as Mr. Edwards regarding the other engines working according to the later patent, No. 15994 of October.

In February, 1891, the Author was asked to test the 6-h.p. Akroyd Stuart compressed-air ignition heavy-oil at Bletchley Iron Works, working as described in the patent No. 7146 of 8th May, 1890. The report, giving the results of the trials, was quite satisfactory to Messrs. Hornsby & Sons, although at that time they had little confidence in *any* kind of oil engine.

The Author referred to this new type of compression-ignition oil engine and test in detail in a paper on " The Uses of Petroleum in Prime Motors", read before the Society of Arts, London, on the 29th April, 1891, and published in the *Journal of the Society of Arts*.

The engine worked on the cycle described above (pages 13 to 16). There was very small clearance in the cylinder. The combustion chamber or vaporizer, always open to the motor cylinder by a small trumpet mouth, had radial ribs on the inside parallel to the axis, exposing a large heating surface. Before starting from cold the vaporizer is heated up in a few minutes by an oil lamp, and is afterwards kept sufficiently heated by the explosions and compression of the air charge, when the engine is working, and the lamp removed. This method of heating adopted for starting somewhat obscured the real discovery of ignition of the oil spray by the hot compressed air, and led some to consider it as merely heated surface ignition.

Other methods of starting by compressed air and firing the first charge had been patented and used, but these required an air pump and compressed-air vessel (see p. 28). Hence Akroyd Stuart found a fuel-oil lamp, or cast-iron pot with asbestos wick, a simple, cheap, and safe means especially for these small engines.

A hood protects the vaporizer from air draughts and forms an air jacket. The temperature of the vaporizer is regulated by sliding open the damper at the top of this hood, and allowing the air to circulate up around it and escape by natural draught, or by lifting off the hood altogether when working at full load. The air inlet valve to the cylinder and exhaust valve are housed side by side underneath the small clearance space, as shown in fig. 4, p. 15, so that some of the heat in the exhaust gases is used to warm the incoming fresh charge of excess air during the suction stroke. The piston had junk rings, into which were fitted the working rings held in place with a back plate and nut. This construction proved of service with unskilled attendants in the early days of oil engines.

This 6-h.p. oil engine had been driving the shafting and machine tools in the workshop all morning, using shale oil of specific gravity 0·854 at 60° F., and flash point 225° F. A friction brake was applied on the fly-wheel, consisting of a leather belt with spring balance at one end and weights hung at the other end. During a trial run of three hours, the *average* brake h.p. was 7·6 at 216 revolutions per minute, while the consumption of this fuel oil was considerably less than 7 pints per hour, or about

0·9 pint per brake h.p. hour. The cost of the oil was 3*d.* per gallon in Liverpool. The exhaust was perfectly clean and invisible, affording evidence of complete combustion. Near the end of the compression stroke the oil spray was injected by the pump through the spraying nozzle into the combustion chamber filled with hot compressed air in excess of that necessary to furnish oxygen for combustion. The little governor effectively regulated the speed by varying the oil supply: simply lifting a valve and allowing the pump to force all or part of the charge back into the tank instead of into the combustion chamber, when the speed was slightly above normal. By using a large fly-wheel, sensitive governor, and high speed, the regularity of running was remarkably steady. The oil-pump plunger was ½ in. diameter, and less than $\frac{3}{32}$ in. lift, giving about 0·015 c. in. of oil for each full charge.

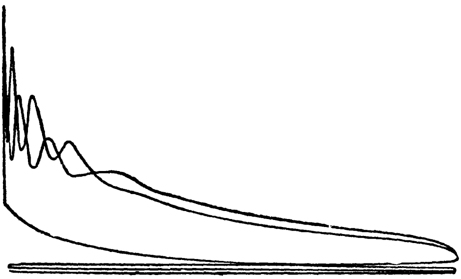

Fig. 10.—Indicator Diagrams: Akroyd Oil Engine (May, 1890, Type)

The excess charge of air was heated chiefly by compression, and by radiation from the surface of the combustion chamber, which was kept hot by the previous explosions. The timed injection of the oil spray near the end of the compression stroke gave perfectly regular ignition, and explosion at constant volume.

Indicator diagrams (fig. 10) were taken frequently during the trial, and showed regular and rapid ignition at a compression pressure of 45 lb. per square inch, but, unfortunately, the indicator springs available were not stiff enough to give thoroughly reliable expansion curves, these being shown wavy after the sharp explosion. The Author was surprised at the good results obtained, the steadiness and regularity of running throughout the test without the slightest hitch, and especially the small fluctuation of speed when the load was taken off and the engine running light. Obviously much heavier fuel oil might be used at higher compression, and the engine run at higher speed, as stated in the above paper. Heating very heavy oil was also suggested to reduce viscosity and keep it in a sufficiently fluid state fit for effective spraying.

At this stage Akroyd Stuart had been granted patents in the

United Kingdom and in many other countries (see schedule in Appendix). In May, 1891, he supplied to Messrs. Hornsby & Sons four small engines, two of each type, for their own experimental purposes. Eventually, on the 26th June, 1891, the sole right to manufacture and develop the Akroyd Stuart oil engines, and *use any of his subsequent improvements* of them, under licence agreement for the whole world, was acquired by Messrs. Richard Hornsby & Sons, Grantham, without any cash payment, but merely on a royalty basis. After signing this agreement Akroyd Stuart found he could not sell any of the oil engines he had built and that were left in stock at his Bletchley Iron-works.

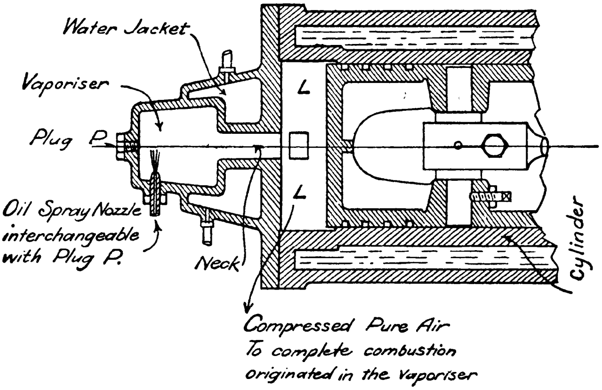

Fig. 11.—Akroyd Water-jacketed Vaporizer (Sectional Plan)

Vaporizer Water Jacket.—When making further experiments with these engines left on his hands, he observed that the combustion chamber sometimes became overheated after prolonged continuous running on full load. He knew that the thermal efficiency could be improved by using higher compression of air and higher piston speed, and in order to attain these he took out Patent No. 3909, of February, 1892, for *a vaporizer fitted with a cooling water jacket* (fig. 11) *around the neck or other parts of the combustion chamber, to control or regulate the temperature.* In the words of this most important patent specification: "*It is to be understood that instead of forming the jacket merely around the neck of the vaporizer, it may be formed also around other parts thereof.*" The water for cooling the vaporizer may be taken from that through the cylinder jacket, or kept separate, and the flow regulated by a cock on the connecting pipe.

This improvement allowed higher compression to be used, giving more power and increased thermal efficiency, and clearly pointed out the line of future development by reducing the uncooled surface of the combustion chamber. Full advantage was taken of this method—only when the patent lapsed after 1906.

These patent specifications of 1890 and 1892 set forth the essential principles of the operations in the heavy-oil engine originated by Akroyd Stuart, and they are fundamentals of modern oil-engine practice to-day, however the mechanical designs have been developed by other inventors. The Akroyd oil engine was the first in which the charge was air alone, into which, near the end of the compression stroke, the fuel oil was injected quickly by pump and spraying nozzle, and ignited by the hot compressed air. This novel method of ignition was at first regarded by many with misgivings, but worked well.

To-day high-compression heavy-oil engines use air only as the charge, and the fuel oil is injected directly by a pump through a sprayer into the hot compressed air by pressure alone, that is, without the high-pressure air blast employed in the Diesel engine. The cycle of operations and principle of action is simply that invented by Akroyd Stuart, and the difference consists chiefly in the use of higher compression and higher speed as well as improvements in the sprayer and fuel pump. The shape of the combustion chamber has also been modified.

Development of the Akroyd high-speed airless-injection heavy-oil engine has led to much research on the injection of the fuel oil, and the stages in the combustion processes affected by the temperature and turbulence of the air charge, by the pulverization of the oil spray, and its penetration. The accelerated rate of combustion or flame propagation is also affected by the turbulence of the air and the shape of the combustion chamber. The investigation of such relations still affords ample scope for research work to obtain definite constants or factors of design.

Pilot Charge Ignition.—Another novel method of working is also mentioned by Akroyd Stuart. Very heavy and viscous hydrocarbon fuel oil for the engine may be heated by flowing through the jacket around the vaporizer, and thereby its spraying and vaporization are made easier. In one of his experiments of 1892–3, palm oil * (which the Author had seen on his visit to the Bletchley Works in 1891, and suggested for trial) was used in

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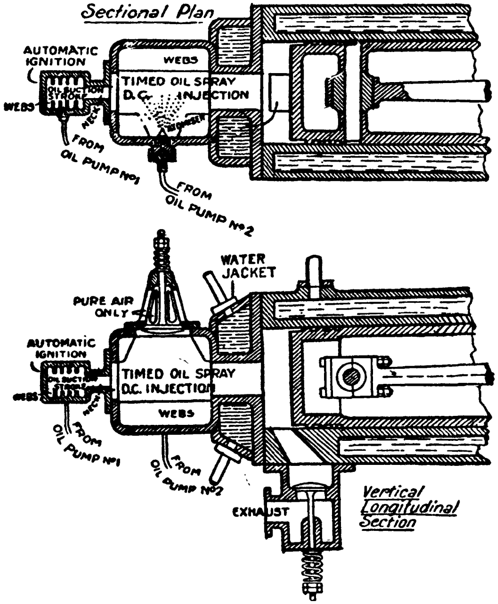
* See *The Engineer*, 4th Nov., 1921: "Palm Oil as Fuel for Oil Engines".

the jacket to cool the vaporizer, and by an additional pump on the engine the palm-oil charge, when heated in the jacket, was sprayed into the *pilot charge* of kerosene from the other pump which originated the combustion. This appears to be the first time (1892) in this country that two fuel oils of different density were sprayed by two injections to give one charge in the heavy-oil engine cylinder, the pilot charge being used to start the combustion of the heavier oil spray. Akroyd Stuart had then in view the possibility of using palm oil and vegetable oils, where the price would permit of their use for power purposes.



Figs. 12 and 13.—Akroyd two methods of Automatic Ignition combined

Experiments were also made by him at Bletchley on the combination of the two Akroyd vaporizers coupled (figs. 12 and 13), one forming a pre-combustion chamber for the main charge in the other; and two oil pumps—No. 1 injects the *pilot charge* of *ordinary fuel oil* into the small (later type) vaporizer on the *suction* stroke, while the charge of air is drawn in through the automatic inlet valve and the large (early type) vaporizer; and oil pump No. 2, with timed injection of the *heavier oil spray* near the end of compression—giving the two methods of automatic ignition and two injections of oil fuel described above.

Compressed-air Starter.—The **Akroyd self-starter** patent specification No. 22664 of 9th December, 1892, for a hydrocarbon oil engine using hot compressed-air ignition, is self-explanatory. A hand pump is employed to compress air, at a sufficiently high pressure, into a reservoir fitted with a suitable pressure gauge. A check valve in the air-pipe connexion close to the vaporizer prevents the explosive mixture entering the air vessel. Another main valve on the air pipe, opened by hand, allows the compressed air to flow into the vaporizer.

To start the engine: with the piston just a little over the dead centre on the power stroke, a charge of oil spray is injected from the oil pump, by hand, into the vaporizer previously heated. Oil vapour is formed and, by opening the main valve on the air pipe, the highly compressed air mixes with the oil vapour in the vaporizer until an explosive mixture is produced, and the explosion drives the piston forward. On the return stroke the products of combustion are discharged, and the engine follows its usual cycle.

General Opinion of Engineers in 1891–2.—Out of fairness to Messrs. R. Hornsby & Sons and their staff, H. Akroyd Stuart desired to emphasize the fact that scores of other British engineers at that early stage, who inspected the Akroyd oil engines at work, said that a lampless automatic ignition oil engine could not possibly be reliable, and even after inspecting indicator diagrams taken from an Akroyd oil engine running steadily under load, in their presence, shook their heads and still remained unbelievers. As stated above, Messrs. R. Hornsby & Sons were also doubtful, and it was not until the Akroyd water-cooled vaporizer patent No. 3909, of 1892, was added that their confidence in the Akroyd compressed-air ignition oil engine was assured.

Although the early type of engine that the Author had tested was the first favourite, strangely enough, it was agreed that the later type of October, 1890, should be redesigned, built, developed, and sold as the " Hornsby-Akroyd " oil engine. The low working pressure giving complete combustion of ordinary burning oils, combined with simplicity and reliability in these self-contained almost " fool-proof " prime motors of comparatively small power output, made them well adapted for agricultural purposes in the hands of unskilled attendants. This type became well known as the " Hornsby-Akroyd hot bulb " oil engine, and gained a reputation for general usefulness.

The early type, Patent No. 7146 of 1890, was left in abeyance by the licencees until the patent lapsed, not without many protests by its inventor. He stated that for this, his greatest invention, he " had never received one penny piece either from royalty payments or any other source ". He also held the opinion that, if he had not discovered the principle of action in the second type, a firm of agricultural engineers, at that early stage, never would have persevered with the manufacture and development of oil engines working on Akroyd cycle of Patent No. 7146. However, this early Akroyd type has been developed by British engineers since the expiry of the pioneer master patent in 1904; and considerable progress was made in using efficiently heavy residual oils in these engines before and during the Great War. A review of this development was given in July, 1920, by Mr. F. H. Livens, of Messrs. Ruston & Hornsby, Lincoln, in a paper on " Some Lincolnshire Oil Engines " read before the Institution of Mechanical Engineers.

Isle of Ely Exhibit.—Messrs. Hornsby & Sons intended to exhibit a 6-h.p. Hornsby-Akroyd oil engine at the Isle of Ely Agricultural Show in the year 1893. At the last moment they wired Akroyd Stuart at Bletchley: could he help them, as they had not a 6-h.p. engine ready. The telegram reached him on a Friday afternoon, and he wired reply: " Yes will exhibit in your name ". He lifted his own workshop 6-h.p. " Akroyd " that had been tested by the Author, and had it in Ely on Sunday. Akroyd Stuart personally superintended the erection and running of that engine. The show opened on the following Tuesday morning, and he was awarded the Society's first prize Silver Medal—the first and only medal ever granted to him for his early " Akroyd " oil engine. He gave this medal to Messrs. Hornsby & Sons.

CHAPTER III

Hornsby-Akroyd Oil Engine

The 1892 type of the safety airless-injection automatic-ignition oil engine is shown in fig. 14, as redesigned by Messrs. R. Hornsby & Sons and one of the first engines supplied to the Fenny Stratford pumping station. The oil-inlet valve box (fig. 15) is water jacketed to reduce heating by contact with the vaporizer or combustion chamber, and to keep the fuel oil cool in the liquid state until, forced by the pump past the horizontal back pressure check valve and injected at high velocity through small holes in a disc, fine oil spray is produced in the vaporizer.

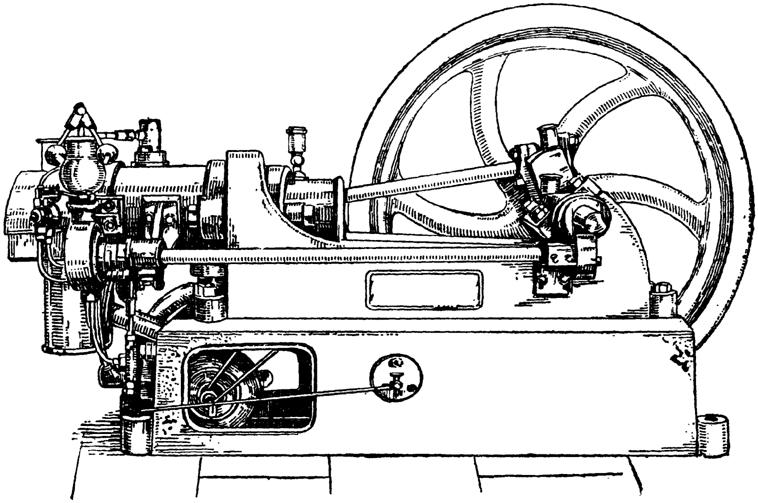


Fig. 14.—Hornsby-Akroyd Oil Engine (1892 Type)

The overflow passage is opened, more or less, when the vertical valve (figs. 15 and 16) is pressed down by the bell-crank lever

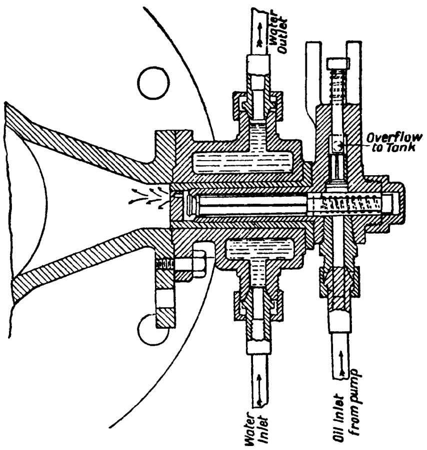


Fig. 15.—Hornsby-Akroyd Oil-inlet Valve Box

L, which is operated by the rod R from the centrifugal governor. The engine is stopped by turning down this bell-crank lever and clamping it. Then all the oil delivered by the pump is passed by the overflow back to the oil tank, instead of being injected into the vaporizer. Before starting the engine, the oil pump is worked by hand to clear out any air from the pipe and connexions, and the oil is allowed to pass by the overflow to the tank. The air inlet and exhaust valves are housed together beside the cylinder

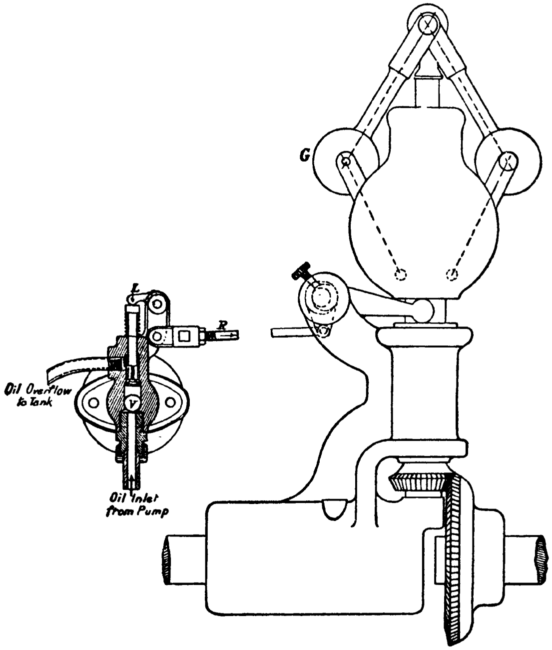


Fig. 16.—Oil Overflow by Governor Control

clearance. The air-valve lever (fig. 17), worked by a cam on the half-speed side shaft (fig. 14), also pushes down the oil pump plunger against the action of a spring, shown above the lever. In addition to the regulation of speed by the governor control of the oil supply, the overflow may be reduced by adjusting the distance between the two flanges on the pump plunger (fig. 17), to reduce the stroke of the pump, so that the quantity of oil charge delivered is suitable to the load on the engine. Near the end of the air suction stroke, the fuel oil is injected into the vaporizer and converted into vapour, which is gradually mixed with the air compressed into the vaporizer through the narrow neck during the return stroke of the piston, until the ignition pressure and temperature is reached at the end of the compression stroke. When the piston is turning for the second outstroke, the charge ignites automatically and explosion takes place at constant volume,

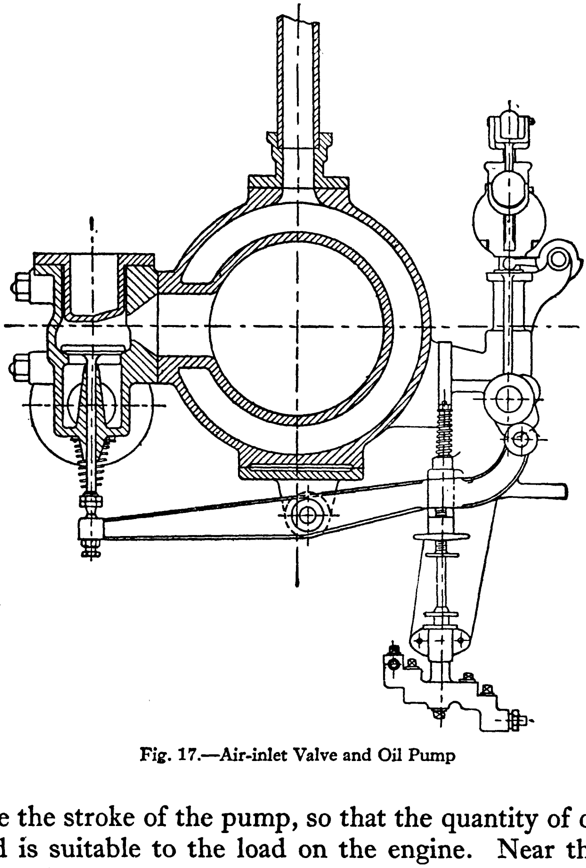


Fig. 17.—Air-inlet Valve and Oil Pump

driving the piston forward by the pressure of the expanding gases. Near the end of this power stroke, the exhaust valve is opened, and during the next return stroke the burnt products are discharged.

In order to ensure rapid automatic ignition and complete combustion, the compression pressure suitable for different oils is best determined by experiment in a new engine. Russolene requires higher compression and gives nearly 20 per cent more power than Royal Daylight. In this engine the compression may be varied by packing pieces between the brasses and big end of the connecting rod. Another later method was to have the volume of the vaporizer changed to suit the oil fuel.

Tests.—In October and November, 1893, the Author made a series of tests on a 5-h.p. Hornsby-Akroyd oil engine at full load, normal working load, half-load, and running light. The oil used was Russolene of specific gravity 0·824 and flash point (close) 88° F., and net effective calorific value of 18,600 B.Th.U. per pound. The oil was taken by the engine from a measuring vessel, and the level of oil brought to a conical point gauge in the narrow neck of the vessel at the start and finish of each run. The overflow was collected separately, and the oil used was weighed. The friction brake was a leather belt passing half round the flywheel with weights at both ends, and a spring balance above the wheel took the varying part off the smaller weight. The explosion and compression pressure varied with the quantity of oil admitted by the governor, and the engine ran steadily owing to this perfect regulation. The indicated horse-power could not be exactly estimated at less than full load without an integrating indicator, because of the variation in charge by the governor. Under ordinary

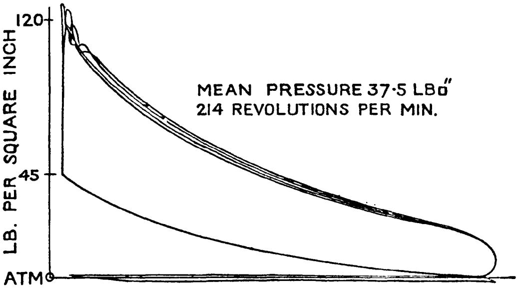


Fig. 18.—Indicator Diagrams: Hornsby-Akroyd Oil Engine (1893)

working conditions 14 per cent of the effective heat value of the oil fuel was converted into useful work at the brake wheel; and 17 per cent into work in the cylinder shown on the indicator diagrams (fig. 18), for several explosions at full load.

Similar results were obtained by the judges, Professor Ewing and Professor Capper, with Mr. J. B. Denison, on a larger Hornsby-Akroyd in the trials of oil engines at Cambridge Royal Agricultural Show in June, 1894. The engines were run at normal load on Russolene for three days, and then on a special trial at full power. The Hornsby-Akroyd oil engine was awarded first prize for simplicity and neatness of design, good mechanical construction, regularity and steadiness of running; and it required least skilled attention. The engine tested was of 8 brake h.p. with cylinder diameter 10 in. by 15 in. stroke. The results of one trial of each engine are given in the table below:

TRIALS OF HORNSBY-AKROYD OIL ENGINES

Date of trial	Oct., 1893	June, 1894	Jan., 1898
Cylinder diameter × stroke, in. ..	8″ × 14″	10″ × 15″	14·5″×17″
Clearance volume, cu. in.	432	638	1170
Load	Practical Working	Full Power	Practical Working
Duration of trial, hours	3·2	2	3
Revolutions per minute, mean ..	214	240	202·6
Explosions per minute, mean ..	90·7	120	101·3
Mean pressure, lb. per sq. in. ..	37·6	28·9	45·4
Indicated h.p.	6·08	10·3	32·3
Brake h.p.	5	8·57	26·74
Mechanical efficiency, per cent ..	82	83	82·4
Oil used:			
Oil per indicated h.p. hour, lb. ..	0·81	0·81	0·61
Oil per brake h.p. hour, lb. ..	0·99	0·98	0·74
Percentage equivalent of net calorific value of oil, B.Th.U.	18,600	18,600	19,100
Useful work at brake	13·8	14	18
Spent in engine friction	3·0	2·9	3
Converted into work in cylinder as shown on indicator diagram	16·8	16·9	21
Carried away in jacket water ..	29·0	29·5	50
Balance rejected in exhaust and other losses	54·2	53·6	29

In the 1896 design (fig. 19) part of the vaporizer has a cooling water jacket, and a separate hot cap, so that the temperature can be regulated to suit the different grades of oil fuel, and higher compression used with increased thermal efficiency without pre-ignition. The hot cap or bulb of the vaporizer is bolted to the water-cooled part, and sealed by a copper wire gasket giving only a small surface of contact for heat flow. This engine worked satisfactorily on such oil fuels as Russian Crude oil of specific gravity 0·88, and Solar oil, specific gravity 0·885 and flash point 258° F.

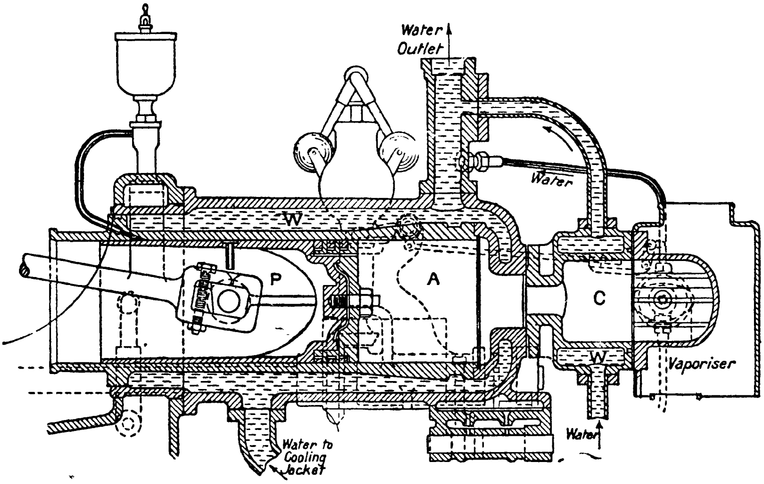


Fig. 19.—Hornsby-Akroyd Oil Engine (1896)

On 4th January, 1898, the Author tested a 25-h.p. Hornsby-Akroyd, at different loads on the brake, during a continuous run of 10 hours' duration, under ordinary working conditions. During a short run of 15 minutes, at the end of the day, this engine running at normal speed gave 39 brake h.p., or more than 50 per cent overload, at the indicated mean effective pressure of 57 lb. per square inch. At ordinary full load the compression of air was 60 lb. per square inch, and the initial explosion pressure 180 lb. per square inch. Fig. 20 shows typical indicator diagrams (reduced in size) taken at varying loads, and during an hour running light without any load. The results of one trial are given in the last column of the table (p. 34). The oil used was Russolene, of specific gravity 0·825, flash point (Abel close test) 88° F., and lower calorific value 19,100 B.Th.U. per lb. The engine converted 18 per cent of this heat into useful work at the brake wheel, and ran with perfect regularity.

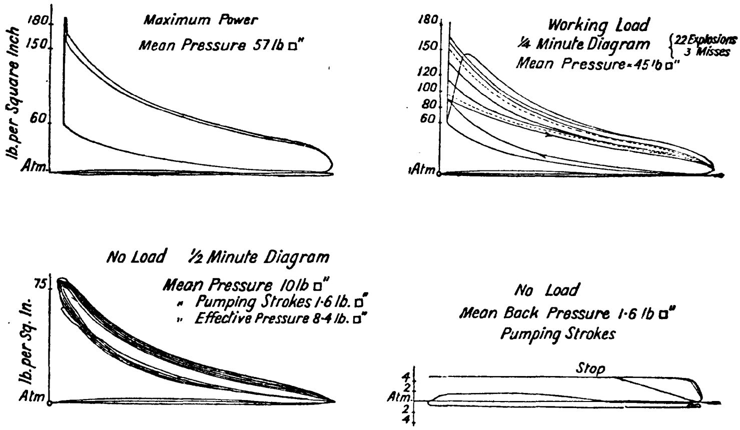


Fig. 20.—Indicator Diagrams: 25 h.p. Hornsby-Akroyd Oil Engine (1898)

The New-Century (1900) design of Hornsby-Akroyd oil engine (fig. 21) is further developed, and simplified in construction.

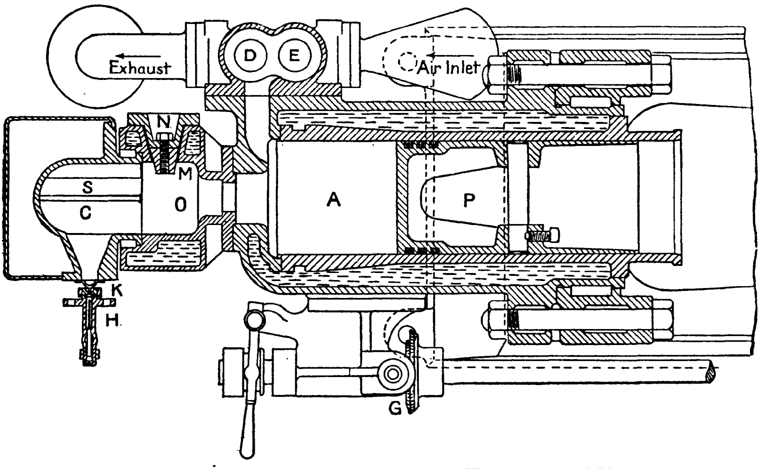


Fig. 21.—Hornsby-Akroyd Oil Engine (1900 Type), Sectional Plan

The oil pump is operated directly by a hardened cam on the half-speed side shaft. There is also a cam, moved by a hand lever, to partly open the exhaust valve and reduce the compression when starting. The compression can be varied to give the best results from different oils by changes in the clearance volume, with or without the block M inside and the hollow dish-shaped cover N fitted as in fig. 21, or outside as in fig. 22. The temperature of the vaporizer is regulated by the water circulation controlled by a cock on the pipe from the cylinder water jacket. The cooling water jacket on the oil-inlet valve box (fig. 15) is dispensed with as shown by fig. 23, and the surface contact reduced to a minimum to reduce the heat flow from the vaporizer to the oil inlet-valve casing.

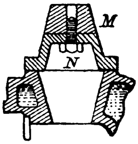


Fig. 22.—Clearance Blocks

To *start* the small engines a *coil lamp* is used to heat the vaporizer. The compression is reduced by a lever (fig. 21), which moves the relief cam to keep the exhaust valve partly open, and so one man may turn the fly-wheel quickly until a charge is fired.

For starting engines of 25, 50, and 100 brake h.p. after warming up, an air pump with hand-wheel forces air into a steel reservoir up to 150 lb. per square inch, or the air may be stored to the desired pressure, while the engine is running, as required, by a small air pump. The air valve box on the cylinder is connected to the air reservoir by a pipe, fitted with two valves, a rocking lever, and linkage worked by a hand lever. With the piston on the power stroke about 15° to 20° over centre, and the valves on their seats, the starting lever is moved forward and back again quickly, allowing the compressed air to enter the cylinder and start the engine.

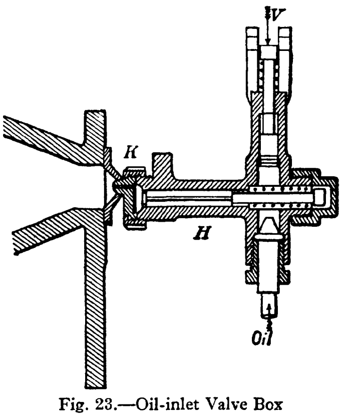


Fig. 23.—Oil-inlet Valve Box

The 100 brake h.p. engine used in the Russian *oil fields* has a water jacket on the exhaust pipe and an air jacket around the hot part of the vaporizer, so as not to ignite the inflammable vapour of light petroleum. The vaporizer is heated internally at starting by igniting with electric spark benzoline pumped into it through the ordinary oil inlet valve. The benzoline is stored in a separate tank and connected to the oil pump suction by a three-way cock. When the vaporizer is hot enough to ignite the crude oil, the cock is turned to shut off the benzoline and admit the crude oil from the main storage tank. The electric ignition is by a sparking plug with current from a magneto driven from the cam shaft, and a tappet breaks contact for the electric spark to pass.

Tractor Trials.—A noteworthy achievement of the Hornsby-Akroyd oil engine was its performance in the Military tractor trials at Aldershot in 1903. The Hornsby tractor, fitted with a two-cylinder Hornsby-Akroyd oil engine, was awarded the prize of £1000 for the tractor that would travel 40 miles, hauling a load of 25 tons over ordinary roads at an average speed of 3 miles per hour, not to exceed 5 miles per hour at any time, carrying its own fuel and water without being replenished during the journey. During the trials of the Hornsby-Akroyd tractor over a distance of 374 miles, the consumption of fuel * was at the rate of 0·329 lb. per gross ton-mile. The results proved the advantages of the heavy-oil engine as regards the low consumption of fuel and water, and the large radius of action. The distance actually covered was 58 miles, an excess of 18 miles, for which a bonus of £180 was added to the prize.†

After the competition the prize-winner was fitted with a chain-track in place of its wheels, and became nick-named " the caterpillar " by the troops during its trials at Aldershot.

This tractor was the forerunner of the famous " Tanks " used in the Great War. " The first definite proposal for a fighting machine on the lines of the existing Tank was due to the appearance of the Hornsby-Akroyd caterpillar tractor, which was tested for military traction purposes in England in 1906-8." ‡

On the 29th September, 1908, the Author made a brake test of a Hornsby oil engine rated at 32 brake h.p. working load. The time taken in starting the engine, with all parts cold, was ten minutes, reckoned from lighting the lamp to heat the vaporizer until the engine was running at full load. The engine was started quite easily.

During the trial the average brake load was 32 brake h.p. at

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* The ordinary fuel oil used in the Service for oil engines, Russian petroleum, having specific gravity 0·8246, and flash point 83° F. (Abel close test).

† " Report on Tractor Trials by the War Office Mechanical Transport Committee at Aldershot, October, 1903."

‡ See article in the *Strand Magazine*, October, 1917, p. 274, by Colonel E. D. Swinton, C.B., D.S.O., Royal Engineers.

230·2 revolutions per minute. The oil fuel was Russolene H.V.O. of specific gravity 0·825 at 60° F., and of lower calorific value 18,450 B.Th.U. per pound. The consumption of this oil was at the rate of 0·61 lb. per brake h.p. hour. Of the heat supplied to the engine in the oil, 22·6 per cent was converted into useful work on the brake.

By the indicator diagrams the compression was 85 lb. per square inch, and the initial explosion pressure 260 lb. per square inch.

The performance of the engine during the trial was entirely satisfactory. The comparatively low working pressure, together with neat and substantial design, perfect smoothness and regularity of running observed in this engine, are all-important factors to ensure durability and little wear of the working parts.

The **Akroyd Stuart** patent No. 28045, of December, 1904, was an extension of this *hot-bulb* type, on the expiry of the two early master patents of 1890, but not built by Messrs. Hornsby. Instead of injecting the whole charge of oil fuel into the hot vaporizer, one pump is used to supply two sprays of oil; the first pilot charge into the hot bulb, and the other into the cylinder clearance by means of a spraying nozzle in the contracted neck. Excess air drawn into the cylinder, during the suction stroke between the two parts of the oil charge, "*serves the twofold purpose of providing automatic ignition of the charge in the vaporizer, and of acting as a cushion to further compress, heat, and fire the charge in the cylinder*".

The air-inlet valve is in the narrow neck (fig. 24), and an extra air valve between the exhaust valve and neck. The piston head is concave. The air required for the complete combustion of oil vapour is about 15 lb. per pound of oil, but when oil spray by No. 1 is vaporized in the hot exhaust gases left in the vaporizer and air compressed into it, only about two-thirds of the total air or about 10 parts by weight of air to one of oil vapour forms an explosive mixture of ignition-temperature about 800° F. in the pilot charge. During the compression stroke, the air is forced through the narrow neck and enters the combustion chamber with considerable velocity, producing great turbulence and rapid admixture with the particles of oil spray, thus tending to accelerate the combustion. The explosion causes rapid expansion into the excess air, increases the compression in the motor cylinder, and completes the combustion.

In some experiments with this engine in Australia, the injection of the oil charges was delayed until late in the compression stroke, and by using a moderate compression pressure from 90 up to 120 lb. per square inch, and compressed hot air in the combustion chamber for ignition, a much higher mean effective pressure, with increase in brake h.p., was obtained than by the ordinary hot-bulb Hornsby-Akroyd type. This engine worked on the principle of *dual combustion*, and when the engine is running on light loads, the pump No. 2 supplying the cylinder charge is put out of action, and the engine continues to work with the vaporizer charge.

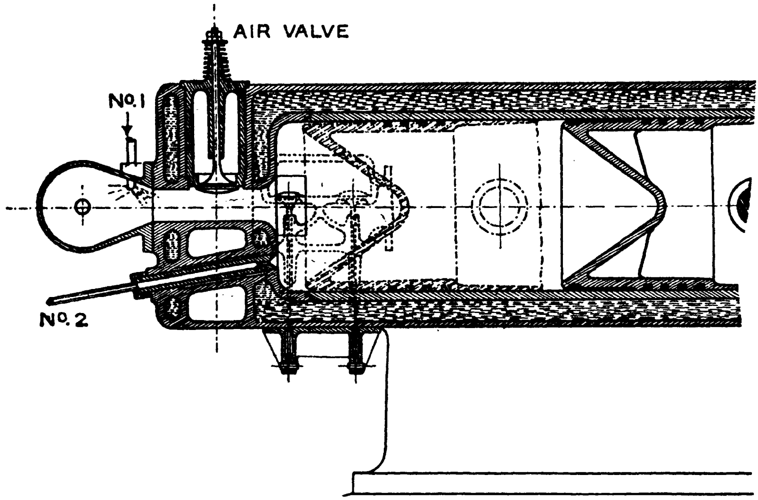

Fig. 24.—Akroyd Dual Combustion (1904)

In 1905 Akroyd Stuart found that neither Hornsby & Sons nor other British manufacturers of oil engines would take up this Patent No. 28045, the latter because the name Akroyd was too well known coupled with Hornsby. So, he allowed the patent to become void in 1908, by non-payment of patent fees. However, after 1908 he observed that several patents were taken out to increase the brake h.p. of oil engines on the same basic principle, in one form or another.

During the years 1905–6, Akroyd Stuart made further experiments in his engineering works in Australia, on a Hornsby-Akroyd engine altered to work exactly as described in his original pioneer patent No. 7146 of May, 1890, with *timed* oil spray injection into compressed air in the vaporizer *only*, near the end of the compression stroke. By taking advantage of the cooling water jacket on the vaporizer, the compression was raised to about 230 lb. per square inch, with greatly improved economy of fuel. The indicator diagram, shown in fig. 25 on reduced scale, was taken from this engine by using a strong spring. Thus he clearly proved that still higher compression pressure ought to have been used in the development of the Akroyd engine, and he adds: " Experience would have indicated the safety limit of compression for practical working " with temperature conditions regulated by the water jacket.

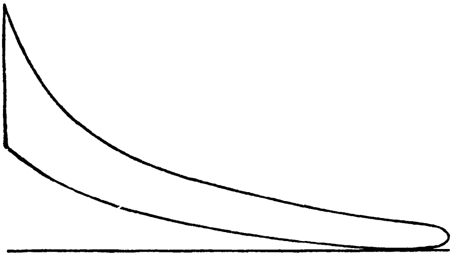

Fig. 25.—Indicator Diagram: Akroyd Experimental Engine

De La Vergne Oil Engines.—The Hornsby-Akroyd oil engine was introduced into the United States of America in 1893 by Messrs. De La Vergne Refrigerating Machine Co. as licencees. The design was changed on American lines and the engine known as the De La Vergne, type " H.A.", at first built by this Company in small powers from 5 to 32 brake h.p. This largest size oil engine had cylinder diameter 16 in. by 20 in. stroke, and speed 200 r.p.m., at low compression about 50 lb. per square inch, to work on kerosene. Fig. 26 is a sectional plan of the vaporizer * generally fitted on the single-acting four-stroke oil engine. The end cap or hot bulb only is uncooled and kept at incipient cherry-red heat by explosions of the working charges, and the compression of the air as described above. The charge of oil from

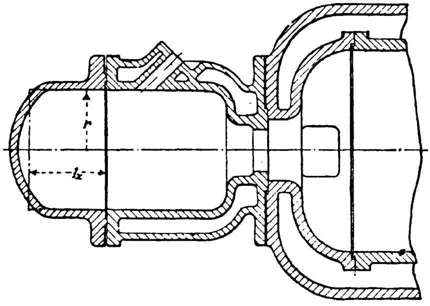

Fig. 26.—Vaporizer " H.A." Type Oil Engine

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* See paper on " Oil Engine Vaporizer Proportions ", by Louis Illmer, at the Annual Meeting, December, 1915, of the American Society of Mechanical Engineers.

a single pump is injected through the spray nozzle as finely pulverized particles towards the hot spot of the vaporizer cap. This spray is converted into vapour by (1) the heat of the residual exhaust gas confined in the clearance space, (2) conduction and radiation of heat from the hot cap into the mass of gas, while the heavier particles may impinge against the surface of the cap and become evaporated, and (3) by compression of air into the clearance space. The dome-shaped end of the cylinder clearance is interesting and was reproduced by other manufacturers. The action is that of the ordinary Hornsby-Akroyd. The engine was very reliable, popular, and easily attended, but the consumption of fuel was 0·8 lb. per brake h.p. hour.

Louis Illmer gives a table of design constants for this " H.A." type: ratio of expansion about $3\frac{1}{3}$, compression 45 to 50 lb. per square inch, full load mean effective pressure 42 lb. per square inch, mechanical efficiency 82 per cent, and at full load the oil consumption was about 0·8 lb. per brake h.p. hour.

An average value of the temperature of the edge of the hot cap of the vaporizer bolted to the jacketed part, and sealed by a copper wire gasket, is taken at 450° F., under full-load conditions.

The vaporizer cap (fig. 26), like the head of a piston or flat plate (fig. 28), may be considered as a thin circular disc, of radius r in., heated at a uniform rate over the surface, and that the heat is removed equally all round the edge. Then the difference of temperature between the centre of the disc or piston head and a point in the face, at radius r in., can be shown to be very nearly $\frac{hr^2}{4kt}$, provided the distance of the point from the edge is not less than the uniform thickness, t in., of the disc or crown, where h is the rate of heat reception in B.Th.U. per square inch per minute, k the average conductivity of the metal, which decreases as the temperature rises.*

Since the surface of a hemisphere is twice that of a disc of equal radius, and the length of heat flow $\pi/2$ as long, the temperature drop from the centre to edge of a thin hemispherical cap, of inner radius r, is $0{\cdot}7\frac{hr^2}{kt}$ nearly. A simple and fairly reliable

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* See *Proc. Inst. C. E.*, Vol. 176 (July, 1909), Appendix II, p. 246; also *Applied Thermodynamics*, by the Author, pp. 339 and 363 (published by Sir Isaac Pitman & Sons).

method is to resolve the cap volume (fig. 26) into an equivalent cylinder of depth l_x, enclosed by a flat plate end; then the equivalent tube length l_e, for heat flow will be $l_x + \frac{r}{2}$.

But for a thin internally heated tube of inner radius r and length l inches, when all the heat is conducted away at one end, the temperature drop over the full length is equal to $\frac{hl^2}{2kt}$, and for unit length the drop is twice that for a disc of unit radius. Hence the equivalent tube length of cap and cylinder makes the heat drop $hl_e^2 \div 2kt$. In larger engines the thickness of this disc depends on the tensile strength of the metal, owing to internal temperature stresses and maximum explosive pressure, so that the tensile stress should not exceed 1500 lb. per square inch. Owing to casting, smaller caps are made relatively thicker, and for the H.A. type the uniform thickness of the plain cap was about 0·075 l_e. It is considered better to avoid the use of ribs, which increase the average temperature of the cap.

When the initial temperature of the charge is 250° F., to deduce the critical proportions of the volumes of clearance and combustion chamber to give the automatic ignition temperature of 900° F. at a compression of 400 lb. per square inch,

Let V = total clearance volume including vaporizer,
V_v = required minimum volume of vaporizer,
V_c = clearance volume external to vaporizer, thus $V = V_v + V_c$,
V_{v1} = volume of products of vaporizer charge V_v, after primary combustion, when the pressure is equal in V_c and V_v,
V_{c1} = volume of charge V_c after compression to the pressure of equalization by the expanding products of combustion.

At constant volume, $P_3 = \frac{T_3}{T_2} . P_2$, for a perfect gas,

where P_3 and P_2 = maximum and compression pressures respectively,
T_3 and T_2 = absolute temperature of explosion and compression respectively.

Assume adiabatic expansion and compression, with index $n = 1{\cdot}25$,

$$\frac{V_{v1}}{V_v} = \left(\frac{P_3}{400}\right)^{\frac{1}{n}}.$$

Then, assume vaporizer proportions such that adiabatic expansion raises the air and vapour in the clearance space to the equalized pressure of 400 lb. per square inch absolute,

$$V_{c1} = V_c\left(\frac{P_2}{400}\right)^{\frac{1}{n}}, \text{ and since } V = V_v + V_c = V_{c1} + V_{v1},$$

we get, the desired relation, $\dfrac{V_v}{V} = \dfrac{1 - \left(\dfrac{P_2}{400}\right)^{\frac{1}{n}}}{\left(\dfrac{P_3}{400}\right)^{\frac{1}{n}} - \left(\dfrac{P_2}{400}\right)^{\frac{1}{n}}}$.

The volume of the combustion chamber is not to be less than this for a high-compression heavy-oil engine. The volume may be reduced, by about one-third, when the mixture is supersaturated, and the ignited vapour projected into the surplus air outside the vaporizer, giving secondary combustion, as in the low-compression Hornsby-Akroyd oil engine (H.A. type). The high-compression oil engine works with a cooler combustion chamber to attain the necessary ignition point, since more heat is produced by compression and less has to be supplied from the walls. This reduces the heat flow and internal thermal stresses. The increased expansion ratio in the high-compression engine also lowers the exhaust temperature.

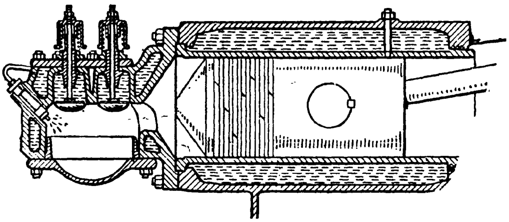

Fig. 27.—De La Vergne Oil Engine, " D.H." Type

Later on, this Company developed, with the help of Mr. Franchetti, the " F.H." type, to meet the demand for an engine of larger power output, 100 to 600 h.p., to use the cheap and heavy crude oils of America and Mexico, working at a medium compression of 280 lb. per square inch.

Louis Doelling, the general manager of the De La Vergne Company, with better sprays and oil pump, reduced the clearance in the Hornsby-Akroyd type by successive stages of natural development, giving improved economy at each reduction, and produced the " D.H." type (fig. 27), and the vaporizer still further reduced in fig. 28, in which the hot cap is a flat disc below the valves.

The mechanically atomized oil spray is injected by oil pump into a large excess of heated air compressed to 300 lb. per square inch, near the end of the compression stroke, giving a maximum explosion pressure of 450 to 475 lb. per square inch, as shown on the indicator diagram (fig. 29). The fuel consumption guarantee is 0·5 lb. per brake h.p. hour of any crude oil or fuel oil produced in the United States or Mexico, having an effective calorific value of not less than 19,000 B.Th.U. per lb.; although the performance recorded on test from three-fourths to full load was only 0·4 lb. per brake h.p. hour.

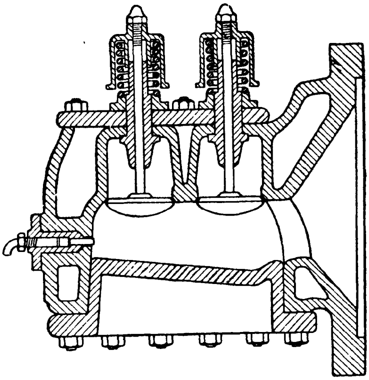

Fig. 28.—Section through Vaporizer

The De La Vergne type D.H. was built in sizes giving 40 to 60 brake h.p. in a single cylinder, and in practical working proved very good as regards reliability and economy.

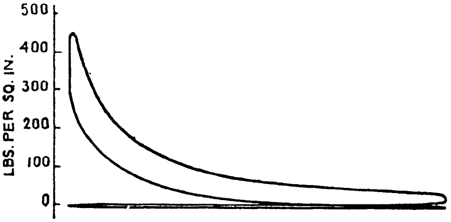

Fig. 29.—Typical Indicator Diagram, " D.H." Type

The engine is started with the piston just past the dead centre, ready to begin the power stroke. The vaporizer is heated, and the oil pump worked to inject a charge of oil spray, then compressed air is admitted to the cylinder and the combustion forces the piston outward; when the engine gathers speed the air is shut off.

Louis Doelling asserted that Akroyd Stuart was the first to invent an oil engine of the D.H. type.

The next design affords an example of the progressive development from the prototype Akroyd of May, 1890, to the cold-starting airless-injection heavy-oil engine. A demand followed for an oil engine of this simplified design, and larger output, 100 to 150 h.p. per single cylinder, hence the " S.I." type (fig. 30) was brought out. Here the next appropriate and natural step in the development was to further reduce the clearance by allowing practically none at all in the motor cylinder, and thoroughly water-cooling the combustion chamber, also dispensing with external heating. The very long trunk piston with conical head compresses the *excess charge of air* into the combustion chamber to a pressure of 330 lb. per square inch, which proves ample to ensure ignition and complete combustion, because, on account of excellent pulverization of the oil fuel at *very high velocity* of the jets, the entire combustion space is filled with a uniformly distributed oil mist, injected into the air near the end of the compression stroke. There are two spray valves on opposite sides of the cylinder head (fig. 31), in connexion with the combustion chamber. The fuel pump is mounted on the governor bracket and operated by a hardened cam on the side shaft; the centrifugal governor acts on an overflow valve on the oil pump by a simple linkage. The engine is of neat and massive design. The initial explosion pressure is about 500 lb. per square inch. Independent tests at full load by oil-engine experts resulted in a fuel consumption of 0·4 lb. of oil per brake h.p. hour, having the lower heat value of the oil fuel not less than 19,000 B.Th.U. per pound, and the fuel consumption guaranteed at full and three-quarter load 0·45 lb. per brake h.p. hour.

In this way the original Akroyd oil engine, working by the spontaneous ignition of oil sprayed into hot compressed air, without any cylinder clearance, became eventually developed in America to the high-compression, cold-starting, efficient heavy-oil engine.

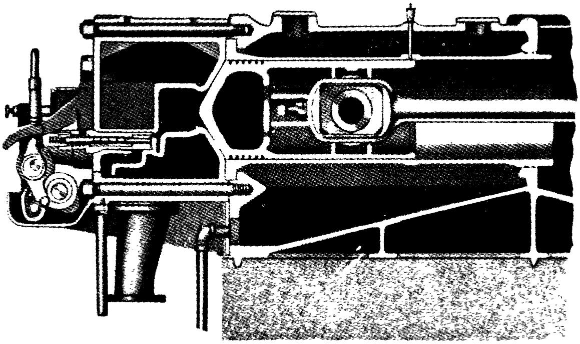

Fig. 30.—DE LA VERGNE OIL ENGINE—" S.I." TYPE

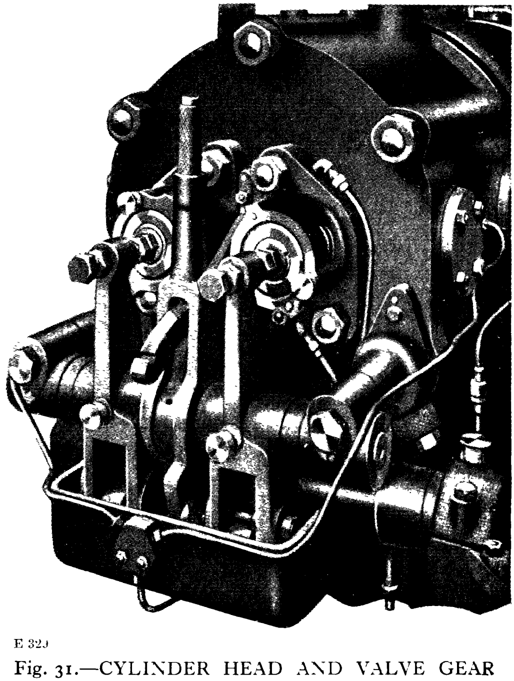

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Fig. 31.—CYLINDER HEAD AND VALVE GEAR —" S.I." TYPE

CHAPTER IV

The Diesel Engine

In the year 1890, the Akroyd patent specifications, describing the two distinct methods of working with ignition by excess of hot compressed air, were taken out in the continent of Europe. Moreover, besides the publication in London of tests of the Akroyd engine in 1891, the other Hornsby-Akroyd type was imported into Belgium, France, and Germany; and the licencees, H. Gebr. Pfeiffer, Kaiserslautern, Germany, took up the sole right to manufacture Hornsby-Akroyd oil engines in Germany, under agreement dated 1st July, 1895, so that Herr Rudolph Diesel and his colleagues had the opportunity of knowing about compression ignition in these oil engines, as well as the spraying of the fuel by compressed air in the Priestman oil engine of 1888. Accordingly, he set out high and extraordinary ideals for an internal-combustion engine.

Diesel described in his British patent specification No. 7241 of 14th March, 1892, and in the pamphlet of 1893, his **Rational Heat Motor.***

This patent claims the use of all kinds of fuels—solid, liquid, and gas—and the proposed engine has the following characteristics:

" The new process of combustion differs completely from all hitherto known processes, and does not produce any increase of temperature and pressure, or only an unessential, insignificant one." The *highest temperature* and pressure are produced at the outset, not by combustion in the cylinder, but entirely by mechanical compression of ordinary air. " The fundamental conditions for perfect combustion " are: (1) Compression of pure air, or of pure air mixed with inert gas, to such a pressure that the temperature produced by the compression is far higher than the ignition

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* English translation entitled *Theory and Construction of a Rational Heat Motor*, by Bryan Donkin (published by Messrs. E. & F. N. Spon, Ltd., London).

temperature of the fuel. (2) Admission of the finely-divided fuel at the dead centre and during part of the return stroke of the piston; this admission being *gradual and at a regulated rate* so that no increase of temperature or pressure takes place during combustion. (3) After the admission of fuel has been cut off, further expansion to be sufficient for the exhaust to be at about atmospheric temperature, so that the exhaust gases carry away only insignificant quantities of heat. By special arrangement the exhaust temperature can be made lower than the atmospheric temperature, and can be used for refrigerating purposes. (4) No artificial cooling of the cylinder walls is necessary; but, on the contrary, they should be lagged to protect against loss of heat by radiation. Because, he adds, " the mean temperature of the cylinder contents necessary for keeping the parts tight and lubricated, and in general for the practical working of the engine, is obtained solely by the process itself, whereby it differs from all known processes." Diesel claims that these characteristics differentiate his engine from all others.

It has been asked, which, if any, of these characteristics are found in the Diesel engine of to-day? Diesel's claim of combustion without increase of temperature is quite incorrect. Experiment proves that in the actual internal-combustion engine cylinder the temperature rises during the process of combustion (see p. 53); and cooling of the cylinder walls is found necessary for continuous working.

Diesel described an engine to use powdered coal, and to work on the **Perfect Ideal Carnot cycle.** (*a*) *Isothermal compression* of the correct weight of air, the heat produced being carried off by water spray, and then (*b*) *adiabatic compression* of the air to the highest pressure and temperature of the cycle, far higher than the ignition point of the fuel, to 250 atmospheres in the coal engine to develop 100 brake h.p., " modified to only 90 atmospheres "; (*c*) gradual and regulated introduction of the powdered coal into the hot air to produce *isothermal combustion*; (*d*) the fuel is cut off after a part of the piston stroke, and the subsequent *adiabatic expansion* of the products of combustion and the surplus air cools the gas to a very high degree and to the initial pressure; it is obvious that no artificial cooling of the cylinder walls is necessary. Therefore, there was no need for a water jacket to the cylinder, nor any lubrication. The Author is not aware of any attempt having been made to work a coal engine under such conditions; although efforts are still being made to burn powdered coal in the internal-combustion engine.

Diesel was fortunate enough to come to an agreement with the Maschinenfabrik, Augsburg, Nürnberg (now known as " M.A.N. "), in February, 1893, who acquired the selling rights for Germany; and in April, 1893, with Messrs. Krupp, Essen, for the patent rights outside of Germany. In June, 1893, both of these firms agreed to establish a laboratory in order to make experiments on this invention.

The first experimental engine was of the vertical type, without a cooling water jacket, but the cylinder was fitted with a sheet-iron jacket presumably to be filled with non-conducting material. The compression space was formed by a cylindrical recess in the piston head, the depth of which was three times its diameter. " The fuel used was paraffin oil delivered to the cylinder through a Kœrting nozzle, from a receiver, under pressure of compressed air." The engine had no governor, but it did not run by its own power, and had to be driven by belt from shafting, and *proved a failure.*

During 1894, various devices were tried to use gas or vaporize the oil by passing it through a spiral tube fitted into the cylinder, and heated by the compression before being ignited. Eventually, water cooling of the cylinder was tried, and Diesel was led to regard " the combustion at constant pressure as normal combustion ", and the fuel had to be sprayed into the cylinder *quickly*, instead of slowly as previously proposed.

In October, 1894, the experiments with gaseous fuel were stopped, and those with paraffin oil fuel resumed. The second Diesel Patent in Germany, November, 1893, and the British patent specification No. 4243 of 27th February, 1895, was for " Improvements in regulating the fuel supply for *slow combustion motors* by varying the form of the combustion curve ". Claim 1:—" Regulation of combustion motors according to which variation of the action is effected by *blowing* a simple or compound stream of combustible into the compression space of the engine under varying excess of pressure and varying duration of the fuel supply."

It would appear that the first patent claims for the isothermal engine having " combustion without increase of pressure or temperature " had to be discarded as theoretically and practically unsound. Diesel and the M.A.N. engineers had learned something by these experiments and by the practical working of other oil engines.

In 1895 an entirely new engine was built with cooling water jacket, the air compressor for injection of oil being driven from the engine. Various spraying nozzles were tried to inject the oil spray into the compressed air. Then the first brake test was made.

In October, 1896, after nearly four years of experimental work by the Maschinenfabrik, Augsburg, Nürnberg (M.A.N.), a larger engine was built in which the cylindrical compression space between the piston and cylinder cover was used for the first time in these experiments. A stepped piston was tried and again discarded. The well-known method of speed regulation, by the governor allowing the excess of fuel oil to flow back through a return valve, was also adopted. The combustion was at nearly *constant pressure* after adiabatic compression of excess air, although ignition was at constant volume, and there was a slight rise of pressure forming the top part of the indicator diagram, which was made " as broad as possible ".

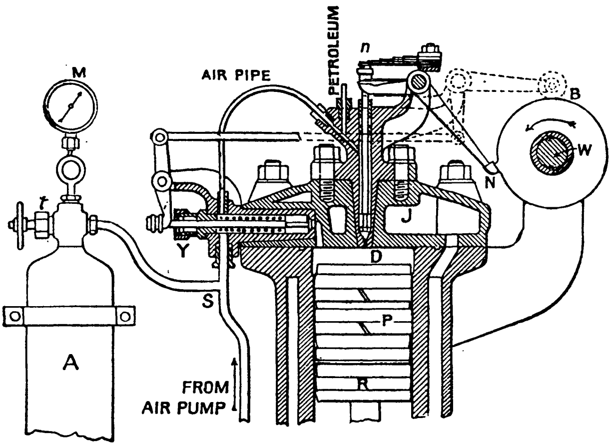

Fig. 32.—Diesel Oil Engine (Sectional Elevation)

Yet it is well known that every unit of heat supplied by explosion at *constant volume* in the engine cylinder has a higher thermal efficiency than that supplied during the piston stroke at constant pressure, since the ratio of expansion is greater, the initial pressure higher, and less cooling surface exposed.

At Augsburg, in February, 1897, Professor Schröter, of Munich, made a series of tests on this vertical engine, having a single cylinder 9·8 in. diameter by 15·7 in. stroke and the air pump 2·7 in. diameter by 7·8 in. stroke. The vertical sections * (figs. 32 and 33) show the piston P, and fuel valve D. A small air pump, worked by the engine, forces air at a pressure of about 50 atmospheres by the pipe S into a bottle A, for injection of the oil fuel through the sprayer D. The half-speed shaft W, driven by bevel wheels from the crank-shaft, is fitted with cams to open the air admission valve V_1, the exhaust valve V_2 (fig. 33), and to work the pump which draws oil fuel from a tank and delivers it to the injection nozzle. The quantity of oil injected into the cylinder is varied by the stroke of the plunger, controlled by a horizontal taper wedge moved by the governor to keep the overflow valve open, when the speed is above normal.

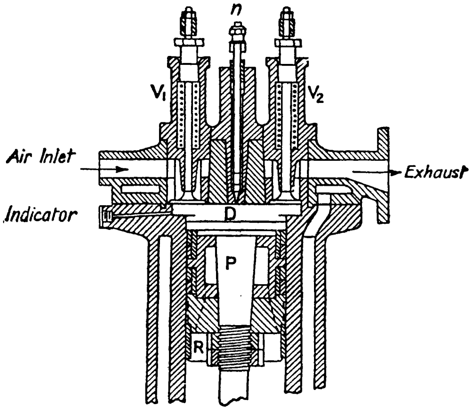

Fig. 33.—Diesel Oil Engine (Sectional Elevation)

The engine is started by highly compressed air from the bottle A, admitted through the valve Y (fig. 32) to the cylinder, and the compression pressure is so high that no preheating is necessary.

The oil used was of specific gravity 0·796, and composition 85·13 per cent carbon and 14·21 per cent hydrogen. Fractional distillation in Engler's apparatus gave 15 per cent from 100° C. to 150° C., 48·2 per cent from 150° C. to 275° C., 11·8 per cent to 300° C., and 25 per cent over 300° C. The low specific gravity and high boiling fractions indicate American Royal Daylight kerosene. Its higher calorific value by Junkers' calorimeter was

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* *Zeitschrift des Vereins Deutscher Ingenieure*, July, 1897.

19,827 B.Th.U., or deducting the latent heat of steam, 18,241 B.Th.U. per pound. In Mahler's bomb, the lower heating value was 18,500 B.Th.U. per pound, and the lowest mean taken was 18,370 B.Th.U. per pound.

RESULTS OF TRIALS OF DIESEL OIL ENGINE BY PROFESSOR SCHRÖTER, FEBRUARY, 1897

	Full Load.		Half Load.	
Duration of trial, hours	1	1	1	1
Revolutions per minute, mean ..	171·8	154·2	154·1	158
Mean pressure (motor cylinder), lb. per square inch	106	105	75	73
Indicated h.p., motor (metric) ..	27·85	24·77	17·71	17·72
„ „ pump „ ..	1·29	1·17	1·14	1·20
„ „ net „ ..	26·56	23·6	16·57	16·52
Brake h.p. (metric)	19·87	17·82	9·58	9·84
Mechanical efficiency, per cent ..	74·8	75·5	57·5	59·6
Oil used per brake h.p. hour, lb. ..	0·54	0·52	0·61	0·61
Percentage equivalent of net calorific value of oil:				
Useful work at brake	25·2	26·2	22·5	22·6
Indicated work (total)	33·7	34·7	38·9	37·9
Carried away in jacket water ..	39·0	40·3	45·1	43·3
Balance rejected in exhaust and other losses	27·3	25·0	16·0	18·8

1 metric horse-power = 0·9863 British horse-power, or 1 British horse-power = 1·014 metric horse-power.

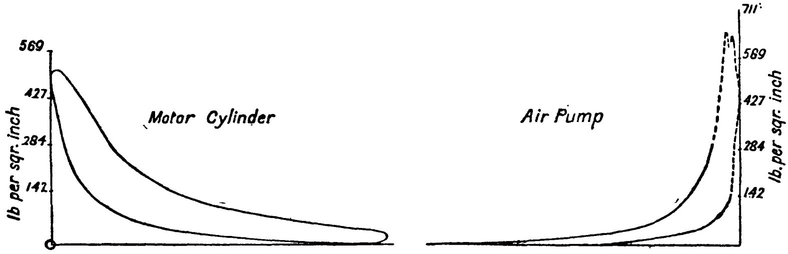

Fig. 34 Fig. 35

Indicator Diagrams: Diesel Oil Engine

Entropy diagrams show that for a compression pressure of 550 lb. per square inch on the Diesel indicator diagram (fig. 34), from the opening of the fuel valve, there is a *rise of temperature* during combustion to the maximum temperature after the fuel valve closes* of about 600° C., which proves that the claim of Diesel for combustion without rise in temperature was erroneous.

It is obvious that this engine, evolved and built by the Maschinenfabrik, Augsburg, Nürnberg, in 1897, is quite different from, and contrary to, the ideas and proposals for practical working stated by Diesel in his original patent specification.

Diesel brought this type of oil engine to public notice in his lecture at the meeting of the " Verein Deutscher Ingenieure ", in Cassel, on 15th June, 1897. He again laid down several fundamental rules governing the action of this type of Diesel engine, including (*a*) compression of air directly from atmospheric pressure and temperature to 30 or 35 atmospheres in one stage, without water spray; (*b*) spraying the fuel by means of *highly compressed but cooled and purified air*, not only for the sake of efficient mixing, but also for gasifying the fuel—which is effected by many fuel particles being first gasified in the total air available, then ignited, thus developing the heat required to gasify the remaining fuel, for which the compression temperature is not sufficiently high. (*c*) It is immaterial whether the combustion curve drops, rises, or is under constant pressure, the most common shape being a line rising slightly convex from the final compression point, forming at the same time the top part of the diagram "*as broad as possible* ". (*d*) The use of two fuels, if the fuel does not ignite easily, or if there are other difficulties in igniting the charge. The methods vary, (1) by placing a drop of ignition oil at the end of the fuel valve, or (2) by changing from the igniting oil to the fuel oil.

A French engineer, Emil Capitaine, had used air blast for spraying the fuel oil into the cylinder of his engine prior to Diesel's proposals, and had referred to the ignition of Masut, sprayed into the engine cylinder by an air blast, by means of paraffin oil which was sprayed into the cylinder just before the Masut, like the present-day pilot charge in use with tar oils. It is stated that Diesel or his Company had to pay an indemnity to Capitaine for the infringement of his patents; but his licencees had their own way in this country, where the name Diesel is still given even to engines of the airless-injection and constant-volume cycle, or Akroyd type.

The outstanding difference between the Akroyd engine of

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* See *Proc. Inst. Mech. E.*, October, 1916, p. 594.

May, 1890, and the Diesel engine evolved by M.A.N. in 1897, was that the latter used very highly compressed air to inject and spray the charge of fuel oil, and was supposed to have combustion at constant pressure, whereas in the Akroyd heavy-oil engine a fuel oil pump and spraying nozzle sufficed to inject the oil spray quickly and directly into the hot compressed air to give explosion at constant volume. The term " airless-injection " of fuel oil has been adopted to distinguish heavy-oil engines of the Akroyd type from the Diesel engine employing high-pressure air injection of the fuel charge. Incidentally, the latter requires, for engines of large power output, a multi-stage air compressor and accessories that have proved, in some instances, to be a " continual source of trouble ".

In the modern Diesel engine, the blast air for injection of the oil must be at a much higher pressure than the ignition pressure necessary for the air in the engine cylinder, because of the very considerable *cooling effect* of air at 1000 or 1200 lb. per square inch when passing through the spraying valve and expanding down to the pressure of the air in the combustion space.

It is interesting to note that Germans are now building the British airless-injection engine, and all credit is given to Diesel. Not only so, but the Akroyd precombustion chamber with the narrow passage to give forced turbulence, Patent No. 15994 of October, 1890, is used to-day as a new device and patented,* with slight modification. This forced turbulence is an essential feature in the small oil engines now being developed for road traction.

Evidently the advantages of working by the simple Akroyd methods, without the air compressor, are recognized and appreciated, though scant acknowledgment or recognition is given to the British pioneer inventor of compression ignition, who in the year 1890 showed this to the world by simply spraying heavy oil by means of a pump and nozzle into an excess of air in the combustion chamber at the end of the compression stroke. The name of Akroyd Stuart is obscured or only associated with the later Hornsby-Akroyd " hot-bulb " engine, while his invention of the *water-cooled combustion chamber* in 1892 is apparently ignored, but since the patent lapsed has been used generally in the development of the heavy-oil engine.

It is necessary to point out that, notwithstanding the world-

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* See, for instance, Sulzer Patent No. 32,492, of 29th Dec., 1923.

wide publicity given to Diesel for the engine which was not his own invention, but *evolved* by the M.A.N. and only advertised by him, high-speed and most efficient oil engines are now practically all coming to the airless-injection type, that is, leaving the Diesel practice of blast air injection and the constant-pressure cycle and returning to that of Akroyd Stuart. The M.A.N. Company has overcome many difficulties in the development of their engine and especially in adapting it in large power units for marine propulsion.

CHAPTER V

Development of English Airless-injection Heavy-oil Engines

Many new oil engines appeared after the expiry of the two Akroyd pioneer master patents in 1904, and that of the water cooling jacket on the combustion chamber two years later. One of the most successful was built in 1909 by Messrs. Ruston, Proctor, & Co., Lincoln; and the evolution of this type into the heavy-oil cold-starting compression-ignition oil engines of 1915 is specially interesting. In the 1909 engine (fig. 36), the charge of fuel oil was injected into the air compressed to 280 lb. per square inch in a hot-bulb combustion chamber, near the end of the compression stroke, by the direct action of an oil pump forcing the oil through an effective atomizer. The bulb was not cooled by water jacket; its temperature was regulated by water injection, about 0·2 lb. of water per brake h.p. hour. There was a contracted neck between the combustion chamber and the working cylinder (fig. 36), in which the air inlet and exhaust valves were fitted. The thorough atomization of the heavy oil was an essential feature of this engine.

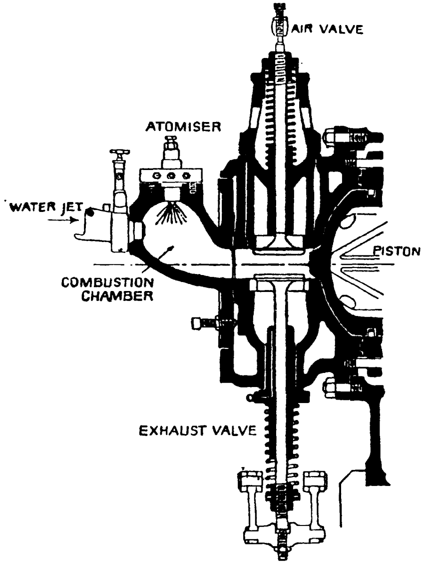

Fig. 36.—Ruston and Proctor Hot-bulb Oil Engine (1909)

In December, 1910, the Author made a series of brake tests on a Ruston & Proctor heavy-oil engine (1909 type of 50 h.p. at 205 revolutions per minute. The fuel pump was operated by a steep cam, and the fuel oil taken from a small tank on a weighing machine passed through a fine strainer or filter, and was quickly injected through a sprayer or atomizer into the vaporizer near the end of the compression stroke. The vaporizer was at a dark heat, never approaching dull red, and the ignition was regular and automatic, as shown by the typical indicator diagram (fig. 37), The compression of the air charge was about 280 lb. per square inch and the initial explosion pressure 420 lb. per square inch.

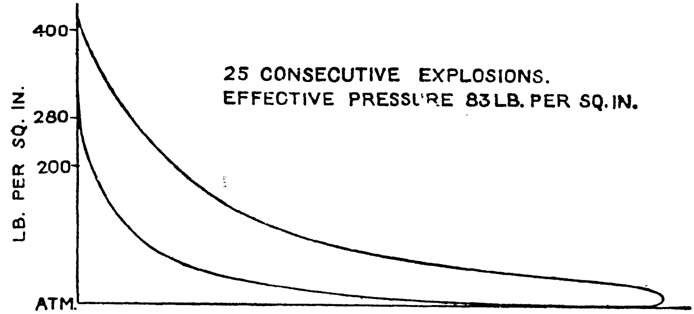

Fig. 37.—Indicator Diagram: Ruston & Proctor Oil Engine (1909)

Samples of the oil used were taken at the end of each trial; and the calorific values afterwards determined by explosion in the Mahler-Cook bomb calorimeter. The following values were obtained:

	Russian Crude Oil.	Italian Refuse Oil.
Specific gravity at 60° F...	0·875	0·947
Higher calorific value, B.Th.U. per lb... ..	19,100	18,620
Lower or effective heating value, B.Th.U. per lb.	18,000	17,600

The results of the three trials are given in the table:

	Russian Crude Oil.	Italian Refuse Oil.	
	Full Load.	Full Load.	Three-quarter Load.
Duration of trial, hours	2	2	1
Revolutions per minute, mean ..	205·7	205·5	208·8
Brake h.p.	51·8	50·8	38·5
Oil used per hour, lb.	23·25	24·9	18.0
Oil used per brake h.p. hour, lb. ..	0·45	0·49	0·47
Percentage equivalent of net heating value of oil:			
Useful work at brake..	**31·4**	**29·5**	**30·8**
Indicated work on diagrams.. ..	40·4	37·5	41·6

At full load the mean effective pressure in the engine cylinder from indicator diagrams with Russian crude oil was 83 lb. per square inch, and 80 lb. per square inch with Italian refuse. The revolutions were recorded by a counter on the crank-shaft, and the speed regularly checked by a tachometer.

The steadiness in running of the engine throughout the trials was excellent, and after the full-load trial, when the load was suddenly thrown off, the speed increased from 206 and kept steady at 208 revolutions per minute.

The thermal efficiency or economy of fuel oil during this test marks an advance in the performance of hot-bulb heavy-oil engines.

One essential of primary importance for rapid and complete combustion in airless injection is the thorough pulverization of the oil fuel into fine mist or fog. At the same time the spray must have sufficient penetration and distribution to mix thoroughly with the compressed air required for its combustion, so that each particle must be completely vaporized and burnt before coming into contact with a cold surface to which it would otherwise adhere and burn slowly, tending to form a deposit of carbon. These two requirements—pulverization and penetration—are apparently incompatible, and it is necessary to effect a compromise in practice; the third factor, distribution, is also essential for complete combustion.

In some modern airless-injection engines the oil spray cloud is quickly discharged through minute orifices of diameter 0·016 to 0·024 in. in the spraying nozzle by direct action at very high liquid pressure from a positively driven pump plunger, and may be given a combined axial and rotary or whirling motion in the atomizer to produce turbulence, which increases the rate of flame propagation throughout the compressed-air charge. Not the least practical advantage of airless injection is its simplicity.

Ruston 1915 Type.—Knowing that thermal efficiency could be increased by higher compression and perfect pulverization of the fuel oil, a further step was taken by Messrs. Ruston, Proctor, & Co. Experiments begun in 1912 led to the design of the 1915 type of airless-injection compression-ignition heavy-oil engine, which gave remarkably good results under ordinary working conditions; and marked progress was made by *starting from cold* and running on low-grade residual oils during the Great War. When ordinary fuel oils were not available these engines used fuel consisting of 75 per cent Anglo-Mexican fuel oil, of specific gravity 0·95, and 25 per cent of creosote; and in one instance a single-cylinder engine of 70 brake h.p. had run with this fuel 144 hours per week during 12 months with thoroughly satisfactory results.

The combustion chamber (fig. 38) is water jacketed, and the engine is easily started from cold by compressed air at 250 lb. per square inch without any external heating. After a few revolutions, in about 30 seconds, the air valves are closed by a little hand wheel, and the fuel-oil pump thereby put in action; then each charge is fired automatically by the hot compressed air. The compression of air in the engine cylinder, before oil-spray injection, is about 420 lb. per square inch and depends upon the ignition point of the fuel oil used.

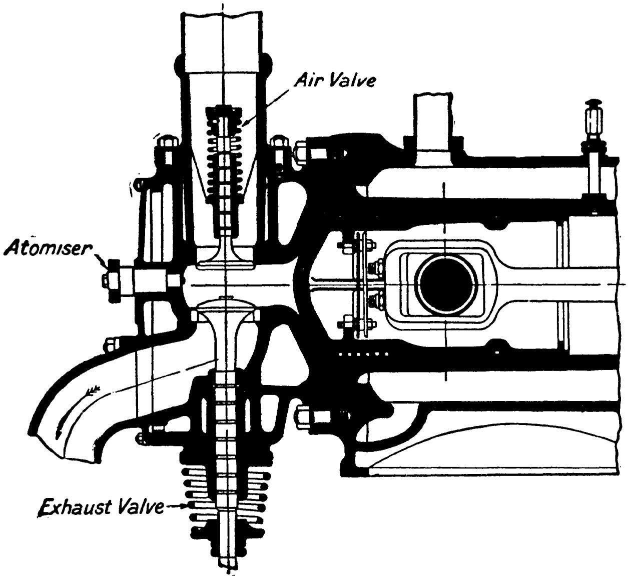

Fig. 38.—Ruston Heavy-oil Engine (1915 Type)

The essential parts are an efficient spraying nozzle, called an *atomizer*, and a fuel pump, driven by a *steep cam* giving abrupt action, as in the 1909 type, which delivers the charge of oil quickly at the correct time, near the end of the compression stroke. The oil pressure lifts the spring-loaded needle valve which closes the opening to the injection nozzle. After injection by the fuel pump, the fuel valve snaps back promptly on its seat and prevents any dribble. The positive and direct action of the fuel pump tends to keep the passages in the nozzle clean, and there is no trouble from leakage or "sticking-up" of the fuel valve, which on certain occasions wrecked Diesel air-injection engines. When working on the heavier oils, the injection generally starts about 15° before the end of the compression stroke. The excellent shape of the combustion chamber greatly increases turbulence, which gives rapid propagation of the flame and complete combustion.

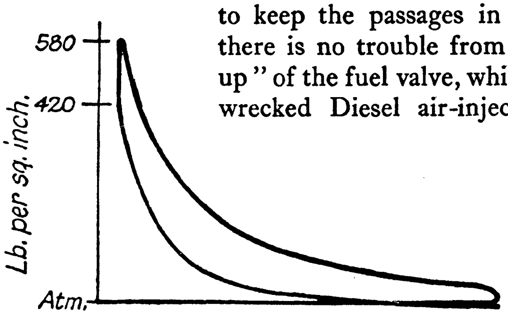

Fig. 39.—Indicator Diagram from Ruston Heavy-oil Engine (1915)

On account of the cooling action of the cylinder walls, the more rapidly the heat can be added, the greater will be the thermal efficiency. The explosion at constant volume gives a vertical line on the indicator diagram (fig. 39), and attains a maximum initial pressure of 560 to 600 lb. per square inch. The typical indicator diagram at full load shows that most of the heat is added at constant volume, but a small portion may be added by combustion continuing for a very brief period at nearly constant pressure. The more the later burning is reduced, the higher will be the efficiency.

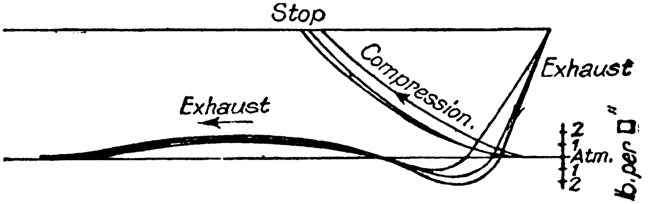

Fig. 40.—Light Spring Diagrams (Pumping Strokes), Ruston Oil Engine (1915)

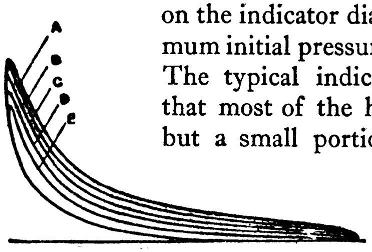

Fig. 41.—Indicator Diagrams showing Governing

The light spring diagrams (fig. 40) indicate very low resistance during the exhaust and suction strokes. The speed regulation is by the centrifugal governor controlling the oil charge, as shown by the full range of diagrams (fig. 41).

Thick sluggish oils of great viscosity and high ignition temperature, like palm oil grease, or tar oils of specific gravity 1·019, are warmed in the tank in order to flow through the service pipes and filters to the exhaust heater. A lighter fuel oil may be used at starting until the exhaust heater warms the tar oil to make it sufficiently fluid. Then, the best results are obtained by *pilot ignition*, of 6 to 10 per cent lighter fuel oil by the device shown in fig. 42. The pilot oil is injected ahead of the main charge of tar oil to start the combustion. The sprayer has two spring-loaded needle valves; the inner discharges the pilot oil, and the outer, which is tubular, injects the main charge of tar oil.

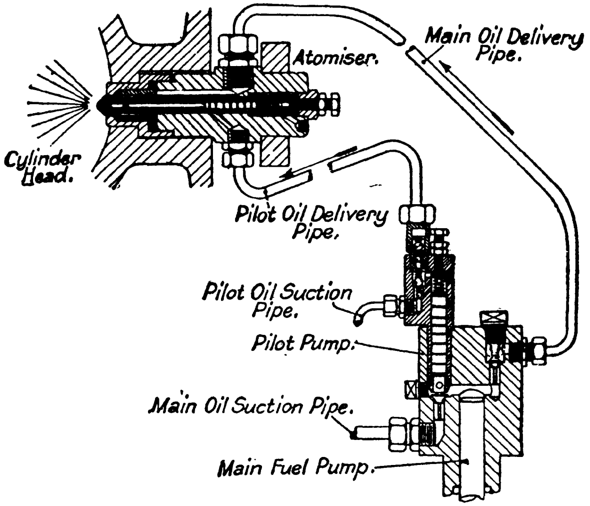

Fig. 42.—Pilot Oil Pump and Sprayer for Tar Oils

The smaller pilot pump is actuated by the impulse of the oil on the stepped plunger in the main fuel pump, so that the igniting jet just precedes the tar-oil spray.

Fuel Distributor.—A novel feature of the larger engines is the Ruston fuel distributor (figs. 43 and 44), devised to prevent one cylinder of a multi-cylinder engine carrying less than its share of the load and causing overloading of one or more of the other cylinders, due to unequal distribution of the fuel between them. A reciprocating plunger P (fig. 44) has inlet and outlet ports and passages through which the fuel oil is directed to the atomizers in correct sequence. This plunger is driven up and down by a double cam from the half-speed shaft. Both illustrations show the outlets A, and fig. 43 the pipe E, leading from the fuel pump to the distributor of a 400 brake h.p. four-cylinder engine. The engine speed may be adjusted by the set-screw C, at the underside of the pump body (fig. 43).

A little leakage serves for lubrication of the working parts, and is returned to the fuel tank by the pumping action of the lower end of the plunger, and by a drain-pipe. In practice, this arrangement of a single fuel pump and distributor gives uniformly equal distribution of fuel to the cylinders.

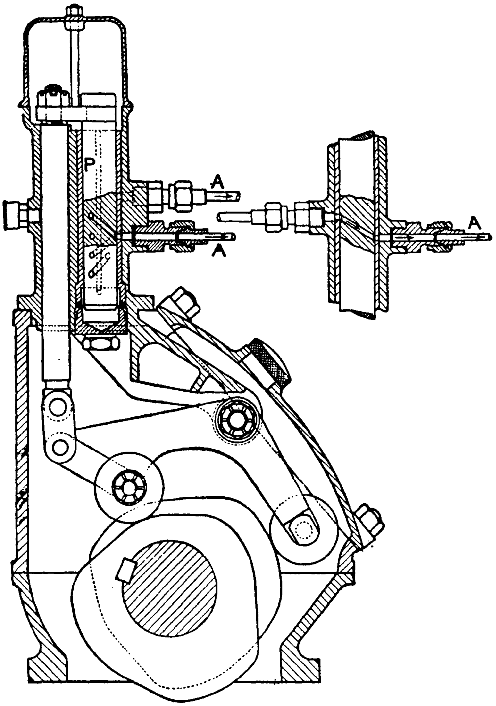

Fig. 44.—Section of Fuel Oil Distributor

Many independent brake tests, and the performance of the Ruston heavy-oil engines under working conditions, and Electric Lighting and Power Station records at varying load factors, give the rate of fuel consumption guaranteed at full working load and three-quarter load, 0·38 to 0·42 lb. per brake h.p. hour, of fuel oils in accord with the British Standard Specifications for heavy-oil engines, page 8. All engines are tested at the Lincoln works of Messrs. Ruston & Hornsby, on oil having a viscosity not exceeding 250 seconds at 100° F., unless the firm is otherwise instructed.

In a brake test of 6 hours' duration made by the Author on a 1915 type of Ruston compression-ignition airless-injection oil engine developing 80 brake h.p. at 210 r.p.m. on " Shell Mexican " residual oil of specific gravity 0·92 at 60° F., having lower calorific value 18,000 B.Th.U. per pound, the rate of fuel consumption

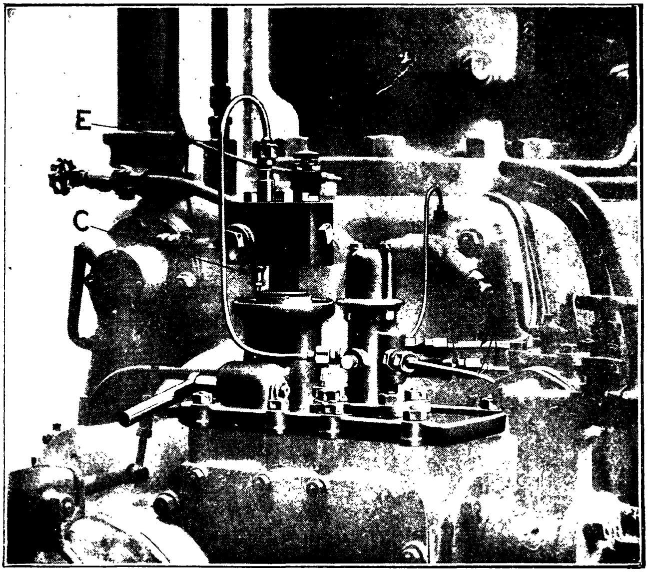

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Fig. 43.—RUSTON FUEL-OIL DISTRIBUTOR

was 0·4 lb. per brake h.p. hour, equivalent to brake thermal efficiency of 35·3 per cent.

The engine was started from cold by compressed air in 30 seconds, and the full load applied to the brake in 5 minutes; the speed was uniform and regular throughout the 6 hours' run without any attention, except supplying fuel and lubricating oil, which were weighed. The cooling water outlet increased in temperature to 120° F., at which it remained. The indicator diagrams (figs. 39 and 40) were taken at regular intervals. At the end of the test the load was increased to 88 brake h.p. or 10 per cent overload which the engine carried easily. When stopped, the bearings were quite cool, and the big end of the connecting rod was only milk warm, the piston was clean and well lubricated. The performance of the engine was in every respect excellent.

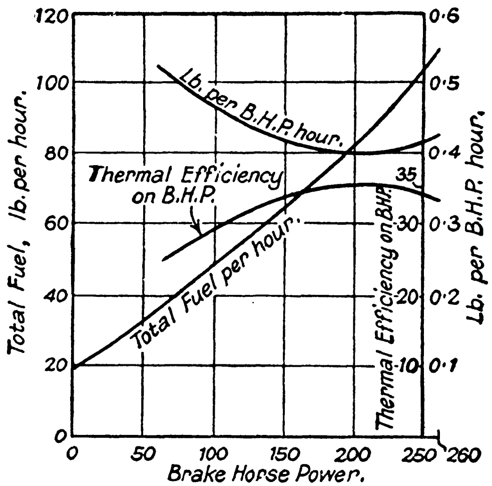

Fig. 45.—Fuel Consumption Curves of Twin-cylinder Ruston Oil Engine (Sankey)

A Ruston twin-cylinder horizontal compression-ignition oil engine of the 1915 type was tested * by the late Captain Riall Sankey in July, 1920. Each cylinder developed 130 brake h.p. full load at 175 r.p.m. The test was started at 8 a.m., and the engine ran perfectly without stopping until 6 p.m. "It was impossible to say by the sound what load was on the engine or when the load was changed." The curves (fig. 45) show the oil consumption at different loads. The best economy of 0·4 lb.

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* *Proc. Inst. Mech. E.*, October, 1920, p. 698.

per brake h.p. hour was obtained at 220 brake h.p. The fuel used was a thick, treacly Anglo-American fuel oil of lower calorific value 18,050 B.Th.U. per pound, and the brake thermal efficiency was 35·3 per cent at full load.

A similar series of brake tests during 11 hours' non-stop run, from no load to 10 per cent overload, was made by Mr. W. A. Tookey on a Ruston & Hornsby vertical type cold-starting heavy-oil engine having four cylinders, each 16 in. diameter and 22 in. stroke, developing up to 419 brake h.p. at 250 r.p.m The engine, just constructed, ran regularly and required no attention throughout the trials, working on Diesel fuel oil of specific gravity 0·895 (analysis, C, 77·3 per cent, H_2, 12·7 per cent), and lower calorific value 18,130 B.Th.U. per pound. At full load the consumption was at the rate of 0·403 lb. per brake h.p. hour, equivalent to a brake thermal efficiency of 34·8 per cent.

The single-cylinder horizontal engines are now built in sizes up to 170 brake h.p. and double cylinders to twice this power output. The demand for engines of higher speed and reduced floor space in central power stations led to the design of vertical engines built in sizes up to 125 brake h.p. in each cylinder, and capable of giving an overload 900 brake h.p. with six cylinders. The speeds vary from 450 in the smallest to 220 r.p.m. in the largest size.

An example of the reliability and efficiency of the airless-injection principle, under actual working conditions in an Electric Light and Power Station, may be given of the Ruston high compression-ignition at 420 lb. per square inch, airless-injection vertical engines using fuel oil of specific gravity 0·897.

The records * from the Electricity Generating Station are:

Year.	Running Plant Load Factor, per cent.	Average Units, per hour.	Total Fuel Oil, per hour, lb.	Fuel per Unit generated, lb.
1922–3	50·2	125	86·0	0·688
1923–4	51·4	128	86·0	0·672
1924–5	45·3	113	78·3	0·693
1925–6	48·9	122	82·2	0·673
1926–7	58·4	146	94·7	0·649

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* See paper " Some Notes on the Working of the Ruston Mechanical Injection Oil Engine ", by C. O. Milton, before the Diesel Engine Users' Association, 9th July, 1925, and 29th April, 1927.

These figures, at a plant load factor of 50 per cent, are equivalent to a fuel consumption of about 0·46 lb. per brake h.p. hour. The consumption at full load was 0·614 lb. per kilowatt-hour generated, or 0·41 lb. per brake h.p. hour, and 35 per cent brake thermal efficiency. The no-load consumption, with the dynamo excited, was found to be 26·3 lb. per hour. If this value be deducted from the total average hourly consumptions, then the fuel consumption per electrical unit generated, varied only from 0·46 lb. to 0·48 lb. over the whole period.

The cylinders are 16 in. bore and 22 in. stroke, and speed 250 r.p.m. The greatest wear in the cylinder liner is 0·03 in. near the top, after 11,984 hours' running. " So far no piston ring has been removed. There is no doubt about the simplicity of operation with this type of engine. In this connexion we have found the absence of an air compressor in continuous operation a great advantage." These results are not exceptional, and, doubtless, a great deal of development has taken place since these engines were installed.

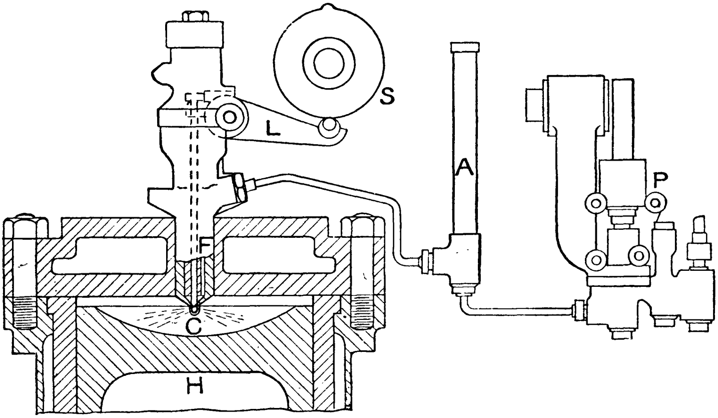

Fig. 46.—Vickers Airless-injection System

Vickers Airless-injection Oil Engine.—Another English type of airless-injection heavy-oil engine was successfully evolved by Messrs. Vickers, Ltd., from the early experimental work of James McKechnie. During the War nearly all British submarine engines were fitted with the airless-injection system. Fig. 46 shows the Vickers method of airless injection by the early timed fuel-oil pump, P, with discharge to the hydraulic accumulator, A, which always maintains a constant pressure, about 4000 lb. per square inch in the supply main and has ample capacity to provide for the compressibility of the fuel oil, and ensures a high volumetric efficiency. In this engine the fuel-valve casing can be made a more reliable measuring device of the oil charge than an ordinary pump, because fuel oil changes in volume under pressure. When the fuel valve, F, is lifted off its seat the charge of oil is forced, by very high pressure, through a number of small holes in the sprayer which break up the oil into a mist, and mix it intimately

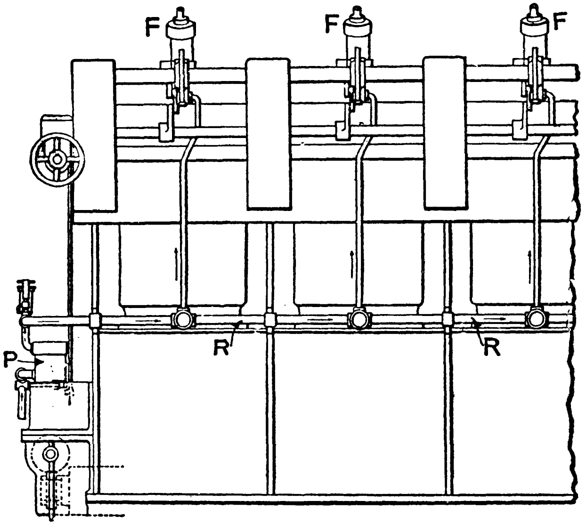

Fig. 47.—Common-rail System, Serving Multi-cylinder Oil Engines

with the excess air compressed to about 380 lb. per square inch in the combustion chamber, C, giving compression ignition and explosion of the charge. The correct moment for the fuel injection is adjusted by means of the timing gear, which alters the position of cam-shaft S, relative to the crank-shaft. The fuel valve is pressed on its seat by a standard spring load of 618 lb., and the valve spindle, of this direct-lift type, is operated by the lever L.

On service the spray valve is more easily kept exact than the pump, which accounts for the sea-going preference for the **common-rail system,** fitted on the standard submarine engine of twelve cylinders. In this system, shown by diagram (fig. 47), a pump P supplies fuel oil to the common rail or pressure main R, from which pipes are taken to each mechanically operated fuel valve F. The Vickers common-rail pump is usually fitted with four plungers to serve the twelve-cylinder engine, and, as the fuel pressure is kept constant, there is no overloading of any one cylinder. An equal quantity of oil is delivered to each cylinder and the engine runs smoothly.

The other system of a separate fuel pump for each cylinder, as close to the cylinder head and fuel valve as possible, is also used for an engine consisting of a small number of cylinders. But in a large engine fitted with multi-pumps for airless injection, experience indicates that the adjustment for uniform distribution of fuel to each cylinder is much more difficult than in one with a single pump. In standard submarine engines fitted with the multi-pump system there are connexions to change over to the common-rail system, which is said to give smoother running, each cylinder doing an equal share of the work when the sprayers are kept clear.

The very high velocity of the oil-spray jets, under constant high pressure, aids vaporization and ensures spontaneous ignition and explosion in the compact combustion chamber (C, fig. 46).

The early type of spray nozzle had five holes each 0·019 in. diameter, and later larger holes 0·0205 in. diameter were adopted. The number and size of these holes depend on the viscosity of the fuel oil, on the mean pressure of the fuel injection, and on the speed of the engine. The shape and size of the combustion chamber determine the slope and arrangement of the oil jets, since it is most important that the oil spray should not strike a cool surface.

During a six-hours official shop trial of a Vickers 12-cylinder engine at average speed 385 r.p.m., with constant fuel-oil pressure for airless injection about 4000 lb. per square inch, the average power output was 1215·2 h.p. at the brake, and the consumption was at the rate of 0·378 lb. per brake h.p. hour of fuel oil, having specific gravity 0·875 at 60° F.; flash point 150° F. (close); the average compression pressure of the air charge 357 lb. per square inch, and maximum explosion pressure 629 lb. per square inch. The diameter of the holes in the spraying nozzle was 0·0205 inch. The engine ran very satisfactorily throughout the trial; and the same consumption was given repeatedly by these engines at Barrow, even when using tar oil of specific gravity 1·019, at full power and speed, only the compression was increased.

Early High-speed Compression-Ignition Engine

In the early days of the war, 1914, Mr. Alan E. L. Chorlton proposed to develop the British type of compression-ignition heavy-oil engine to obtain more power than the standard submarine engine, using airless injection and automatic ignition, by the use of a forged aluminium-alloy piston of high conductivity, and light reciprocating parts to run at higher speed. A four-stroke engine, having a single cylinder of diameter 14·5 in. by 15 in. stroke, was constructed under Mr. Chorlton, and the first tests made by him at the works of Messrs. Ruston & Hornsby, Lincoln. These trials were very successful, and the engine was run up in speed from 380 to 600 r.p.m., and very efficient operation obtained. He has stated that the Farnborough aircraft engine is a lineal descendant of this engine. At the higher speed of the engine, the velocity of air and gases, through the inlet and exhaust valves, rose to over 300 ft. per second; and a very rapid rate of firing was obtained, mainly due to turbulence.

The nominal output was 100 brake h.p. at 380 r.p.m. The engine gave such promising results that it was the first *Unit* engine installed in the Admiralty Engineering Laboratory, South Kensington, where it was used by Professor C. J. Hawkes, Engineer-Commander, R.N. (Ret.), in an interesting research* on the injection and combustion of fuel oil, and other problems of the heavy-oil engine, intended for use in the Naval Service.

In these experiments on airless injection of fuel oil the compression pressure was 380 lb. per square inch, and the initial or maximum explosive pressure was in all cases adjusted by the timing gear to 630 lb. per square inch. With the sprayer having five holes, each 0·019 in. diameter, and fuel-oil pressure 4000 lb. per square inch, at 100 brake h.p. and 380 r.p.m., the consumption was 0·45 lb. per brake h.p. hour. The shale fuel oil used throughout the experiments had specific gravity 0·86 at 60° F., flash point 220° F. (close test), and viscosity 43 seconds at 70° F. (Redwood No. 1).

The sprayer holes were reduced to 0·016 in. diameter, and by filing flats around each hole, the length of the hole was made $\frac{1}{32}$ in. By these changes in the sprayer, for the given size and shape of the combustion chamber, the best all-round results were obtained, with a clear exhaust, and fuel consumption just under

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* *Trans. N.E. Coast Engineers and Shipbuilders*, 1920, Vol. 37, p. 3.

0·4 lb. per brake h.p. hour, when developing 100 brake h.p. at 380 r.p.m. Further trials with a compression of 440 lb. per square inch gave a slight improvement in economy of fuel.

The experiments pointed to the desirability of using higher fuel injection pressures up to 5600 lb. per square inch, and the load on the automatic inlet fuel valve was increased from 618 to 750 lb. The *volumetric efficiency* of the fuel pump of $\frac{1}{2}$ in. bore and an effective stroke $\frac{15}{16}$ in., pumping against atmospheric pressure, was about 95 per cent, which was reduced to 75 per cent when pumping against the maximum pressure, due chiefly to the compressibility of the fuel oil, and leakages of glands, valves, &c. Allowance has to be made for this decrease when working with higher oil pressures.

Owing to the very small holes in the spraying nozzle, thorough filtration of the fuel oil is very essential, and fine strainers are usually fitted on both the suction and discharge sides of the fuel pump before the oil reaches the fuel valve. The occasional choking of sprayers on service was supposed to be probably caused by very small particles of packing from the glands of the fuel-valve spindle and fuel pump, which points to the desirability of dispensing with packing glands, and the use of *ground* spindles.

In the discussion on this paper, Mr. Alan E. L. Chorlton " wished to say very definitely that the English high-compression oil engine was a different engine from the Diesel; it was the child (rather the grandchild) of the original engine of Akroyd Stuart—the hot bulb with contracted neck. It had grown step by step through the years, with gradually raised compression and lessened uncooled surface, till it had arrived at the all-cooled type of which the Ruston might be taken as an example—simple to a degree and yet having the remarkably low consumption of 0·4 lb. per brake h.p. hour. It might be said to work on a dual cycle, constant volume and constant pressure. Such an engine was essentially an English engine and deserved recognition as such.

" The Diesel engine had arisen more or less out of theoretical claims—ultimately modified to an engine working on the constant-pressure cycle. The Vickers engine was the nearest in design, using airless injection, in this country. If members of the Institution were going over to the use of airless injection or the English type, they ought to acknowledge it fully, if only in justice to Akroyd Stuart, from whom it had sprung.

" Returning to the experiments, both types, English and Diesel, had now run on 0·4 or even down to 0·385 lb. of fuel. To what would the English type fall when it had had the concentrated consideration and development of the other? To 0·35 lb. or even less per brake h.p. hour?"

Professor Hawkes agreed with these remarks, and subsequently said: " I was very pleased to hear Mr. Chorlton refer to the use of the word ' Diesel ' and the claims of Mr. Akroyd Stuart in regard to the airless-injection heavy-oil engine. As a tribute to the work of a British engineer, I should like to associate myself with his remarks in this connexion."

Vee Oil Engine.—After the war, a Vee type (fig. 48) was built by Messrs. W. Beardmore & Co., in which the Akroyd Stuart combustion chamber with contracted neck was adopted for experimental purposes. This engine had aluminium alloy pistons 17 in. diameter, the largest at the time, and was *supercharged* from the pressure set up in the enclosed crank-case by the downstroke of the two pistons. There were ring valves rotating over ports in the liner at the extent of the piston travel. The supercharge took place through these ports at the end of the suction stroke, and by means of the ring valves was directed first to one cylinder and then to the other, in the right phase.

The main inlet valves had their spindles at right angles to the cylinder axis, to use the Akroyd Stuart combustion chamber. The speed through the neck was about 230 ft. per second; a higher one could not be used because of the throttling of the charge.

This interesting engine marks a rather important direction in oil-engine development. For instance, a six-crank Vee engine with 12 cylinders, 18 in. bore by 22 in. stroke, gives 3500 brake h.p. at 480 r.p.m. Hence six of these engines would propel the standard ocean liner of 20,000 tons, and take up very little space, but their development has not come yet.

Nomenclature.—The Oil Engine Nomenclature Committee of the Institution of Mechanical Engineers, appointed in 1920, with the late Captain H. Riall Sankey, President (Chairman), included builders of various oil engines, engineers familiar with the development of the oil engine industry, the Engineer-in-Chief of the Fleet, representatives of the Aeronautical Inspection Directorate, Directorate of Research, Air Ministry, Institution of Automobile Engineers, and the Diesel Engine Users' Association.

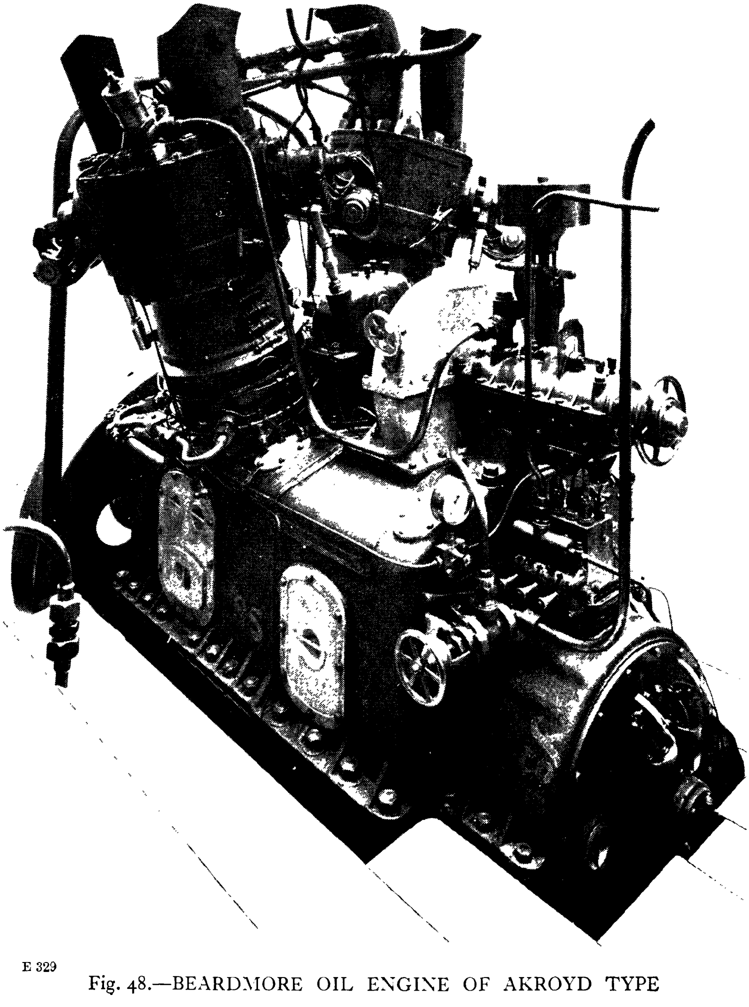

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Fig. 48.—BEARDMORE OIL ENGINE OF AKROYD TYPE

In the Report * of November, 1922, it is stated, *inter alia*: " The Committee is of the opinion that the modern oil engine, as distinct from the automobile type of liquid-fuel engine, has been evolved mainly from the principles enunciated by Mr. Herbert Akroyd Stuart in his Patent No. 7146 of 8th May, 1890, and as embodied in the engine constructed at Bletchley (Buckinghamshire), and tested by . . . a Member of the Committee, in February, 1891. . . . This Akroyd engine is the prototype of those in which the liquid fuel is introduced into a compressed, or partially compressed, charge of air, and which does not need an extraneous source of ignition. In this respect the Akroyd engine anticipated the engine subsequently evolved in Augsburg, Germany, by the Maschinenfabrik, Augsburg, Nürnberg, from the original proposals of Rudolph Diesel in 1893. . . . It may thus be said that the pioneer work of Herbert Akroyd Stuart has been adversely cloaked by nomenclature.

" The Committee considers that the term ' Semi-Diesel ', as applied to oil engines, is subversive of the fact that this type of oil engine is a British production and an evolution from the Akroyd engine."

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* *Proc. Inst. Mech. E.*, Nov., 1922, p. 1113.

CHAPTER VI

Marine Airless-injection Oil Engines

During the last decade an enormous amount of research work has been carried out on experimental heavy-oil engines in the engineering laboratories of the Admiralty, Air Ministry, oil-engine builders, and engineering colleges, resulting in rapid advance in the development of engines of British design and manufacture, though this advance must necessarily proceed step by step with practical experience under ordinary working conditions.

The outstanding feature is the adoption of airless injection and combustion at constant volume in vertical heavy-oil engines applied to the propulsion of the *mercantile marine*, *railway cars or locomotives*, and *airships*.

The temperature stresses and heat flow in the cylinder liner, cover, and piston from the burning charge to the cooling water, are all-important as the cylinder dimensions are increased, and form a difficult problem for the designer of oil engines to give large power output. The heat flow on unit area depends on: (1) the difference in temperature of the working charge in the cylinder and that of the cooling water; (2) the thermal conductivity of the material used in the construction; and (3) the distance to the cooling water, as well as (4) the interval of time allowed; (5) the density and turbulence of the working fluid.

The shape of the combustion chamber and the volumetric efficiency are also important to ensure rapid and complete combustion with high thermal efficiency; so that the conditions given by Beau de Rochas still hold good.

The cylinder liner and other parts exposed to the intense heat of the explosions have to be as thin as possible, and yet fit to withstand the highest explosion pressure in the cylinder.

In spite of all efforts to prevent it, a very large proportion of the heat supplied by combustion in the oil-engine cylinder inevitably passes with the exhaust gases * to the atmosphere, and another portion is carried away by the cylinder jacket cooling water. The problem is to reduce this waste of heat to the practicable minimum. Attempts to conserve some of this wasted heat have been made from time to time, by using the exhaust gases for heating purposes or for generating steam in a low-pressure boiler for heating or auxiliary purposes. Supercharging by means of exhaust gas turbo-blowers is most important.

The Still principle carries this a step farther, for not only does it provide means for recovering a portion of the heat in the exhaust gases, but it utilizes also the whole of the heat passing to the cylinder-jacket cooling water for generating steam. The cylinder liner is surrounded by water in circuit with a regenerator, and in this way the liner is maintained at a temperature corresponding to the working pressure of the regenerator boiler.

A peculiarity of this system is that *all* the heat added to the boiler water by the cylinder jackets is added as *latent heat*, and is wholly used for steam-raising. It is this feature of the Still principle which distinguishes it from all other attempts that have been made to utilize the waste heat of the internal-combustion engine, and it is due to this that the amount of steam produced is of commercial advantage. The application of the Still principle to the propulsion of ships at sea is best seen in the Scott-Still engined vessel *Dolius*.

Scott-Still Marine Oil Engine.—The regenerative oil engine invented by Mr. W. J. Still consists of a combined oil engine and steam engine, in which a portion of the heat from the exhaust gases, also the whole of the heat usually carried away by the cylinder-jacket cooling water, is recovered and utilized to generate steam, which does work in steam-engine cylinders. The exhaust steam from the low-pressure cylinders is passed through a steam turbine which drives the scavenge air blower for the two-stroke cycle heavy-oil engine with simple port exhaust and scavenging. The scavenge air is delivered by the turbo-blower at about 1·6 lb. per square inch, and deflected upwards by the curved piston head (fig. 49). This ingenious combination of internal-

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* The kinetic energy of the exhaust gases escaping from the motor of an aeroplane was utilized in war time by Professor A. Rateau to drive a special turbo-compressor at very high speed to *supercharge* the motor to an amount that varied with the altitude, and so maintaining the power as the density of the air diminishes. See *Proc. Inst. Mech. E.*, 1922, p. 818.

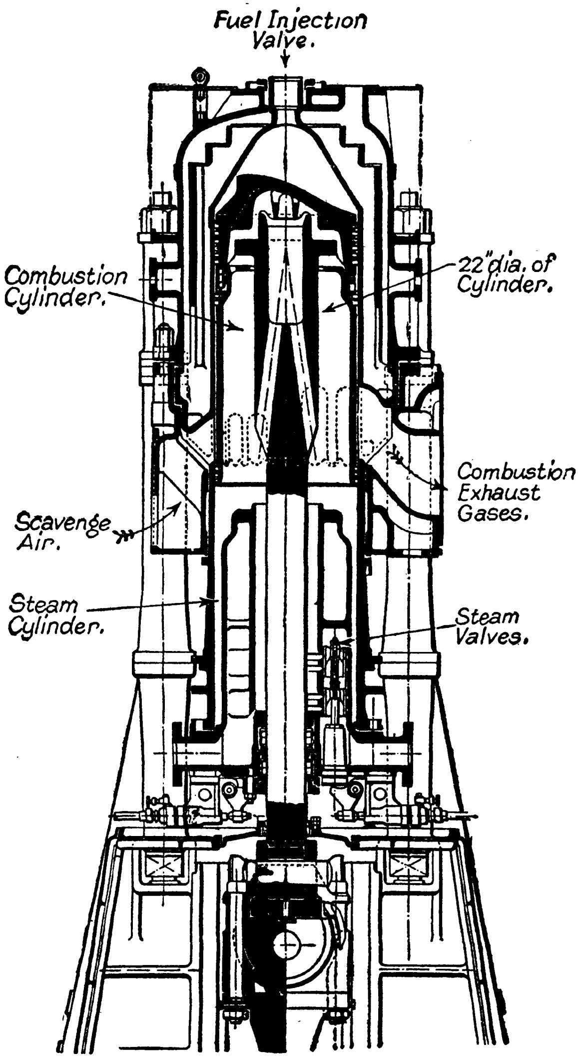
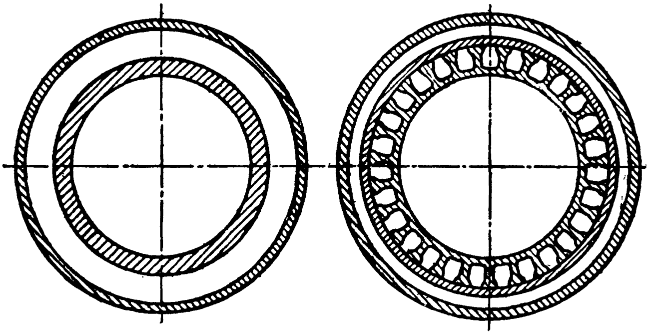


Fig. 49.—Scott-Still Combined Heavy-oil Engine and Steam Cylinders (Vertical Section)

combustion engine and steam engine for waste heat recovery gives great flexibility and efficiency.

The marine oil engine designed and built by Messrs. Scotts' Shipbuilding and Engineering Company, Ltd., of Greenock, for the propulsion of the motor-ship *Dolius*, is chosen as an example of airless injection, because of the complete tests,* both on the test bed and at sea, which gave a performance in every way superior to other types of marine heavy-oil engines, and proved this Scott-Still to be the most efficient marine engine afloat at the present time, being more economical and reliable in service than any other type of marine engine.

The combustion cylinder, shown in vertical section † at the top of fig. 49, has a thin liner, ribbed parallel to the axis (fig. 50), fitted into the steam cylinder for cooling, and is free to expand upwards, while the steam cylinder expands downwards. The liner, $\frac{5}{8}$ in. thick, is reinforced by forged steel hoops (figs. 50 and 51), shrunk over the liner webs to take the bursting pressure stresses. This construction, with shrouds, also assists circulation of steam within the water jacket, while the small difference of temperature, only 50° F. or 60° F., between the inner and outer skin of the liner, greatly reduces the temperature stresses.



Ordinary practice: cast-iron liner and jacket

Still practice: cast-iron liner, mild steel hoop, mild cast-steel jacket

Fig. 50.—Comparison of Cylinder Construction

The exhaust gases from each combustion cylinder pass through a **primary regenerator** (fig. 52), wherein heat is given to the water as it flows up through vertical tubes on its way from the water drum to the cylinder jacket. Then the exhaust gases from all the combustion cylinders enter a common exhaust manifold, and pass along to the water drum of the **main regenerator.** This water drum contains a bank of straight cross tubes through

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* *Proc. Inst. Mech. E.*, March, 1925.

† *The Engineer*, Nov., 1923.

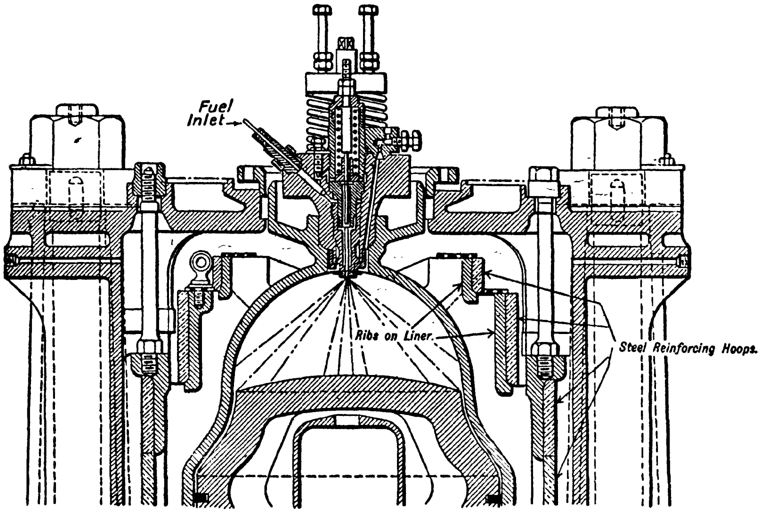

Fig. 51.—Section through Oil-cylinder Head

which the exhaust gases flow and give up more heat; and the last quantity of heat is taken from them while passing through a

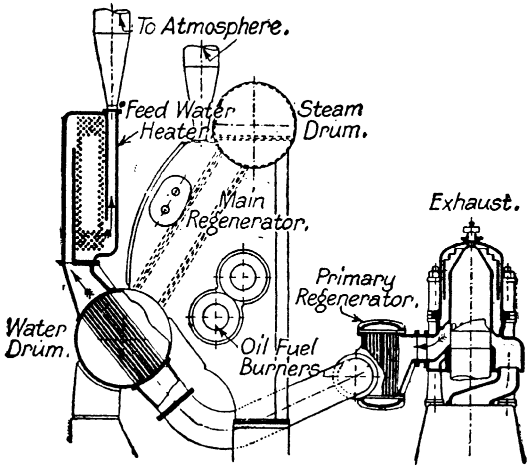

Fig. 52.—Regenerators in Scott-Still Marine Oil Engine

counter-current **feed-water heater**, which consists of a nest of water tubes. The exhaust, thus reduced in temperature, escapes up the funnel to the atmosphere.

By the bold step of putting the cylinder water jacket under boiler pressure, the heat from the combustion that passes through the liner and head of the cylinder to the water jacket, produces the evaporation which takes place in the cylinder jacket and is thus all utilized to generate steam at practically constant temperature. The mixture of water with the steam raised in the cylinder jackets flows up a rising main (not shown) to the steam drum or boiler, where the steam is separated. The circulation is by thermosiphon due to the difference in density of the steam and water. The steam passes from this steam drum or boiler to the high-pressure steam cylinder, through inlet valve and distributor, to the underside of the combustion cylinder piston, where in addition to adding power to the engine it serves to cool the piston head, and is itself slightly superheated in the process.

In the four-cylinder engine under ordinary running conditions, only the aft cylinder of the set receives the high-pressure steam and exhausts into a receiver which supplies the other three steam cylinders at low pressure. After leaving the cylinders, the steam passes through the turbo-blower, which supplies the scavenge air to the combustion cylinders, and exhausts direct to the condenser. The water is pumped from the condenser back to the feed-water heater.

The main regenerator (fig. 52) is virtually a half Yarrow type boiler, fitted with oil burners under the water tubes connecting the steam and water drums in order to augment the steam supply whenever necessary.

This important feature of the Scott-Still engine, namely, by burning fuel oil under the boiler for the generation of steam, allows the engine to be run as a steam engine in starting, and greatly improves flexibility when manœuvring in and out of harbour; also, the steam may be used to propel the vessel at a moderate speed in case of emergency arising at sea, as well as to help the combustion cylinders when more power or extra speed of the ship is required. The combined internal-combustion and steam engines can give ample power for the heavy overload needed, without increasing the heat stresses in the engine cylinders above the limit of perfect safety.

For starting the engine, the fuel-oil burners are lighted under the regenerator boiler, so enabling the oil engine cylinder jackets to be heated up, and providing steam to give the necessary starting effort. When starting and manœuvring, all four steam cylinders of each engine act as high-pressure cylinders with a late cut-off, and receive high-pressure steam; but for ordinary working only one cylinder receives high-pressure steam. Once the engine is under way, the fuel oil supply to the burners is stopped, and the demand for steam is adjusted to equal the amount raised by the waste heat recovery.

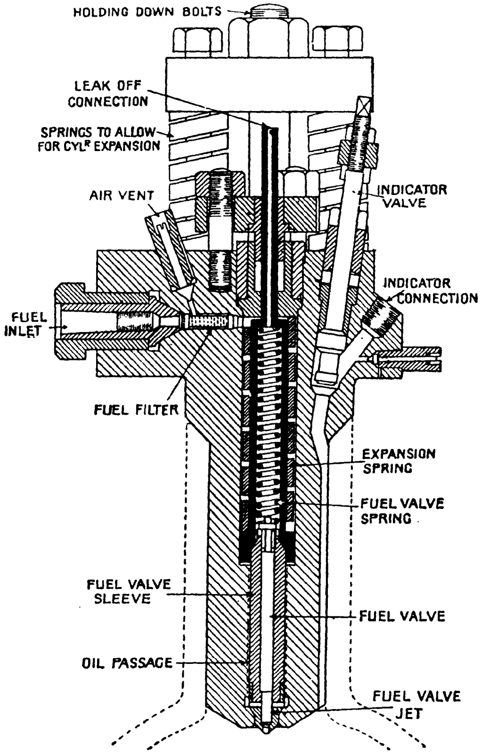

Fig. 53.—Fuel-injection Valve on Scott-Still Experimental Engine

The extremely good manœuvring of this engine is effected by the movement of the steam valves, through operators and distributors, by oil pressure at 400 lb. per square inch from a multi-cylinder pump of the *Hele-Shaw* type, which is driven by a constant-speed continuous current electro-motor. When the pointer of the manœuvring hand wheel indicates " stop " on the attached dial, all the steam inlet valves are closed by releasing the oil pressure to the operators, and the valve in the scavenge-air supply pipe is also closed. The engine will run " ahead " or " astern ", depending on the direction in which the manœuvring hand wheel is turned to the points " set ahead " or " set astern ", and " start ", &c. At " steam and oil ", the governor automatically brings the " spill valve " control lever into action, and the engine is put on fuel oil.

The fuel-oil charge is supplied to the atomizer when the *spring-loaded injection valve* (figs. 51 and 53) is automatically lifted off its seat by the fuel pressure from the pump. It is fitted

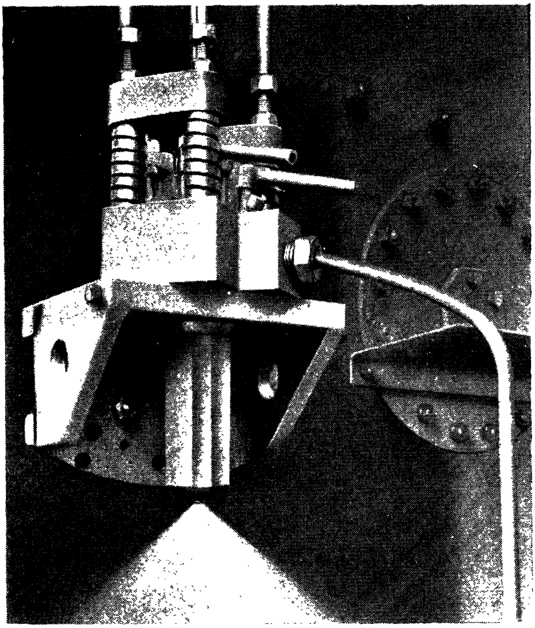

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Fig. 54.—FUEL JET SPRAYING, SCOTT-STILL EXPERIMENTAL ENGINE

with a relief valve loaded to about 6000 lb. per square inch, and an indicator connexion is shown in the outer casing. The central plunger forms a conical valve at its lower end which covers the injection orifice; the upper end is under atmospheric pressure, and the leak-off connexion returns the oil to a drain tank.

Each cylinder receives the oil charge from a separate fuel pump. The pump delivers the oil charge into the annular space around the injection-valve plunger. A pressure of about 3500 lb. per square inch lifts the injection valve off its seat, and the fuel oil is injected at 4000 to 5000 lb. per square inch. The arrangement of the fuel pumps is such that one cam operates two pumps, with 180° difference of phase. To operate four pumps there are two cams for " ahead " and two for " astern " running. The astern cams are placed close to their corresponding ahead cams, and to change from one to the other, the cam rollers are moved sideways by a ram under oil pressure to engage with either set of cams for reversal of direction. Each pump plunger is 1·25 in. diameter by 1·3 in. stroke, so that the capacity is 1·59 c. in. per full stroke. No packing is used on the pump plunger.

The commencement of the fuel injection is fixed by the cam which operates the pump, and the end of the period of injection is also controlled by cam-operated gear which lifts the spill valve at a variable position of the pump stroke, then the fuel injection valve is forced down to its seat quickly by the spring, and prevents the formation of drips. The injection starts at the same point of the compression stroke of the piston for any load, and the opening of the spill valve varies the period of injection for different loads, thus regulating the engine speed by the quantity of oil injected. The governor operates only when the predetermined engine speed is exceeded, or either the oil or water pressure fails.

Too fine a jet (fig. 54) readily gives excellent pulverization, and good results in the engine at lower power, but lacks penetration and the combustion is bad at higher powers. On the other hand, larger holes in the sprayer give jets of great penetration, deficient in pulverization, and tend to impinge upon the piston crown.

After many experiments, Messrs. Scotts determined that: (1) " *Atomization* depends on the relation between the size of the holes in the sprayer and the pressure which can be maintained by the pump. (2) *Distribution* depends on the number of holes at the requisite angle necessary to cover the zone of maximum air content of the combustion chamber. (3) *Penetration* depends on the diameter of the hole for a given degree of atomization. (4) The shape of the fuel-pump cam must be such that it will give pressure and quantities of oil to meet the combination of atomization, distribution, and penetration found most suitable from experiments." *

Eventually a range of jets was found most suitable for the experimental engine; one hole 0·02 in. diameter in the centre of the spraying nozzle, surrounded by a ring of 8 holes each 0·024 in. diameter at an angle of 45° to the vertical. A sprayer of this type having six holes in the circle is shown spraying in fig. 55, on the single-cylinder experimental engine at Greenock.

Instantaneous automatic ignition is ensured by airless injection of the fuel-oil charge into the air compressed to about 325 lb. per square inch in the nearly hemispherical combustion chamber (fig. 51). This low pressure is sufficient to start combustion because the temperature of the air during compression is augmented by heat from the cylinder liner.

Reliability being even more important than economy of fuel-oil consumption in a marine oil engine, many trial runs were carried out by Messrs. Scotts with the single-cylinder experimental engine, using various heavy-oil fuels. In one endurance trial, during fourteen days' and nights' continuous working, this engine gave an excellent performance. Whole-day trials, on the 5th and 6th October, 1921,† were also made by the late Captain H. Riall Sankey, in which this single-cylinder engine developed 345 brake h.p. at 125 r.p.m. on a consumption of shale oil (Lucigen) at the rate of 0·367 lb. per brake h.p. hour. The Scottish Shale Oil (Lucigen) was of specific gravity 0·879 at 60° F.; higher calorific value, 19,426 B.Th.U. per pound, and lower calorific value, 18,065 B.Th.U. per pound; flash point, 266° F.; ignition temperature in air, 698° F.; viscosity (Redwood No. 1), 96 seconds at 60° F. and 40 seconds at 120° F.

From the data obtained in these tests Captain Sankey deduced the " results that might be expected in a three-cylinder unit when

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* "The Still Engine for Marine Propulsion", by Archibald Rennie, *Trans. Inst. Engineers and Shipbuilders in Scotland,* Vol. 65, Feb., 1922.

† *Engineering,* 10th Feb., 1922; *The Engineer,* 17th and 24th Feb., 1922; and *The Motor Ship,* Oct., 1921.

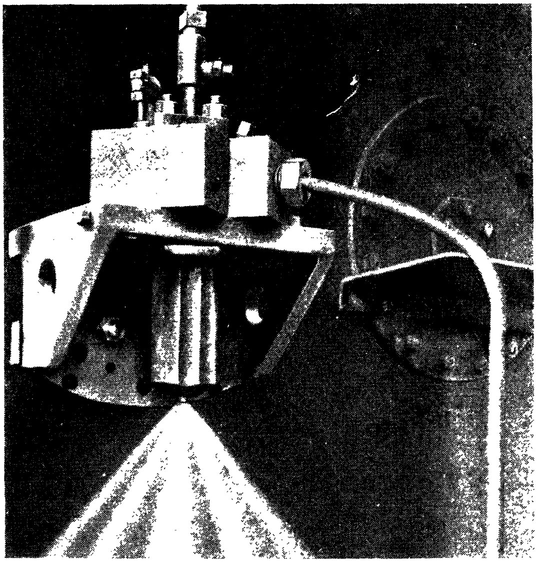

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Fig. 55.—FUEL JET SPRAYING, SCOTT-STILL EXPERIMENTAL ENGINE

the steam is exhausted into a low-pressure turbine driving the air-scavenge blower" as follows:

	Over Load.	Full Load.	Three-quarter Load.
Total indicated h.p.	463·0	404·0	302·0
Brake h.p.	404·0	359·0	256·0
Mechanical efficiency, per cent ..	87·2	88·8	84·6
Oil per brake h.p. hour, lb... ..	0·364	0·353	0·355
Brake thermal efficiency, per cent ..	38·7	39·9	39·7

The Marine Oil-engine Trials Committee, appointed jointly by the Institutions of Mechanical Engineers and Naval Architects, with representatives from the Admiralty and the Institute of Marine Engineers, to carry out tests of oil engines and oil-engined ships, presented their Second Report in March, 1925, giving the results of tests carried out on the first motor ship *Dolius*, propelled by Scott-Still regenerative oil engines built by Messrs. Scotts' Shipbuilding and Engineering Co., Ltd., at their engineering works at Greenock, being their engine No. 592, under licence from Messrs. The Still Engine Co., Ltd., Westminster.

The displacement of the *Dolius* when fully loaded is 11,533 tons, and the dead-weight capacity 8100 tons, the estimated service speed 11 knots, and the propelling power to give this speed being 2500 shaft h.p. at 120 r.p.m. developed on two shafts.

The rating of each main engine is 1250 brake h.p. at 120 r.p.m., the power being developed in four cylinders, working on the two-stroke single-acting cycle. The fuel admission to the cylinders is by airless-injection intermittent-pressure system, from engine-driven pumps, and the firing of the fuel-oil charge is obtained by the temperature of compression of air in the combustion chamber to about 355 lb. per square inch. The dimensions of the port engine, tested ashore, are: bore of each combustion and steam cylinder, 22 in.; stroke 36 in.; and ratio of compression 8·56.

The fuel used in test No. 10 was Anglo-American Diesel oil, of specific gravity 0·864 at 59° F.; higher calorific value, 19,490 B.Th.U. per pound; flash point (Pensky-Martin closed test), 172 F.; burning point 194° F.; viscosity (by Redwood No. 1 Viscometer), 42·7 seconds at 70° F. and 33·1 seconds at 150° F. Ultimate analysis: C, 86·4; H_2, 13·02; sulphur, 0·42; and N_2, 0·06 per cent;

carbon residue, 0·2 per cent; ash, nil; soft asphaltum, 0·1; hard asphaltum, 0·16 per cent. Cold test: there was practically no reduction in fluidity at —4° F.

In this trial at full rated power, of 4 hours' duration, average speed 121·9 r.p.m., the indicator diagrams (fig. 56) were taken. These diagrams indicate the pressures in the combined oil engine and steam cylinders at ordinary working load. The greater part of the combustion is at constant volume, and a little at constant pressure.

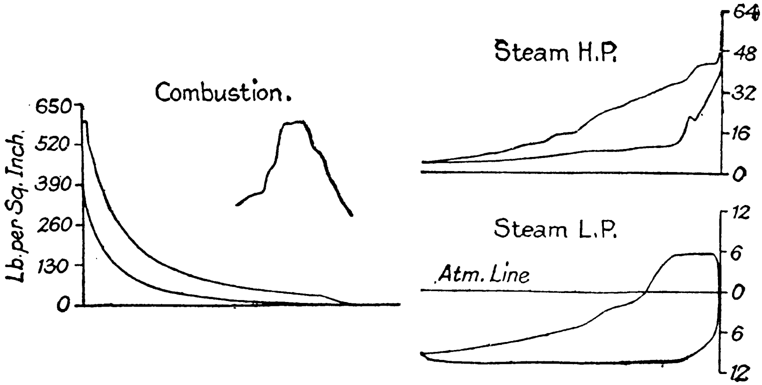

Fig. 56.—Indicator Diagrams, Scott-Still Marine Oil Engine

Results recorded from the *combustion cylinders*:

Pressure at end of compression stroke	355 lb. per sq. in.
Initial or maximum explosion pressure	582 „ „
Pressure at end of expansion	39·3 „ „
Mean indicated pressure, average in all cylinders	76·6 „ „
Indicated h.p. (combustion only)	1290
Thermal equivalent of indicated h.p. for one min.	54,700 B.Th.U.

On the *steam side*:

Temperature at exit from water drum	344° F.
Pressure in steam drum	115·8 lb. per sq. in.
Pressure at admission, high-pressure cylinder	47·5 „ „
Pressure at admission, low-pressure cylinders	4·8 „ „
Pressure at exhaust (below atmosphere)	—10·6 „ „
Average mean indicated pressure of all cylinders	6·9 „ „
Thermal equivalent of indicated h.p. for one min.	4920 B.Th.U.
Total indicated h.p. combustion and steam cylinders	**1406**

Work done by exhaust steam from one engine in turbo-blower (intended for both sets of engines):

Heat drop in turbine per pound of steam .. 88 B.Th.U.
Effective brake h.p. of engine by Heenan and Froude absorption dynamometer **1271**
Brake mean effective pressure .. .. .. 75·4 lb. per sq. in.

$$\text{Mechanical efficiency} = \frac{\text{brake horse-power}}{\text{indicated horse-power}} = \frac{1271}{1406} = 90{\cdot}5 \text{ per cent.}$$

Oil fuel consumption per brake h.p. hour = **0·353** lb.
Oil fuel consumption per indicated h.p. hour = 0·322 lb.
Thermal efficiency on total I.h.p. (not including the L.P. Turbine) = 40·5 per cent.
Thermal efficiency on effective brake h.p. = 37·1 per cent.

$$\text{Efficiency ratio} = \frac{\text{thermal efficiency on total indicated h.p.}}{\text{efficiency of ideal engine (50 per cent)}} = 0{\cdot}81.$$

In order to enable comparisons to be made with the performance of other engines, the combustion side of the engine is debited by the Committee with all the frictional resistances, and so may be said to give at the brake a quantity called the "combustion brake h.p.". Then the effect of the assistance of the steam is to add all its indicated h.p. to this combustion brake h.p. to make up the observed effective brake h.p.

Thus, Friction h.p. = 1406 − 1271 = 135 h.p.
Combustion brake h.p. = 1290 − 135 = 1155 h.p.
Effective brake h.p. = 1155 + steam I.h.p. 116 = 1271.
Thermal equivalent of effective brake h.p. for one min. is 53,912 B.Th.U.

Thermal Balance Sheet, from results of Test No. 10, of the Marine Oil Engine Trials Committee (Second Report):

Fuel-oil supplied—0·353 lb. per brake h.p. hour .. 100 per cent

Distribution of Heat:

	per cent	
Effective brake h.p., 1271 at 121·9 r.p.m. (combustion b.h.p. 1155 + steam I.h.p. 116). ..	37·12	
Power for scavenger blower from L.P. Turbine	2·37	
Friction	3·93	
Total indicated h.p.	..	43·42 per cent

Heat Losses:

Finally carried away in exhaust gases	23·07	
Rejected in condenser-cooling water	25·82	
Radiation	7·69	56·58 per cent
Heat in fuel oil	100·00	

The indicated power is made up as follows:

Combustion indicated h.p.	37·67 per cent
Regenerated steam indicated h.p.	3·38 „
Regenerated steam in L.P. Turbine (heat drop)	2·37 „
Total indicated h.p.	43·42 per cent

The power developed by the low-pressure steam turbine was not taken into account, although obtained from the fuel oil burned in the combustion cylinders, and is here added to the indicated power of the engine, as part of that from the steam generated by the waste heat, and therefore should be credited to the engine. This makes the total indicated horse-power 1457, and the rate of fuel consumption 0·31 lb. per indicated h.p. hour, increasing the thermal efficiency to 41·2 per cent, instead of 40·5 per cent as in the curves (fig. 57). Then the mechanical efficiency becomes 87·2 per cent.

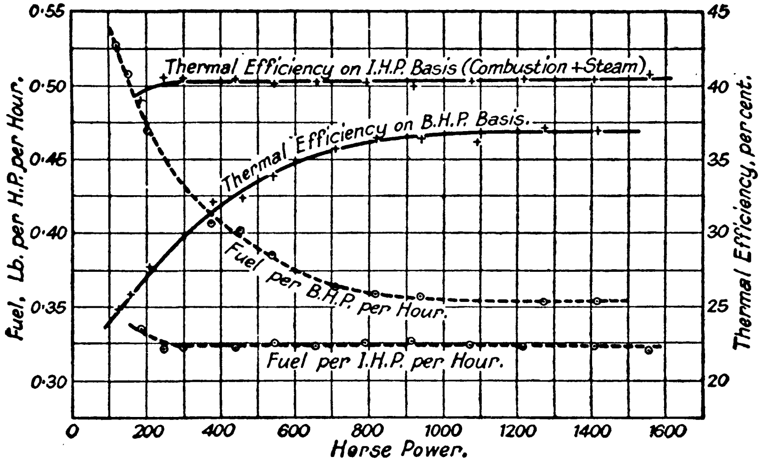

Fig. 57.—Fuel Consumption and Thermal Efficiency Curves (Scott-Still Regenerative Oil Engine)

The trials of the *Dolius* at sea were carried out by the Committee in the Firth of Clyde: the measured mile runs off Skelmorlie, and to Ailsa Craig and Greenock for consumption trials. The ship's speed was from 12·25 knots to 8 knots, at the average engine speeds 133 and 85 r.p.m. respectively. In the manœuvring trials at slow speed, thirteen consecutive orders from the bridge, " ahead " to " astern " and vice versa, were carried out in the engine-room in less than three minutes.

Still the best test of the marine oil engine is at sea on service conditions. The maiden voyage of the motor ship *Dolius* was from Cardiff with a cargo of coal to Algiers, and thence with iron ore to Rotterdam. During the outward journey the fuel consumption recorded by Lieutenant G. W. B. Hext, R.N. (Department of the Engineer-in-Chief, Admiralty) was 8 tons a day at the lower speed of 122 r.p.m. and 2250 indicated h.p. hour, and 9 tons a day at the higher speed and 2450 indicated h.p., which worked out at 0·338 lb. per indicated h.p. hour, *for all purposes*, including fuel oil for ship's services, heating, cooking, electric lighting, steering, and auxiliary machinery. On the return journey from Algiers to Rotterdam, the consumption worked out at almost the same figure, namely, 0·334 lb. per indicated h.p. hour, or an average of 0·371 lb. per b.h.p. hour, *for all purposes.*

The owners of this vessel, Messrs. Alfred Holt & Co., of the Blue Funnel Line, Liverpool, compare ships' performances over a standard run from Liverpool to Port Said, and on the home voyage Port Said to Liverpool.

The *Dolius* has now (1930) been in commission for six years, and during that time has given the owners very satisfactory service. Her performance remains constant and machinery troubles are nil. She has completed over 300,000 miles at sea, and on two occasions was away from her home port for eleven months each time. During these times, she recorded runs of 51 days and 55 days continuously without a stop. As illustrating the high efficiency performance of the *Dolius* and her machinery under service conditions, it might be stated that on a recent run from Liverpool to Port Said an average speed of 11·53 knots was maintained when displacing 11,100 tons, on a fuel-oil consumption of 8·67 tons per day or 0·363 lb. per brake h.p. hour for all purposes. On her sixth outward voyage, with displacement 11,070 tons and average speed 11·53 knots, the fuel-oil consumption was 0·364 lb. per brake h.p. hour for all purposes, which shows that this excellent performance has been well maintained.

The second Scott-Still marine oil engine built by the same shipbuilders, in the M.S. *Eurybates*, is an improved design of greater simplicity, making the parts more accessible, with total power output double that of the *Dolius*, namely, 5000 shaft h.p. at 105 r.p.m. High elastic-limit steel is used in the construction of her hull. The engines, apart from their size, differ from those fitted in the *Dolius* in that the steam cylinders are separated entirely from the combustion cylinders. The two double-acting steam cylinders, 24 in. diameter by 45 in. stroke, arranged at the forward end of each main engine, work in combination with the five single-acting two-stroke cycle combustion cylinders (fig. 58), 27 in. diameter by 45 in. stroke, on to a common crank-shaft.

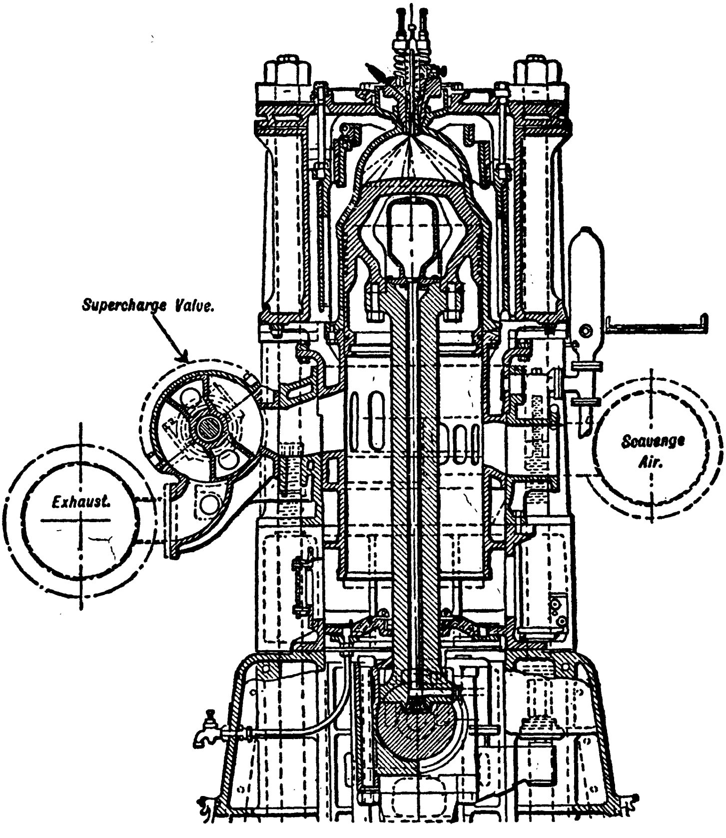

Fig. 58.—Section through Combustion Cylinder

As the steam generated from waste heat is not used on the undersides of the combustion cylinder pistons (fig. 58), in this case a system of fresh-water cooling for these pistons has been provided, by means of ordinary trombone or telescope pipes rigidly attached to the crossheads with an independent pump for circulation. The hot water returned from these pistons is used to heat the feed water for the boilers, and passes to a special section of the main condenser, where it is cooled before returning to the reservoir which supplies the piston cooling water.

The Still type of cylinder liner in the oil engine is retained, as shown in figs. 51 and 58, and the fuel oil is sprayed by airless injection.

The jacket water around the cylinder liners is in circuit with the **low-pressure regenerator** boiler at a working pressure about 15 lb. per square inch, so that air compression of 375 lb. per square inch is sufficient to give efficient automatic ignition and easy starting, because the temperature of the air during compression is increased by the cylinder liner. A separate fuel pump for each combustion cylinder, driven from the main crankshaft by a train of spur gears, delivers the fuel oil at a pressure of 4000 to 5000 lb. per square inch, and the quantity of oil charge passed through the automatic lift valve in each cylinder head is controlled by the spill valve. The fuel pumps are grouped together in a convenient position behind the engine.

As a safety device an *emergency governor*, of the marine steam turbine type, cuts off the supply of fuel oil, by lifting the suction valve in case of overspeed, or of failure in the pressure of forced lubricating oil, or loss of pressure in the piston cooling water supply, and so stops the engine.

The scavenging air is supplied by a steam turbine-driven rotary blower, the steam coming from the exhaust of the steam cylinders.

An ingenious feature is the rotary *supercharging valve* * (fig. 58), driven by spiral gears from the crank-shaft at half the engine speed, in the exhaust outlet passage of each combustion cylinder. This valve has a broad lip to close the exhaust when the scavenge ports are covered, on the up-stroke of the piston, so that compression then commences and a greater quantity of air is retained in the cylinder, giving several important advantages: namely, **supercharging** by the greater weight of scavenge air per cycle from the turbo-blower, tending to reduce the temperature and therefore also the heat stresses in the cylinder, while the mean pressure and power of the engine are increased considerably. Further, the common long skirt of the piston can be made shorter; and the air enclosed below the piston gives cushioning on the down-stroke and steadier running of the engine. This arrangement reduces the weight, height, and friction of the engine, and

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* For drawings of this engine, see *The Engineer*, 30th March, 1928.

allows inspection or cleaning of the ports from the space below.

The two ordinary double-acting steam cylinders (fig. 59), arranged at the forward end of each main engine, are fitted with the Marshall type of valve gear, worked by eccentrics from the crank-shaft, giving late cut-off when starting and early cut-off for ordinary running, also for reversing and manœuvring.

The *high-pressure regenerator* boiler at 180 lb. per square inch (fig. 60) is of the Scotch cylindrical multitubular type, and has the centre and two wing furnaces fitted with oil burners to generate steam for starting, manœuvring, and overload; whilst the other two at 15 lb. per square inch take the exhaust gases of the port and starboard combustion cylinders respectively. After passing through the high-pressure boiler, the exhaust gases are led through a nest of tubes immersed in water in the *low-pressure regenerator*, and collected in a large chamber at the top end of the tubes, then conveyed in a circular flue to the top of the regenerator and passed up the funnel to the atmosphere. The low-pressure regenerator also serves as a reservoir for the combustion cylinder jackets, and connecting pipes from the regenerator supply the jackets with water which returns by natural thermal circulation through other pipes as a mixture of steam and water. The turbines driving the blowers are of the mixed-pressure type, using high- and low-pressure steam.

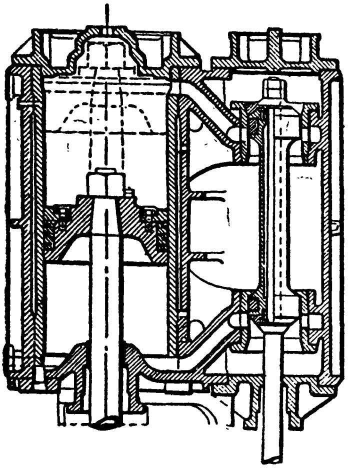

Fig. 59.—Section through Steam Cylinder and Piston Valve

When running under normal conditions at sea, the oil burners are not in use, and the high-pressure steam, at 180 lb. per square inch, generated by the exhaust gases is partly used as a direct supply to the turbo-blowers; the remainder is reduced by a special valve to 15 lb. per square inch. It is then admitted, together with the low-pressure steam generated in the combustion cylinder jackets, to the two double-acting steam cylinders on each main engine. The steam from the engine cylinders exhausts at about 18 in. vacuum to the steam turbine to drive the blower, from

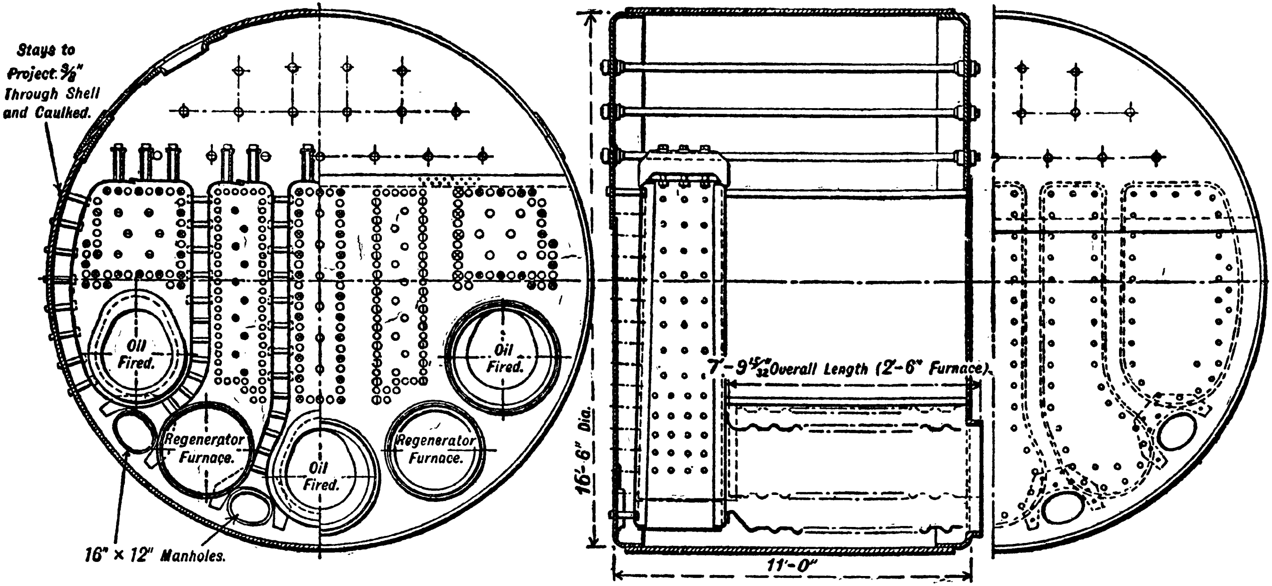

Fig. 60.—The Five-furnace Return-tube High-pressure Boiler

which it is rejected to the main condenser at 28 in. vacuum. The boiler and regenerator, besides serving for waste heat recovery, also form efficient silencers, and no other is needed.

Both fuel and lubricating oils are treated in centrifugal separators and passed through filters.

Ship trials were made in the works with only the portions of the waste heat recovery plant that were necessary for the actual running of the engines. The port engine during a continuous run of 48 hours developed 2485 brake h.p. at 106·5 r.p.m. on 0·375 lb. of fuel oil per brake h.p. hour.

The average of trial runs of the M.S. *Eurybates* at sea over the measured mile were: Speed 15 knots, and 5371 indicated h.p. at 110 r.p.m. Steam in the high-pressure boiler, 177 lb. per square inch, and low-pressure regenerator 13·25 lb. per square inch. Tests at low steady speed, with high-pressure boiler burners lighted, gave 39 r.p.m.; and the engines were run at steady speed as low as 20 r.p.m.

This M.S. *Eurybates* has been in continuous service since she left the builders' works two years ago, and has covered 125,000 miles in that time, keeping station with other vessels of the Company's fleet of much less speed and power, and has, therefore, been developing less than four-fifths of full power. Owing to this limitation, the rate of fuel oil consumption is, meantime, not so good as that obtained by the *Dolius*. Thus, with average displacement 12,130 tons, and speed 13·89 knots, the power was only 3910 brake h.p., and the fuel oil per day 17·33 tons, or 0·414 lb. per brake h.p. hour, for all purposes.

In both of these ships the arrangements have been very satisfactory and successful in service.

However, to meet the demand for a cheaper engine, Messrs. Scotts also build a modified design in which the steam generated by waste heat is used solely to drive the turbo-blowers for the scavenge air; and the main engines are started by means of compressed air as usual in heavy-oil engines. The engine consists of six combustion cylinders of this type (fig. 61), to develop 3000 brake h.p. at 105 r.p.m. Each cylinder is 27 in. diameter by 45 in. stroke, and works on the two-stroke cycle with port scavenging, and airless injection of fuel. A rotary valve is fitted at the exhaust gas outlet from each cylinder for supercharging, and the piston is short skirted, as above (fig. 58).

One fuel pump is provided for each cylinder, actuated by a crank, and delivers the fuel-oil charge at 4000 to 6000 lb. per square inch to the automatic spray valves at the cylinder head.

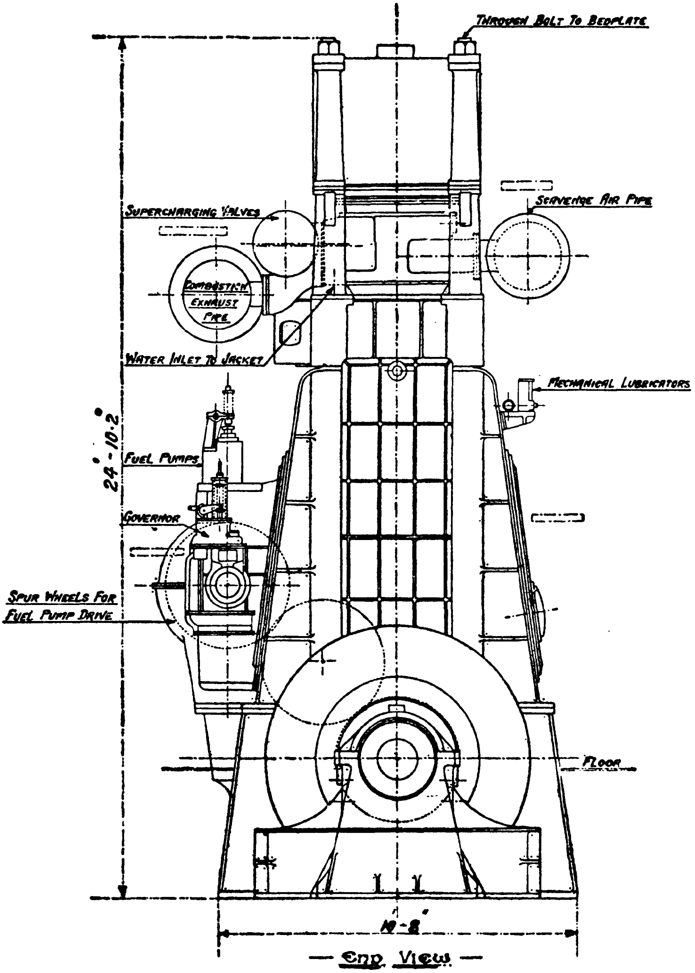

Fig. 61.—3000 brake h.p. Scotts' Two-stroke Heavy-oil Engine (end view)

An automatic air starting valve is also fitted on each cylinder, the manœuvring gear being grouped at the control panel below. Starting air is stored in receivers replenished by independently driven air compressors. No cam-shafts with overhead driving gear are required, so that the engine is extremely free from gear, with consequent ease of operation and overhaul.

Fresh-water cooling arrangements are applied to the pistons, the water being introduced and taken away through trombone or telescope pipes attached to the crossheads, with an independent pump for the circulation under pressure. All working parts inside the crank-case are supplied with forced lubrication, and mechanical lubricators are fitted for the cylinder liners. For the top ends of the main connecting rods a special type of bearing is fitted, originated by Messrs. Scotts, which renders it unnecessary to supply high-pressure oil to this part.

The engine is of rigid construction, and through bolts transmit the combustion load from the cylinders to the bed-plate, as in the other two engines.

Reports of Trials.—The brake thermal efficiencies shown in the table below are taken from the reports * of trials carried out by the Marine Oil-engine Trials Committee. In the trials of the Werkspoor engine (fifth report), the extremely low values of mechanical efficiency led to a suspicion of the high indicated power, which is probably due to the method of driving the indicator drums by cams. The two airless-injection two-stroke cycle engines, Scott-Still and Doxford, gave the highest thermal and mechanical efficiencies recorded. Improvements in the scavenging arrangements in the two-stroke cycle have increased the thermal efficiency higher than that of the four-stroke cycle in these marine engines.

Airless injection by a fuel pump through a small and simple automatic fuel valve, fitted with adjustable spring-loaded needle valve, saves not only the first cost and complication of the blast-air compressor but also the power required to drive it, so that a smaller engine cylinder can be used for a given power.

Reliability is also improved, and the risk of a serious explosion arising from the sticking of the fuel needle or leaky high-pressure air-injection fuel valve, allowing extra fuel into the cylinder, is practically eliminated. The " Diesel " pulverizer is a piece of apparatus which requires delicate adjustment when it is being altered for various fuel oils. The danger of over-lubrication in the multi-stage air compressor is also obviated. With leaking delivery valves in this compressor, lubricating oil may be carried over into the storage bottle or receiver, and the highly heated air may pass back during the suction stroke and increase the

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* *Proc. Inst. Mech. E.,* Dec., 1926, p. 1060.

SOME RESULTS OF MARINE OIL-ENGINE TRIALS ASHORE

Report	First.	Second.	Third.	Fourth.	Fifth.
Date	Nov., 1924.	March, 1925.	Jan., 1926.	May, 1926.	December, 1926.
Motor vessel	*Sycamore.*	*Dolius.*	*Pacific Trader.*	*British Aviator.*	*Cape York.*
Oil engines	Richardsons Tosi.	Scott-Still.	Doxford.	Palmar-Fullagar.	Hawthorn-Werkspoor.
Cycle single-acting ..	Four-stroke.	Two-stroke, regenerative.	Opposed pistons, two-stroke.	Opposed pistons, two-stroke.	Four-stroke.
Fuel injection	Blast-air.	Airless.	Airless.	Blast-air.	Blast-air.
Cylinder bore and stroke, in.	24·41 × 38·39	22 × 36	22·83 × 45·67	23 × 36	22·05 × 39·37
Rating, b.h.p. (on one shaft)	1250 at 125 r.p.m.	1250 at 120 r.p.m.	2900 at 87 r.p.m.	2700 at 86 r.p.m.	1020 at 125 r.p.m.
Fuel oil, specific gravity	0·880	0·864	0·909	0·891	0·884
Gross calorific value, B.Th.U. per lb.	19,320	19,490	19,180	19,105	19,190
Fuel, lb. per b.h.p. hour	0·425	0·353	0·394	0·413	0·422
Brake thermal efficiency, per cent	31·1	37·1	33·7	32·4	31·5
Mechanical efficiency, per cent	79·8	90·5	87·3	81·9	66·1

compression temperature. Thus explosions in high-pressure air reservoirs have been frequently traced to the ignition of the lubricating oil sucked from the crank-case of the compressor.

In view of the simplicity, proved reliability, and efficiency of the airless-injection system, it is not surprising that leading Continental manufacturers are now building airless-injection heavy-oil engines in preference to the Diesel type.

A notable example of British engines is the Doxford marine oil engine giving the high efficiency recorded in the above table; while at full power the average daily consumption of heavy Mexican fuel oil is 0·38 lb. per brake h.p. hour, equivalent to a brake thermal efficiency of 36·8 per cent.

A most interesting and valuable paper * by Alan E. L. Chorlton, C.B.E., on " Working practice in the design of large double-acting two-stroke engines ", is a veritable mine of information on the development work that was then done, including his marine engine of the Duplex type. A number of these engines were made and used to drive electric generators on land. But the people concerned, instead of backing up sufficiently the pioneer work of the British engineer and securing a lead in oil-engine design, had as usual to " wait and see ", looking abroad, and go to the Continent for licences—at a price.

Further advance in the development of the large-power marine oil engine has been made by the use of the **double-acting two-stroke cycle** principle.

Richardsons, Westgarth Marine Oil Engine

With the aim of reducing the size, weight, and first cost of the marine oil engine, Messrs. Richardsons, Westgarth & Co., Ltd., Hartlepool, have recently designed and built a heavy-oil engine † of the double-acting two-stroke type with special port scavenging, working with a moderate compression-ignition pressure about 375 lb. per square inch, and employing airless injection of the fuel oil by controlled pump, and automatic fuel valves.

The design of a single-cylinder experimental unit oil engine of this type to develop 800 brake h.p. at 90 r.p.m. was commenced

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* *N. E. C. Inst. Engineers and Shipbuilders*, 3rd Nov., 1922.

† See Papers by W. S. Burn, M.Sc., " High-Powered Oil Engines ", *N. E. C. Inst. of Engineers and Shipbuilders*, 1926; " Double Acting Oil Engines ", *Inst. of Marine Engineers*, 1926; " The Development and Performance of the R. W. Oil Engine ", *N. E. C. Inst. of Engineers and Shipbuilders*, 1929.

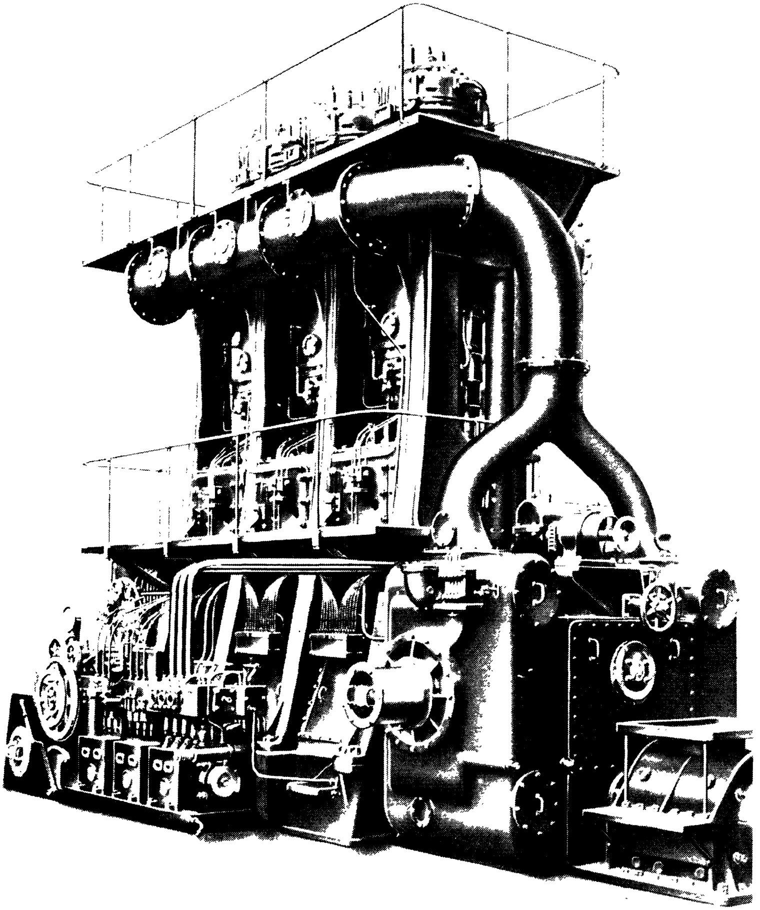

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Fig. 62.—RICHARDSONS, WESTGARTH ENGINES, M.V. *IRANIA*, SCAVENGE-PUMP END

in 1924 by Mr. W. S. Burn, M.Sc., of this firm, and the engine was built in March, 1926, when a series of experiments were carried out under different conditions of load and speed, until the end of April, 1927. The characteristics of the design were simplicity, reliability of every part, and the readiness with which the engine could be manufactured in standardized sizes of various powers.

One of the tests of the experimental engine was a non-stop run of 24 days. The single double-acting cylinder had a bore 26·75 in. and stroke 47·25 in. In a test run of 100 hours, the brake h.p. was 787·5 at 89·7 r.p.m., and the consumption of fuel oil obtained was 0·38 lb. per brake h.p. hour, a very promising result of excellent performance.

The first commercial engine of this type is the three-cylinder unit (fig. 62), in the M.V. *Irania* of 4690 tons displacement. The engine has three cylinders of diameter 21·5 in. and stroke 38 in. of rating 1200 brake h.p. at 85 r.p.m. The manœuvring controls and fuel pumps are arranged at the front of the engine, with a special form of direct-driven scavenge-air pump, shown to the right.

Shop test.—During an official trial run of 4 hours' duration, the load was applied by a water brake, and the engine developed 1133 brake h.p. at 89·5 r.p.m., and the mechanical efficiency was 87·2 per cent. The average maximum pressure in the top and bottom cylinders was 557 lb. and 549 lb. per square inch, respectively; the average scavenge-air pressure 1·35 lb. per square inch. The consumption was 0·378 lb. per brake h.p. hour of Roumanian fuel oil of specific gravity 0·881. The exhaust was invisible and its average temperature only 430° F., that of the cooling water main inlet 79° F., and at the piston and cylinder-jacket outlets 112° F., which indicate that the engine was running very cool.

While the *Irania* has been in service at sea, except for minor mechanical troubles successfully overcome in the beginning, the engines have given every satisfaction under, at times, very adverse circumstances. The fuel-injection system has proved a complete success and free from trouble of any kind. The original design was so well thought out on sound general principles that no departure of any note has been made from these, as a result of three years' experience.

The section (fig. 63) shows the general construction of the

C type. The *crank-shaft* of forged steel is of the built-up type, and each crank has steel balance weights cast integrally with

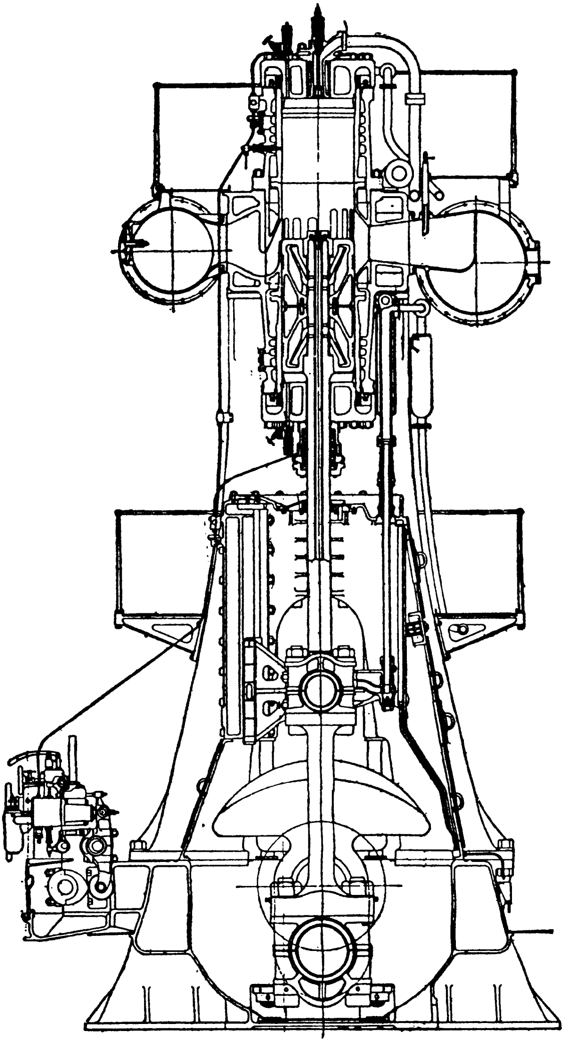
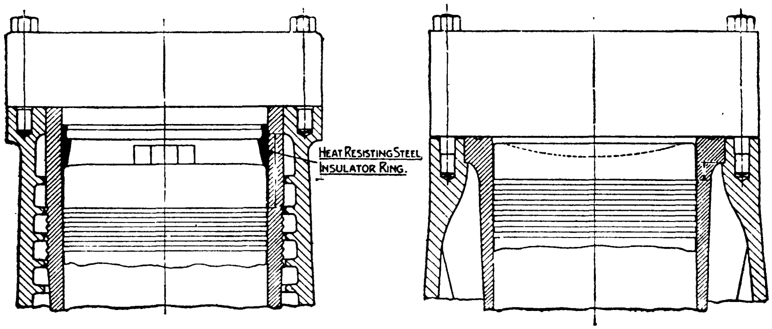


Fig. 63.—Section through R.W. Oil Engine (C Type)

the webs to balance fully the rotating weights, so that each cylinder is balanced, which obviates the use of a fly-wheel. This is confirmed by the smooth and vibrationless running of the engine on the *Irania* with three cylinders, each with two power strokes per revolution, and no fly-wheel. The *cylinder liner* is held at the centre, which carries the scavenge and exhaust belt, by the upper cylinder jacket, so that all grooves and rubber rings are dispensed with, and both ends of the liner are free to expand. The cylinders have internal spiral webs on the casing to increase the velocity of the cooling water flow round the liners, giving greater scrubbing and cooling effect. The cylinder head is cooled by four water outlets from the cylinder to the cover, and two outlets from the cover. The *cylinder cover* projects into the cylinder liner, and the gas joint is made by a special form of gland in which a wedge-shaped lead alloy ring is pressed against the cylindrical surface of the cover by being compressed between the end of the liner and a spring unit, the two latter being formed to give a suitable wedge-shaped recess. The spring unit ring encircling the head is provided with spiral springs which are compressed between the end of the liner and the underside of the cylinder cover. The axial expansion of the liner compresses the springs and makes the joint tighter.



R.W. cylinder end liner water cooling, and liner insulating ring

Normal two-stroke cylinder end

Fig. 64.—Comparison of Cooling Liner End, above Top Piston Ring

An *insulator ring*, of special heat-resisting steel, is shrunk on the inner end of the cylinder cover (fig. 64), the objects of which are to prevent the sprays impinging on the cold liner and to shield the liner surface from the full combustion heat, as well as to promote good combustion conditions, and to reduce the effective cooling surface of the combustion chamber. Incidentally, a further advantage of this ring is that the filling up of the corners of the cylinder ends slightly improves the shape of the combustion chamber and tends to give better scavenging. The piston end faces are made slightly convex at the edge to reduce the combined heat and pressure stresses.

The top and bottom covers of the cylinder are identical in construction, and all the valves and fittings for them are interchangeable.

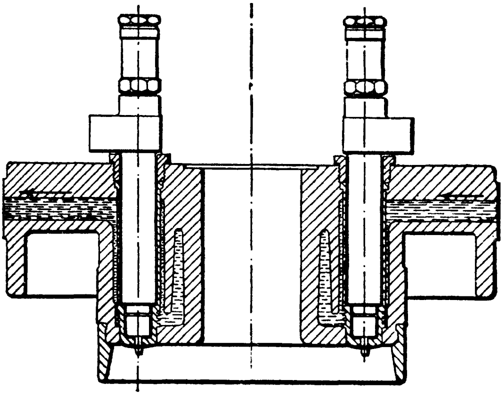


Fig. 65.—R.W. Cylinder Cover with Fuel Valves *

The *automatic fuel-injection valves* are fitted with adjustable spring-loaded needle valves working in ground bushes. In order to keep the fuel-injection valve cool, and to prevent the formation of carbon " trumpets " at the nozzle end, the valve fits into and is cooled by means of an aluminium sleeve, of high heat conductivity, which is surrounded by the cooling water (fig. 65), and fins are formed at the lower end of the sleeve to aid the heat transference from the nozzle portion of the valve to the water.

In practice properly designed and manufactured automatic airless-injection fuel valves are found to operate even more quickly than mechanically operated valves, and as a result the tendency to dribble is reduced.

The opening in the centre of the top cover (fig. 65) serves to house the starting-air valve, and that in the bottom cover for the piston rod. There are two identical airless-injection fuel valves, with a relief valve and indicator connexions on the top and bottom covers of each cylinder, those at the top being clearly shown by the photograph (fig. 66). The absence of the usual valve-operating gear at the cylinder head is a feature of this engine.

The upper and lower halves of the *piston* (fig. 63) are similar, with water ports and passages cored in, and held centrally on

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* Figs. 65, 69, and 72 from *The Engineer*, 8th March, 1929.

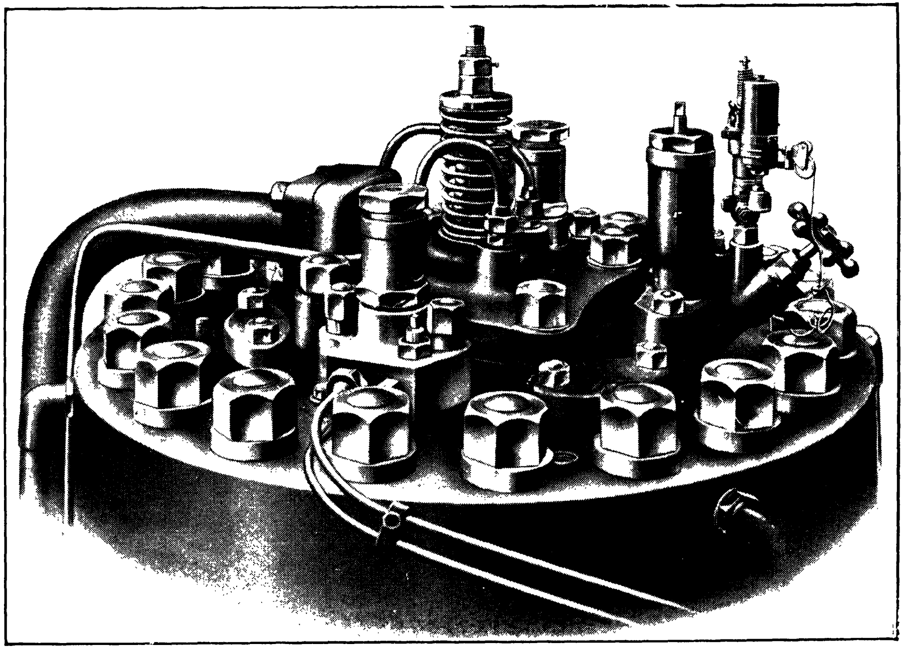

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Fig. 66.—CYLINDER COVER OF R.W. OIL ENGINE—C. TYPE

the piston-rod between a collar and special cap nut. The piston cap nut, having an acme thread, is made of special bronze to resist the heat action and corrosion.

Each half of the piston carries five piston rings, free to move in their grooves and placed well back from the working face. The piston rods are made of 3 per cent nickel steel, of 50 tons tensile strength, and are cored to carry the inlet and outlet tubes for cooling water which enters at the cross-head by telescopic pipes of cupro-nickel having long ebonite bushes in the spring-loaded glands and neck rings. Distilled fresh water is used for cooling both the cylinder jackets and pistons in a closed system with a cooler, to prevent aeration of the water.

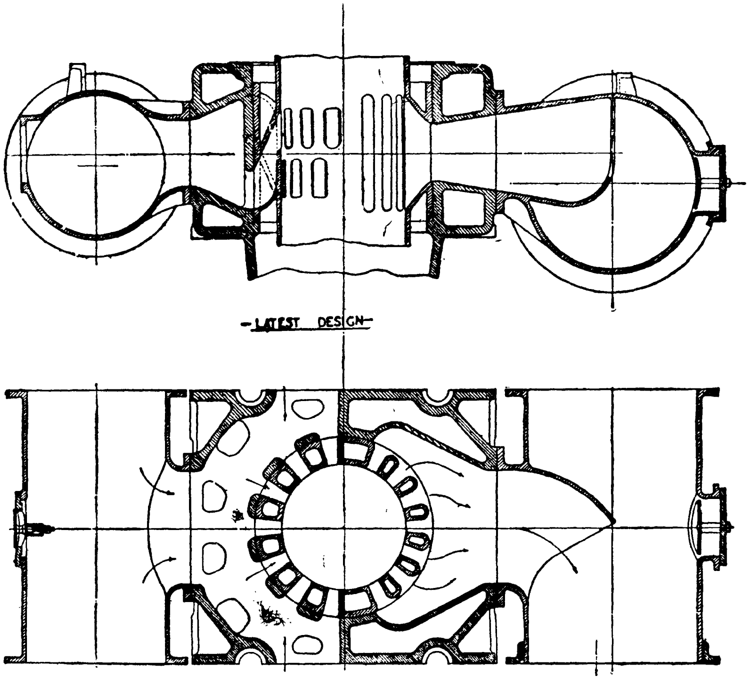


Fig. 67.—Section through Scavenge-exhaust Belt, R.W. Supercharging

The method of effective *scavenging and air-charging* is most important in any two-stroke engine. In this engine the scavenge air and exhaust ports in the belt at the centre of the cylinder liner are shown in figs. 63 and 67. The alternate nozzle air ports about half round the circumference of the liner at one side direct the air flow up along the liner wall, across the cover, and down the other side to the large exhaust ports and main pipe. The shape and depth of the exhaust ports—with ample water cooling within the port bars to ensure low temperature—and the air ports have been designed after much experimental research, in order to obtain efficient scavenging and air charging by improving the stream-line air flow. Increased size of both the scavenger air main and exhaust is adopted to reduce eddies and turbulent air flow as well as back pressure in the exhaust, and interference from adjacent cylinders. This scavenging action is shown by the sketch (fig. 68). The scavenge system was tested in model glass cylinders; sufficient indication of the stream-line air flow was obtained, and a partial vortex action shown, but a satisfactory photograph could not be taken.

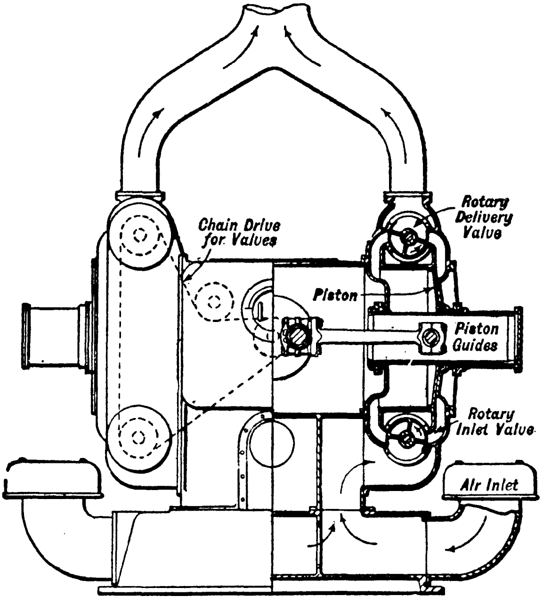
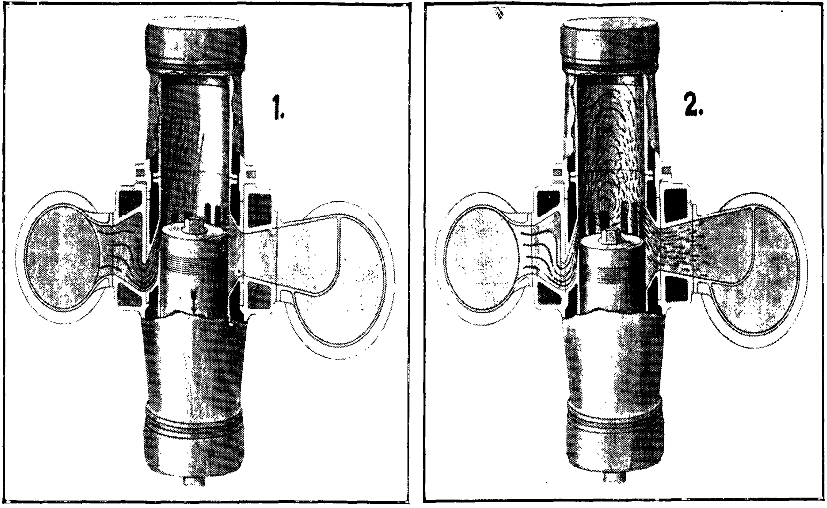


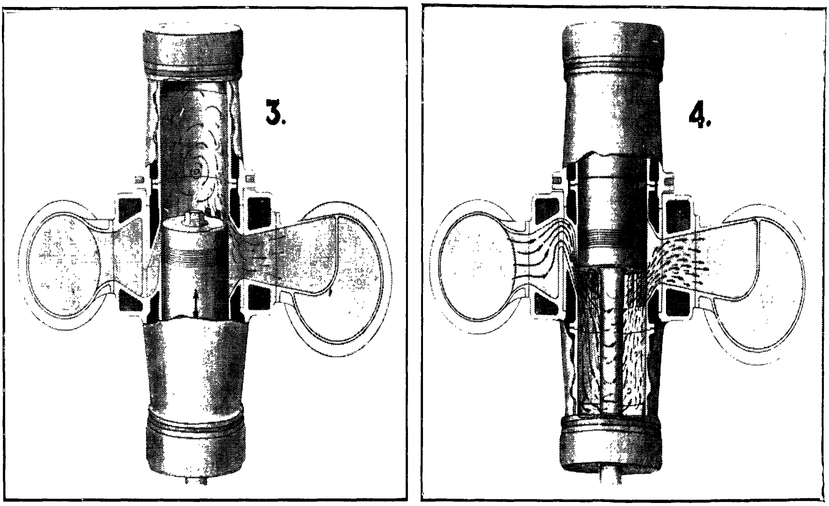
Fig. 69.—Uniflow Scavenge-air Pump and Drive

The *scavenge air pump* (fig. 69) is driven from the crank-shaft, at three times the engine speed in the *Irania*, by helical gear. The driven shaft has two cranks at 180°, and short connecting rods to the horizontal and opposed double-acting pistons. The pistons and



Upper Scavenge Port opening

Upper Scavenge Port fully open



Upper Scavenge Port closed

Lower Scavenge Port fully open

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Fig. 68.—SCAVENGING ACTION IN R.W. DOUBLE-ACTING OIL ENGINE

guides are made of light aluminium alloy. The pump works very silently, without vibration. The large area suction and delivery rotary valves, running in ball bearings, are driven by a duplex chain from the pump shaft and ensure steady low suction and delivery pressure. The synchronized port opening and pump delivery are shown by the scavenge pump indicator diagrams.

The *fuel pump* (fig. 70) is driven by two horizontal coupling rods from cranks at the forward end of the main crank-shaft. There is a separate pump for each cylinder end, each plunger thus operating two injection fuel valves. The quantity of fuel oil delivered to the spray valves is controlled both on the suction valves and by the spill valves.

The fuel-pump body is a steel forging, attached to the bed-plate by brackets (fig. 70), which also carry the cam and control shafts of the fuel-injection mechanism. The pump plungers are operated by cams, of

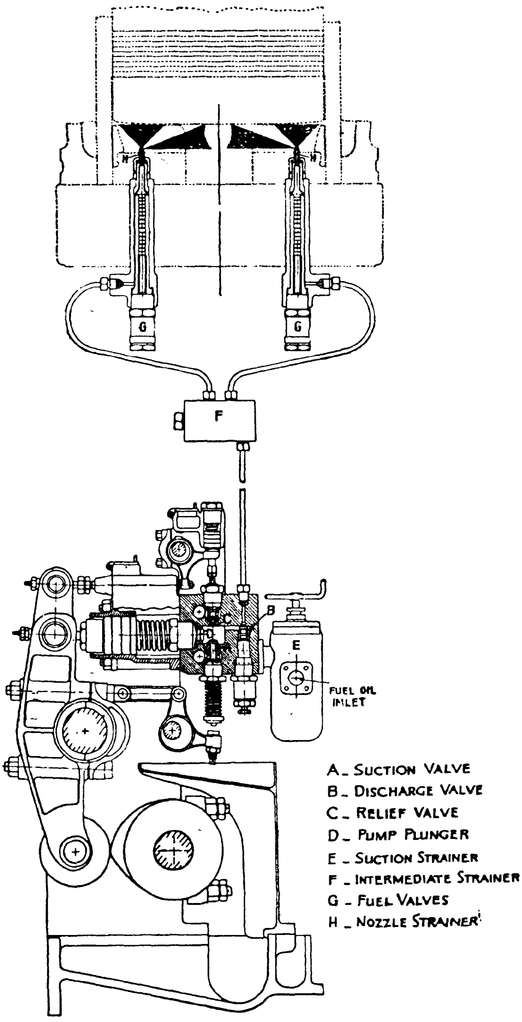

Fig. 70.—R.W. Fuel-oil Pump and Airless Injection: Diagrammatic Sketch

smooth profile, through rockers mounted on an eccentric shaft capable of angular movement. The return stroke is made by a spring. The suction valves are worked by tappets and bell-crank levers connected to the pump plungers by links which are mounted on an eccentric control shaft. Control of the fuel injection is obtained by angular movement of the eccentric rocker shaft, on which a cam operates the eccentric shaft controlling the suction valves, and so raises or lowers the tappet bell-crank lever according to the load. In this way the period during which the suction valve is closed is regulated and the useful stroke of each fuel pump.

Two small hand wheels, directly above the main manœuvring wheel (fig. 62, p. 95), controls the time of closing of the suction valves and the opening of the spill valves. By this means any desired time of opening and closing the automatic fuel valves can be fixed.

The starting-air valve gear is very similar to the fuel pump plunger mechanism, viz. a rocker on an eccentric shaft operated by a cam and roller.

There are separate ahead and astern cams for the starting air and fuel pump valves.

To start the engine from cold, compressed air is admitted to the top cylinders, while fuel oil is injected into the lower cylinders towards the end of the starting period. Thus the engine can be started quickly in either ahead or astern directions.

The *governor*, driven by spiral bevels from the fuel-pump shaft, operates a simple but powerful relay cylinder.

Filtration.—Thorough and efficient filtration of the fuel oil, in addition to the usual centrifuging, is considered of supreme importance, in order to avoid choking or erosion of holes in the spray nozzles, and of gritty particles that cause abrasion of the valve seats. A large filter of the self-cleaning type is fitted on each fuel-pump suction inlet (fig. 70), and is arranged immediately after the fuel heater, which is only used for very viscous fuel oils. In the distributor to the pair of fuel valves there is a special high-pressure magnetic strainer with holes smaller than those in the fuel-valve nozzles; whilst, last, but by no means least, in the spraying nozzle itself is arranged a small strainer of the grooved type. By these precautions, there has not been a single nozzle hole choked on the *Irania* engine since the engine first started.

Spraying.—After careful tests with 87 different nozzles, that shown in fig. 71 gave the best results. There are five holes in each spraying nozzle: two penetrating horizontal jets on each side of the piston nut in the top cylinder, and piston rod in the bottom cylinder; one central whirling jet, made by special-shaped passages: wide spreading and very finely atomized spray is formed at the nozzle end to suit the short distance between the cylinder cover and piston crown. This finely atomized spray quickly causes ignition in the air compressed to 375 lb. per square inch, and acts like a pilot igniter to the penetrating side jets, which are the principal distributors of the fuel oil throughout the compressed air in the combustion chamber.

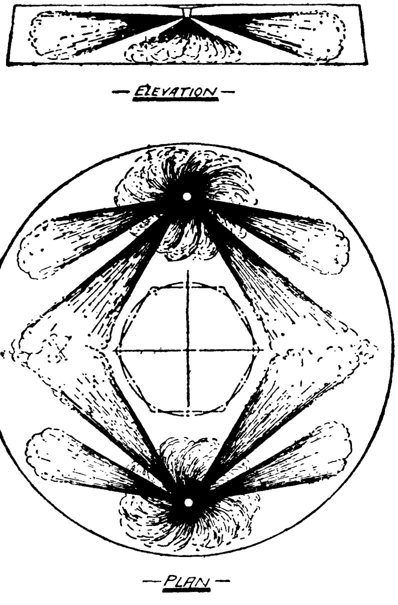

Fig. 71.—Nozzle Sprays in Combustion Space

The typical indicator diagrams (fig. 72) were taken from the " A " type engine on the M.V. *Irania.* The diagrams from the top and bottom of the cylinders appear practically identical. The fuel-pump diagram shows rapid rise in pressure, nearly constant delivery, and quick release pressure to give sharp cut-off at the fuel valve. The low suction and delivery pressure are features of the scavenge air pump due to the timed port opening and

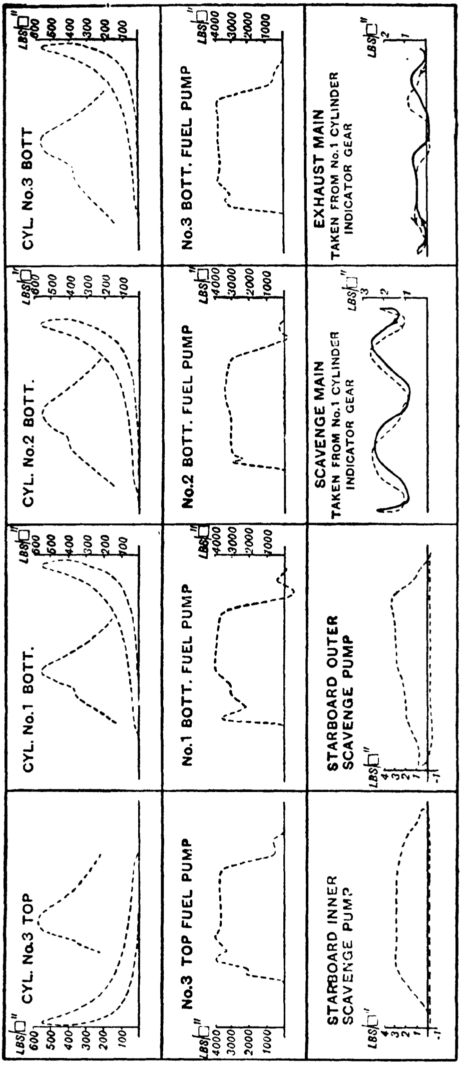

Fig. 72.—Typical Indicator Cards from R.W. Oil Engine

pump delivery, and the large area of rotary suction valves and mains.

The space occupied and the weight of an oil engine of this type are much less than that for a steam boiler and engine or geared steam turbine of the same power. Already powers from

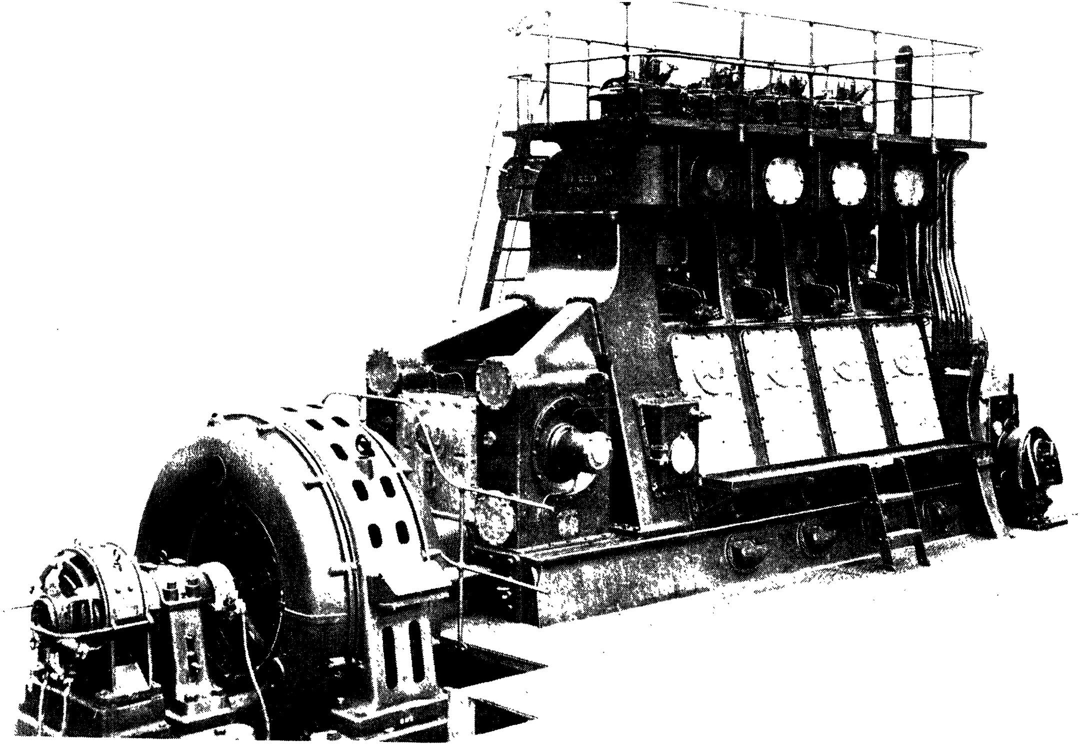

Fig. 73.—RICHARDSONS, WESTGARTH DOUBLE-ACTING TWO-STROKE OIL ENGINE DRIVING ELECTRIC GENERATOR

1250 brake h.p. with a three-cylinder A type engine, to 6400 brake h.p. with an eight-cylinder C type engine, are obtainable with the normal marine type of engine working at low mean pressures and moderate speeds of revolution.

There is no doubt the British type of double-acting two-stroke airless-injection oil engine, with its great power output combined with simplicity, smoothness of torque, and high thermal and mechanical efficiency, appears admirably suited for marine propulsion.

Similar engines for land purposes * are run at higher speed with shorter piston stroke. Fig. 73 shows a Richardsons, Westgarth four-cylinder, double-acting two-stroke oil engine with airless injection, having cylinder bore 15 in. and 18·75 in. stroke, of 1340 brake h.p., coupled to a 940 kilowatt generator running at 300 r.p.m. This double-acting two-stroke airless-injection heavy-oil engine, having every detail of construction carefully designed, and giving high mechanical and thermal efficiency, the whole accessories taking up small space, ready at any time to start promptly from cold for full-load service, with little or no preliminary consumption of fuel, is well qualified for a *peak-load* and *stand-by* prime mover in electricity generating stations. Moreover, relatively small oil-engine units have almost the same fuel economy as large ones, and are self-contained, quite unlike steam plant, and are thus more suitable for generating electricity economically in small installations at low first cost and running charges.

* See Paper on " High-powered Oil Engines for Land Purposes ", read by W. S. Burn, M.Sc., before Diesel Engine Users' Association, Jan., 1930.

CHAPTER VII

The High-speed Heavy-oil Engine

Evaporative Cooling.—The highest thermal efficiency of the marine heavy-oil engine, with airless injection, was obtained with high temperature of the cylinder water jacket in the Scott-Still regenerative engine of the motor ship *Dolius*. The improved results are due to the high temperature of the cylinder which reduces the loss of heat to the water jacket, and ensures prompt ignition and rapid combustion of the fuel-oil spray at comparatively low compression of the air charge, while the cylinder and combustion chamber are kept at a constant high temperature.

At Coventry, early in 1898, high temperature of the water jackets was tried in brake tests carried out by the Author on one of the first Daimler *petrol motors* brought to this country. The engine had two vertical cylinders, each 90 mm. diameter by 120 mm. stroke, developing 6 to 6·5 brake h.p. as the speed was increased from 700 to 750 revolutions per minute.

When the motor was running at full power and highest efficiency, the jacket water was kept at the boiling-point, and only steam escaped by a pipe from the outlet of the water jackets to the atmosphere. There was also less loss of heat from the cylinder gases through the liner as the jacket temperature was gradually raised.

Again in October, 1898, the Author made a full-load trial run of a " National " gas engine (Bickerton and Bradley patents), built by the National Gas Engine Company at Ashton-under-Lyne. The engine used Ashton coal gas of lower heating value 630 B.Th.U. per cubic foot and gave 23 brake h.p. at 170 r.p.m. The best results were obtained when steam was formed in the water jacket and was allowed to escape to the atmosphere. The charge of gas and air in the cylinder was not rich, and with compression of 110 lb. per square inch the brake thermal efficiency was 25 per cent, and the mechanical efficiency 87 per cent, which was considered very good at that time.

Measurements * made by Professor A. H. Gibson of Manchester, of the temperature of small high-speed petrol engines, showed that the distribution of temperature in the cylinder is more uniform when the jacket water is brought to the boiling-point; and the temperature of the hottest point in the cylinder head is reduced when the formation of steam begins.

In experiments on a small high-speed engine of cylinder diameter about 4 in., with cooling water and aniline in the jacket, over a range of jacket temperature from 40° C. to 230° C., the best results were obtained at about 130° C. (266° F.).

Dr. W. R. Ormandy has pointed out that *ethylene-glycol*, which boils at 197° C., is one of the few organic fluids that can be heated to that temperature for long periods without decomposition. It is made in large quantities from ethylene, which is obtained from the cracking process in the manufacture of petrol, and is a suitable cooling medium when high temperature of the engine cylinder is desired. Besides the improved results which are obtained with combustion at the higher temperature, there is a great reduction in size of the cooling plant.

Aircraft Oil Engine.—High temperature of water jackets is used in the heavy-oil, airless-injection, and high-speed engines installed in the British airship, R 101, described † by Mr. Alan E. L. Chorlton at the British Association meeting in Glasgow, on 10th September, 1928.

The system was first applied in an experimental " Unit " engine at the Royal Airship Works, Farnborough. The cylinder jacket water is always near the boiling-point about atmospheric pressure, and the waste heat from combustion in the engine cylinder that passes through the liner generates steam from the circulating water in the jackets. The steam carries some water with it from the cylinder heads to a manifold which leads to the *separator* with baffles that stop the water and guide it down to a circulating pump, while the steam is conveyed in pipes up to a *radiator* where it is condensed and then falls back into the water circuit. The *latent heat* of this steam is used in the radiator to warm the passenger quarters of the airship. The radiator is of triangular shape, with

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* *Proc. Inst. Mech. E.*, Jan., 1926; also Advisory Committee for Aeronautics, L.A.S.C., Report No. 13, May, 1918.

† *Engineering*, 21st Sept. and 5th Oct., 1928.

air vent at the apex, and the steam flows upwards. A small pump returns the condensed water to the engine, and maintains a slight vacuum in the radiator, so as to assist the flow of steam through the long pipe.*

This steam cooling of the cylinders is automatic in control, reduces the size of the radiator 25 to 30 per cent, keeps the engine cylinder and combustion chamber at a regular temperature, and works well. The average rate of steam generation in the jackets of a standard service aircraft engine running at full power is from 50 lb. to 60 lb. of steam per hour per square foot of heating surface. The vibration of the hot surfaces assists in the liberation of steam.

It was considered urgent and all-important to the aircraft industry, to develop a safe and reliable compression-ignition airless-injection engine of small weight-to-power ratio, that would use economically heavy fuel oil, in order to reduce the cost of maintenance, above all to obviate the danger of fire in case of accident, and dispense with the carburettor and magneto which are the weak points in the very high-speed petrol engine.

After several years of research and development work by Messrs. William Beardmore & Co., a satisfactory heavy-oil engine of light weight and running at high speed was described † by Mr. Chorlton in March, 1926.

This high-efficiency airless-injection and compression-ignition oil engine, specially constructed for direct driving the propeller in an airship, has eight cylinders in line, of 8¼ in. bore by 12 in. stroke, develops 650 brake h.p. at 950 r.p.m., and weighs 7 lb. per brake h.p. with steel cases, and about 4 lb. with aluminium cases. When constructed of alloys of light metals, as aluminium and magnesium, the weight of each engine in a later design comes down to 3 lb. per brake h.p., and the engine is suitable for long-distance flights as proved by the trials of the British airships, R 100 and R 101, which were built for experimental purposes. A main engine in one of these airships is made variable in speed, the control by hand lever being from 1000 down to 250 r.p.m. The driven propeller is of the variable pitch type in order to check the flight of the airship when approaching the mooring mast.

The five engines in R 101 had run very well. One completed

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* *Journal of Royal Aëronautical Society*, Jan., 1926.

† " The High Efficiency Oil Engine ", by Alan E. L. Chorlton, C.B.E., *Proc. Inst. Mech. E.*, March, 1926.

a continuous test run of 225 hours' duration.* The airship R 100, sister ship to the R 101, beat all airship speed records on flight-speed trials, by attaining the highest speed of 81·5 miles per hour, with 600 h.p. in reserve. The motion of R 100 was very smooth and steady at 80 miles per hour, and although the flight was in January, 1930, the interior of the ship was at a temperature of 60° F., and felt quite comfortable. Also from the statement issued by the Air Ministry: " For the greater part of the day the ship flew at a height of 2000 ft., above thick fog and low clouds which generally obscured the ground. Positions were obtained by wireless telegraphy when required. After a trial flight of 13½ hours, which was quite successful, the mooring tube was dropped at 10.2 p.m. and the airship was moored in the dark in 22 minutes." The R 100 made non-stop flights of three thousand miles to and from Canada at 70 miles per hour.

The heavy Anglo-Persian fuel oil used in these aero-engines has flash point 210° F., giving safety from fire, viscosity of flow 100 seconds at 100° F., and must flow at 0° F., that is 32° F. below the freezing-point of water at normal atmospheric pressure. The fuel consumption, about 0·35 to 0·32 lb. per brake h.p. hour, gives 30 per cent saving in weight, and even greater reduction in volume, so that the fuel tanks in aircraft may be smaller than for petrol. The price of heavy fuel oil is only about one-third that of petrol at present, but it is always liable to vary according to the supply and demand.

Some results of tests of the early Beardmore high-speed heavy-oil engine are given in Table I. Those trial runs marked " A " and " D " were carried out by Professor A. L. Mellanby on different engines of the same size.

Test " A " represents the performance of a normal engine at ordinary maximum compression; while test " D " was run to show the improvements at higher pressure and increased speed or rate of expansion, also higher mechanical efficiency, the object

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* The enlarged airship R 101 was wrecked in a disastrous crash against a hill at Allonne near Beauvais in France, on 5th Oct., 1930, on her flight to India, while flying low in a storm. A sheet from an engine log confirms the following statement of two engineers who survived: " When the disaster occurred, *the motors were working perfectly at normal speed.* The airship, battling with storm and rain, nose-dipped twice, then *the engines were run* '*slow*', a violent gust caused a *steep dive* and hurled the ship against the hill." There followed a violent explosion of hydrogen gas, escaping from leaky gasbags, and ignited, most likely, by electric sparks from short-circuits of electrical conductors.

Table I.—Tests of the Beardmore Early High-speed Heavy-oil Engine

Test Series.	Duration of Test, Hours.	Speed, Revolutions per Minute.	Brake Horsepower.	Oil Fuel per Brake h.p. hr., lb.	Cooling Water Temperature.		Oil Fuel.
					Inlet, °F.	Outlet, °F.	
A	4¼	689·3	160·26	0·418	121·5	127·4	Shell-Mex. Diesel.
B	3	700·0	172·0	0·385	120·0	128·0	,, ,,
C	3	1007·0	424·0	0·365	140·0	150·0	,, ,,
D	1	1023·3	263·0	0·355	181·0	185·5	Anglo-Persian.

being to determine what efficiency could actually be obtained from the standard engine " A ". In " B ", the mechanical efficiency only had been improved; and in " C " a higher speed and maximum pressure were tried as shown in Table II. This engine had six cylinders of 8¼ in. bore by 12 in. stroke, the indicated power in test " C " was 493, and the mechanical efficiency, 86

Table II.—Three Hours' Trial of Beardmore S. 1/6 Engine

Time, a.m.	Revolutions per Minute.	Brake h.p.	Fuel Oil.			Lubricating Oil Temperature.		Jacket Water Temperature.	
			Header Pressure, lb. per sq. inch.	Lb. per Hour.	Lb. per Brake h.p. Hour.	Inlet °F.	Outlet °F.	Inlet °F.	Outlet °F.
9.15	1002	418	27			119	127	140	151
9.30	1010	428	26			121	130	140	150
9.45	1010	428	25			125	135	140	150
10.0	1002	421	28	155·25	0·366	122	135	140	150
10.15	1010	426	28			122	135	141	150
10.30	1008	425	28			125	138	140	150
10.45	1010	426	28			118	132	140	150
11.0	1008	422	27			118	131	140	150
11.15	1008	425	27	156·25	0·367	119	132	140	150
11.30	1008	422	27			122	134	140	150
11.45	1008	425	27			124	136	140	150
12.0	1002	420	27			122	135	140	150
12.15p.m.	1002	418	26	152·5	0·362	118	132	140	150
Average	1007	424	27	154·7	0·365	121	133	140	150

per cent; the brake mean effective pressure, 92·5 lb. per square inch. The fuel oil, " Shell-Mex.", had specific gravity 0·885 at 15° C.; flash point, 89° C. (close); and calorific value, 17,550 B.Th.U. per pound. The lubricating oil was " Sternol " aero oil No. 1, of specific gravity 0·93 at 60° F. The water through the lubricating oil cooler was raised from 49·5° F. to 120° F. increased to 125° F., and the lubricating oil pressure was 47 lb. per square inch. Fuel control was 22·5° and timing 0·5° advance.

This performance, and economy of fuel consumption, probably a world's record at that time, improved with the higher temperature of the jacket water. A later test of a standard engine gave the remarkable consumption of 0·325 lb. of fuel oil per brake h.p. hour, without any special precaution being taken to secure low consumption.

Professor Mellanby stated that the figures for fuel consumption were so low that he examined them for any possible source of error, and the feat was the result of combining efficiency and simplicity.

Further progress has been made, and a six-cylinder engine having the same size of cylinder gives 750 brake h.p. at 1400 r.p.m.

In these high-speed airless-injection oil engines 40 per cent of the heat in the fuel may be converted into work, 15 per cent going to the cooling jacket, and 40 per cent rejected in the exhaust gases which may be utilized in boilers.

The striking and most characteristic feature of the design is the **flash-valve fuel-oil pump**, designed by Mr. Alan E. L. Chorlton, which successfully overcomes the chief difficulties in the correct measurement of the extremely small quantities of oil for each charge, and its airless injection with precision to ensure rapid and complete combustion in the high-speed multi-cylinder engine. The principle of its action is shown by the diagrams (figs. 74 and 75). Each pump plunger, actuated by an eccentric, gives the fuel oil a to-and-fro motion in the passage A (fig. 74), leading to the atomizer. The quantity of oil for a charge is regulated by a piston valve of the flash type B, " which functions whilst in motion ", and has helical cut-off edges working against a suitable feed port in the suction pipe, and when twisted by the governor partially blocks the passage momentarily, at the correct instant, in its quick travel across the feed port. A vibration is thus sent through the column of oil between this valve and the atomizer, which lifts the automatic valve off its seat, and the small oil charge is forced past it at very high pressure and velocity through the spraying nozzle of the pepper-castor type. The atomizer valve is rapidly drawn back to its seat by the reflex action of the oil column, giving sharp cut-off as the control valve B reopens.

The governing * of the quantity of fuel oil injected is effected by twisting the control valve to regulate the amount of overlap on the port passage to the plunger chamber. This variation is obtained in multi-cylinder pumps by a rack engaging a pinion E (fig. 75), through which each valve slides at its upper end, and there is free circulation of fuel oil above and below the cut-off portion, the valve being made hollow with communication passages above and below. During part of the overlap period the fuel is forced positively to the atomizer by the pump plunger.

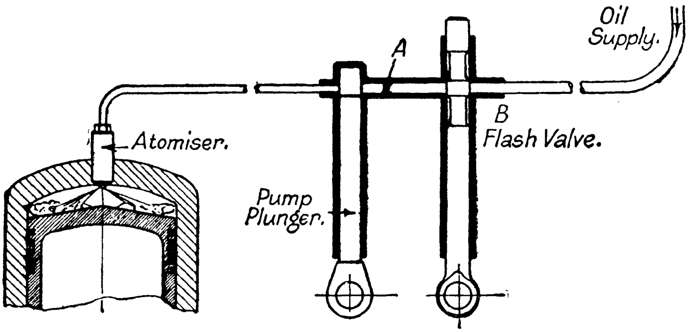

Fig. 74.—Diagram of Flash-valve Fuel Pump (Chorlton)

In the smaller engines direct governor connexion to the rack-twisting helical valves, shown in fig. 75, effectively controls the quantity of oil delivered to suit the load. The flash or control valve O (fig. 75) is reciprocated by a lever coupled to the main plunger Y. The timing of injection is varied by adjusting the eccentric W, on which the fulcrum of this lever is mounted, to the correct phasing of the overlap period in relation to the crank position.

A *switch valve* is fitted between each pump and two atomizers. The pump runs at engine speed, and the switch valve at half that

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* See the paper on " The Heavy-oil Engine on Road and Rail ", by A. E. L. Chorlton, The Institution of Automobile Engineers, *Trans.*, March, 1929, p. 502, with figs. 75, 76, and 77.

D, Delivery valves.
E, Rack.
F, Seal.
G, Relief chamber.
H, Auxiliary tank.
J, Overflow.
K, Fuel tank.
L, Relief block.
M, Ball check valve.
N, Switch valve.
O, Control valve.
P, Filters.
Q, Gear pump.
S, Motor-driven pump.
T, Emergency by-pass.
U, Atomizer.
V, Drive from gear-box; half-speed.
W, Adjustable timing.
X, Pivot.
Y, Main fuel pump.
Z, Hand throttle.
b, Ball joint.
c, Pilot valve.
d, Release to sump.
e, Oil inlet from main pump.
f, Speeder spring.
g, Governor weights.
j, Floating ball bearing.

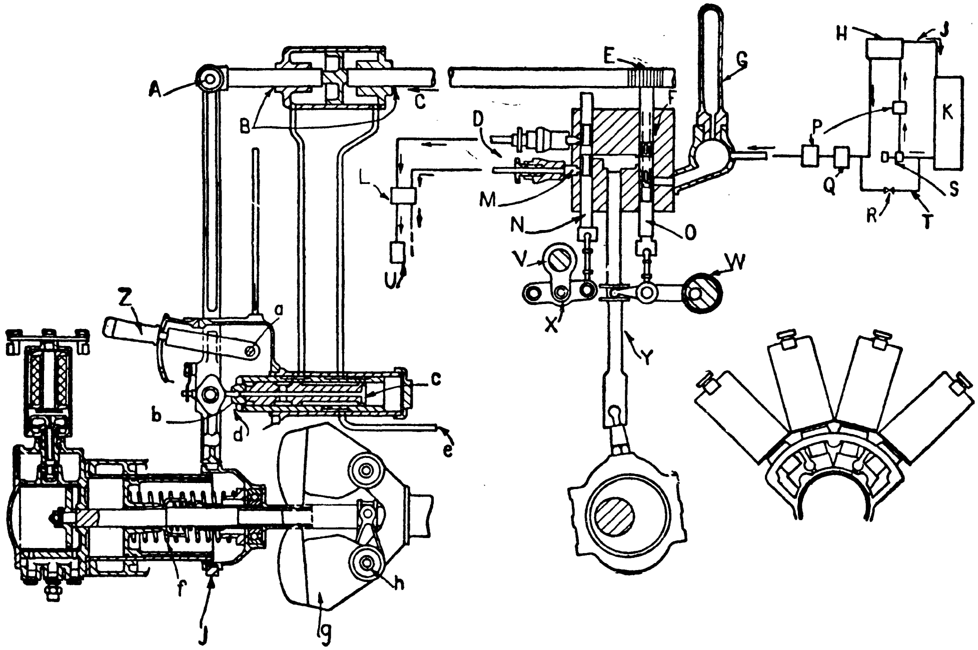

Fig. 75.—Oil Engine Remote Control Diagram

speed. This system gives correct timing of the fuel injection to each of the two cylinders, just before the end of the compression stroke; and four fuel pumps feed eight cylinders.

The positively-operated plunger, replacing the cam and return spring, and the piston valve of the flash type, have been used in practical service for four years on all sizes of this high-speed engine, giving very quick action, a sharp cut-off, and good penetrating sprays of high pressure without dribble. This system also gives precise delivery and steady slow-speed running. The flash valve enables high speeds to be run quietly without knock from lost motion, and the pump having no cams also gives quiet running. This pump is also a very accurate measuring device whereby the exact amount of fuel oil can be delivered to each cylinder with precision and constancy. The pump body is made of mild-steel forging, and has inserted cast-iron liners in which the main plunger and the control valve reciprocate.

The German patent specification of the Chorlton **flash-valve pump** (earlier than that of Bosch, who obtained a workshop right to make it in Germany), described it as " a valve that functions whilst in motion "; it is also called a " float type of fuel pump " and the " jerk pump ". The Bosch patent fuel pump is a modification, taken out at a later date, and has the controlling valve fitted on the top of the plunger and integral with it, whereas Chorlton has it separate. In the original pump he had them combined, but separated them in order to get better action and a wider degree of control for the varying speeds, &c. Thus, by the separate valve, increased speed of the flash action can take place. The position of the valve can be altered relative to the plunger, enabling injection to take place earlier in the stroke, giving a gradual increased speed to the point of cut-off. The advance of injection can also be modified as the speed of the engine varies.

Bosch has produced a well finished and accurate instrument, and this has been a considerable aid in developing the direct or airless-injection oil engine. Few people have realized that the success of the modern high-speed heavy-oil engine is largely due to the accuracy of the fuel pump and its control.

Mr. Chorlton may have some satisfaction in seeing such progress founded on his invention of the flash-valve fuel pump, which has set a fashion to the world, so much so that all fuel pumps, supplied for general sale to fit to any high-speed oil engine, are of this type.

It is remarkable that the invention of an Englishman is almost overlooked in this country, but appreciated abroad; and in this instance the Bosch, Junkers, R.E.F., &c., have come from this class of fuel pump.

The fuel oil must be well filtered, as at P (fig. 75), so as not to block the small holes in the pepper-castor nozzle of the sprayer. Sometimes a spiral groove is inserted, shown in fig. 76, to cause the issuing jet to revolve and get broken up more readily. The form of the issuing jet must be suitable for the shape of the combustion chamber. High pressure is important in breaking up the jet after it leaves the spraying nozzle.

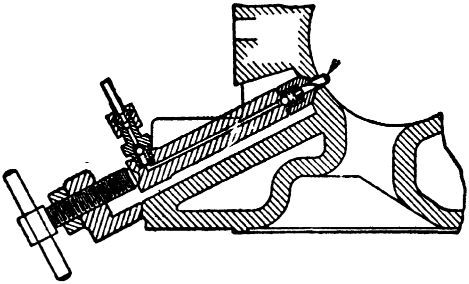

Fig. 76.—The Beardmore Oil Engine Sprayer

By the above means complete combustion of heavy oil is obtained at speeds up to 1500 r.p.m.

Compression of excess air in the combustion space to 450 or 500 lb. per square inch, to the requisite temperature for rapid and complete combustion, and maximum explosion pressure of about 1000 lb. per square inch, have been employed.

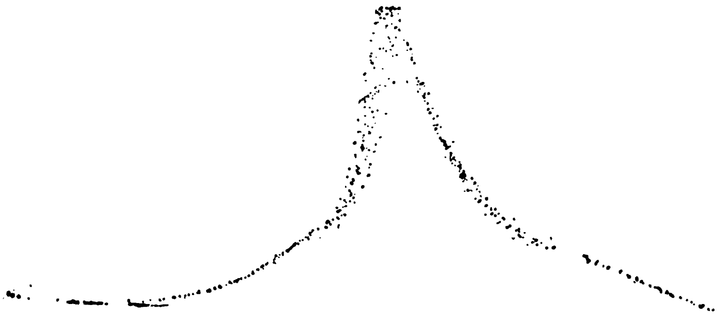

Fig. 77.—Electrical Indicator Diagram from Beardmore Engine

This single-acting high-speed engine works on the four-stroke cycle, and the heavy oil is burned at constant volume as shown by the indicator diagrams (fig. 77), on a time base with the peak near the top dead centre, taken by the electrical indicator * of the Royal Aircraft Establishment from Beardmore engines running at 1000 r.p.m.

After the injection and ignition of the oil spray or mist near the end of the air compression stroke, immediate or instantaneous explosion of the whole charge does not take place. There appears to be a slight lag in the combustion, during which the very fine particles of oil evaporate before bursting into flame. This pause is shown by a slight change in the compression curve before the sharp rise in pressure due to combustion.

Oil-Electric Railway Cars and Locomotives

In his interesting paper of March, 1926, referred to above, Mr. Chorlton advocated the possibility of obtaining greater economy and higher thermal efficiency, in the quick running heavy-oil engine, by working at higher pressure and speed, compression ratio and rate of expansion, with airless-injection, compression ignition at constant volume, which also increased the power output in the four-stroke single-acting oil engine. Experiments by Professor W. T. David showed that the specific heat of gases at high temperatures decreased as the initial pressure or density increased, and that there was probably less " after burning " with higher compression ratio in the constant-volume explosion cycle, which tended to increase the thermal efficiency.

With high piston speed the reciprocating parts are increased in weight, so that the increased inertia forces at high speeds have a counteracting or balancing effect and help to reduce the pressures on the crank-pin and main bearings. Incidentally, high speed is valuable by allowing the use of fewer piston rings necessary to maintain the piston gas-tight, thereby giving higher mechanical efficiency than was usual with ordinary slow-speed compression-ignition heavy-oil engines.

That higher piston speeds gave higher efficiency was clearly proved by practical experience, and as shown by the results in Table I, p. 110. The difficulties to be overcome in this line of development were chiefly mechanical, and special construction with suitable materials was necessary. Practical experience, during several years under ordinary working conditions, clearly proved

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* See *Applied Thermodynamics*, pp. 22–4, by the Author (published by Sir Isaac Pitman & Sons, London).

that *reliability* was quite as great as that of the ordinary slow-speed engine.

Application of the heavy-oil engine to locomotive work was found in the evolution of the light-weight high-speed high-efficiency oil engine suitable for driving a small high-power electric generator, and originated in the Unit engine constructed at Lincoln and developed into that built by William Beardmore & Co., in connexion with the production of an engine running on heavy fuel oil for aircraft service, in which the main requirements are similar. The difficulty was the inability of the existing oil engine to burn its fuel properly at high rotational speeds, and this was overcome by the fuel-oil pump (figs. 74 and 75).

The materials subject to wear have been greatly improved and hardened, and with more accurate workmanship, and forced lubrication, the cost of repair and renewal over a given period is actually lower than in the slow-speed engine, as the parts are smaller and cheaper. There is now a special method of hardening steel that gives a glass-hard surface, which gets over the difficulty of wear, and is also useful against corrosion.

These engines have been built for railway service in various sizes with 4, 6, 8, and 12 cylinders.

Within the last four years, these Beardmore high-speed heavy-oil engines have been successfully applied to railway cars, especially on the Canadian National Railways, and in service thereon the total mileage has reached about two million. Others are operating on a railway in Spain, having some very steep gradients and curves of extreme severity, and the oil engines are giving a very satisfactory performance.

The engine works on the four-stroke constant-volume cycle, with airless injection. The characteristic features*, besides economy of fuel, are light weight and great strength. In the construction of this engine (figs. 78 and 78A), thin cast steel gives adequate strength and rigidity to carry the stresses due to the explosion pressure, while the weight is about 15 lb. per brake h.p. The engine crank-case and cylinders are in a single monobloc multi-cellular steel casting in the form of a box to each cylinder, and the crank-case is bored to receive the cylinder liners, which are made of wear-resisting hard carbon steel or nitrided steel, and free to expand downwards. The lower half of the crank-case supports the engine

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* See paper on "Railway Traction by Oil Engines", by Alan E. L. Chorlton, C.B.E., *Proc. Inst. C.E.*, Vol. 229, p. 202.

on the base plate, and is extended to carry the lower half of the armature housing for the electric generator. The piston head is

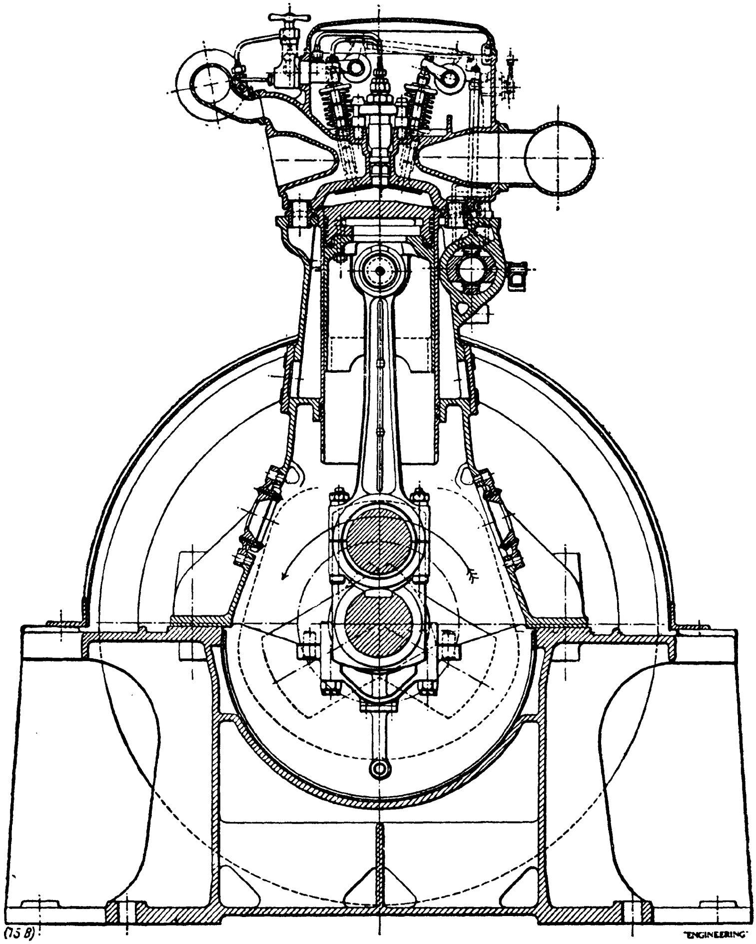

Fig. 78.—Beardmore High-speed Airless-injection Heavy-oil Engine

of Y * metal alloy forgings, and the skirt copper aluminium alloy. Each piston is fitted with four rings and a scraper. The cylinder

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* Y metal contains the following percentages: aluminium, 92·5; copper, 4; magnesium, 1·5; nickel, 2; specific gravity, 2·8; thermal conductivity factor, 0·385 (that of cast iron is 0·1 to 0·12). Yield point 20·8 tons/sq. in.; ultimate tensile strength, 26·9 tons/sq. in.; and elongation 17 per cent.

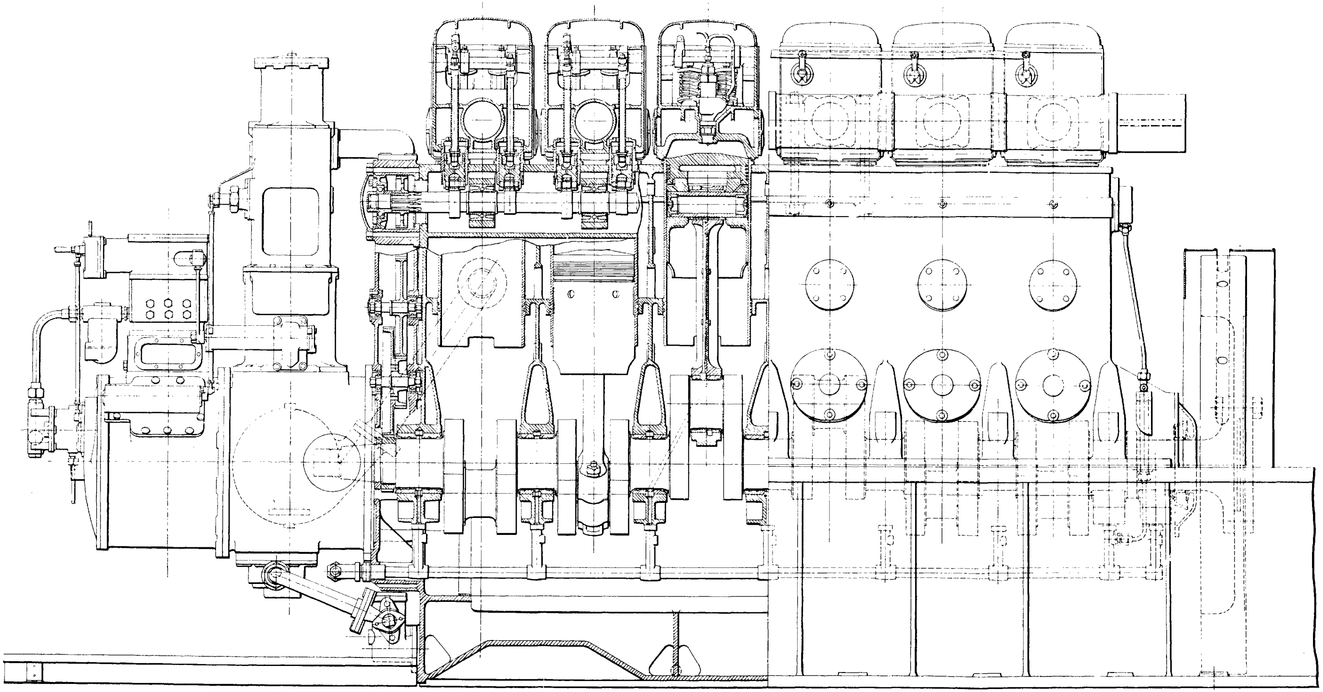

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Fig. 78A.—BEARDMORE HIGH-SPEED AIRLESS-INJECTION HEAVY-OIL ENGINE

cover is an aluminium casting, and the valve seats of nickel chrome steel cast in position. Each cylinder cover is fitted with one oil-spray automatic-injection valve set in the centre between two inlet and two exhaust valves of nickel steel, which are used because of the high speed, and are operated from a cam-shaft, near the top of the cylinder, by push rods and bell-crank levers. The second push rod to the inlet valve is across the top of the head.

The crank-shaft (fig. 78A), of large diameter solid-forged high-grade steel, is supported between each pair of throws; the heavy main bearings being fitted with shells lined with white metal and thoroughly lubricated by a continuous pressure-oil system. A friction vibration damper is fitted on the end of the shaft remote from the fly-wheel, because in a variable-speed multi-cylinder engine there are critical torsional vibration speeds which must be reduced and passed through quickly.

The centrifugal governor, operated from the crank-shaft, directs the quantity control valves on the fuel-oil pump through an oil-pressure relay. A variable-speed engine running between 250 and 1000 revolutions per minute, with only a small total variation at any speed, requires a constant percentage variation at all positions of control, and remote control is necessary for motor trains. In practice, the governors are controlled on a common electrical circuit, through valves acting on a hydraulic speeding device on each engine. The automatic injection valve discharges the fuel oil at high pressure through a fine pepper-castor spraying nozzle into each combustion space just before the end of the compression stroke. Double filters are fitted to the forced lubricating-oil circuit. The lubrication pumps and those for circulating the cooling water through the engine and radiator are driven direct from the engine.

The roof type of radiator fitted to the train tried on the London, Midland and Scottish Railway may be automatically emptied when the engine is stopped, to provide against freezing at night. The engines have constant torque at variable speed, the range of speed extending to a maximum of three or four times the minimum or idling speed.

The engine is directly coupled to a special compound-wound continuous electric-current generator, which supplies current to standard traction electro-motors geared to the truck axles. Each axle is driven by a separate motor through spur gearing.

The generator is separately excited, has commutating interpoles, and, at starting, the field current is supplied from an iron-clad storage battery. Under normal running conditions the field current is supplied by a separate exciter mounted on the generator shaft. The train is started, while the engine is running at its minimum speed, by closing the excitation circuit, and the generator voltage may be built up gradually. Increase of speed is obtained by accelerating the engine in stages through electro-magnetic control valves, by successively connecting the motors in series and parallel, or by varying the field of the electro-motors. The relay closing the exciter circuit is automatically operated at a predetermined speed.

All the operations are performed by **master controllers** of the conventional barrel type, just as in the multiple-unit electric train. A master controller is mounted at each end of this oil-electric locomotive, so that it can be driven from either end, and only one man is required, like the motor-man of an electric train.

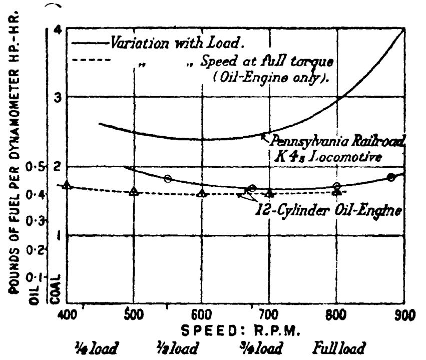

Fig. 79.—Comparative Fuel Consumption

The oil-electric unit develops its full power at a low train speed, and is, therefore, well suited to local passenger train and heavy freight train services. The rate of acceleration depends on the ratio of the power of the oil engine to the weight of the train, as well as on the method of control. The economical rate of acceleration for the oil-electric train is found to be between that of the steam locomotive on similar service and that of the electric train, since both the former carry their own power plant, and the latter draws its electric supply from an outside source. The oil engine has a higher thermal efficiency than any other prime mover, and attains a maximum of 40 per cent on a brake h.p. basis, while the steam locomotive has only reached 15 per cent thermal efficiency on an indicated h.p. basis or about 12 per cent on brake h.p. basis. Both of these are test-bed results, which cannot be realized under ordinary running conditions at varying loads.

Fig. 79 gives the fuel-consumption curves* on a power basis

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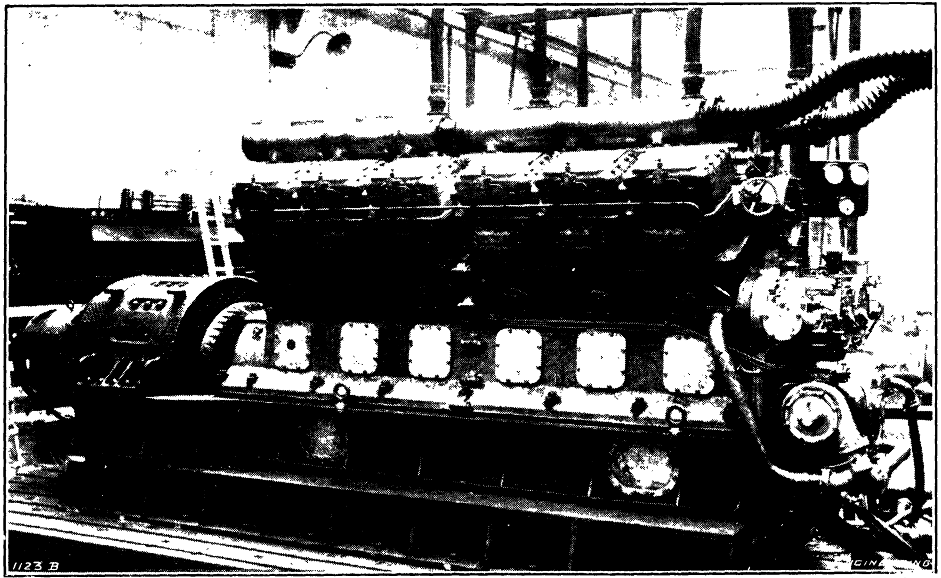
* *Proc. Inst. C.E.*, Vol. **229**, p. 206.



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From *Engineering*

Fig. 81.—TWELVE-CYLINDER V-TYPE 1340 B.H.P. ENGINE FOR OIL-ELECTRIC LOCOMOTIVE, AND GENERATOR, WITH SUPERCHARGER

for this oil engine and a steam locomotive, and on a speed basis at full torque for the oil engine only. The scales for oil and coal consumption are approximately in the ratio of the relative costs of the fuel, the price of fuel oil in this country being taken at 70 shillings per ton or four times that of coal at 17*s*. 6*d*. per ton.

This oil engine has nearly constant efficiency throughout its range of operation, but this does not represent its other gains in economy due to the absence of stand-by losses, and shed duties such as fire-cleaning and fire-lighting, coaling, boiler-washing, &c., which take more time and manual labour for the steam locomotive than for the oil-electric locomotive.

In modern practice, the steam locomotive consumes about 4 lb. of coal per draw-bar horse-power hour, while the oil-electric locomotive takes 0·5 lb. of fuel oil, thus at the above prices of these fuels, the oil-engine locomotive costs only half as much as the steam locomotive in fuel.

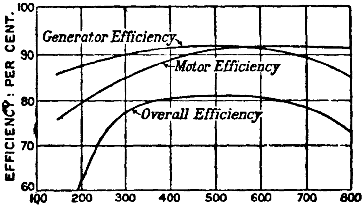

Fig. 80.—Efficiency of Electric Transmission

Again, fig. 80 shows the over-all efficiency of the electric transmission, or of the combined generator and electro-motor, about 80 per cent, practically equal to the mechanical efficiency of the steam locomotive in ordinary practice.

Although the oil-engine electric cars have been in service on the Canadian National Railways only four years, the savings in the cost of operation have led to the use of twenty of them already.

The development of the oil-engine electric locomotive for high power is indicated by the 2680 brake h.p. locomotive built in the year 1928. This locomotive weighs 290 tons and consists of two similar engine units which develop a tractive effort of 125,000 lb. during acceleration, and 42,000 lb. continuously. It will handle trains of 2800 tons weight, made up of 45-ton cars, at a speed of 40 miles per hour on the level, and at about 19 miles per hour on a ruling gradient of 1 in 250. Each unit consists of 12 cylinders of 12 in. bore by 12 in. stroke arranged in V-formation (fig. 81), and drives an electric generator which supplies current to four series-wound traction electro-motors geared to the axles.

Automatic Field Regulation.—The main electric generator is of ample capacity to convert the full output of the engine into electrical energy. There are eight selected field strengths to vary the voltage of the generator, so that the power output may be set to suit the load, consequently the engine will not be overloaded and yet the available power will be fully utilized. The automatic field regulation on the generator is by means of a torque governor, similar to a little motor which only rotates through a small angle. Its armature and field are connected to take a small proportion of the currents through the armature and field of the main generator respectively. Therefore, the saturation characteristic of this torque governor is in proportion to the torque loading of the main generator. If the torque is low the governor closes the control circuit to the automatic regulating field switch, which increases or adjusts the field of the generator, keeping it loaded by a gradual increase of the field as the train accelerates and the motor current decreases.

By control, each main engine can run at any speed from 300 to 800 r.p.m., and develops 1340 brake h.p. at 800 r.p.m. on a consumption of about 0·4 lb. crude oil per brake h.p. hour. The overload capacity is 1500 brake h.p. developed at 900 r.p.m. Water cooling is by radiators on the roof; and superchargers may be used to increase the power.

The engine exhausts to a boiler of the thimble-tube type, and with a separate auxiliary oil-fired boiler supplies steam for heating the cars. When there is no demand for steam, the auxiliary boiler is cut out, and the exhaust boiler acts as a silencer.

One locomotive unit weighs 167 tons loaded, and has successfully made several trial runs with the following results:—

TRIALS OF 1340 H.P. OIL-ENGINE ELECTRIC LOCOMOTIVE UNIT

Trial Run.	Weight of Train and Locomotive, Tons.	Average Speed, Miles per Hour.	Fuel Oil per 1000 Ton-miles, Gallons.
Montreal to Ottawa Ottawa to Montreal	361	43·0	2·8
Belleville to Toronto ..	920	—	1·6
Toronto and Hamilton ..	925	33·6	1·49
Montreal to Belleville ..	1503	28·6	1·22
Belleville to Toronto ..	1950	25·0	0·98

Higher maximum speeds were attained, and 65 miles per hour was reached in the first trial run of the locomotive. The quantity of lubricating oil is not more than three per cent of the fuel oil. These results, plotted in fig. 82, give the traction characteristic curves.

One of the small earlier oil-electric rail cars had seating accommodation for 56 passengers and ample baggage space. Shortly after being placed in service this railway car made a through run from Montreal (Quebec) to Vancouver (British Columbia), a distance of 2937 miles, in 67 hours. On this remarkable run the engine was not stopped once, and on the long climb through the Rocky Mountains the speed never fell below 40 miles per hour, even on the steepest gradients, whilst the average speed for the whole journey worked out at 43·5 miles per hour. The official report of Mr. S. J. Hungerford, Operating Vice-President, stated that "the oil-electric car left Montreal 16 hours *after* the crack Trans-Continental train 'The Continental Limited', passed it at Winnipeg, and arrived in Vancouver 22 hours *ahead* ".

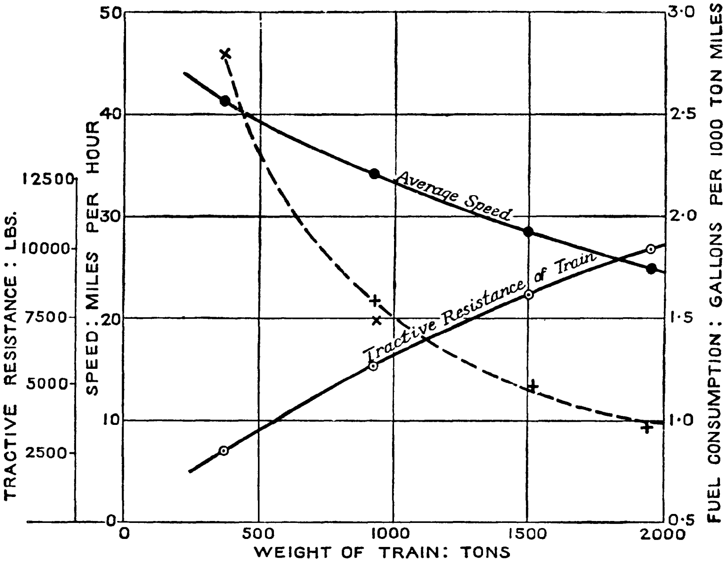

Fig. 82.—Traction Characteristic Curves for 1340 h.p. C.N.R. Locomotive Unit

For two of the oil-electric cars in the service between Edmonton (Alberta) and Saskatoon (Saskatchewan), and aggregating 700 miles per day, the working costs, as determined by selected accounts, averaged 23 cents (11½*d.*) per train mile, as compared with $1·01

(50½*d.*) per train mile, the costs for the corresponding steam trains superseded by the oil-electric cars, making a saving of 78 cents (39*d.*) per train mile. However, the two oil-electric cars had replaced four steam locomotives.

In a statement to a Parliamentary Committee at Ottawa, on 24th April, 1928, Sir Henry Thornton, President of the Canadian National Railways, said: " Where the oil-electric cars had been put on, loss had been turned to profit during the year, of that service, of 211,500 dollars (£42,300). He believed that the development of the heavy-oil electric unit offered a solution of the problems which involved the provision of service on branch lines, which could not profitably be operated by a steam train."

Mr. C. E. Brooks, Chief of Motive Power of the Canadian National Railways, reported * that " the cars were given to the regular organizations to operate, to steam engineers who received this new type of equipment with some doubt, but who, in most cases, now prefer them to steam locomotives, and to maintainers who had to be taught the equipment's operation from the ground up—and it is a credit to the fundamental design of the car and its equipment that, under all these trying conditions, the cars ran and proved the economic advantage of the oil-burning internal-combustion engine over other types of motor power available ".

There are also obvious advantages in the operation of this high-speed oil-engine electric unit for railway traction. Only one man is required to operate the controller for the complete working of the train from either end, and practically no attention to the engine is needed in unit trains up to 200 tons in weight, when supplied with fuel and lubricating oil. The trains have driving compartments at each end, and in order to increase the capacity two or more units can be worked together, from one master controller switch, similar to an ordinary electric train. By this method of working there is the saving of the fireman's wages in the steam locomotive.

The larger oil-electric locomotive may require an engine attendant in addition to the driver or motor-man.

The greatly reduced total *cost of operation* of oil-engine electric cars on the Canadian National Railways is given in Table III, which shows the average total costs of two years' working, after experience was gained by the drivers, and modifications made in details of the design and the material used in the con-

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* *Railway Age*, Vol. 84 (1928), p. 1319.

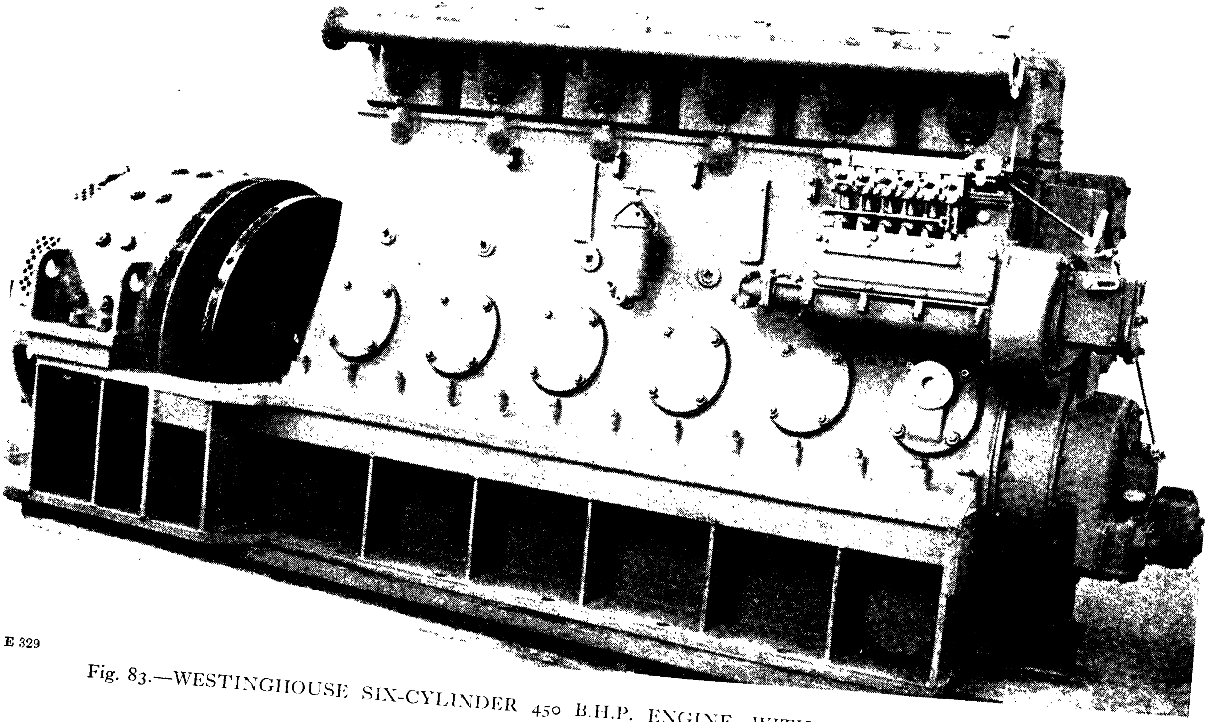

Fig. 83.—WESTINGHOUSE SIX-CYLINDER 450 B.H.P. ENGINE, WITH ELECTRIC GENERATOR

struction of the engine as revealed in actual service. The average cost of fuel oil was 12 cents (6*d.*) a gallon, and lubricating oil 80 cents (40*d.*) a gallon, also wages are higher in Canada than in this country.

TABLE III.—COSTS OF OPERATION OF OIL-ENGINE ELECTRIC TRAINS *

Cents per train-mile (one cent = one halfpenny)

In Order of Service

						Average.
Wages of motor-men ..	5·39	6·96	9·06	8·54	7·02	7·76
Supervision	—	—	—	—	1·82	
Repairs	6·95	10·37	10·49	8·59	6·03	8·48
Lubrication	1·81	1·02	2·46	1·28	0·56	1·43
Other supplies ..	3·02	1·53	3·92	0·59	2·53	2·32
Fuel oil	3·09	3·65	4·24	3·71	2·64	3·46
Total	20·26	23·53	30·17	22·71	20·60	23·45

The Ministry of Transport returns for the average costs of operation of steam locomotives in this country are given in Table IV. The most striking feature is the economy of fuel by the oil-electric cars, when compared with that of the steam locomotive using a much cheaper fuel.

TABLE IV.—COSTS OF OPERATION OF STEAM LOCOMOTIVES ON BRITISH RAILWAYS IN 1927: Pence per train-mile

	L.M S.	L.N.E.	G.W.	S.	Average.
Wages	14·09	14·50	13·45	11·86	13·48
Miscellaneous ..	0·26	0·44	0·18	0·26	0·28
Repairs	8·08	8·90	7·92	6·49	7·85
Lubrication	0·25	0·23	0·16	0·22	0·22
Other stores	0·42	0·50	0·41	0·40	0·43
Fuel	8·78	9·46	7·84	11·03	9·28
Water	0·56	0·62	0·48	0·55	0·55
Total	32·44	34·65	30·44	30·81	32·09

The highest fuel-oil consumption of the 1340 h.p. Canadian National Railway unit, with total weight 361 tons at an average

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* *Proc. Inst. C. E.*, Vol. 229, 1930, p. 217, "Railway Traction by Oil Engines", by Alan E. L. Chorlton.

speed of 43 miles per hour, compares favourably with the best results obtained between Manchester and Blackpool at a similar speed with a London, Midland and Scottish railway train, when the weight of the locomotive is included. In this largest and latest development of the heavy-oil electric unit, the lubrication costs have also been reduced.

The Beardmore type of heavy-oil engine for railway service in Canada at first had eight cylinders in line; these were followed by similar design four-cylinder oil engines, and later by six-cylinder engines, all having cylinders 8¼ in. bore by 12 in. stroke.

Fig. 83 is a photograph of the American Westinghouse reproduction oil engine of the same type having six cylinders of 9 in. diameter by 12 in. stroke, with a hydraulic governor and electric transmission. These engines are run up to 450 brake h.p. at 1000 r.p.m., though rated at less. Some of them are now in service on American railways.

The external view (fig. 84) and section (fig. 85) show a smaller size of Beardmore high-speed heavy-oil engine of the six-cylinder type, using high-pressure airless injection, having cylinders of 6·5 in. bore and 9 in. stroke, as used in rail coaches and short trains. It develops 200 brake h.p. at 1250 r.p.m., and is controlled by a governor through a relay with electrical solenoids and valves, and can be varied in speed between 600 and 1250 r.p.m., at all loads, by the driver at either end of the train or coach. A trip is provided to operate at 1400 r.p.m.

The engine is a self-contained unit, automatically controlled and complete with its own cooling water and lubricating oil circulating pumps, which give perfect heat control. The cooling water is circulated through the cylinder jackets and thence to the cylinder heads. The radiator is of the Reliance patent tubular type, mounted in the side of the car and ventilated by engine-driven fans. The lubricating oil is cooled in a separate section of the radiator, and the consumption of this oil has been reduced to about 0·007 lb. per brake h.p. hour. Monitor regulating valves are fitted in the water and lubricating-oil circulating systems, to which electric contacts are arranged, so that in the event of either of these systems failing to function, pilot lights give warning to the driver at either end of the train.

The engine exhaust is taken by vertical pipes into a silencer on the roof.

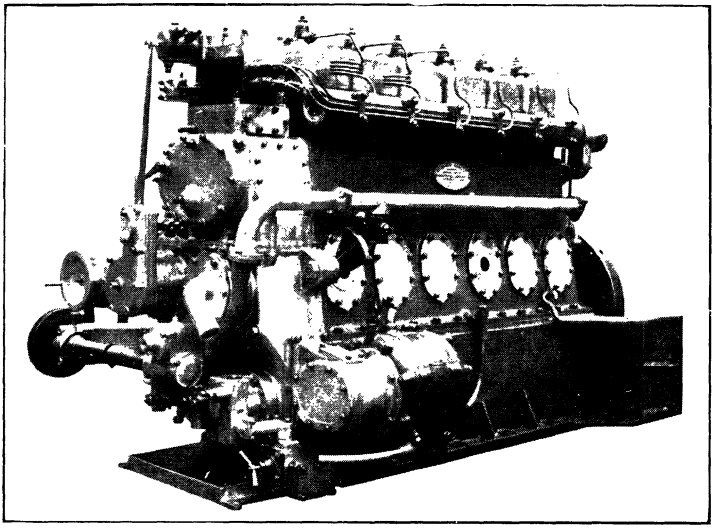

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Fig. 84.—BEARDMORE SIX-CYLINDER 200 B.H.P. OIL ENGINE

The engine is started by the generator used as a motor and supplied with current from the storage battery, which also serves for lighting the train and supplying current for the control apparatus. The engine is accelerated in starting the train in order to raise the voltage of the generator. The electrical control allows good flexibility through the engine and the electric transmission, and is very simple and effective.

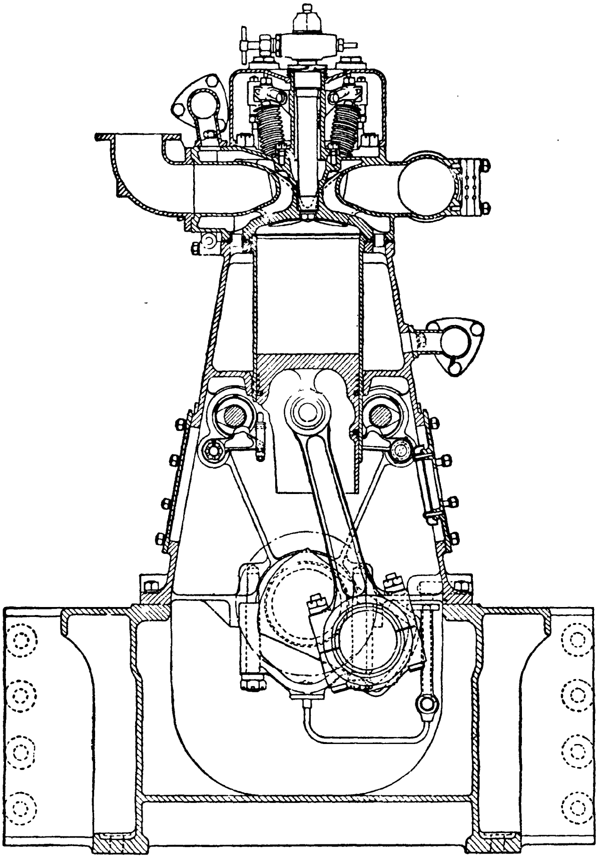

Fig. 85.—Cross-section of Beardmore Oil Engine

It is interesting to compare the performance of the 150 brake h.p. heavy-oil electric car with that of the petrol geared car having an engine of the same power. The fuel consumption of the two types is shown in fig. 86.* It will be seen that of the heavy-oil engine is about 0·42 lb. of fuel oil per brake h.p. hour at full load, and increases very slightly as the power is reduced, which is a great advantage of the airless-injection type of engine. On the other hand, the petrol engine consumes 0·7 lb. per brake h.p. hour at full power with a slight rise to half power, followed by a rapid rise as the power is further reduced, owing to the lowering of the compression pressure by throttling.

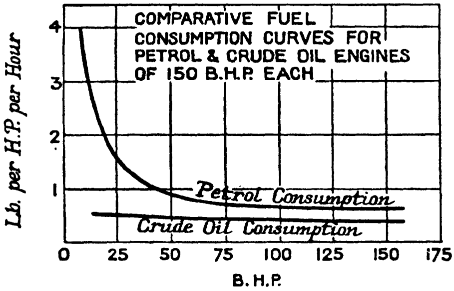

Fig. 86.—Comparative Fuel Consumption Curves

The consumption of crude oil by the 150 brake h.p. engine, when propelling a car and trailer of total weight 45 tons on average service, is about 2·5 lb. per 100 ton-miles; that of the petrol engine would be 5·2 lb. The most important point in this comparison is that of *safety* in the use of heavy oil, whereas the storage of petrol on trains demands serious consideration as regards fire risks.

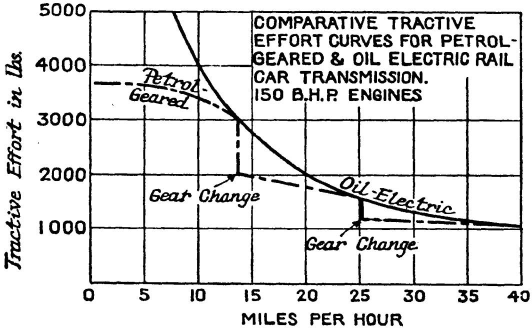

Fig. 87.—Comparative Tractive Effort Curves

Again, the improved tractive effort by the oil-electric drive is shown by the curves, fig. 87. The sudden drops in tractive effort when the gear change is made in the petrol geared car are clearly brought out, while the heavy-oil electric rail car trans-

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* *Engineering*, 20th May and 24th June, 1927.

mission gives an ideal smooth curve, owing to the perfect flexibility of the electric transmission, which protects the oil engine from direct shocks and enables it to be totally enclosed and automatically lubricated.

Moreover, considerable skill is required, when driving a petrol geared transmission, owing to the great inertia of a heavy train; whereas, with the heavy-oil electric car, it is easy to train a driver quickly.

The Beardmore eight-cylinder high-speed oil-electric engine, with airless injection, of 500 h.p., on a four-coach train on the London, Midland and Scottish Railway, replaced three steam locomotives, and was completely controlled by a master electric switch similar to that in a suburban electric train. It was started from a secondary battery, the generator being used as a starting motor.

The electric accumulator can be designed to drive the locomotive at half voltage to the nearest siding, in case of engine failure. In order to prevent the load from rising above the torque curve of the oil engine, one method is to have reverse series winding on the generator field, which automatically reduces the voltage when the current becomes too heavy, but this reduces the efficiency of the generator at low speeds, and retards the initial rate of acceleration. Another method provides for the automatic control of the main generator torque, keeping it constant over the range of the engine speed.

Speed variation in this train is obtained by a combination of engine control and electro-motor field taps. The first steps of the controller operate the governor valves, so accelerating the engine from idling speed to running speed, at which it develops its full power. Subsequent steps weaken the fields of the motors, which are connected in parallel. Some of the steps are very close together, and a run of at least three miles is necessary in order to utilize the full range of the speed control. Acceleration curves are given (fig. 88) for a full-load test and for normal running. The weight-to-power ratio of this high-speed oil engine and its equipment is so low that the limits to development in the speed of railway transit are far wider than with the steam locomotive, especially for freight traffic on railways of steep gradients.

This oil engine electric train weighs 10 cwt. per passenger and carries 285 passengers, at a fuel cost of about 3*d.* per mile.

A typical road omnibus weighs only 4 cwt. per passenger, and carries 60, at a petrol fuel cost of 1½*d.* per mile. With one driver and guard in each case, the fuel cost of the oil engine electric train is about 0·001*d.* per passenger, as compared with 0·025*d.* per passenger for the road vehicle. The cost of fuel is generally about half of the total running costs of the petrol public service motor omnibus.

Allowing an ample margin for capital charges and maintenance, and in view of the adaptability of the oil-electric train to traffic requirements, proved by experience on the Canadian railways, the light-weight oil-electric train affords the railway companies the means of meeting road competition, and should, at least, prove more economic than the steam locomotive on a secondary passenger service.

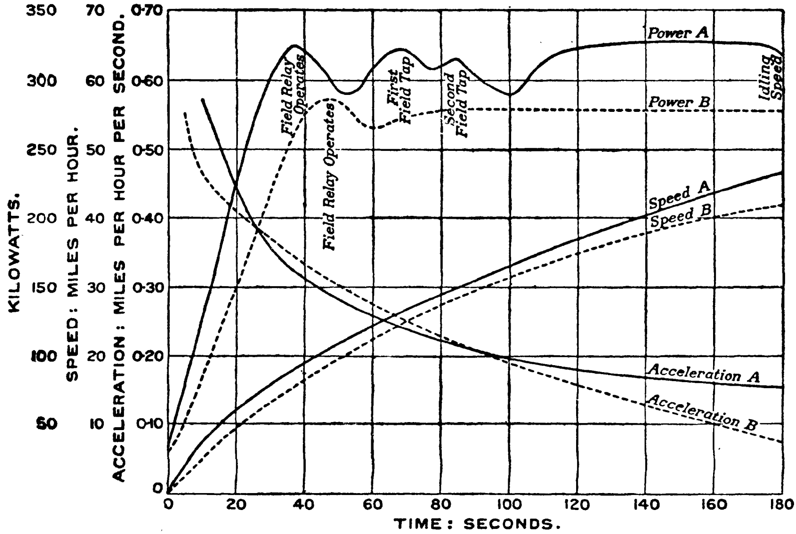

Fig. 88.—Speed Curves, L.M.S. Railway Oil-engine Electric Train

Curves A.—Full-load test; generator field current before field relay operates, 6·8 amperes; after relay operates, 5·8 amperes.

Curves B.—Normal working; generator field current before field relay operates, 6·2 amperes after relay operates, 5·1 amperes.

Road Vehicles.—A test of this high-speed type of heavy-oil engine installed in a *lorry* was made by the Royal Automobile Club, and the report gives: " The total distance covered was 691·75 miles. The average speed, excluding stops, was 17·7 miles per hour. Fuel consumption was at the rate of 13·48 miles per gallon." The weight of the lorry was 5 tons 6½ cwt., and the load carried 6 tons 5¾ cwt. The average time taken for starting from cold was 28 seconds, and when warm only 4 seconds, by using the electric plugs. The oil engine had six cylinders with a bore 105 mm. (4·134 in.) and stroke 165 mm. (6·496 in.). The fuel used was gas oil.

The first application of the high-speed light-weight heavy-oil engine to heavy haulage of the tractor, motor-truck, omnibus, and lorry for long-distance transport has already made considerable progress, and depends chiefly on economy of fuel and reliability.

The high-speed oil engine, used in some double-deck omnibuses of the London G.O.C., is that of the Associated Equipment Co., of Southall, built on the lines of the Acro-Bosch, Saurer design, and has two combustion chambers connected by a narrow throat passage—a direct derivative of the Akroyd. The engine works on the Akroyd four-stroke cycle, air alone being drawn into the cylinder during the suction stroke. The air is compressed to about 520 lb. per sq. in., and at the moment of oil injection near the end of the compression stroke; the air is in a state of *turbulence*, owing to the shape of the combustion chamber. The fuel is sprayed into the lower part of the combustion chamber and is directed towards the throat between the two parts. Combustion is rapid, and the maximum pressure is attained about 10 degrees after the top dead centre.

The engine gives 95 brake h.p. at 2000 r.p.m. on less than half a pint of Diesel oil per brake h.p. hour. Taking the price per gallon of this oil at 4*d.* and petrol at 1*s.*, the *comparative fuel cost* per h.p. hour, shown by power curves,* is:

Percentage of Full Load	25	40 Normal Average.	75
Oil Engine . . *d.*	0·3	0·26	0·2
Petrol Engine . . *d.*	1·7	1·3	1·0

It is stated that during a short run at Southall, in a London G.O.C. *double-deck bus* fitted with this oil engine, "the most remarkable feature was the easy and rapid acceleration. . . . The

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* *Modern Transport*, 8th Nov., 1930.

running was both smooth and silent, only slight knocking being apparent at very low speed. On the level the vehicle was easily accelerated on top gear from about 5 m.p.h. to 40 m.p.h., and there was only a suspicion of exhaust or oil fumes on stopping and starting." The opinion formed by the observer was that " the introduction of this engine in service, even in congested streets, would not be generally noticeable ".

In careful tests extending over several months' duration, this high-speed oil engine fitted to a *lorry*, in place of a petrol engine, in the same chassis and doing the same work, gave 9·7 miles per gallon of oil fuel, as against 5 miles per gallon of petrol for the petrol engine.

The Manchester Corporation have arranged to acquire a Crossley double-deck omnibus having the chassis equipped with a Gardner high-speed heavy-oil engine for experimental service.

The weight and first cost are still high, while the oil engine is more noisy than the same power standard petrol engine. Other difficulties are: gear changing and control on rough hilly roads that cause vibration, and the smell of the exhaust in dense street traffic.

Doubtless the paramount considerations of public *safety* from fire risks, and the great economy in low consumption of fuel, will hasten the further development of the high-speed, light-weight, airless-injection heavy-oil engine for road, rail, and air transport.

The general trend in oil-engine practice is coming to the airless-injection constant-volume cycle, that is, leaving Diesel practice and returning to that of Akroyd Stuart, the pioneer of automatic compression ignition.

APPENDIX

AKROYD CRUDE-OIL ENGINE

SCHEDULE OF PATENTS GRANTED AND APPLIED FOR

Prior to Hornsby & Sons' Licence Agreement to manufacture for the whole world

Country.	Number.	Date.	Title.
United Kingdom ..	9866	31 July, 1886	Improvement in Hydro-carbon engines.
” ” ..	15319	24 Nov., 1886	
” ” ..	10667	24 July, 1888	
” ” ..	14076	1 Oct., 1888	
” ” ..	18868	20 Sept., 1889	
” ” ..	7146	8 May, 1890	
” ” ..	15994	8 Oct., 1890	
” ” ..	3909	29 Feb., 1892	Water-jacketed vaporizer.
” ” ..	22664	9 Dec., 1892	Compressed-air starter.
Belgium	86441	29 May, 1889	Improvement in hydro-carbon engines.
”	88275	31 Oct., 1889	
”	Certificate of addition 93062	12 Dec., 1890	
France	198721	4 June, 1889	Improvement in hydro-carbon engines.
”	198721	25 Oct., 1889	
”	Certificate of addition 210261	16 Dec., 1890	
Germany	52455	25 May, 1889	
”	53959	26 Oct., 1889	
” .. .	Certificate of addition 59882	7 Dec., 1890	
Austria-Hungary ..	55855	24 April, 1891	
Italy	28775	31 Dec., 1890	
United States of America	376148	4 Nov., 1890	
	439702	29 Dec., 1890	
Spain	11589	28 Feb., 1891	
Australia.			
Victoria	8433	16 Jan., 1891	
South Australia ..	1833	19 Jan., 1891	
New South Wales	2754	20 Jan., 1891	
New Zealand ..	4827	2 Feb., 1891	
Russia	12648	29 Dec., 1890	
”	55623	Feb., 1891	

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