INVESTIGATIONS OF SOME LOW GRADE SOLAR DEVICES

THESIS
Submitted in partial fulfilment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY

By
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Under the Supervision of
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Dedicated

to

My Parents

&

My Brother, Late Shri R.K. Kashiramka

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CERTIFICATE

This is to certify that the thesis entitled "INVESTIGATIONS OF SOME LOW GRADE SOLAR DEVICES" submitted by M.K. Kashiramka, I.D. No. 77E94501 for award of Ph.D. Degree of the Institute, embodies original work done by him under my supervision.

Signature in full of the Supervisor Aparna Gupta

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LIST OF ABBREVIATIONS

CR - Concentration ratio

DST - Deptt. of Sc. & Tech., Govt. of India

DWH - Drum water heater

GDP - Gross domestic product

GNP - Gross national product

LPG - Liquid petrolium gas

MM^3 - Million m^3

MT - Million ton

NTC - Nontracking concentrator

OPEC - Oil producing and exporting countries

PrV - Present value

PV - Photovoltaic

R&D - Research & Dev.

SWH - Solar water heater

TCE - Ton coal equivalent

TWH - Terra watt hour (= 10^{12} WH = 10^{9} KWH)

TWY - Terra watt year (= 8.76×10^{12} KWH)

UINTC - Uniform illuminating nontracking concentrator

CONTENTS

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SYNOPSIS

The thesis entitled "Investigations of Some Low Grade Solar Devices" presents the results of the investigations done on various low grade solar thermal devices (by the author.) In Chapter I,
A comprehensive
an overview of solar thermal devices
given [illegible] much
is presented. This includes recent trends in the global energy profile and the resulting awareness in the field of nonconventional energy sources (in terms of increased R&D activities. It also discusses how all the countries of the world are affected by the energy crises in one way or the other. The developing countries are concerned because an increase in the price of oil has become a major constraint on their development. The oil producing and exporting countries are concerned by the ever-increasing rate of depletion of their oil resources. On the other hand, the industrialized countries are anxious about the security of supplies and the changed international relationships. A projection of energy requirements upto the year 2010 is also presented.)

In this Chapter, the

The Indian energy scenario and the national energy
in detail.
policy (formulated way back in 1976) are discussed (in Sec. 1.2). (It also discusses
T
the environmental impact of the energy projects and the rate at which demand of the energy is

increasing, as a result of increasing population as well as because of increase in the standard of living.

A brief discussion about the nature of the incoming solar radiation is given in Sec. 1.3. A detailed discussion regarding various methods of harnessing solar energy i.e., photovoltaic conversion, thermal conversion, wind energy conversion, ocean thermal gradient conversion, photogalvanic conversion and photosynthetic conversion is given in Sec. 1.4. The [illegible] Various problems are encountered in harnessing and popularising nonconventional energy devices in general, and solar energy devices in particular. These are discussed in Sec. 1.5.

The description of solar energy programme in India for both the rural and the urban sectors is given in Sec. 1.6. A comprehensive list of institutions and laboratories in the country, where solar energy research is being carried out, is given in Appendix I. A review of low grade thermal devices e.g., flat plate collector, solar concentrator, solar pond, solar water heater, solar cooker, solar still and solar dryer is presented in Sec. 1.7.

Performance study of various low grade solar devices is presented in Chapter II, which apparently starts with a brief discussion about the apparent motion of the sun at Pilani where all these investigations have been carried out. The design, fabrication and performance of the drum solar water heater - cum - storage system, both finned and unfinned types are discussed in Sec. 2.1. Both these varieties show about 30°C rise in the temperature of water, the finned variety giving a slightly better performance (2°C higher) than the unfinned one. The design considerations of the coil type solar collector are discussed in detail in Sec. 2.2, showing how the number of turns n of the coil can be determined from the tube radius R, initial coil radius a, and centre to centre distance between adjacent turns of the coil d, using the equation:

$$n^3 d^3 + 3\left[(1/2)pR + a\right]n^2 d^2 + 3a\,(pR+a)nd + a^2(a+pR) = 0 \quad \ldots(1)$$

where p is a rational number and has been determined to be -23, for obtaining optimum value of liquid bulk temperature T_b in the coil. The maximum instantaneous efficiency of this type of water heater comes out to be as high as 78%.

The details of solar water heating system installed in BITS to provide continuous supply of hot water to all the hostels, messes and guest house are described in Appendix II. The system gives an output of 53,800 litres of hot water per day. Various methods of maintaining such a hot water system are discussed in some detail in Sec. 2.3. An inexpensive method of maintenance, as adopted in BITS, is discussed in sufficient detail in this section. Annual cost of maintaining this system comes out to be only Rs.

1,25,000/- which is nearly 3% of the total cost (i.e., Rs. 38.17 lacs) and is much less as compared to the usual annual maintenance charges i.e.,around 8% of the cost. In Sec. 2.4, starting with the discussions of desirable features of a solar cooker and its utility, in urban as well as rural sectors, a number of new designs are presented. Design-I is a non-imaging type device and concentrates a divergent beam of light by maximum amount allowed by the phase space conservation rule. The specific model, which has been constructed, has an operating period of four hours and has a height of the concentrating mirrors as 0.6 m for 0.45 m base cooker. This decrease in mirror height from the full height of 1.2 m results in decreasing the concentration only by 8.5%, but makes it much more manageable to operate. Design-II gives a modified version of Design-I in that the height of the box has been decreased and a mirror is put on the back of the box. Investigations are carried out using this model in both the tracking and nontracking modes and with/without parabolic reflectors. As expected, best performance was obtained in the tracking mode using parabolic reflectors and the worst performance was got in the nontracking mode without parabolic reflectors, the average heating time being 57 minutes and 128 minutes, respectively. Design-III uses mirror strips instead of aluminium foil in the construction of the parabolic reflectors and has a drawer type of arrangement for keeping and taking out utensils for cooking. These modifications result in achieving better reflectivity and also minimise the heat losses while taking out/keeping the cooking utensils.

The fabrication and performances of a paraboloid solar cooker and sun baskets are presented in Sec. 2.5 and 2.6, respectively. These models are very cheap and can be made out of locally available materials but do not give high efficiencies.

The design of the solar oven is described in Sec. 2.7. Expressions have been derived for the determination of the ratio of target B to the aperture A for nontracking mode as:

$$\frac{A}{B} = \frac{\sin(3\alpha + \delta)}{\sin(\alpha + \delta)} \cdot \frac{\cos(2\alpha + \delta)}{\cos(\alpha + \delta)} \qquad \ldots(2)$$

where α is the angle made by the reflector surface with the normal and δ is the half-acceptance angle of the oven. Putting $\delta = 0$ we get the following simplified version of the above equation for the tracking mode:

$$A/B = 2 \sin 3\alpha \cdot \cot 2\alpha \qquad \ldots(3)$$

from which we can determine A/B for a given a or vice versa. Thus, taking A = 2B we get $\alpha = 20^{\circ}45'$. The efficiency of the oven was found to be 21.8%, which is reasonable. In Sec. 2.8 two types of solar stills have been discussed. The yield of distilled water from the first was found to be 2.31 $l/m^2/day$ (peak efficiency being 29.9%) and the second still produced about 5-6 l/m^2 / day of distilled water and has an efficiency of 40-50%. The details of solar dryer are given in Sec. 2.9, while the investigations done on space heating and cooling are discussed in Sec. 2.10. Investigations presented in Sec. 2.10 are of preliminary nature and more work has to be done before any field trial can be done for the same.

[illegible]

Chapter III presents detailed economic analysis of
in chapter III
various solar thermal devices. In this chapter we first list
the following
various factors which should be taken into account for
we
carrying out any meaningful economic analysis. These factors include, among others, rate of interest, inflation rate, discount rate to take care of depreciation, subsidies available e.g., on purchase of solar cooker, prices administered by Government e.g., LPG price, electricity
[illegible] quite useful
tariff, etc. A brief description is also given of various methods of economic analysis e.g., life-cycle costing method (which calculates the total present value of the life-time rupee costs associated with each alternative energy system under consideration) and the payback method (which calculates
[illegible]
the period over which a device pays for itself). A case is made that life-cycle costing method is the most appropriate to carry out the economic analysis even though the payback method is more appealing to a wider range of audience. In view of this, economic analysis of various solar energy devices has been carried out using the life-cycle costing

method (taking uniformly an interest rate of 8%, averaged out inflation rate of 8% and discount rate of 10%. Impact of subsidies and administered prices has also been taken in account, if applicable, on a case by case basis. A simpler formula has been suggested for calculating the payback period

$$\sum_{j=1}^{Y_r} a^{j} = I/S \qquad \ldots(4)$$

where I is the total first-time cost of the device,

S is the rate of annual saving taken to be constant

and a = (1+i)/(1+d), i and d being the interest rate and the discount rate respectively.)

The payback period has also been calculated for all the devices along with the above analysis (so that those who are more familiar with the payback period find the same

The author has rightly discussed

information for various devices.) An overall conclusion from this economic analysis is that most of the solar thermal devices are highly cost effective and should be used more widely.

(Chapter IV presents briefly the discussions and)

and presented in Chapter IV

Conclusions on the work done on low grade solar thermal

The author is quite right in

devices reported in the thesis.) It is obvious that to meet the energy needs, we should make increasing use of nonconventional energy sources (which are renewable in character like the solar energy. This is imperative) because ever increasing energy demands can only be met from these resources without damaging the environment which is very essential for us in the long run. After all we should remember that we have not inherited this planet (the earth). We have only got it from our forefathers for passing on to the next generations in as much environmentally and ecologically balanced condition as possible. The author hopes that with time, various solar thermal devices will find wider acceptability as a result of the increased awareness of the energy problem we are facing.)

CHAPTER I

SOLAR THERMAL DEVICES: AN OVERVIEW

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SOLAR THERMAL DEVICES: AN OVERVIEW

1.1 GLOBAL ENERGY PROFILE AND RESULTING AWARENESS IN TERMS OF R & D ACTIVITY

It is generally recognized that the state of development of a country goes hand in hand with the per capita consumption of energy. In fact, the modern way of life is called 'Energy-Intensive' because of rapidly increasing dependence of all human activities on energy.

One of the major effects of the Industrial Revolution two centuries ago, was the creation of two distinct categories of countries, namely the manufacturing or industrially developed countries, and the producers of only raw materials i.e., the underdeveloped or so called developing countries. This distinction continues in somewhat modified form even today, so that the developing countries, which make up the Third World and which contain three-quarters of the world population, produce about one-third of global energy supplies but consume only about 15 per cent of total world commercial energy. Yet the U.S.A. with only about 5 per cent of the world population, consumes about 30 per cent of the total energy output.

During last 40 years, the developing countries doubled their oil and electricity consumption every 10 and 7 years, respectively, whereas for the advanced countries the corresponding periods are 13 and 12 years, respectively.

The developing countries must therefore give urgent attention not only to the husbanding of present resources, but also to the short and long-term development of future energy resources. As long as oil prices remained cheap, and their consumption of commercial energy severely limited by their slow rate of economic growth, the oil importing and developing countries did not feel the need to assess their medium and long term energy problems, or to take cognizance of the opportunities for developing their domestic sources of energy. Traditional development strategies and the assistance supporting these strategies have emphasized the adoption of economic and technological practices similar to those employed by the advanced industrial societies. We are now beginning to understand that such strategies implicitly assume the continued availability of cheap energy resources. Based on this belated, but greatly desired awareness, we have to recognize that the countries of the Third World have a common fundamental interest in facing their energy needs and developmental problems on a collective and regional basis. In this regard, there is no basic difference between the oil exporting and oil importing developing countries.

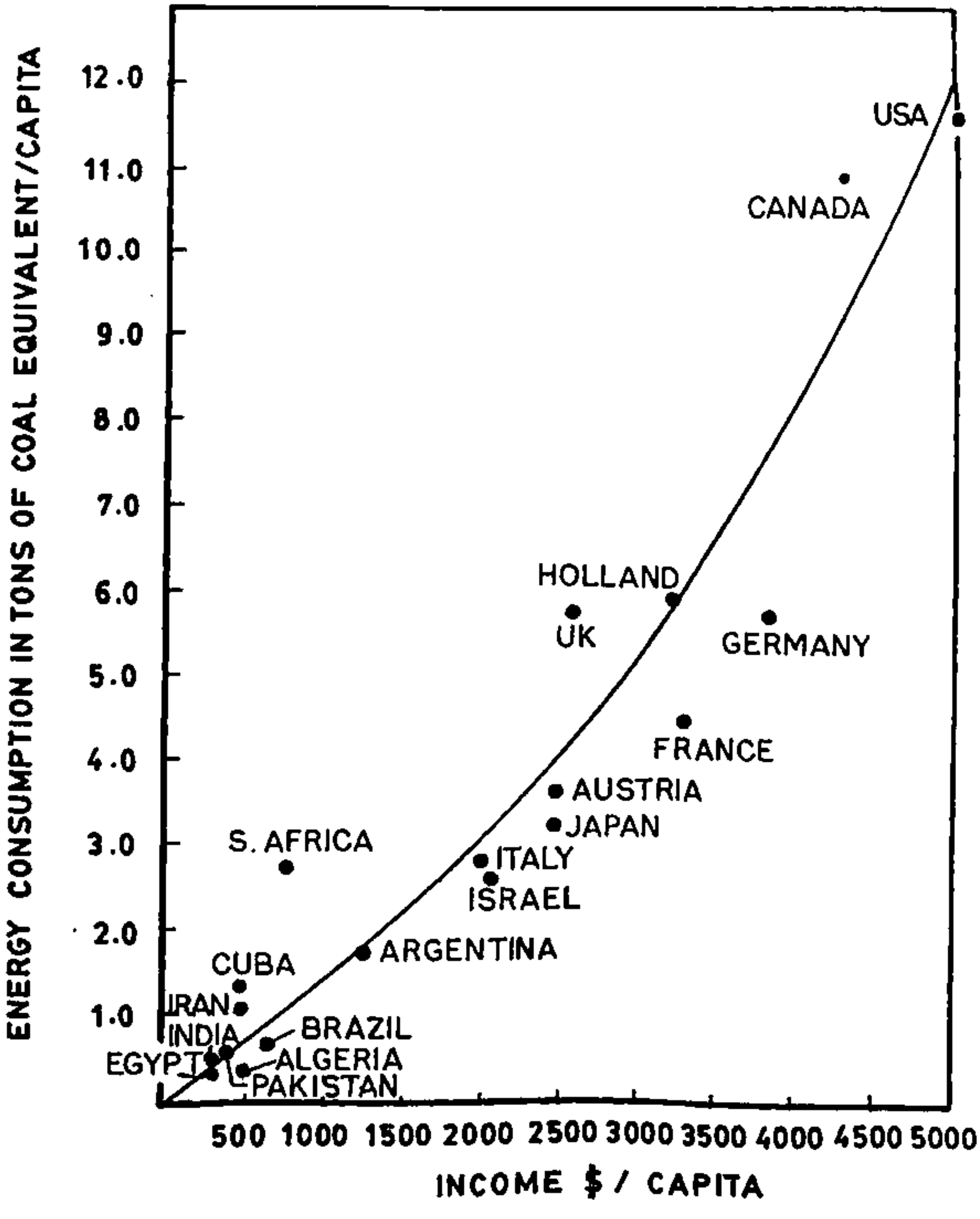


FIG.1.1 ENERGY CONSUMPTION VERSUS PER CAPITA INCOME FOR VARIOUS COUNTRIES.

accelerated the pace of their development to attain a high standard of living before their oil reserves are dried up. All this has led to increased interest in the development of new and renewable sources of energy and nuclear power. It is widely recognized that the world cannot do without alternative sources of energy to meet the ever growing requirement, as the conventional fossil fuels may not last for more than 20 to 30 years.

To sum up, the developing countries are concerned because the price of oil has become a major constraint on development. On the other hand, industrialised countries are worried anxiously about the security of supplies, the effect of high energy prices on inflation and above all about the changed international relationships[2].

Sources of energy

Let us understand where energy comes from. Almost all available energy can be traced back to the sun (fossil fuels, biomass, wind and incoming solar radiation) or to the processes of cosmic evolution preceeding the origin of the solar system (nuclear power). Smaller amounts are drived from lunar motion (tidal power) and from the earth's core (geothermal power). The total solar radiation that strikes the earth's surface every year is equivalent to 178,000 TWY i.e., about 12,000 times the world's present energy supply. Of this, however, 30% is reflected back to space and 50% is absorbed, converted to heat and reradiated. However, the remaining 20% is also 2400 times the present total energy supply.

Primary energy demand is expected to vary from one part of the world to another. According to a recent study of the U.S. Department of energy, the worldwide demand for oil is projected to rise from about 67 million barrels a day in 1993 to about 85 million in 2005 and to about 100 million in 2015. The price per barrel is expected to rise from about $ 16 a barrel in 1995 to about $ 25. Most of the increase will probably occur in the developing world, where population growth rates are high and industrialization and urbanization are under way. In contrast, demand is expected to remain more or less stable in the industrialized countries, where population growth rates are low[3] (Fig. 1.2).

Energy policies greatly vary from one country to another. For some governments, energy is a source of revenue, while for others it is an opportunity to provide relief for the poor by delivering subsidized energy. As time passes, most governments will like to control the impact on environment of all aspects - from installation to decommissioning of a power plant. In doing so, all governments should strive to provide its people with an adequate, safe economical and equitable power supply. Our demand on energy will persist, but it must be met keeping

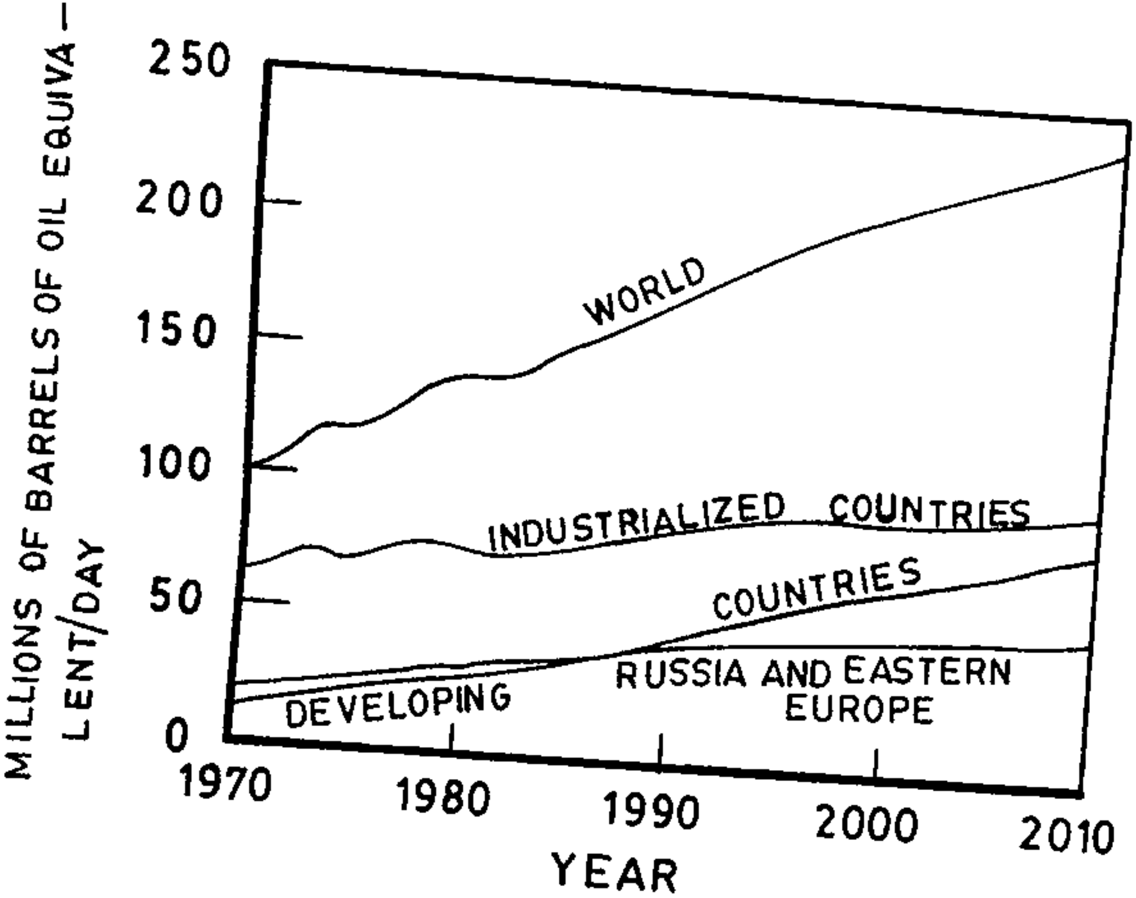


FIG.1.2 PRIMARY ENERGY DEMAND DURING 1970–2010.

ecological aspects in mind so that our planet earth remains ecologically sound.

1.2 INDIAN ENERGY SCENARIO

India's energy requirements are met from age old traditional as well as from modern sources of energy, the per capita energy consumption in India being only one tenth of the world average[4]. The consumption of modern commercial forms of energy has been continuously growing during the last four decades and consequently the fractional share of traditional forms of energy has been diminishing. Presently both are consumed more or less equally. Oil and electricity have been the most preferred form of energy and consumption has grown at an average rate of 7.5% and 10% annually during this period. Table 1.1 gives these trends in consumption of commercial energy[5].

Table 1.1 Trends in consumption of commercial energy.

Year	Primary Energy						Secondary Energy		
	Coal	Lignite	Oil	Natural	Hydro	Nuclear	Coal	Oil	Electricity
	MT	MT	MT	MM^3	TWH	TWH	MT	MT	TWH
1960-61	49.90	0.05	6.70	-	7.80	-	40.4	6.7	16.9
1970-71	71.23	3.37	14.97	704	25.25	2.42	54.1	12.5	48.5
1980-81	109.42	4.99	26.01	1566	46.53	3.00	70.3	22.2	89.7
1990-91*	220.00	7.50	50.00	3000	90.00	4.00	85.0	40.0	210.0

* Provisional

Rural electrification has been given very high priority during the last four decades. Initially the emphasis was on electrification of villages and rural areas, but later on greater need was felt for rapid exploitation of ground water for irrigation purposes. By now about 2/3rd of the villages are electrified, more than 5 million pump sets have been energized and about 3/4th of the rural population has access to electricity.

A comprehensive national energy policy was formulated in 1976. This policy underlines the importance of coal as the principal source of energy and the need for reducing reliance on imported oil by increasing indigenous oil production. Priority has also given to substitution of oil, wherever it is technically and economically feasible, and to develop new and renewable sources of energy.

The environmental impacts, resulting from the execution of energy projects and their operation, manifest themselves in several ways. Also , indiscriminate use of firewood has led to deforestation and soil erosion. Thermal power projects have led to atmospheric and water pollution. Hydro projects lead to several complex ecological implications and are therefore resisted e.g. Narmada & Tehri Dam projects have attracted organised protests from groups of environmentalists. Nuclear power plants are riddled with safety problems of alarming proportions, Chernobyl disaster of April 26, 1986 being a case in point. These days there is growing awareness regarding environmental impact of production and using various forms of energy. In fact, all power projects should go through an environment appraisal and should incorporate necessary safeguards to protect, if not improve, the environment. We should set up an inter-agency task force under the aegis of the energy ministry to monitor and assess political, economic and strategic developments relating to energy security and to assess all energy projects from ecological and environmental points of view throughly at the very initial stage.

Forecasting the energy demand is a hazardous task as it must be based on projected economic growth profile and on possible substitution trends in energy consumption. If we project the energy demand based on past trend assuming that no measures would be taken to monitor or restrict the demand, it is expected that in the year 2000 the energy demand would increase to 531 MT of coal, 93 MT of oil and 552 TWH of electricity. However, if vigorous efforts are made to manage the energy demand, it may increase to the level of 427 MT of coal, 69 MT of oil and 458 TWH of electricity. In the ultimate analysis it would be necessary to evolve a coherent energy policy taking into account the country's resources, more efficient utilisation of energy and development of new energy technologies appropriate to Indian conditions. The biggest constraint is likely to be the financial resources to sustain the required development. Already it has led to our seeking investment from abroad in setting up power projects in the country. Foreign investors are quite willing to come in the power sector but they want guarantees of a minimum return on their investments. This may require a delicate balancing between our desire to have more power and our capacity to pay for it.

1.3 HARNESSING SOLAR ENERGY

Attempts for the utilization of solar energy date back to ancient times. Archimedes destroyed the enemy armada by a battery of mirrors on the shores, concentrating sunlight on the ships. Egyptians are reported to have built a printing press and irrigation pump working on solar energy. Though solar energy is abundantly available, its exploitation presents certain technological problems. This is obvious from the fact that even after almost 20 years of efforts, use of solar energy has been rather limited. In this section we briefly discuss the nature of solar radiation and the problems faced in harnessing and popularising the use of the solar energy.

Nature of Solar Radiation

Energy is created in the interior regions of the sun as a result of a continuous fusion reaction. Sun with its radius

$R = 6.96 \times 10^5$ km and mass $M = 1.99 \times 10^{30}$ kg is almost an inexhaustible source of energy. Only a small portion (4×10^{-10}th) of this reaches the earth because of the large earth to sun distance as compared to the radius of the earth. The intensity of the solar radiation, known as the solar constant G_s, has been determined to be[6-8]:

$$G_s = 1353 \text{ W/m}^2 = 4871 \text{ KJ /m}^2\text{hr} \qquad \ldots(1.1)$$

This is the incident solar radiation on a plane normal to the sun's rays, just outside the earth's atmosphere when the earth is at its mean distance from the sun. As the earth has elliptical orbit around the sun, the actual value of G_s varies approximately ± 3.4% around the mean value i.e., from 1399 W/m^2 on December 22 to 1307 W/m^2 on June 21. Then the solar energy G_o, incident normal to the outer surface of the earth's atmosphere becomes.

$$G_o = G_s \cos\Theta \text{ W/m}^2 \qquad \ldots (1.2)$$

where G_o is called the extraterrestrial solar irradiation, Fig. 1.3.

The solar radiation reaching the earth's surface must have propagated through the atmosphere, approximately 99% of which is contained within 30 km from the earth's surface. Fig. 1.4 shows the effect of atmospheric attenuation on the spectral distribution of the solar radiation[9], $G_{s\lambda}$ which when summed up over all possible wavelengths gives back G_s

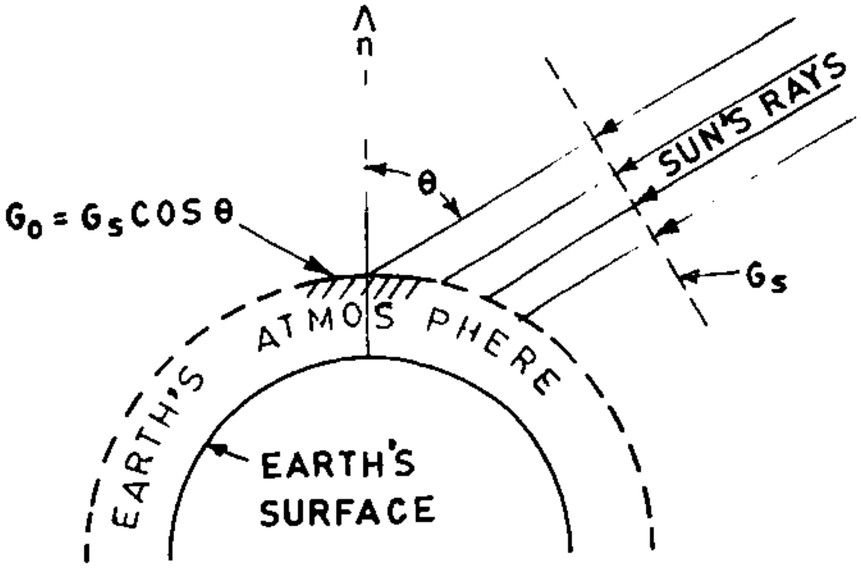


FIG.1.3 THE SOLAR CONSTANT G_s AND THE EXTRATERRESTRIAL SOLAR RADIATION G_0.

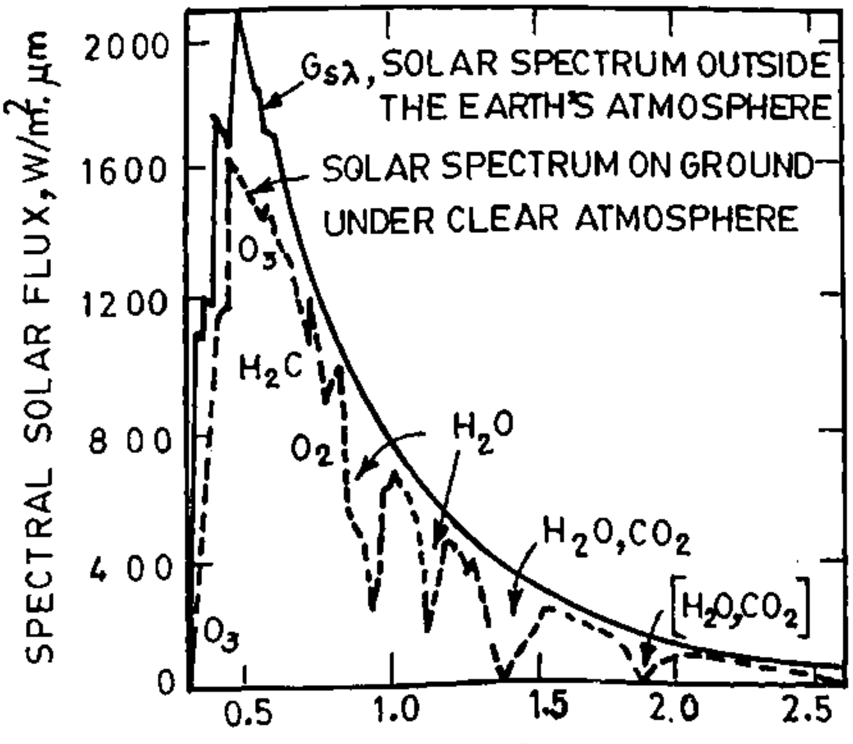


FIG. 1.4 EFFECTS OF ATMOSPHERIC ATTENUATION ON THE SPECTRAL DISTRIBUTION OF THE SOLAR RADIATION.

i.e.,

$$G_s = \int_0^\infty G_{s\lambda} \, d\lambda \qquad \ldots (1.3)$$

The several dips in the solar spectrum on ground are due to the absorption of the solar radiation by O_3, O_2, CO_2 and H_2O at various wavelengths. Also the solar radiation gets scattered by air molecules, water droplets and dust particles during its passage through the atmosphere. The part of the solar radiation that ultimately reaches the earth's surface is called the direct solar radiation. The earth's surface also receives the diffused solar radiation from all directions from the sky. The diffused part varies from 10% of the total on a clear day to almost 100% on a cloudy day.

The extent of absorption and scattering of radiation by the atmosphere depends on the length of the atmospheric path traversed and the composition of the atmosphere. To take into account the effect of inclination on the length of the path traversed, a dimensionless quantity, m, called the air mass ratio is defined as:

$$m = \frac{\text{Mass of the atmosphere in the actual path of the beam}}{\text{Mass of the atmosphere which would exist if the sun were directly overhead.}} \qquad \ldots (1.4)$$

Obviously m = 0 refers to no atmosphere and m = 1 refers to when sun is directly overhead. The average amount of solar energy reaching the ground could be around 20% of the solar constant. Even this is a large quantity if the economics of its harnessing becomes attractive.

1.4 BRIEF REVIEW OF VARIOUS METHODS FOR HARNESSING SOLAR ENERGY

Various methods are used to convert solar energy into useful form. A brief discussion of these methods is given below:

(i) Photovoltaic conversion

The photovoltaic (PV) effect is the process by which the photovoltage (emf) is produced at the junction of two dissimilar materials by the incident photon flux. The junction can be a metal-semiconductor or a p-n junction. When a photon of energy $h\nu$ enters the p-region, it is absorbed by an electron in the valance band. If $h\nu$ is greater than the energy gap E_g of the p-region, the electron will be able to migrate to the n-region. Similarly, if $h\nu$ is greater than E_g in the n-region, the photon will be absorbed by a hole which will migrate to the p-region. This results in a net positive charge in the p-region and a net negative charge in the n-region, a lowering of the initial potential barrier between n- and p-regions. If the external circuit connecting the p- and n-region is closed, the electrical current will flow through the external load.

(ii) Thermal conversion

When a body is exposed to the sun, it absorbs radiation and is raised to an excited state i.e., its temperature increases. The way in which it gains and loses energy is quite complicated. For understanding the behaviour we simplify the problem by assuming that the body does not lose heat by convection and conduction. Let I be the intensity of solar radiation and α be the absorption coefficient of the body. If the body is exposed to sun, its temperature will rise until it reaches a temperature called the equilibrium temperature T . At this temperature, the rate of emission of radiation will be equal to the rate of absorption. So we have

$$\alpha I = \varepsilon\ \sigma\ (T^4 - T_a^4) \qquad \ldots (1.5)$$

where ε is the emissivity of the body and σ is the Stephen-Boltzman constant and T_a is the ambient temperature. Now from Eq. (1.5) we get,

$$T^4 = T_a^4 + \frac{\alpha I}{\varepsilon \sigma} \qquad \ldots (1.6)$$

This rise in temperature of the body can be used as a source of heat to any working fluid.

(iii) Wind energy conversion

The wind blows because the temperature of the air at various locations on the earth are different. If an area is heated by solar radiation, the air that comes in contact with it is also heated and is raised up, cooler & heavier air from the surroundings rushes under the warm lighter air. This movement of air along the surface of the earth is called wind. So any project to harness the wind is a project to harness indirectly the solar energy.

(iv) Ocean thermal gradient conversion

Due to the incoming solar radiation, the upper layers of the sea are much warmer than those deep down. The warm water is evaporated rapidly at a low temperature under vacuum. The evaporated water, now a vapour, passes through a turbine that is connected to an electric generator. This conversion of heat energy in sea water into electricity can be attempted only along tropical coasts where the surface temperature of the water is about 28 °C; where the temperature difference is sharp near shore and where storms are not frequent. There are very few places which satisfy all these requirements.

(v) Photogalvanic conversion

In photogalvanic conversion the light impinges on an electrode and electrons are emitted. These drive the cell from which power can be drawn. For semiconductor electrodes, holes can be activated to be available as acceptors of electrons at the anode. This conversion process is less understood than photovoltaic one. In this conversion, it is not required to have the pure single crystals in the collectors as in photovoltaic conversion and hence this is cheaper. However, the efficiency of conversion is $\simeq 0.04\%$ which is very low compared to photovoltaic conversion efficiency ($\simeq 10\%$).

(vi) Photosynthetic conversion

Solar energy is used when the plants grow. These plants can be burnt directly to work a heat engine. Similarly, algae could be force grown, collected and decomposed by heat to form hydrocarbons. The photosynthetic conversion is less attractive since the average efficiency of solar energy conversion this way is only, about 1%.

1.5 PROBLEMS IN HARNESSING & POPULARISING SOLAR ENERGY

Solar energy is available in plenty in India as we have about 300 days of sunshine in a year. However, there are certain problems which come in the way of harnessing and popularizing it. These are the following:

(i) Solar energy is available only in rather diffused form i.e., unless the incoming solar radiation is either concentrated or converted to electrical energy by photovoltaic conversion or to thermal energy using low grade thermal devices, it is difficult to be used.

(ii) Solar energy is intermittently available i.e., it is available only for 8 - 10 hours in a day and that also only on sunny days, whereas we would like to use power at all times. This means that the energy has to be stored for use during nights and during cloudy/rainy days. This implies that storage capacity has to be sufficiently big to last even for a few days at a stretch. In case we cannot achieve this, we have to be satisfied using the solar energy as an add-on to the regular sources of energy.

(iii) The most important constraint in the wider utilization of renewable energy systems is the high initial capital cost. The cost of a solar device is considerably higher than that of the product based on conventional fuels. This factor is all the more important for photovoltaic use of solar energy. Though PV electricity costs have down by a factor of 3-4 since 1980, still these costs are prohibitive even now e.g., in America a unit of electricity from coal costs 4-8 cent and from PV cells it is about 25 cents[10]. Here it will be desirable to add that even the cases where the technology is already well developed, e.g., hydropower, larger initial investments are required to fully exploit the potential, besides a long gestation period for hydroelectric projects. However, the capital investment in conventional energy systems is born by the state or by the energy supply agencies, e.g., state electricity boards, whereas for renewable energy utilization, the user has to incur this initial investment. In our country where capital is really scarce, this indeed is a big deterrent. It is therefore very much desired that government gives sufficient subsidies and incentives so that the renewable energy systems become economically competitive.

(iv) In using a renewable energy device, the user does not get any return on his investment (which he would have got by alternative use of the capital) but may be getting convenience for him and his family. Now it is well known that the valuation of convenience is much lower for the poor than for the rich. This factor restricts the use of new energy devices by the poor people who are much larger in number.

(v) There exists a wide gap between the individual and social preception regarding the utilisation of alternative sources of energy. For example, an individual may not attach much importance to maintaining ecological balance but for the society as a whole it is very important so that it can sustain itself over a long period.This necessitates concerted effort to make people aware of their social responsibilities so that they are able to use the alternative energy sources in a proper perspective.

(vi) Certain habits and practices may have to change if renewable energy devices are to be used more widely. Thus, use of solar cookers require certain changes in cooking schedules and methodology. In fact, any attempt of popularising such devices should be associated with an awareness building programmes showing the advantages and applicability of these devices that can be realised by way of changing/modifying certain outmoded traditions.

(vii) There is a great need for standarizing various energy devices without which we have serious problems in getting replacement of parts off the shelf. Also repair and maintenance services are not readily available at most of the places. Unless adequate support services are provided, it will be difficult to gain wider social acceptability of these devices.

All these issues have to be sorted out before solar energy is accepted much more widely by the people.

1.6 SOLAR ENERGY PROGRAMME IN INDIA

Realising the importance of the utilisation of solar energy, the Government of India has established a seperate department of new energy sources, the Department of Nonconvensional Energy Sources (DNES), which looks after all the research, development and utilization of alternate energy sources. Formulation of energy policy and programmes for the development of new and renewable sources of energy is done by the Commission for Additional Sources of Energy (CASE), the Government of India. The national solar energy programmes which has been formulated consists of (i) development of solar thermal energy hardware and systems, (ii) development of direct energy conversion devices like photovoltaic solar cells and (iii) establishment of solar energy data collection observatories, data processing and information transfer to solar research scientists.

It is recognised that an early, smooth and successful transition from fossil fuels to new and renewable sources of energy depends on a strong, integrated and purposeful R&D programme. Accordingly, a comprehensive R&D programme in different areas of alternative sources of energy has been undertaken. Initially a coordinated R & D programme was initiated in several existing research and academic institutions. This is being followed by creating research centres for various forms of energy to promote research and product development and later popularising them through education and demonstration programmes.

Studies have been carried out on the spatial distribution, seasonal variation and frequency distribution of incident solar radiation. Annual range of bright hours of sunshine at various meteorological stations in the country are also recorded. From these studies[11-13] the annual distribution of incident solar radiation in India can be summarized as given in Table 1.2.

The energy requirements of a typical Indian village is of the order of 20 KW which is very less compared to the requirement of urban sector. Therefore the research and development projects have been divided into two categories:

(a) For rural sector

(i) Irrigation pump of 2.5 horse power.

(ii) Solar convective dryers of one ton capacity.

(iii) Distillation plants for conversion of brackish water into potable water.

Table 1.2 Distribution of Global Solar Radiation in India

Characteristics	Percentage of total surface	Surface area in sq. kms.	Area covered by
Areas receiving>500 $cal/cm^2/day$	8.7	2,85,035	Saurashtra, Kutch, Gujarat, West Rajasthan
Areas receiving 450-500 $cal/cm^2/day$	38.5	12,56,640	Peninsula and Central India, East Rajasthan
Areas receiving 400-450 $cal/cm^2/day$	32.2	10,50,370	Punjab, Haryana, Uttar Pradesh, Bihar, Orissa and West Bengal
Areas receiving<400 $cal/cm^2/day$	20.6	6,73,555	North Eastern parts of the country.

(iv) Solar refrigeration devices for food preservation in rural areas.

(v) Electric supply through solar cells for domestic lighting, radio and television sets.

(vi) Minielectric stations and prime movers delivering about 10 KW to 20 KW of power in remote areas.

(b) For urban/industrial sector

(i) Solar water heater of about 150 litres for domestic water heating.

(ii) Large scale water heating systems for installations in hotels, hospitals, hostels, factories etc.

(iii) Dryer for tea, tobacco, milk and paper industry.

(iv) Desalination plants for supply of water to coastal industries.

(v) Refrigeration and cold storage facilities of 1-5 tons capacity working on vapour absorption cycles.

Since the electricity can be used most conveniently for most of the energy requirements, major emphasis has been given on the utilisation of solar energy through direct conversion to electricity.The Central Electronics Limited, has been entrusted with the overall responsibility of research, development and production of economically viable photovoltaic system in cooperation with national laboratories and institutes of higher learning. The programme consists of the following:

(i) To conduct research on various types of low cost solar cells.

(ii) To identify the most promising type of solar cell.

(iii) Setting up of plant for production of low cost photovoltaic energy systems.

Solar energy research activities in India are going on in many laboratories/ Institutions as given in Appendix-I.

1.7 LOW GRADE THERMAL DEVICES: A REVIEW

In harnessing the solar power the various stages are : (i) collection, (ii) usage, and (iii) storage. The collection of solar energy is one of the most important technology. Hence collectors are the nerve centres of the solar energy devices. Various low grade thermal devices are reviewed here briefly.

(i) flat plate collector

Flat plate collectors are most widely used for collecting solar energy. A flat plate collector consists of a blackened absorbing metal (copper or aluminium or steel) with parallel pipes in the form of a grid attached to it (Fig.

1.5). The whole assembly is kept in a box insulated from the back. Glass cover on top allows the sunlight in and protects the collector from dust etc. The glass cover also acts as a heat trap. Mostly the incident radiation in the range of 250 nm to 500 nm enters through the glass cover since the transmissivity of glass is maximum in this range. The re-emitted radiation will have longer wavelength and hence lesser transmissivity . Therefore, it gets trapped partially by the glass cover. Commercially available flat plate collectors have efficiency ranging from 50% to 67% depending on the number of glass covers and the extent of air gap between the absorber and the glass cover[14].

In a sheet and tube arrangement, the distance between the tubes is W and the diameter of the tube is D and the sheet is of thickness δ (Fig. 1.6). The sheet above the bond is at temperature T_b, say. Neglecting the temperature gradient in the sheet, we get the energy balance equation as

$$\frac{d^2T}{dx^2} = \frac{U_L}{K\delta}\,[\,T - T_a - (S/U_L)] \qquad .....(1.7)$$

Where U_L = Overall loss coefficient for the collector,

T_a = Ambient temperatures,

K = Conductivity of the sheet,

S = $(\tau\alpha)_{eff}$ I,

$(\tau\alpha)_{eff}$ = The effective transmittance absoroptance product of the cover system for solar radiation,

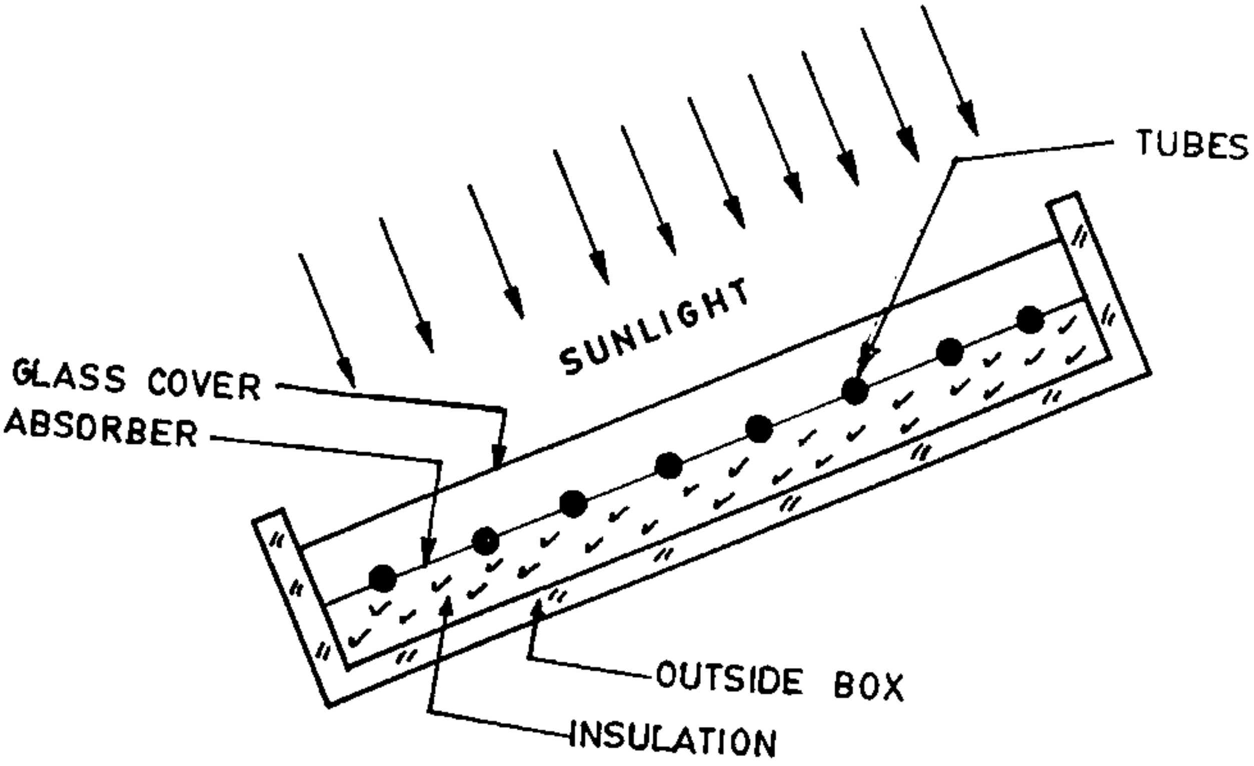


Fig.1.5 CROSS-SECTION OF A FLAT PLATE COLLECTOR.

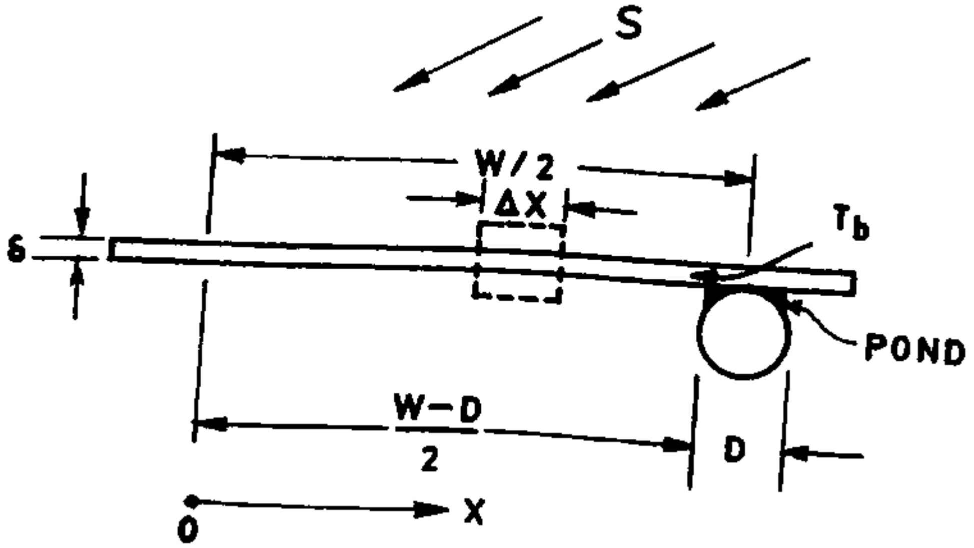


FIG.1.6 DETAILS OF SHEET AND TUBE ARRANGEMENT.

and I = the rate of incidence of solar radiation on a unit area of surface of any orientation.

The boundary conditions are:

$$\left.\frac{dT}{dx}\right|_{x=0} = 0 \qquad \ldots. \quad (1.8a)$$

and

$$T \Big|_{x = (W-D)/2} = T_b \qquad \ldots. \quad (1.8b)$$

The solution of Eq. (1.7) is given by

$$T = A_1 e^{bx} + A_2 e^{-bx} + (S/U_L) + T_a \qquad \ldots.. \quad (1.9)$$

where $b = (U_L/K\delta)^{1/2}$,

$$A_1 - A_2 = 0 \qquad \ldots.(1.10a)$$

and A_1 , A_2 are solutions of the equations

and

$$T_b = A_1 e^{b(W-D)/2} + A_2 e^{-b(W-D)/2} + (S/U_L) + T_a \qquad \ldots.(1.10b)$$

got by using the boundary conditions as given by Eq. (1.8). This gives us the following expression for the standard fin efficiency η

$$\eta = \frac{\tanh\,[b(W-D)/2]}{b\,(W-D)/2} \qquad \ldots.(1.11)$$

If we include the energy collected above the tube region, we get η' the collector efficiency factor which is essentially a constant for any collector design and fluid flow rate[14]. Evaluation of the overall loss coefficient for many different designs of flat plate collectors are given by Duffie and

Beckman[15]. Temperature distributions in the flow direction and across the plate have been studied by Charters[16] both in the steady state as well as in the transient state. Garg[17] has carried out investigations to study the effect of dirt, accumulated on the transparent cover of the flat plate collectors, the efficiency of the collector and has concluded that the correction factor due to dirt is more for plastic covers as compared to that for the glass covers.

(ii) Solar Concentrator

The solar energy received on the earth surface is diffused and should be concentrated before it can be used in quite a few applications. This can be achieved using concentrators. The concentrators are broadly classified as nontracking and tracking types.

In case of nontracking concentrators (NTC) no tracking is done for diurnal motion of the sun. However,the tilt of the concentrator is adjusted periodically i.e.,once a week or so. In tracking concentrators one uses a tracking mechanism e.g., electronic sensors or clockwork mechanism[18]. Recently a passive tracking system has been reported[19] which gives 20-30% increase in efficiency. Pioneering work in the field of nontracking concentrators was done by Tabor[20] in 1958. He showed that one could obtain concentration ratio (CR) of the order of three for an operating period of 8 hours or so per day. This could be increased to about 4 using second stage concentrator. The next breakthrough came in 1974 when Winston invented a new design[21] called compound parabolic concentrator (CPC). CPC acts as a radiation funnel and is a nonimaging device. Calculations of the surface of CPC for various types of absorbers was done by Winston and Hinterberger[22] and by Rabl[23]. To improve its performance various modifications have been made in this design[24]. Gupta et al have developed a new type of concentrator[25] called the uniform illuminating nontracking concentrator (UINTC) which makes optimal use of solar cells for photovoltaic conversion of solar energy by avoiding shadow formation on the area covered by the solar cell panel by obtaining more uniform illumination of the base area. Three models of the UINTC type were fabricated and were found to have uniform illumination within 10 - 12% during the operating period[25]. Some more models[26-30] of NTC have been developed by various investigators, which have been discussed and compared by Gupta[14].

Concentrators, capable of giving medium to high CR i.e., roughly 20 and above necessarily require diurnal tracking[31]. There are several ways of achieving this as briefly described below:

(a) One-axis tracking concentrators

These concentrators are generally linear or cylindrical in shape and are often called as 'line focus' devices. The most common concentrator of this type is 'parabolic trough' type which can have CR upto 200 due to finite size of the sun. Other reported concentrator designs include segmented plane mirrors arranged to form the parabolic trough, circular, cylindrical and Fresnel reflector.

The axis about which the above concentrators are tracked could have any of several possible orientations. Most commonly used is the axis parallel to the cylindrical axis of the concentrator which may be horizontal or vertical, the later being specially suited for photovoltaic systems. All one-axis tracking systems suffer end losses,the extent of which depends upon the concentrator focal length to longitudinal length ratio and upon the orientation of the tracking axis.

(b) Two-axis tracking concentrators

These concentrators have always normal to their aperture pointed at the sun. Such models yield higher energy collection and higher efficiency but not necessarily higher CR which is more controlled by the optical design of the concentrator and not so much by the tracking mode. Two axis systems are of point - focussing type.

Two-axis tracking works best if the two axes are mutually perpendicular. Two commonly used configurations are: (a) one axis vertical and the other horizontal and (b) One axis parallel to the earth's axis and the one horizontal. Overall performance of concentrating collectors depends on a number of parameters and detailed economic analysis is necessary in order to assess various designs. Obviously, the best system is the one that involves the lowest cost for delivered energy over a period of time for a particular application. Any attempt to maximise the useful energy gain will imply minimising both optical and thermal losses.

(iii) Solar Pond

Solar ponds[14,32,33] are simple type of flat plate collectors, combining both collection and storage. When the incident radiation is incident on the surface of a pond, the infrared component of the radiation gets absorbed with in a few centimeters, near the surface. The visible and ultraviolet components penetrate clear water to a depth of several meters. This radiation can be absorbed at the bottom of the pond if the bottom surface is blackened.This makes the lowermost layer of the water hottest. This hot layer tries to go up unless the bottom layer is made heavier than the upper layers by dissolving salt in the water. This type of pond is called non-convecting solar pond in which salt concentration gradually decreases as we go from the bottom layer to the top layer. Since the stationary water is quite an effective insulator, it is also possible for the lowest layer of water to boil which may result in destroying the stable concentration gradient. To avoid this, an efficient arrangement for heat removal is necessary. The hot layer of water can be removed without disturbing the gradient in the main body of water. The removed layer of the pond is then passed through a heat exchanger for removal of useful heat and then the water is returned to the bottom of the pond. Since the returned fluid is cooler than the main body, the concentration gradient in the pond remains undisturbed. However, the horizontal flow of the bottom layer may disturb to some extent the concentration gradient of the main body by creating a mixed layer at the bottom in which convection can occur.

Solar ponds allow collection as well as partial storage with negligible energy transport losses over large areas but show diurnal and seasonal fluctuations of output. However, due to existence of salinity gradient, the diffusion of salt starts from regions of high concentration to low concentration. Therefore, salt is added to the bottom of the pond and the surface is washed with a weak brine solution.

Water is also added to the top to replace that evaporated from the bottom layer. Therefore, the net flow of water is downward whereas that of salt is upward. Nielson and Rabl[33] have proposed to use a plastic cover over the solar ponds for maintaining the concentration gradient and for not letting winds, waves, rain affect the concentration gradient.

Salts like NH_4NO_3 or KNO_3, whose solutions are as transparent as water and whose solubility increases with temperature, are best suited to be used in solar ponds. On the other hand, salt like Na_2SO_4 is unsuitable since it has opposite solubility characteristics.

One method to extract heat from the pond is to decant the hot bottom layer from opening at one end of the pond.This hot brine is flashed in a chamber maintained at sub-atmospheric pressure,the vapour either driving a heat engine or passing over a heat exchanger. The brine which is left is more dense and is returned to the other end of the pond resulting in a reduction of pond mass. Alternatively, a heat exchanger can be placed at the bottom of the pond. This requires a large quantity of tubing and repairing of a damaged element of the heat exchanger cannot be easily done.

The heat extraction efficiency η_o of a pond is defined as:

$$\eta_o = \frac{\text{Heat extracted}}{\text{Solar input}} \qquad \ldots (1.12)$$

whereas the collection efficiency of the pond η is given by:

$$\eta = \frac{\text{Heat stored}}{\text{Solar input}} \qquad \ldots(1.13)$$

where heat stored is the accumulated heat in the no-heat extraction condition and is calculated from the temperatures of all layers. A typical solar pond is shown in Fig. 1.7.

(iv) Solar Water Heater

Heating of water for bathing, washing and commercial purposes is one of the oldest and cost effective uses of solar energy. The combination of moderate temperature requirements and more or less uniform annual demand makes the solar water heater particularly attractive. Such systems have been in use since 1920 and were installed at increasing rate until 1941 after which for about 30 years the sale of such systems decreased sharply. This decrease can be mainly attributed to the decrease in the cost of electrical energy making solar water heating less attractive, increase in the cost of solar water heating systems, development of leaks in the steel storage tanks in the existing systems and the reluctance of builders to add the cost of a solar heating system to the cost of the building. This trend continued till 1970s when concern was expressed about the long term availability of fossil fuels.

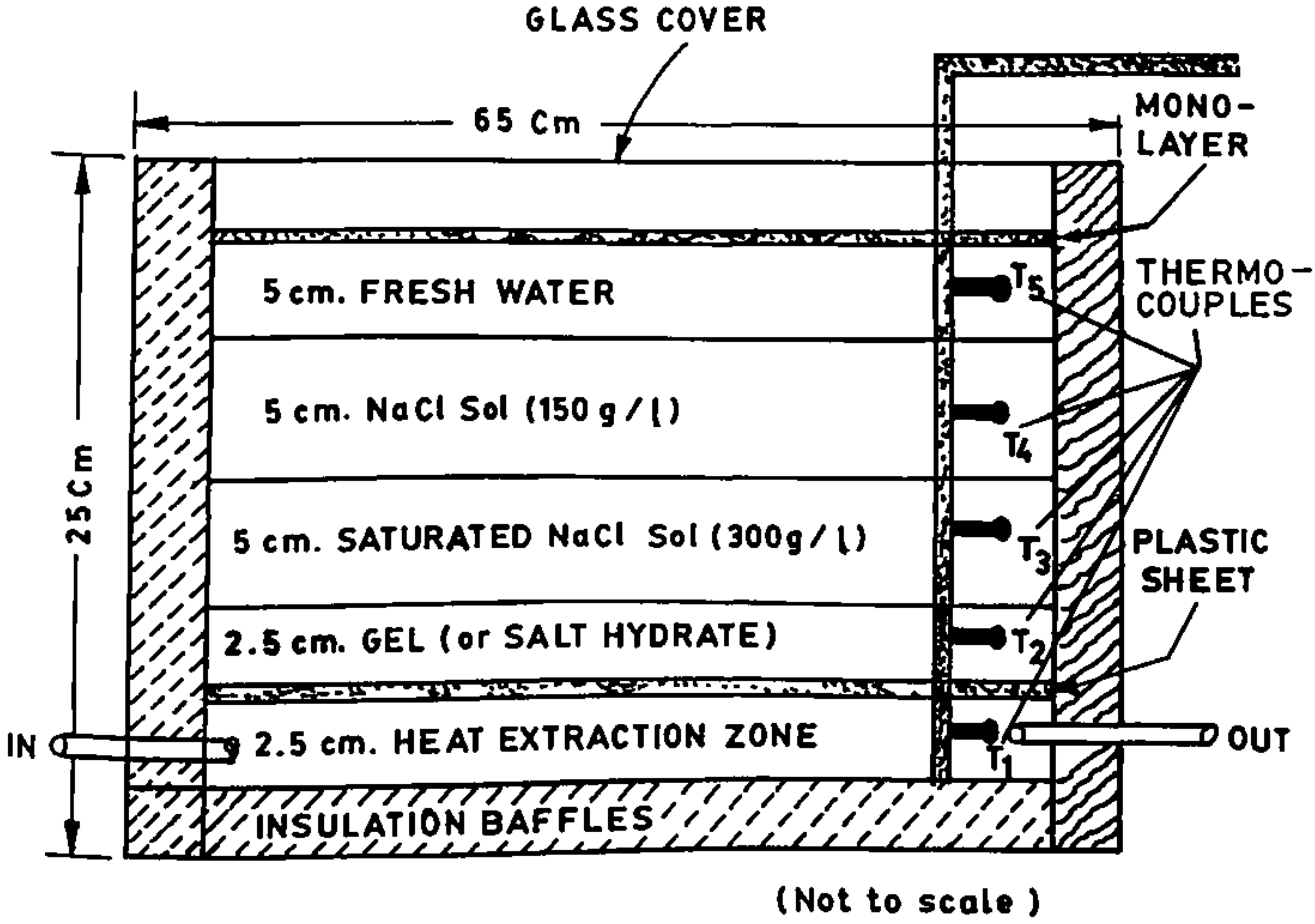


FIG.1.7 SCHEMATIC OF THE VANCOUVER MODEL SOLAR POND.

Solar water heating systems normally consists of 1m x 2m flat plate collectors connected to a vertical cylindrical tank. Various system configurations used for the purpose are:

(a) Thermosiphon system

(b) Forced circulation system

  (i) Direct

  (ii) Indirect

(c) combined collector-storage system

(d) Heat pipe system.

A proper choice of storage material is very important. In doing so we must first decide which of the following storage is to be used:

(a) Sensible heat storage

Heat stored Q in a material can be expressed as

$$Q = mS\Delta T \qquad \ldots(1.14)$$

Where m and S are the mass and the specific heat of the material and ΔT is the change in its temperature. If the material is in a container having volume V and density of material is ρ then

$$Q / V = \rho S\Delta T \qquad \ldots(1.15)$$

Thus the ability to store sensible heat is dependent on the value of the product ρS. Whereas quite a few other materials have ρS within a factor of 2 of that of water, (see Table 1.3), water is cheap and good but the container for water should be better quality than that for solid.

(b) Latent heat Storage

It is more practicable to have phase change from solid to liquid as the heat storage mechanism rather than from liquid to gas. Although storage is less in the former case than in the later case, yet it is to be preferred because liquid to gas change requires proper container e.g., storing steam at gigantic pressures can be extremely dangerous. The temperature at which the phase change occurs is very important and this should preferably match with the temperature of the system. For solar energy applications LiOH, NaOH, B_2O_3, KNO_3 and Al_2Cl_6 are found to be suitable materials, (see Table 1.4).

Table 1.3 Volume heat storage capacities[34]

Material	Water	iron (cast)	Marble	Concrete	Brick	Dry earth	Wet earth
Volume heat capacity ρs	1.00	0.84	0.57	0.54	0.34	0.24	0.86

(v) Solar Cooker

There are a number of basic types of solar cookers. A brief review shows that in the developed countries most attention is paid to small production units. These units are either of the collapsible umbrella reflector types or hot box types and are designed to be portable and compact. There are three different types of solar cookers:

(a) Hot box type

Insulated solar cooker with double glazing, generally in the form of a box is set out in the sun and oriented manually

Table 1.4 Heat of Phase change for solid to liquid phase.

Material	Transition temperature °C	Heat of change cal/g
$BeCl_2$	547	310
NaF	992	168
NaCl	803	123
LiOH	462	103
$LiNO_3$	264	88
KCl	776	82
B_2O_3	449	76
Al_2Cl_6	190	63
$FeCl_3$	306	62
NaOH	318	40
H_3PO_2	26	35
KNO_3	337	28
$Na_2SO_4 \cdot 10H_2O$	32	56*
$CaCl_2 . 6H_2O$	30	41*

* These are congruent melting materials, so the value of heat of change depends on the degree of "aging" of the solid - solution mixture.

at intervals. To increase the efficiency, reflectors are often added to obtain higher temperatures in the interior cooking chamber. By its very nature, this type of cooker requires cooking to be done in the open, which makes it less acceptable particularly during summer.

(b) Reflector type

Solar rays are concentrated onto a focal point or area on which is placed a cooking pot or frying pan. This also requires cooking to be done in the open. These units are less efficient in areas where there is higher percentage of diffuse radiation.

(c) Detached solar collection and cooking chamber type

In this type of cooker the heat transfer fluid (water or oil) heated in a separate collector. The heated fluid is transferred to a separate insulated cooking chamber which can be located inside the house at any convenient place. Thus this type of cooker can be used from inside the house itself.

A study undertaken by the Brace Research Institute for the United Nations Environment Program has concluded that solar cooking with a smokeless wood stove as a backup (i.e., during about 25% of the time when climatic conditions do not permit use of solar cooker) is the least expensive alternative compared to LPG or charcoal. Following technical considerations should be kept in mind in designining solar cookers:

(a) Calculations should be made to determine the amount of solar energy available for cooking and how does it vary with time of the day and with change of seasons.

(b) Thermodynamic analysis should be undertaken around the cooking pot to determine the rate of heat transfer to the pot after accounting for heat losses in the collection system and in the transmission system. In the case of hot box cooker the two are effectively combined in one system.

(vi) Solar still

This is a device in which solar distillation is done for the production of fresh (potable) water from saline water. Economically, the initial cost of the stills are less than any other method to obtain fresh water. The price of fresh water produced by the still comes out to be less than the cost of transporting it. The common type of solar still is the roof type still. As the solar radiation reaches the glass cover, the long wavelength portion is absorbed by the glass, but a part of the radiation reaches the saline water and the remaining reaches the bottom of the trough. The thermal performance of the still can be analysed by solving the heat balance equations for the glass cover and for the bottom of the trough simultaneously. From this we can calculate the tray and glass cover temperatures. Thermal efficiency of a still is defined as[14]:

$$\eta = \frac{\text{Energy used in saline water}}{\text{Incident solar radiation}} \qquad \ldots(1.16)$$

In the steady state the glass resistance can be neglected and the water temperature is taken to be equal to the tray temperature. Air leakage is a damaging factor to the good performance of the still. The thermal efficiency of a still is limited by the heat of vaporization of water and solar insolation.

Two different types of solar stills which are discussed here:

a) Commercial Stills

The essential features of a typical commercial solar still are:

1. Concrete side walls,
2. Internal lining of 0.76 mm butyl rubber.
3. Saline water basins insulated with 25 mm polystyrene.
4. Glass roof structure thoroughly vapour sealed.

The normal mode of operation consists of supplying the saline water continuously at a rate of about $1.7\ l/m^2/hr$. which is about twice the maximum distillation rate. In this way, water is provided continuously to make up for the loss and the rate of deposition of salts from the saline solution is reduced.

A reduction in output of up to 50% can result from allowing the unchecked formation of reflecting layers of salt on the basin liner. A cover slope of 10^0 is the minimum for drainage while a slope of 18^0 has been used to given increased structural stability against high winds. For economic reasons, the cover slope should be as low as possible. In practice no more than 80% of incident solar radiation will be absorbed in a solar still. For proper performance, it is necessary to keep the cover free of dust.

(b) Domestic Stills

Domestic stills are small units for distilling water for household purposes. These are made from 25 mm thick polyurethane foam to form a box of internal plan dimensions of 74.3 cm x69.2 cm with a single glass cover of slope 10o supplied through a float valve which maintains the depth between 6 mm and 12 mm. They have a life of about 10 years.

(vii) Solar Dryer

One of the oldest uses of solar energy has been the drying and preservation of agricultural surpluses. The process is labour intensive and little capital is required. The solar drying has been practised in almost all the countries for diverse products such as fruits, vegetables, cereals, grains, skins, hides, meat , fish and tobacco etc.

There are two principal aspects of the crop drying process: the solar heating of the working fluid (usually air) and the drying chamber where in the heated air extracts moisture from the material to be dried. The solar heating consists of (a) separate solar air heater collectors or (b) heating of air directly over the produce. Solar dryers are classified according to their heating modes, or the manner in which the heat derived from the solar radiation is utilized[35] :

(a) Passive systems

Dryers using only solar or wind energy for their operations.

(b) Sun or natural dryers

Dryers using solar radiation, ambient air, temperature, relative humidity and wind speed.

(c) Direct Solar dryers

Dryers in which material to be dried is placed in a enclosure, with a transparent cover or side panels. Solar radiation is absorbed by the material itself as well as by the internal surfaces of the drying chamber. This heat evaporates the moisture from the product being dried. Also, it serves to heat and expand the air in the enclosure, causing the removal of this moisture by the circulation of air.

(d) Indirect solar dryer

Dryers in which solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector and then ducted to the drying chamber, to dehydrate the product.

(e) Solar lumber dryer

Dryers in which forced ventilation is used as proper circulation of air helps to control the drying rate so as to avoid case hardening .

(f) Chamber dryer

Dryers in which the material to be dried is kept in an enclosure.

(g) Rack or tray dryer

One in which material to be dried is placed on wire mash or racks.

A small dryer for household applications has been designed, fabricated and tested in BITS[36]. It consists of a packed bed collector and a storage cabinet. The drying air is heated in the collector and goes past the vegetables, being kept in the cabinet. The collector box size is 191 cm x 94.8 cm x 28.4 cm having wooden walls and glass glazing of 3 mm thick ordinary glass on the top. To increase the surface area so as to heat uniformly the incoming air, black painted scrap material is kept in the box. Inside surface of the box is painted black. There is a provision in it to accommodate a blower at the lower end and a polythene ducting at the upper end.

The storage cabinet is essentially of glass having necessary wooden frame. The panel of the cabinet facing north is of wood and is the access door to the cabinet.the panels facing east and west are made of glass. The cabinet glass roof is kept slanting at an angle of $28\frac{1}{2}^{\circ}$ with the horizontal, 28.5°N being the latitude of Pilani.The cabinet has arrangements to accommodate multiple trays and an adjustable ventilator opening is provided in the upper portion of the side panel. The flow of air through the system can be natural or forced, the latter being achieved by using a blower.

The performance of the dryer has been studied by varying the

(a) Flow rate of heating air,

(b) Area of heating surface,

(c) Natural draft effect.

1.8 PLAN OF PRESENTATION

The main results of the work done on low grade thermal devices by the author are presented in Chapter II of this thesis. A number of students have done their Master's theses in this area under the supervision of the author. The work done has been presented[37-42] in various workshops/ symposia. Sec 2.1 gives the investigations carried out on the drum water heater (DWH), whereas Sec 2.2 gives the details of the work done on the coil type solar collector. Sec 2.3 presents the details of the work done for maintaining the solar water heater (SWH) system installed for BITS hostels, messes and guest house. Secs 2.4 - 2.7 give the results of the studies carried out on different designs of solar cookers, sun basket and solar oven. The investigations on solar still are presented in Sec 2.8 while Sec 2.9 gives the work done on the solar dryer. Space cooling and refrigeration studies are presented in Sec 2.10.

The detailed economic analysis of the various low grade solar devices is given in Chapter III alongwith certain case studies while Chapter IV gives discussion and conclusions.

CHAPTER II

PERFORMANCE STUDY OF LOW GRADE SOLAR DEVICES

CHAPTER - II

PERFORMANCE STUDY OF LOW GRADE SOLAR DEVICES

The results of our investigations carried out on various low grade solar devices are presented in this chapter. We take up various devices one by one and present the work done on each of them.

Before doing that we shall put a word about Pilani in respect of receiving solar energy as all these studies are carried out here. Pilani is situated at $28\frac{1}{2}^{\circ}$ N latitude(λ).The local noon time is 1230 hrs. At local noon position Zenith angle of the sun varies from 5^{0} to 52^{0}S, Fig. 2.1. The total solar insolation is around 450 $\mathrm{cal/cm^{2}/day}$. This intensity of solar radiation is measured using solarimeter.

2.1 DRUM TYPE SOLAR WATER HEATER-CUM STORAGE SYSTEM

In this section we present a novel drum water heater-cum-storage system[40,43] which has been found to be efficient as well as cost effective. This solar water heater consists of a drum enclosed in a double - walled casing with glass cover to give green house effect. The external casing is made of wood, 3.5 cm thick and window glass, 3 mm thick, is fitted as cover, Fig. 2.2 and Fig. 2.3. The glass cover is used as glazing. Glass wool is used as insulating material in between the two walls. The outer surface of the drum is painted black with Japan black paint so as to act as absorber.

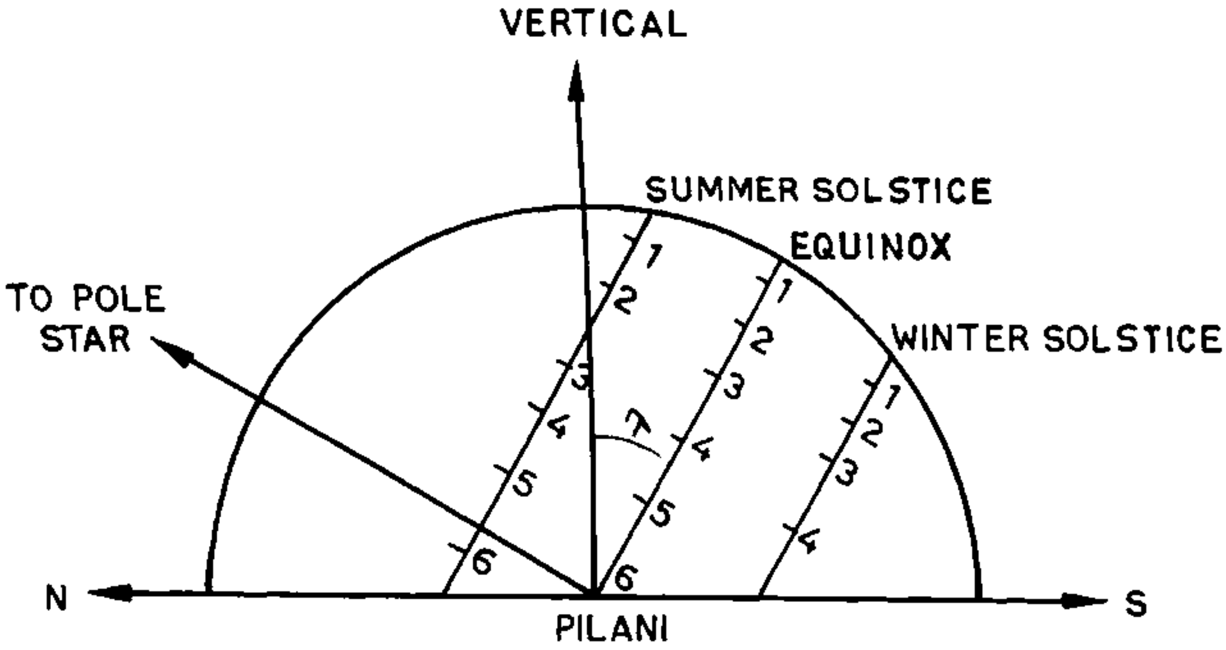
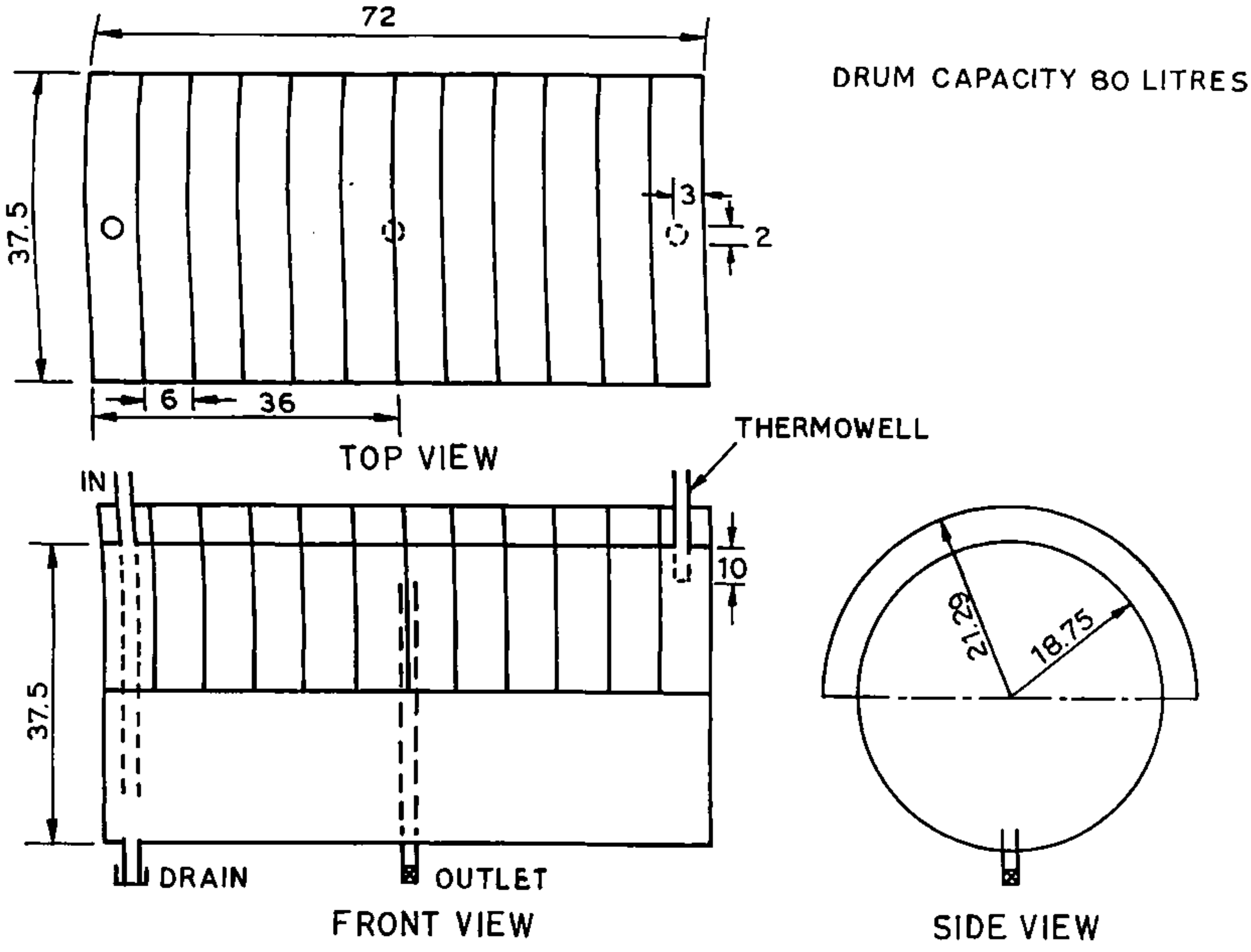


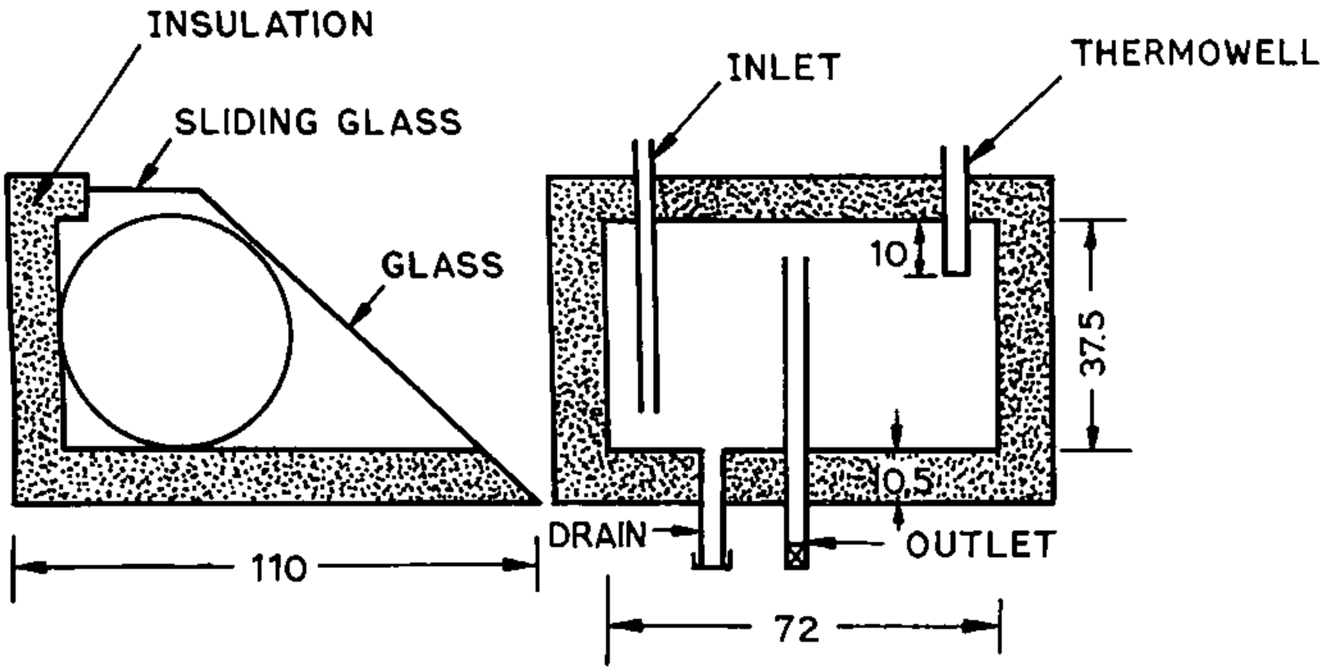
Fig.2.1 APPARENT MOTION OF THE SUN AT PILANI.



DRUM CAPACITY 80 LITRES

ALL DIMENSIONS IN cms

Fig.2.2 FINNED TYPE DRUM HEATER.



ALL DIMENSIONS IN cms

Fig. 2.3(a) SETUP OF DRUM HEATER.

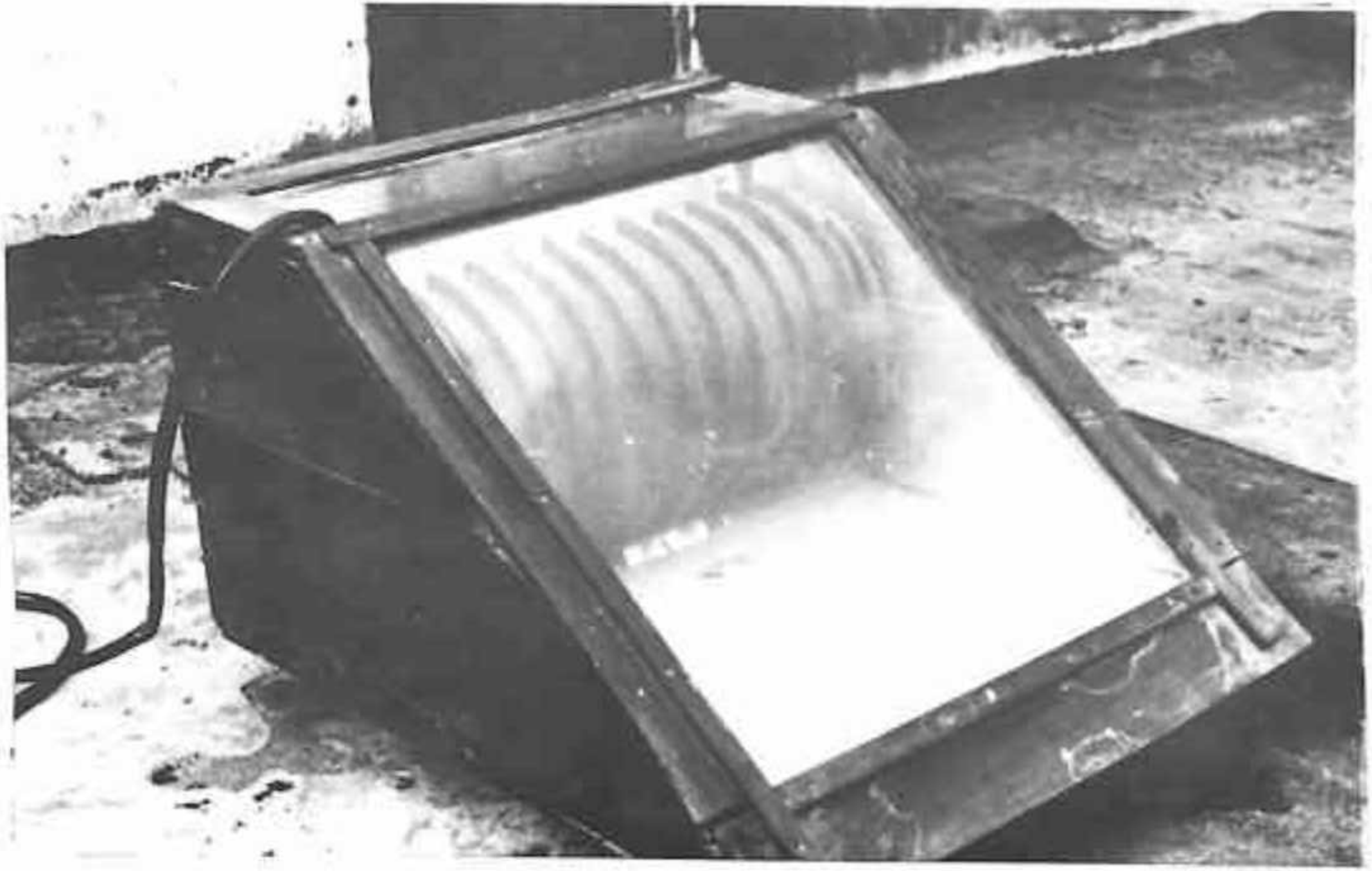


Fig. 2.3(b) Drum Heater.

The two types of drum water heaters that have been developed are:

(a) Finned

(b) Unfinned.

In finned type water heater, mild steel fins are attached in transverse direction on the exposed surface of the drum. All other features of finned heater are same as that of the unfinned one.

Experiments show that the best results are obtained when the drum axis is kept horizontal. The drum is provided with a suitable inlet, outlet, drain and a thermowell for measuring temperatures. It should be noted that the water circuit inside the drum is of displacement type. Specifications of the water heater are given below:

Drum - Capacity 80 litre, length 72 cm, diameter 37.5 cm.

Fins - Semicircular shape with inner radius 18.75 cm, outer radius 21.3 cm, thickness 3 mm.

Glass cover - Horizontal 81.3 cm x 25.4 cm. and inclined 81.3 cm x 82.8 cm

The whole system is oriented such that the inclined glass cover faces the south. This system acts both as collector as well as storage and hence reduces the possibilities of loss of energy through pipe lines. This system requires very less maintenance and suits the needs of both rural as well as urban areas. It attains fairly good temperature, which varies between $20\,^{\circ}C$ to $30\,^{\circ}C$ above ambient depending upon the intensity of solar radiations.

Theory

The energy balance equation on the surface of the cylindrical vessel may be given as,

$$I\,A(\alpha\tau g) = m_w\,S\,(dT_w/dt) + m_p\,C_p\,(dT_p/dt) + A_p\,U_L\,(T_p - T_a) \qquad \ldots.\ (2.1)$$

where

	Parameters	Value of parameters
A	Effective surface area over which solar radiations are incident	$1.30\ m^2$
A_p	Surface area through which heat is lost	$2.60\ m^2$
S	Specific heat of water	$4.179\ KJ/Kg\,^{\circ}C$
C_p	Specific heat of plate material	$0.486\ KJ/Kg\,^{\circ}C$
I	Total beam radiation	$700\ watt/m^2$
m_p	mass of vessel	26.3 Kg
m	Mass of water	314.0 Kg
T_a	Ambient Temperature	$30\,^{\circ}C$
T_{pi}	Initial surface temperature	$30\,^{\circ}C$
T_p	Temperature of surface at any instant ($^{\circ}C$)	
T_w	Temperature of water at any instant($^{\circ}C$)	

	Parameters	Value of parameters
t_i	Initial time (Sec)	
t	Any instant of time (Sec)	
U_L	Overall heat transfer coefficient from surface to ambient (watt/m^2 °C)	8W/m^2 °C
U_∞	Overall heat transfer coefficient from water to ambient	

Assuming that for a short duration the ambient temperature T_a remains steady, and also that surface of the vessel attains quasi-steady state condition so that, the heat loss by the water to ambient is equal to that by plate to ambient, i.e.,

$$U_\infty A_p (T_w - T_a) = U_L A_p (T_p - T_a) \qquad \ldots(2.2)$$

Hence Eq. (2.1) may be modified as,

$$I\,A(\alpha\tau g) + U_L A_p T_a = (m\ S\ (U_L/U_\infty) + m_p C_p)\ (dT_p/dt) + U_L A_p T_p \qquad \ldots(2.3)$$

On solving Eq (2.3) , following expressions for surface temperature of the vessel and water temperature are obtained :

$$T_p(t) = (IA(\alpha\tau g)/U_L A_p) + T_a + \{T_{pi} - T_a - IA\ (\alpha\tau g)/(U_L A_p)\}.\exp\{(t_i - t)\ Y\} \qquad \ldots(2.4)$$

where,

$$Y = (U_L A_p)/(m\ S\ (U_L/U_\infty) + m_p C_p)) \qquad \ldots(2.5)$$

and

1/Y being the time constant;

Also

$$T_w(t) = (U_L/U_\infty)(T_p - T_a) + T_a \qquad \ldots(2.6)$$

After sunset the expression for the surface temperature T_p is given as,

$$T_p = T_a + (T_{pi} - T_a)\{\exp(t_i - t)Y\} \qquad \ldots(2.7)$$

Results and Discussions

Results of some typical numerical calculations made on the basis of the analysis are shown in the graphical form in Fig. 2.4. The graph shows the variation of T_p and T_w with time both during sunshine hours as well as off-sunshine hours. As expected the value of T_p is always greater than T_w and both saturate after sometime during the sunshine hours. However, after sunshine hours these temperatures start decaying and reach the ambient after certain period of time. The theoretical time constant 1/Y can be compared with actual decay or recovery time . The time constant is calculated theoretically as 14 hours.

Comparisons of finned and unfinned type solar water heaters are presented in Fig. 2.5, where,

Curve A : water temperature in unfinned heater.

Curve B : water temperature in finned heater.

Curve C : insolation on horizontal surface.

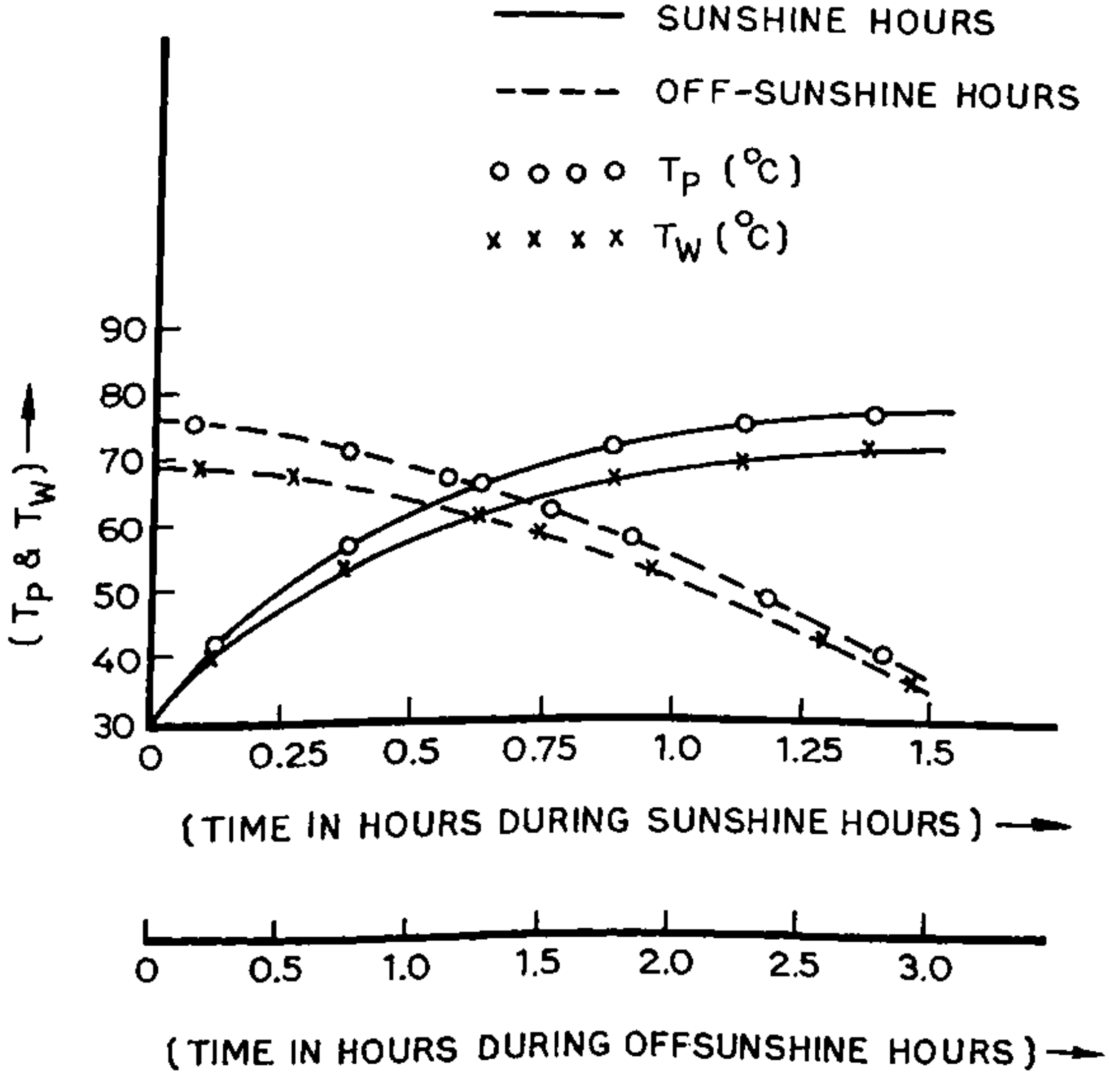


Fig. 2.4 VARIATION OF SURFACE AND WATER TEMPERATURE WITH TIME.

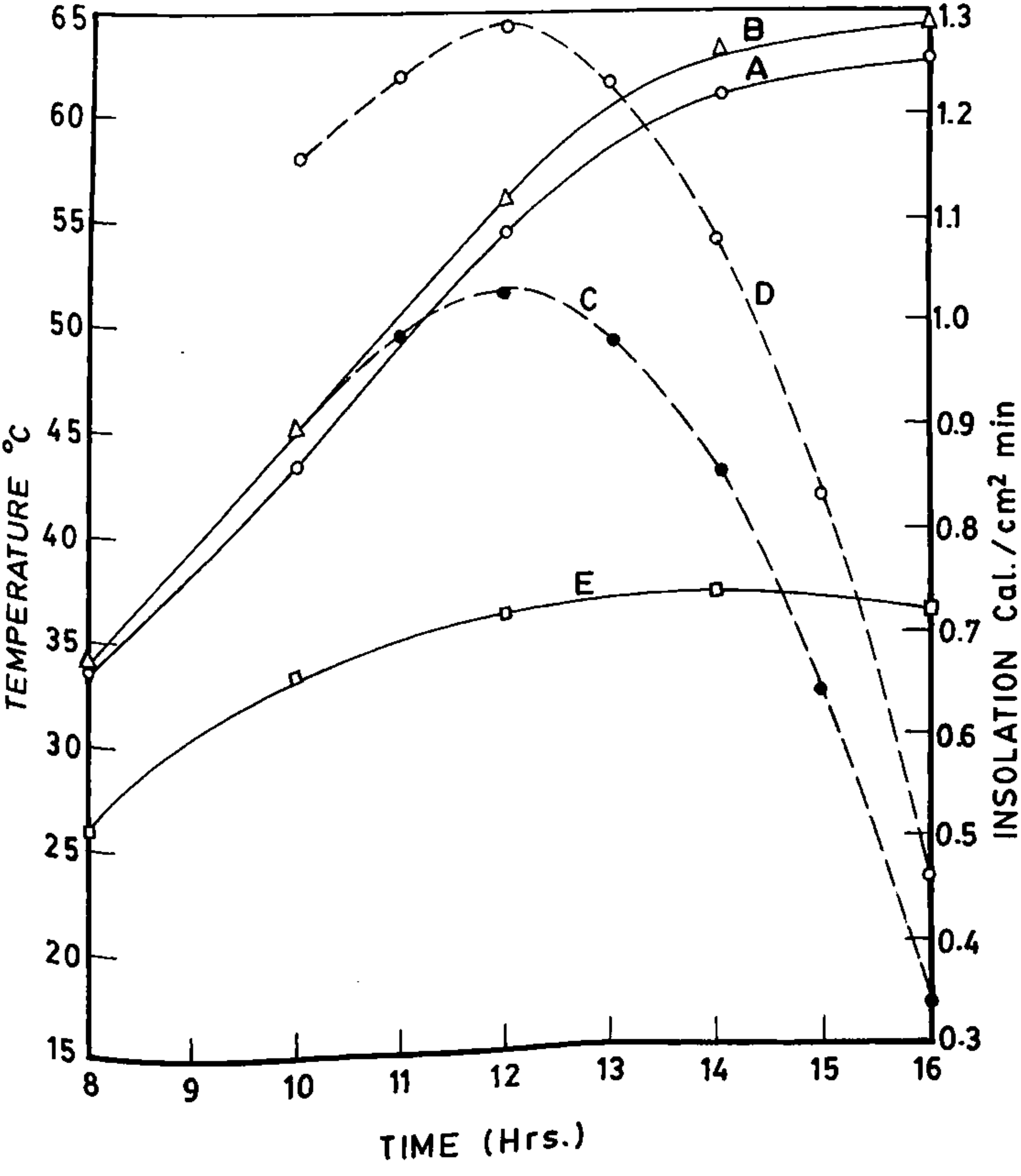


FIG. 2.5 VARIATION OF TEMPERATURE AND INSOLATION WITH TIME.

Curve D : insolation on titled surface (36.44°).

Curve E : the ambient temperature.

From Fig. 2.5 the period efficiency of the system is obtained. Period efficiency η_p is defined as:

$$\eta_p = 100 \; (\epsilon_{out} / \epsilon_{in}) \qquad \text{.... (2.8)}$$

where, ϵ_{in} - mean input energy for the period

ϵ_{out} - mean output energy for the period

ϵ_{in} is given by

$$\epsilon_{in} = I_H + I_T \qquad \text{...(2.9)}$$

where,

I_H = (area under curve C) x Horizontal glass area

I_T = (area under curve D) x Tilted glass area

ϵ_{out} is determined from the relation,

$$Q = m \, S \Delta T \qquad \text{...(2.10)}$$

where, ΔT is the rise in temperature of the water during of the time for which the insolation curves are plotted.

S - the specific heat of water (1 kcal /kg°C)

and m - mass of water.

One should remember that the period efficiency will be meaningful only when the corresponding data within the period are within reasonable limits.

The best and worst performance of the two types of drum water heaters are tabulated (Table 2.1).

TABLE 2.1 Performance of drum water heaters

	Type	Highest Temp. of water (°C)	Ambient Temp. (°C)
Best :	Finned	66	36.1
	Unfinned	64	36.5
Worst:	Finned	56	24.5
	Unfinned	54	24.5

Pay-off period is just about 1 year for both types of heaters, cost being Rs. 1100/- and Rs. 1150/-, respectively. To enhance the life of the drum, the inside surface should be coated with red oxide before welding its lid. From the results it follows that the finned heater is only marginally more efficient as compared to the unfinned one[43]. Both types are quite useful specially in rural areas.

2.2 COIL TYPE SOLAR COLLECTOR

The coil type solar collector[44] consists of a collector box, coil collector and a constant head tank. The details of various components are described below:

The collector box

The collector box is a double - walled wooden box with 7.5 cms. of glass wool separating them. The top of the box has a glass panel to allow the solar radiation to fall inside the box. Two truncated Winston's compound parabolic concentrators are mounted on the east and west sides of the box. The parabolic concentrators are made of strips of glass mirrors, so arranged as to form parabolas. The focii of these concentrators are kept such that the rays reflected by these, cover the entire glass panels. The northern side of the box has a single plane mirror hinged to it. The southern side is kept free (Fig. 2.6).

The Collector

The coil collector is fixed on a plate made up of aluminium with a collecting area of 45 cm x 45 cm. The thickness of the plate is 10 mm.

Since the driving force in a thermosiphon system is only a small density difference and not a pump, larger than normal plumbing fixtures must be used to reduce pipe friction losses. Under no conditions should piping smaller than $\frac{1}{2}$ inch be used. Hence the collector tubing used is 1.25 cm diameter copper tubing of 1.5 mm sheet thickness, wound in a flat coil of 4.7 turns. MAXORB foil covers the entire collector area. The coil collector is kept at an angle of $28\frac{1}{2}^{\circ}$ which is the latitude of Pilani. The water is circulated through the coil by thermosiphoning and stored in a constant head water tank. For the purposes of temperature measurement, iron-constantan thermocouples are fixed to the coil inlet and outlet.

The Constant Head Tank

This tank has a capacity of 12 litres. The tank is

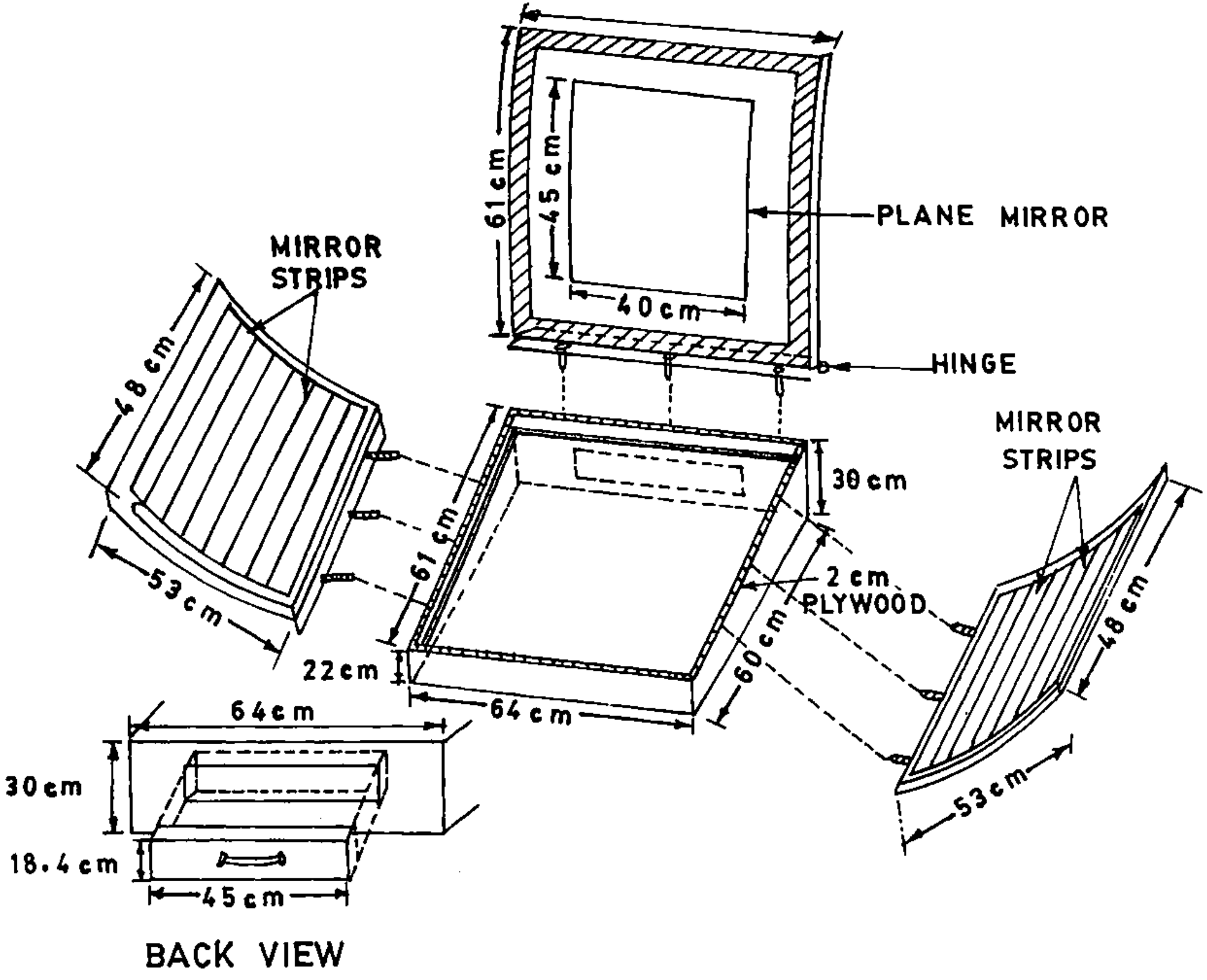


FIG. 2.6 THE COLLECTOR BOX.

double - walled with the inner wall made of copper and the outer wall made of mild steel. Insulation of 4 cm thick glass wool separates the two walls of the tank. An inlet leg and outlet leg are provided at the sides of the tank. These legs are made of copper tubing of the same diameter as that of the coil. The inlet and outlet legs are connected to the two ends of the coil by means of flaring nuts which facilitate easy separation of the tank from the coil. A half-inch diameter tap, stop-cock type, is fixed to the side of the tank. The tank is complete with an inlet for filling fresh water, a drain and a thermo-well. The tank is mounted on a mild - steel stand fitted with 2 rollers.

For proper functioning of the solar water-heater, certain points have to be kept in mind:

(a) The cold water leg has to be located below the hot water leg in the tank. This is to enhance the stratification of the fluid in the tank. The specimen water heater has the hot water inlet 3 cm below the top and the cold water outlet 3 cm from the bottom of the tank.

(b) The fresh water inlet should open into the bottom of the tank.

(c) The tap for drawing out hot water should have its leg commencing from the top of the tank.

(d) After sunset, a thermosiphon system can reverse its flow direction and lose heat to the environment during the night. To avoid reverse flow, the top header of the absorber should be at least 30 cm below the cold leg fitting on the storage tank, as shown in Fig. 2.7.

Hot water removal from the tank is effected by opening the tap and pouring in fresh water through the fresh water inlet. This ensures that the tank has a constant head. Two different views of the coil type solar collector are given in Fig. 2.8.

Problem formulation

For a flat plate collector, the energybalance equation is given by[45]

$$IA\ (\tau\alpha) = m\ S\ (T_o - T_i) + AU\ (T_c - T_a) \qquad \ldots(2.11)$$

where

A = Collector area, m^2

S = Specific heat, KJ/kg^oK

I = Solar insolation, W/m^2

k = Liquid conductivity, W/m^oK

m = Mass flow rate of liquid, kg/s

T_a = Ambient temperature, ^oC

T_c = Coil wall temperature, ^oC

T_i = Temperature of liquid at inlet, ^oC

T_o = Temperature of liquid at outlet, ^oC

U = Overall heat loss coefficient, $W/m^2\ ^oC$

$\tau\alpha$ = Transmittance absorbance product

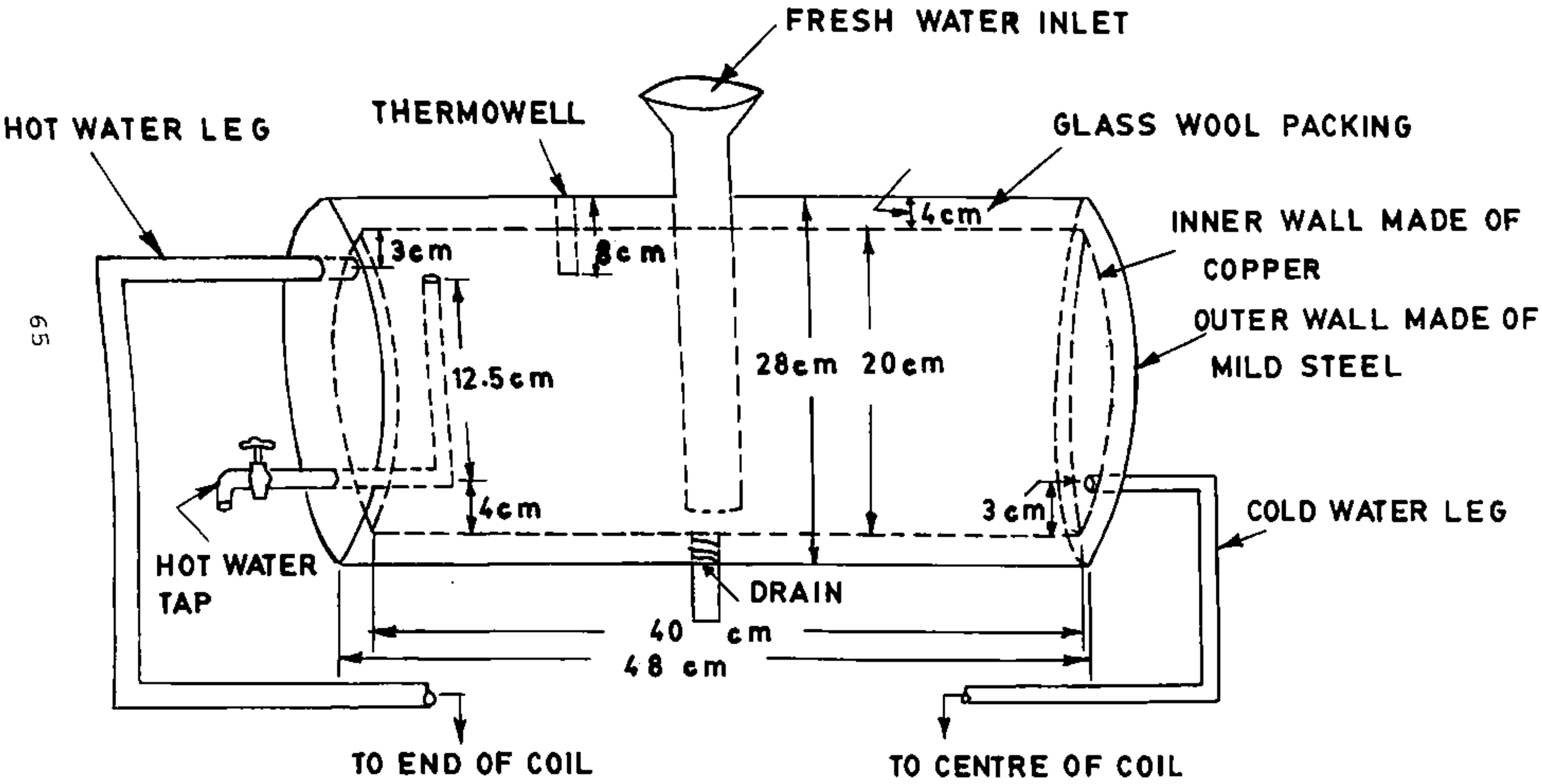
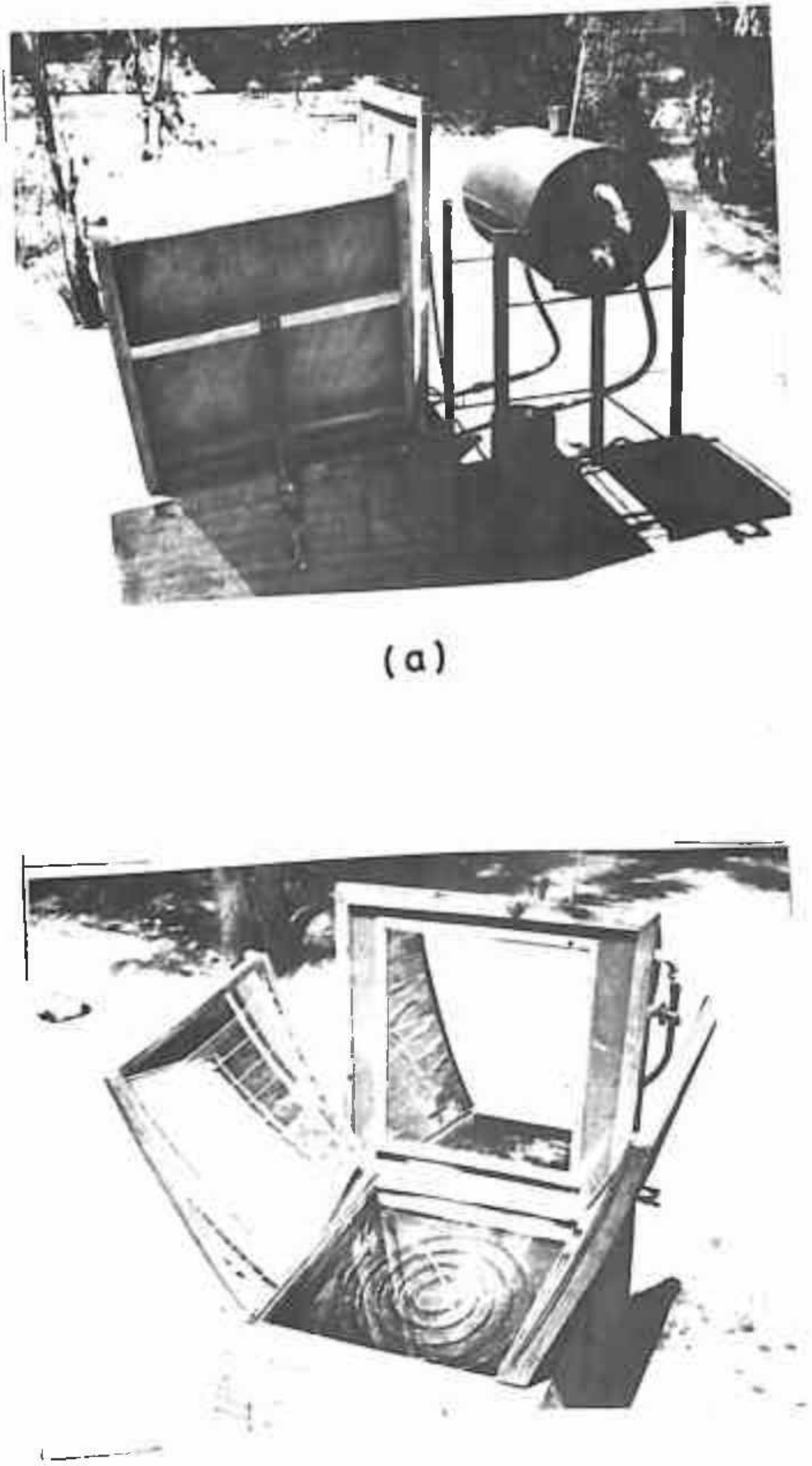


Fig. 2.7 TANK FOR COIL-TYPE SOLAR WATER HEATER.



(a)

(b)

Fig. 2.8 Views of Coil – Type Solar Water Heater.

and the instantaneous efficiency η of the collector expressed as:

$$\eta = \frac{mS\ (T_o - T_i)}{IA} = \tau\alpha - (U/I)\ (T_c - T_a) \qquad \ldots(2.12)$$

Assuming laminar flow in thin circular tubes with constant wall flux Q, the gradient of bulk temperature of[46] the fluid along the direction of flow can be expressed as

$$\frac{dT_b}{dZ} = \frac{2\ Q}{\rho\, S\ RV_{av}} \qquad \ldots(2.13)$$

where Q is the incoming heat i.e., solar radiation falling on the tube which makes dT_b/dZ as positive.

Here

T_b = Liquid bulk temperature, °C

Z = Measure of length of the coil from centre, m

ρ = Liquid density, kg/m^3

R = Tube radius, m

V = Liquid velocity, m/s.

Considering dT_b/dZ to be constant and using other boundary conditions we have,

$$T_c = T_b + (11/24)\ (QR/k) = T_b + (Q/h) \qquad \ldots(2.14)$$

where h = heat transfer coefficient in straight tubes, W/m^2 °C.

From this we can define Nusselts number Nu_D as:

$$Nu_D = 2hR/k = (Q/(T_c - T_b)).\ (2R/k) = (48/11) = 4.36 \qquad \ldots\ (2.15)$$

and is independent of all flow parameters as long as the flow is laminar.

Now considering the case of a coil with n turns and maximum diameter D_c, the above expression for straight tubes is modified[44] as:

$$T_c = T_b + (11/24)\ (QR/k)\ [D_c/(D_c+D_t)]^p \qquad \ldots(2.16)$$

where p is a rational number and D_t is the diameter of the tube which is much smaller compared to the coil diameter D_c. The modified expression, as given by Saksena & Mani[45], is, however, of the form:

$$T_c = T_b + 11/24\ (QR/k)\ (D_c/D_t)^p \qquad \ldots(2.17)$$

Out of these two modified expressions we work with the first one because in the limit $D_c >> D_t$ it reduces to the straight tube case as:

$$D_c/(D_c+D_t)^p \simeq 1^p = 1 \qquad \ldots(2.18)$$

whereas the second expression diverges to

$$(D_c/D_t)^p \longrightarrow \infty \qquad \ldots(2.19)$$

under these conditions.

Taking $D_c >> D_t$ we can simplify Eq. (2.16) to the form

$$T_c = T_b + (11/24)\ (QR/k)\ (1-p(D_t/D_c) \qquad \ldots(2.20)$$

by neglecting $(D_t/D_c)^2$ and higher order terms. This gives

$$p = [(11/24)\ (QR/k)\ (1/(T_c - T_b)) - 1]\ (D_c/D_t) \qquad \ldots.(2.21)$$

To find a suitable value for p, data from Table (2.2) is employed[45].

Table 2.2 Coil Collector Performance Data*

Water Flow Rate (Kg/s)	Insolation (W/m^2), I			T_c (°C)			$Q (W/m^2)$		
	9am	12.30pm	4 pm	9am	12.30pm	4pm	9am	12.30pm	4 pm
0.002	300	900	400	45.3	70	51.6	142.3	427	189.8

* This data is for a 1.25 cm diameter copper coil of 5 turns.

Inlet temperature T_i = 25°C.

For I = 400 W/m^2, we have

$$p = \left[\frac{11}{24}\;\frac{189.8 \times 6.25 \times 10^{-3}}{0.65}\;\frac{1}{20.6} - 1\right]\frac{0.3}{1.25 \times 10^{-2}} \qquad \ldots(2.22)$$

where we have taken

$k = 0.65\ W/m\,^{\circ}K$

$Q = 189.8\ W/m^2$

$D_t = 1.25 \times 10^{-2}\ m$

$D_c = 0.3\ m$

$T_b = 31\,^{\circ}C$

$p = -23.025$ ...(2.23)

Similarly, for I = 300W/m^2 and I = 900W/m^2, the corresponding values of p are -23.104 and -22.75. Thus, a suitable value for p is -23.

For a pancake coil the basic equation is

$$r = a + (\theta/2\pi)\ d \qquad \ldots.(2.24)$$

where

r = radius of the coil

a = initial coil radius

Θ = angle swept by the coil tube, radians

d = centre to centre distance between adjacent turns

Now

$$Q = q \pi D_t l \qquad \ldots(2.25)$$

where q = wall heat flux / unit surface area

l = tube length of coil,

The tube length l can be calculated from the expression

$$l = \int_0^{2n\pi} r\,d\theta = \int_0^{2n\pi} (a+(\Theta/2\pi)d)\,d\Theta = (2a+nd)\pi\, n \qquad \ldots(2.26)$$

where n = number of turns of coil

From Eq. (2.25), $Q = q \pi D_t \times (2a+nd)\pi \times n$ ...(2.27)

Now for n turns of coil, $\Theta = n \times 2\pi$

From eqn. (2.24), $r = a + nd$

$$D_c = 2r = 2(a + nd)$$

$$\frac{D_c}{D_t} = \frac{a + nd}{R} \qquad \ldots(2.28)$$

To maximize T_b in Eq. (2.21) with respect to the number of turns n,

$$\frac{dT_b}{dn} = (-11/24)\,(R/k)\left[\frac{dQ}{dn} \times \frac{1}{(1 + p(D_t/D_c)} + Q\,\frac{d}{dn}\,\frac{1}{1+p\,(D_t/D_c)}\right] = 0 \qquad \ldots(2.29)$$

Now $$\frac{dQ}{dn} = 2q\pi D_t^2 \,(a + nd) \qquad \ldots(2.30)$$

And $$\frac{d}{dn}\;\frac{1}{1+p(D_t/D_c)} = \frac{d}{dn}\;\frac{1}{1+p\,[R/(a+nd)]}$$

$$= \frac{Rpd}{(a+nd+pR)^2} \qquad \ldots(2.31)$$

Substituting Eqs (2.30) and (2.31) in Eq. (2.29) and simplifying,

$$\frac{Rnpd(2a+nd) + 2\,(a+nd+pR)\,(a+nd)^2}{(a+nd+pR)^2} = 0 \qquad \ldots(2.32)$$

That is

$$a\,pRnd + \tfrac{1}{2}Rp\,n^2d^2 + (a+nd+pR)\,(a^2+n^2d^2+2\,and) = 0$$

or

$$n^3d^3 + 3\,[(1/2)\,pR + a]\,n^2d^2 + 3\,a\,(a+pR)\,nd + a^2(a+pR) = 0 \qquad \ldots(2.33)$$

From this equation, it is seen that n depends only on the parameters R, a and d. Using the above equations, the coil collector is designed.

Application

The example given below is the design based on which the specimen solar water heater has been made. Suppose a 1.25 cm. tube is to be used with a = 6R, d = 6R and p = -23, then Eq.(2.33) reduces to

$$6n^3 - 16.5n^2 - 51n - 17 = 0 \qquad \ldots(2.34)$$

For $n = 4$, $f(n) = -101$

$n = 5$, $f(n) = 65.5$

By trial and error, the value of n is found to be 4.69. From Eq. (2.26) and (2.28) we get

$$D_c = 42.7 \text{ cm}, \quad l = 3.7 \text{ m} \qquad \ldots(2.35)$$

Thus for various values of R, a and d, the optimal value of n, the number of turns of the coil, can be determined.

Performance Characteristics

To obtain the efficiency, the solar water heater was kept in the open and its position was altered three times during the day so as to allow maximum solar radiation to fall on the collector. The system was tested from 10:30 AM to 4:45 PM, when solar radiation varied from 640 W/m^2 to 880 W/m^2, ambient temperature from 36 °C to 44 °C, and wind speed from 1 m/s to 5 m/s. The variation of solar insolation with respect to time, and the rise in temperature with time are plotted in Fig. 2.9 and Fig. 2.10. From this data we find that for the interval between 12:00 noon and 1:00 PM the average intensity of solar radiation is 830 W/m^2, and the rise in water temperature is 8.5 °C.

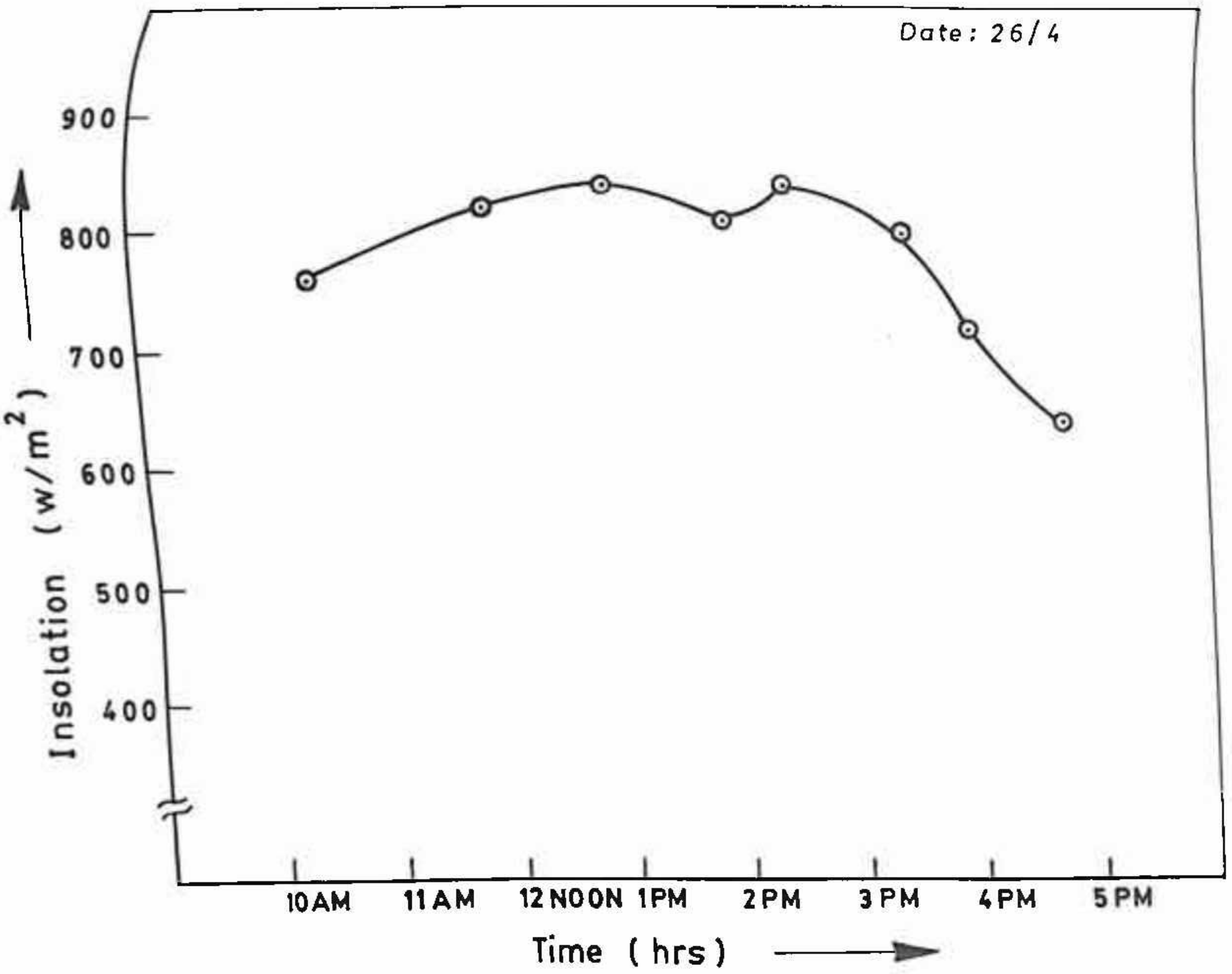


Fig. 2.9 INSOLATION VS TIME.

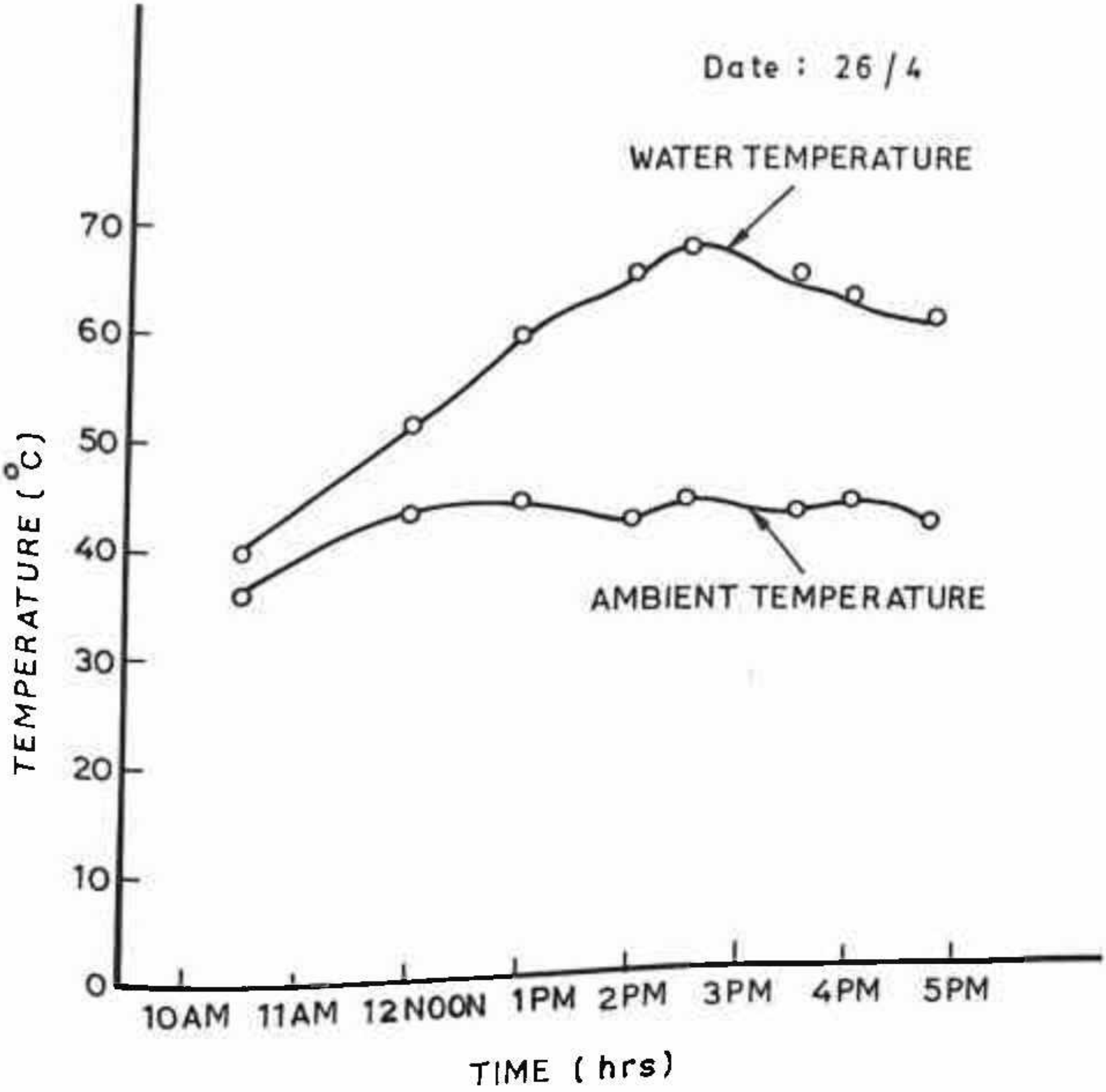


Fig. 2.10 RISE IN TEMPERATURE Vs TIME.

Area of the collector = 45 cm x 45 cm = 0.2 m^2

Volume of water = Vol. of water in tank + Vol. of water in 7.92 m of tube.

$= 0.012\ m^3 + 0.000988\ m^3$

$= 0.013\ m^3$

Mass of this water = 1000 x 0.013 = 13 Kg

$$\text{Efficiency } \eta = \frac{\text{mass of water} \times S \times \Delta T}{I \times A \times t} \quad \ldots(2.36)$$

where S = specific heat of water = 4.2×10^3 J/Kg°C

ΔT = rise in temperature of water in time t.

$$\eta = \frac{13 \times 4.2 \times 10^3 \times 8.5}{830 \times 0.2 \times 60 \times 60} = 0.78$$

So

$= 78\%$ ...(2.37)

Conclusions

This design procedure is based on simple geometry and heat transfer equations and it gives the number of turns of coil required for optimum value of T_b. The limitation of this procedure is that the value of p is based on the set of readings obtained from a single specimen coil collector. A better value of p might be obtained by experimenting on coils of different tube diameters.

The maximum instantaneous efficiency of the solar water heater for a typical summer day is 78%. Heat loss occurs in the inlet and outlet legs of the tank, and through the glass panel. To reduce this, the two legs are insulated with a glass wool covering layer. It is also recommended that a double glass cover should be used over the collector for better retention of heat. Air bleed can be provided on top of the tank to avoid building up of air pressure within the tank.

2.3 SOLAR WATER HEATING SYSTEM AT BITS

A massive project has been undertaken at BITS to supply hot water to the hostels, to the guest house and to the students' messes using solar energy. The system consists of 85 solar water heaters (SWH) of the type shown in Fig. 2.11. Each SWH has six flat plate collectors of 2.11 m x 1.014m size having effective collector area of 1.94 m^2 and an insulated storage tank connected to the collector. It is a thermosyphon system and thus has no pump sets or controls. The entire system was installed by the Rajasthan Energy Development Agency (REDA) and the details are given in Appendix-II. Here we present the following investigations carried out after the system was installed in order to maintain the flat plate collectors and solar water heating systems.

Maintenance of Flat Plate Collectors

Generally every industrial/municipal/domestic water system contains suspended or dissolved minerals, organic matters and dissolved gases acquired from contact with earth,

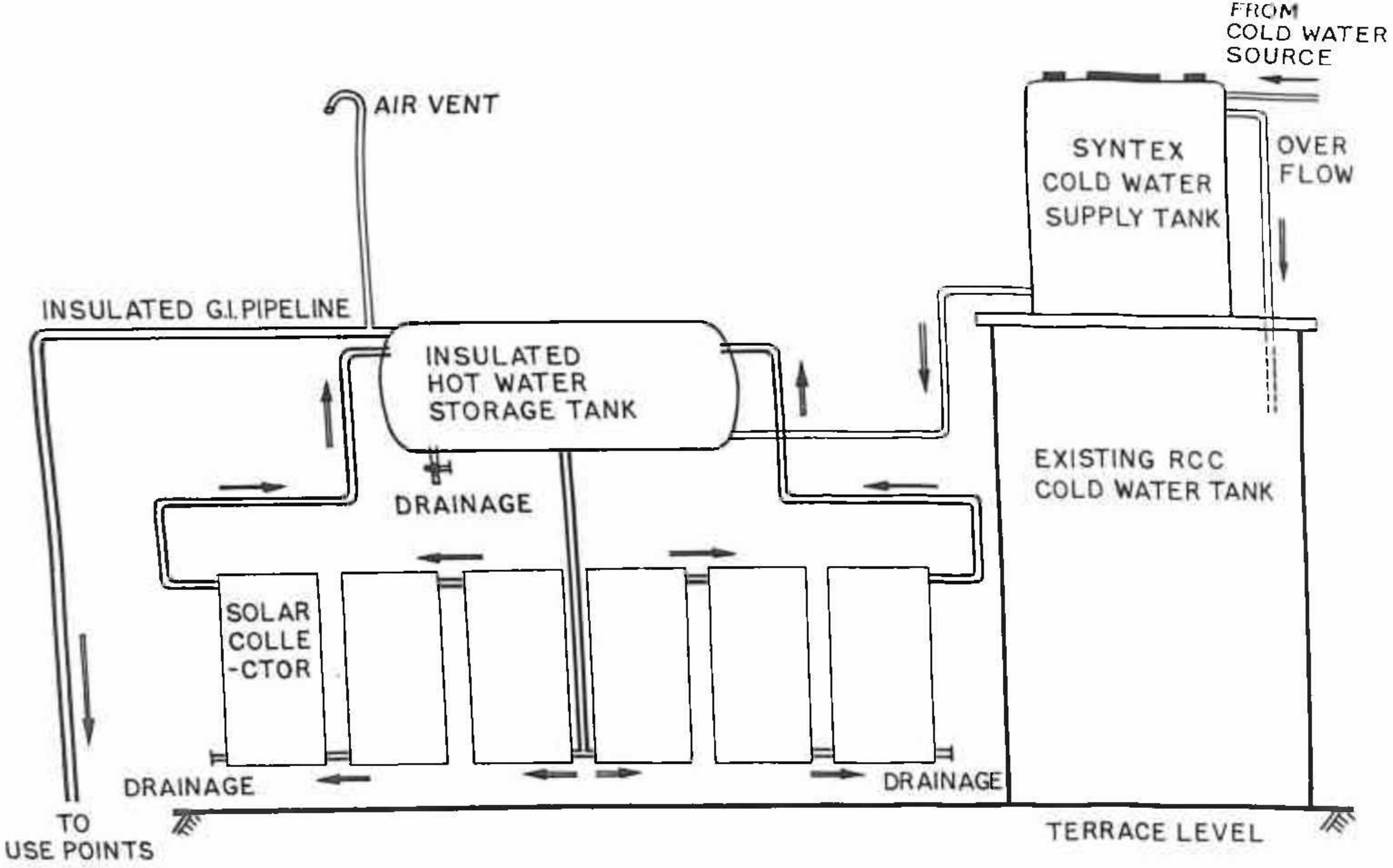


Fig. 2.11 (a) BLOCK DIAGRAM OF SOLAR WATER HEATER AT BITS.

Fig. 2.11(b) Solar Water Heater at BITS.

atmosphere and industrial/municipal waste. As the temperature of water increases, the solubility of some salts reduces, thereby resulting in the beginning of precipitation with sedimentation forming a layer deposited in the collectors/tanks surface. These solid deposits in the pipelines are termed as scales.

The formation of scales results in :

- Flow of water being restricted
- Heat transfer being hindered
- Wastage of energy
- Increased corrosion
- Efficiency of equipment being reduced
- Increased habitat for growth of bacteria and micro-organism
- Increased maintenance costs and
- Shortened life of the system

There are three distinct techniques for the descaling of the system:

(i) Using electromagnetic devices

Many different electromagnetic devices (like Scaletron and Solavite etc.) are being manufactured by different companies which can be installed either in the system or in the main line to eliminate scale formation.

Scaletron is a special metal alloy device in which water is passed in a turbulent state. An electrolytic action changes the supersaturation ratio of the water and ensures that deposits of lime occur only as microscopic particles and do not form hard scales.

Solavite is an electromagnetic device which consists of a catalytic cell that causes neutralization of the bonding process. With this change in their bonding characteristics, the scale producing elements, can no longer adhere to one another or to system's surface.

The following is to be kept in mind while using these devices.

(a) These devices do not change the chemistry of the water i.e., there is no addition/ removal of elements or compounds from the water.

(b) These devices can be installed in the main water line. In this arrangement there is a benefit for the entire house rather than it being just a part of the solar system, which will mean an increased capital outlay for user.

(c) It is noticeable that this device would result in accumulation of soft white deposits/sludge in the storage tank, hence there must be regular draining of the tank.

(ii) Chemical Descaling

There are a number of descaling chemicals available these days. The most suited chemicals for copper flow passages with descaling capability are as given below:

'Scalgun Saf' which removes 80% scale and dissolves 1.5% base metal in 24 hours.

'Scanil 506' which removes 99% scale and dissolves 2% base metal in 24 hours.

General Method of Chemical Cleaning

Two methods of chemical cleaning are possible:

(a) Circulation method

In this method, after filling the unit, the solvent is to be recirculated until cleaning is complete. Samples of the return of solvent are tested periodically during cleaning. The process is considered 'complete' when the acid strength of the returned solvent reaches equilibrium, indicating that no further reaction with the deposits is taking place. Compared with the soaking method, since a solvent of lower strength may be used and the solvent is drained from the unit as soon as the reaction is complete, the possibility of damage to the cleaned surface is less. As the concentration is half of that used for soaking method, the cost may also be similarly low.

The cost of chemical is somewhat less because of the controlled testing of solvent strength. However, this process will involve cost of pump, handling and transport.

(b) Soaking method

Soaking method can be advantageous if only soft scale like carbonate scale is formed. In cleaning by the soaking method, after filling with the solvent the unit is allowed to soak for a period of about twelve hours depending upon the condition of the deposit. To ensure complete removal of deposits, the acid strength of the solvent should be somewhat greater than that required by the actual condition. Unlike the circulation method, testing during the course of the cleaning is not conclusive as samples of solvent drawn from convenient locations may not fully represent conditions in all parts of the unit.

The soaking method is not advisable for routine maintenance in case of SWH systems. Either the SWH systems are small in size and therefore are generally of thermosiphon type or these SWH systems are of large size having pressurised water circulation system. In either case, circulation method is ideally suited, whereas soaking method needs more chemicals,it avoids pump cost and transportation and handling charges.

In both the processes soda wash is necessary at the end. It is usually found that choked collectors are impossible to descale. Attempts made to descale such collectors using the circulation methods might result in damage to piping. The use of soaking method of filling the collector with the chemical may be more effective.

Descaling of thermosiphon systems should usually be undertaken every year as they are more prone to scale deposition due to low fluid velocity.

(iii) Mechanical descaling

This method has been developed and has been used by the author and his group for ensuring proper maintenance of SWH system at BITS. The maintenance of SWH system includes the following:

(a) Weekly clearing of glass cover of the flat plate collectors.

(b) Periodic checking of leakage through joints.

(c) Descaling of the system once a year.

This cleaning method is briefly described here:

Main parts of a collector are risers and headers as shown in Fig. 2.12. The path through which water circulates generally is choked partially or completely due to scale formation. The path is opened (cleaned) through mechanical drilling and vibrations (hammering of risers at various places). While carrying out this process first time holes are drilled through headers using a drill bit of 1/32". A drill bit of 1/4" (6mm) is welded to a steel rod 6 mm diameter and length 2.25 meter. This rod rotates through the riser through and through. Cleaning of riser is done by repeating the drilling and hammering. The drilled holes at header end are

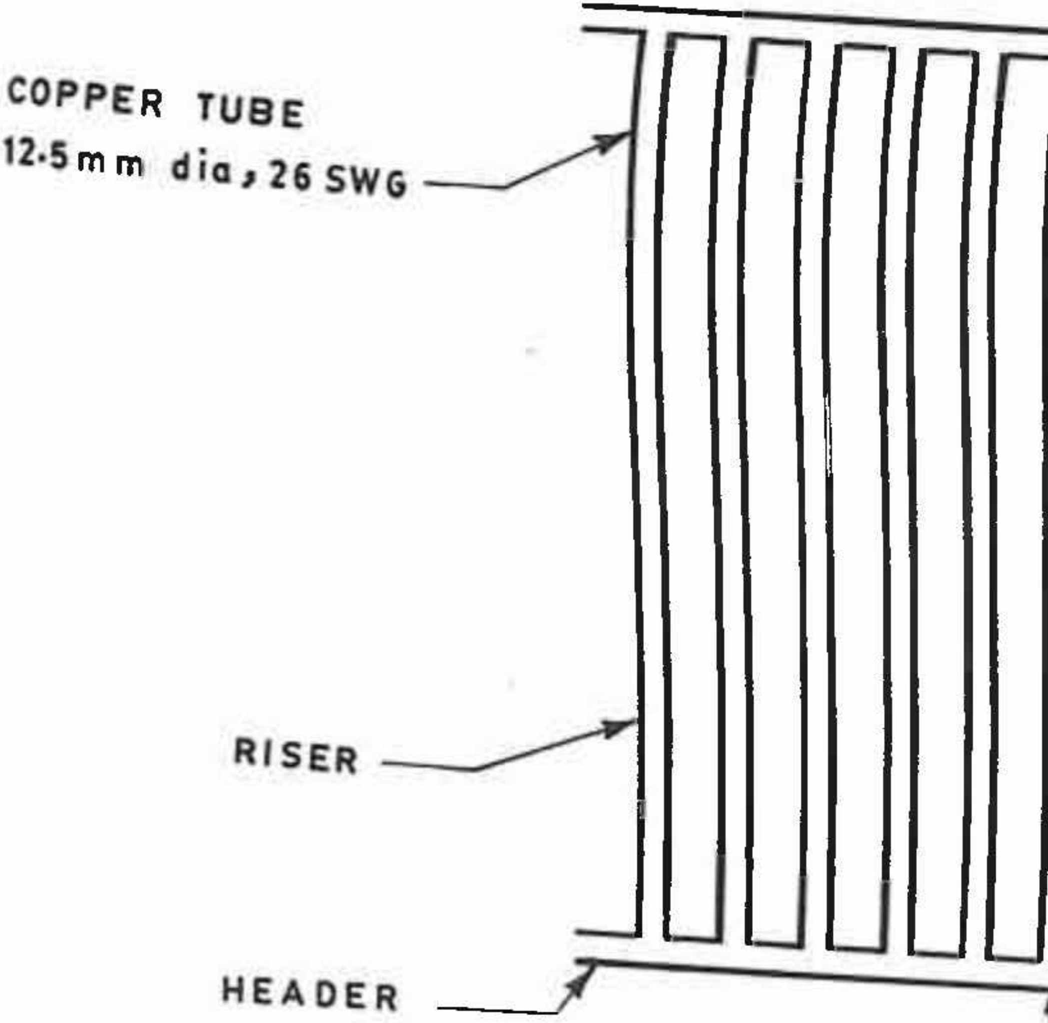


Fig. 2.12 DETAILS OF FLAT

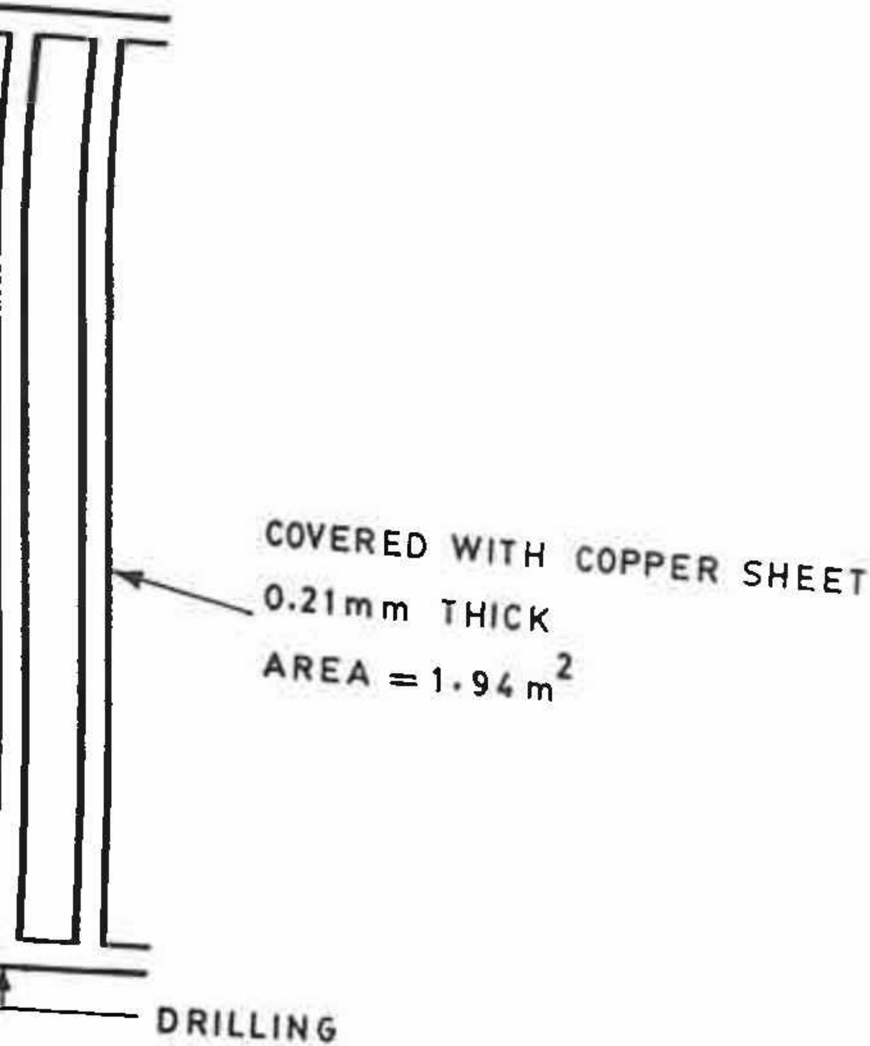


PLATE COLLECTOR.

closed by brazing the copper sheet pieces. Next time whenever cleaning is required it becomes easier to remove braged piece of copper by heating. Thus, there is no need of drilling holes in header again. This method is cheaper as chemicals or electromagnetic devices are not required.

It has been observed that the thermosyphoning system works well through one way valves. Taking a SWH with a capacity of 1000 litres/day as an example, it has been observed that such a system needs 5 persons working for 8 days for fitting and clearing work and therefore the annual maintenance cost of this system works out to be:

Labour cost = 5 x 8 x 50 = Rs. 2000/-
(@ Rs. 50/- per day per person)

Material cost = Rs. 300/- (approx)
(Nuts, bolts, gascuts & welding rod)

Maintenance cost = 2300/-

Capacity of the total SWH system = 53,800 litres
= 54,000 litres (approx.)

Total Maintenance cost = 2300 x 54.00
= Rs. 124200/- ...(2.38)

Therefore, the total annual maintenance cost is Rs. 1,25,000/- approximately.

2.4 SOLAR COOKER

Cooking in India is a major consumer of energy. It can be effectively done by using solar cooker, so that the consumption of conventional fuels is reduced to the extent of nearly one third.

Solar cookers can be broadly classified into two types:

(a) Tracking

(b) Nontracking

Tracking type cookers follow the motion of the sun to give maximum efficiency. Under this type come the cookers using plain mirrors for concentration of energy.

Nontracking type cookers need not follow the motion of the sun, thereby eliminating the need for tracking mechanisms. These cookers use parabolic reflectors for concentration.

There are three basic methods of transfering the energy to the food (a) direct concentration onto utensil containing food (b) concentrating energy into a blackened box, containing the utensil and (c) heating a carrier fluid (oil or water) to a high enough temperature and then circulating it around the utensil containing food.

Of these the second type method has been found to be most popular because of its simplicity in construction and handling. A solar cooker, in general should meet the following requirements:

- It should be possible to manufacture it with local labour and materials so that it is cheap and easily available.

- It should require little or no maintenance except cleaning.
- Its operation should be easy and convenient so that a rural house - wife can use it.
- It should have good insulation and head losses should be minimized.
- It must be rugged, safe and dependable.
- It should achieve a temperature of about 100°C within an hour with food inside.
- It must be able to cook a variety of food stuffs and in a reasonable time.
- It should be as air tight as possible.
- It should have provision for storing heat.
- It should have efficiency preferably in the range of 15 - 20%.

The various existing ways of cooking involve (a) Boiling, (b) Roasting, (c) Frying and, (d) Baking.

Boiling and baking processes require temperatures between 100°C to 110°C while frying and roosting require temperatures between 150°C to 200°C.

It has been estimated that the utilization of energy for heating food, convective losses and vaporization of water during cooking is roughly as follows:

(a) Heating food to boiling temp. - 20%

(b) Convection losses from vessel - 45%

(c) Vaporization of 1/4th water - 35%

So with cookers at medium or low efficiency (10 - 15%) the cooking time will be long (1.5 - 3 hrs). The higher efficiency cookers, though cook faster, tend not only to be costly but also require frequent attention during cooking.

Box type solar cooker

A number of box type solar cookers have been designed and fabricated. The performance studies of these devices have been carried[47-49] out. Here we describe three different designs in some detail.

Design - I

A hot box type solar cooker[47] with boosters has been designed and fabricated as a flexible model to determine the appropriate angles of the tilt for the glass cover and reflectors. The tilt of the top glass cover is appropriately adjusted for seasonal motion of sun and two reflectors placed in the east-west direction in such a way that the entrance aperture of the box cooker is at their absorber position. The design of the parabolic reflectors was based on Winston's CPC type reflectors[21]. A plain mirror was placed on the back surface of the inside of the box (Fig. 2.13) The advantages of this design are:

a. There is no need for diurnal tracking; only seasonal adjustments are required.

b. The efficiency for accepting diffuse light is much larger than for focussing type of collectors.

The design of the reflector can be explained in the following way:

The ideal light collector is a non-imaging reflector that concentrates a divergent beam of light by the maximum amount allowed by phase space conservation. If half-angle of maximum beam divergence is Θ, the maximum permissible concentration, ratio of entrance aperture CD to exit aperture AB (Fig. 2.14) may be shown to be $(CD/AB) = (1/\sin\Theta)$. The reflector is a parabola with focus at the opposite edge of the exit aperture, and axis inclined at an angle Θ with respect to the optical axis OA. At its termination, the tangent to the parabola is parallel to the optic axis. It follows from phase space conservation that the length of the collector is given as $L = \frac{1}{2}(AB + CD) . \cot \Theta$. In this cooker the reflectors are placed in the east-west direction unlike the Winston CPC which are placed in the north-south direction.

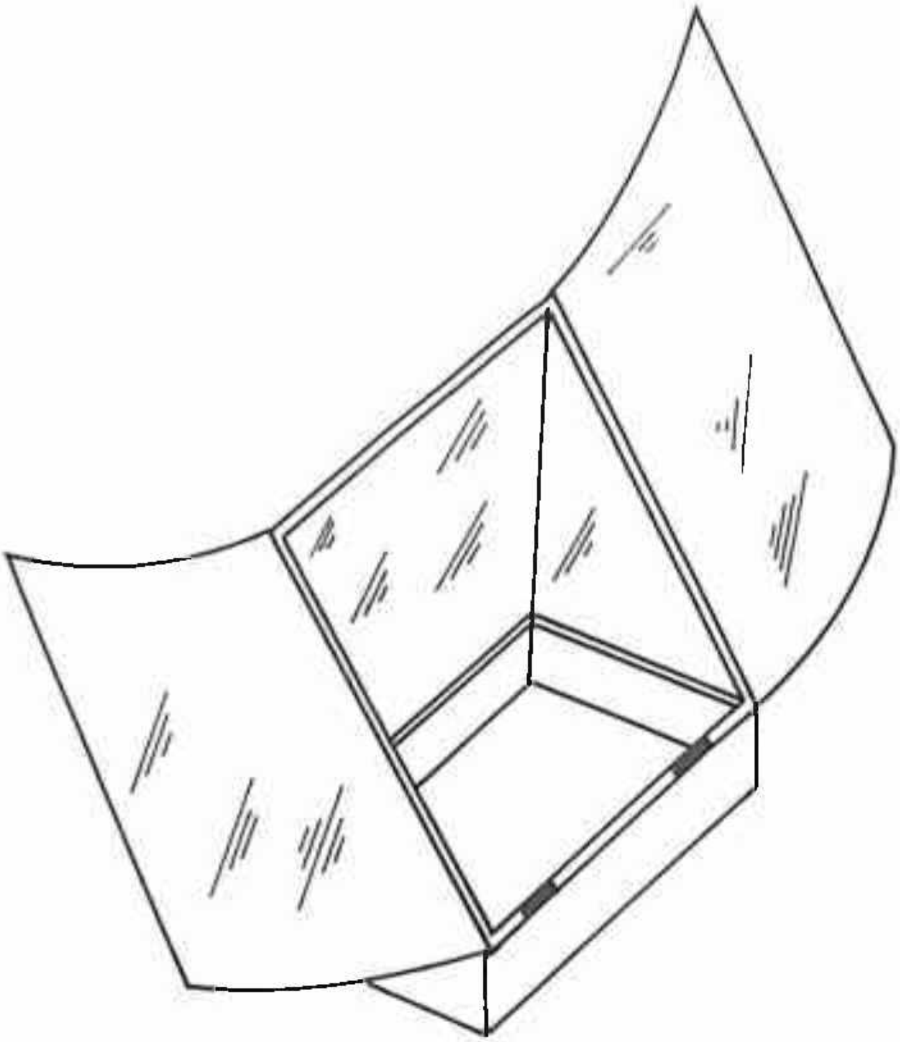


Fig. 2.13 ISOMETRIC VIEW OF THE SOLAR COOKER.

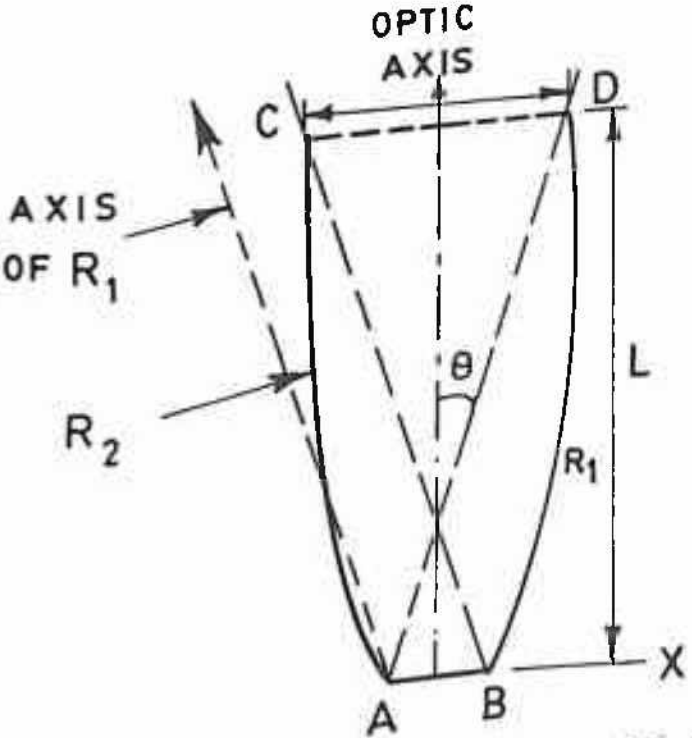


Fig. 2.14 TRANSVERSE SECTION OF WINSTON'S CPC.

The operating period of the solar cooker depends on the half-angle of the maximum beam divergence, Θ. Each degree shift, increases or decreases the operational time by 8 minutes. An operating period of 4 hours corresponds to half-acceptance angle of 30^o.

The full CPC height of the reflector for 30^o half-acceptance angle was found to be about 1.2 m for a 0.45 m base cooker. As this was not convenient for operating, it was truncated to about half this height. The concentration factor for full CPC was 2.00, while for the truncated CPC it was about 1.83, resulting in loss of concentration by 8.5% only. Similar calculations can be easily done for any other half-acceptance angle Θ corresponding to another operating period.

The reflectors are of detachable type, which are screwed to cooker box with the help of butterfly bolts and nuts. By means of this arrangement one can easily handle it and shift it from one place to another. The unique feature of this box cooker is that it has a variable tilt double glazing at the top of the box to collect the maximum solar insulation seasonally. The noon position of the sun at Pilani varies between 5^oS and 52^oS from the vertical during the whole year. Hence the inclination of the collector cover surface is made to vary between 5^o and 52^o. To enable the collector cover to vary, the rear wall is designed to move up and down by means of nuts and bolts arrangement. The rear wall also carries a plain glass mirror, which reflects the sun rays on the tray. The box is made air tight by providing felt lining between the cover and the box.

The triangular portion along the breadth of the box is made to slide with the collector cover for absorbing the normal rays of the sun. The triangular portions are also provided with aluminium foil on the inside to enable any stray rays to be reflected into the tray.

The solar cooker was set-up in the east-west direction with the back mirror wall facing south. The inclination of the collector cover was kept at 5^0 with respect to the horizontal. One thermometer was placed in the cooker tray and the initial temperature noted at about 10.00 AM. Another thermometer was placed in a vessel, outside the cooker box, which contained water. The initial temperature i.e. the ambient temperature was noted. Within half an hour the temperature had increased from 26^{0}C to 62^{0}C inside the cooker. By 12 noon it had reached a temperature of about 84^{0}C, which was maintained till about 2.00 PM. After this there was a steady fall. Since the experiment was conducted in March, the noon position of the sun was almost 28^0 from vertical; so the collector tilt was 28^0 with respect to the horizontal and was facing south so that it could receive the normal solar radiation at noon time.

The temperature steadily increased, in this case, and reached a peak at about 1.30 PM (Fig. 2.15). Between 12.15 PM and 2.45 PM a high temperature above 80^0 centigrade was maintained. The peak temperature reached was $90\,^0C$. The ambient temperature remained a constant of $36\,^0C$ in the period between 12.15 PM and 2.45 PM.

Similar experiments were conducted using rice as the cooking media. About half a kg. of rice was added to the water in the tray, at about 11.30 AM, and rice was cooked in about an hour.

Design - II

A modified version of the above was fabricated incorporating certain changes like decreasing the height of the box, keeping the inclination of glass cover fixed, placing a plain mirror at the back top edge of the box instead of inside, Fig. 2.16.

This cooker[48] has its front side at a height lower than the black side by 8 cm. This difference in front and back heights is kept so that the glass is perpendicular to the solar radiation during summer solistice. It has a single glass cover. The box is made of 1 cm thick wood. The glass wool insulation of 1.5 cm thick is provided between wooden walls of the box and the galvanised iron tray which contains two aluminium boxes to hold the food. Both the tray and the aluminium boxes have been painted black using blackboard

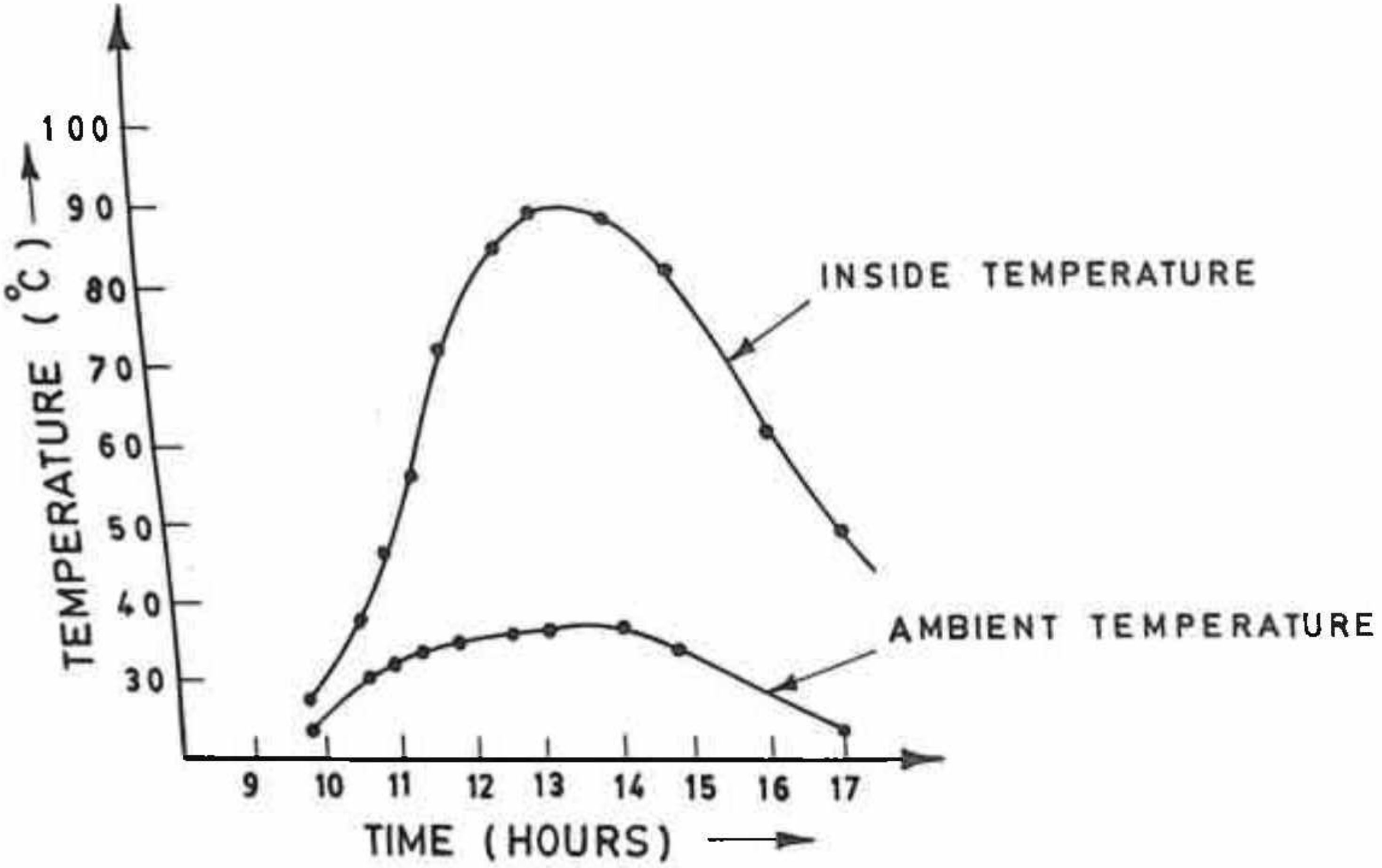


Fig. 2.15 OBSERVATION WHEN COLLECTOR COVER IS TILTED AT 28° FROM HORIZONTAL.

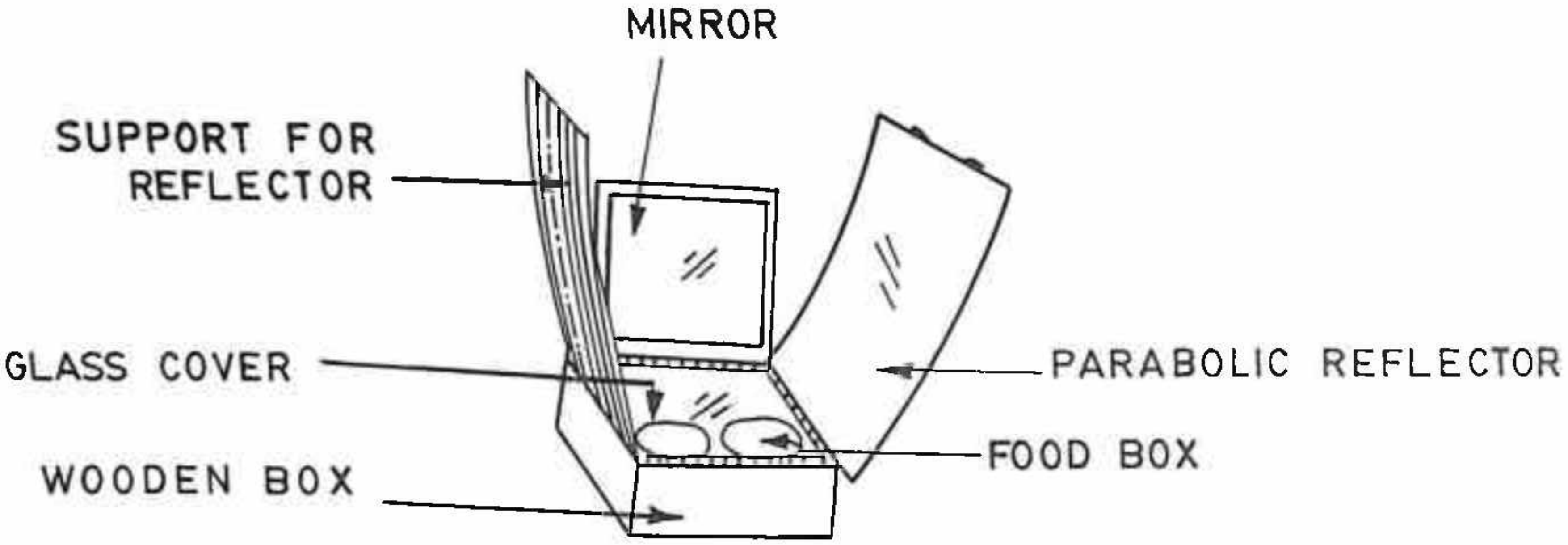


Fig. 2.16 (a) SOLAR BOX COOKER.

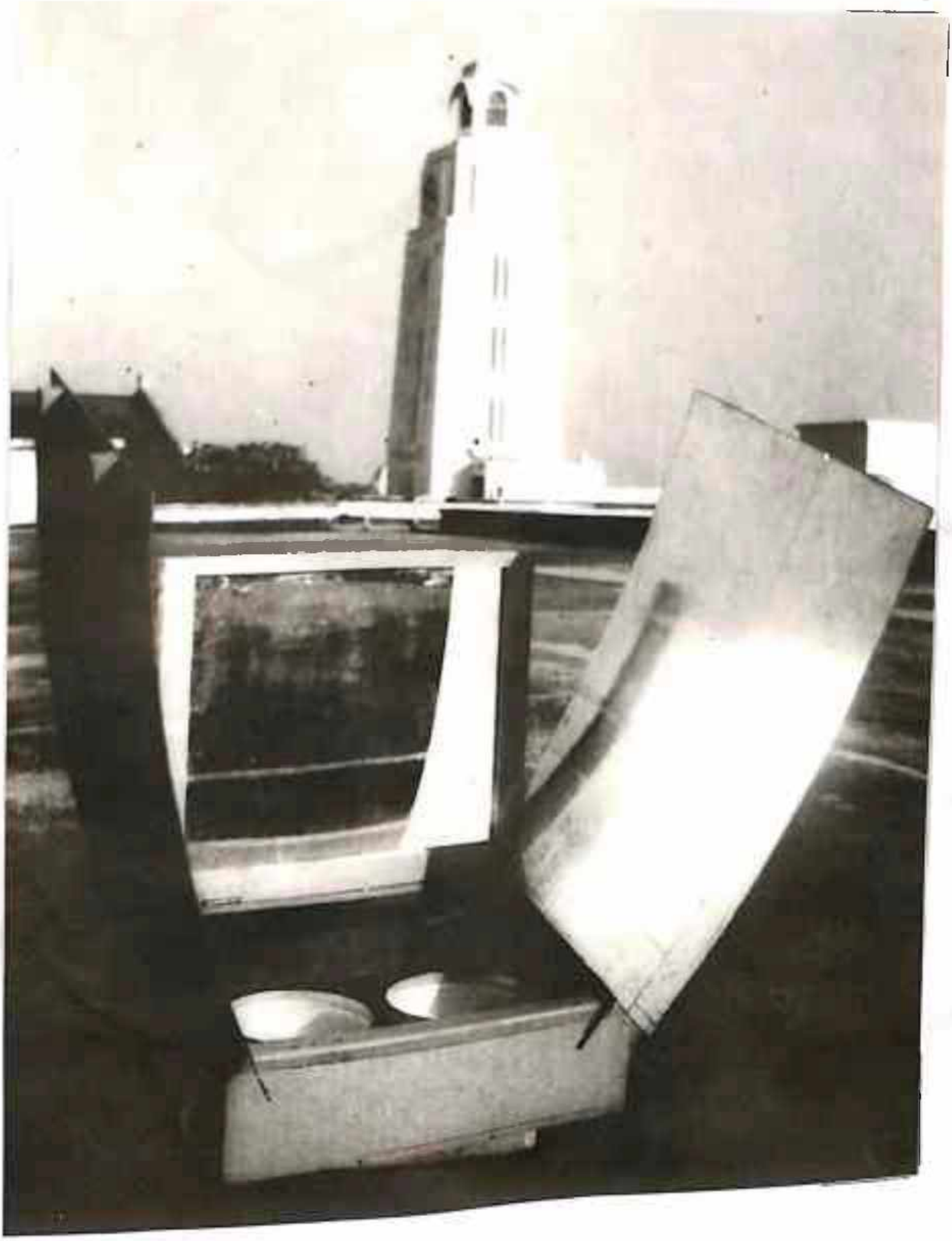


Fig. 2.16(b) Solar Box Cooker.

paint. The twin parabolic reflectors are fixed using fly nuts to the sides of the box. There is also a plain glass mirror attached to the top back edge with hinges (see Table 2.3).

Table 2.3 : Specifications of solar cooker.

Box Base = 32 cm. x 46 cm.

Front height = 12 cm.

Back height = 20 cm.

Glass cover area = 1376 sq. cm.

Specific heat of glass S_g = 840 J/Kg ^{o}C.

Transmittance of glass τ_g = 0.88

Thickness of wood = 1 cm

Thickness of insulation 1.5 cm.

Approx. collection area = 3012 sq. cm.

Concentration factor = 1.4

Tray Base = 24 cm x 39 cm

Height = 6 cm

Thickness = 0.05 cm

Specific heat of tray S_{tr} = 500 J/Kg ^{o}C

absorbitivity of tray α_{tr} = 0.95

Food Boxes

Number of boxes = 2

Diameter = 17 cm

Height = 5.5 cm

Total weight of boxes = 400 gm.

The following experiments were conducted to evaluate the performance of the cooker:

(a) For cooling time constant evaluation, the cooker was placed outside in the sun till it attained the maximum temperature. Then it was carried inside a room and the fall at inside temperature against time was noted. Ambient temperature was also noted.

(b) For heat transfer coefficient determination, the temperature of glass surface, tray temperature, water temperature and the wood surface temperature was noted against time with cooker placed in the sun. Thermocouples were used to measure the temperature. The ambient temperature was noted using a thermometer.

(c) For heating time constant, the cooker was placed in the sun and the variation of inside temperature was noted against time. The ambient temperature was also noted.

(d) For studying the effect of parabolic reflectors on the cooker thereby justifying its utility.

The best indicator of the effect of reflectors would be the heating time constant of the cooker. The tray and ambient temperatures were noted for the following cases (Table 2.4):

Case	Type	Average heating time (min.)
A1	Tracking with parabolic reflectors	57
A2	Tracking without parabolic reflectors	92
B1	Nontracking with parabolic reflectors	85
B2	Nontracking without parabolic reflectors	128

From the time constants above it is quite evident that the parabolic reflectors reduce the heating time very much. It is also evident that a slight amount of tracking does reduce the heating time.

The efficiency of the cooker is quite a good indicator of its performance. The efficiency is defined as

$$\eta = \frac{\text{Rate of heat gain by food}}{\text{Rate of heat input}} \qquad \ldots(2.39)$$

and comes out to be:

$$\eta = 11.2\% \qquad \ldots(2.40)$$

This gives us a cheap and easy-to-handle model with reasonable efficiency.

To get an idea of the heat storage capability of the cooker, the cooling time constant was determined. For this the cooker was allowed to attain the maximum temperature and then was brought inside a room. The fall of temperature

Table 2.4. Relative performance of solar cookers.

Case Date	A1 14/9		A2 15/9		B1 12/10		B2 15/10	
Time (hrs.)	Amb. Temp °C	Tray-Amb. Temp °C	Amb. Temp °C	Tray-Amb. Temp °C	Amb. Temp °C	Tray-Amb. Temp °C	Amb. Temp °C	Tray-Amb. Temp °C
9.30	34.0	4.0	29.0	11.0	25.2	4.8	22.6	7.4
10.00	34.4	39.6	31.0	25.0	26.2	11.8	24.0	8.0
10.30	35.0	49.0	31.4	44.6	27.0	29.0	27.0	8.6
11.0	35.8	60.2*	33.2	50.8	27.2	52.8	28.8	15.2
11.30	37.2	50.8	35.2	56.8	28.0	64.0	29.0	29.0
12.00	38.0	46.0	35.6	58.4	28.4	71.6 *	28.4	35.6*
13.00	38.2	47.8	36.0	56.0	28.8	73.2	28.8	63.2
13.30	38.6	41.4	36.4	57.6	29.0	71.0	28.8	65.2*
14.00	38.0	34.0	37.2	56.8	30.2	57.8	30.0	64.0
14.30	38.2	11.8	36.0	54.0	30.0	46.0	30.0	60.0
15.00	38.2	5.8	36.0	50.0	28.2	37.8	29.8	52.2
15.30	37.4	4.6	35.8	44.2	28.2	33.8	30.0	46.0
16.00	37.0	5.0	35.8	40.2	28.0	28.0	29.6	40.4
16.30	36.0	4.0	35.8	36.2	28.2	21.8	29.8	36.2

* Maximum difference from ambient

against time was noted (Table 2.5). From this data the cooling time constant was determined.

$$\tau \text{ (Cooling)} = 60 \text{ min.} \qquad \ldots(2.41)$$

Table 2.5. Cooling time constant.

Date: 30/8

TIME hr min	TEMP ^0C AMB.	TRAY
12.20	33.0	102
12.22		100
12.24		96
12.26		90
12.29	32.8	86
12.32		82
12.36		78
12.42		74
12.48		70
12.52	32.6	68
12.58		64
01.08		60
01.17		56
01.27	32.6	52
01.37		50

This is quite satisfactory and can be improved if the back plain mirror is brought down so as to close on to the glass cover.

With an idea of improving the heat storage capability an experiment was carried out using blackened stones to serve as a heat storage element. In this experiment small stones ranging from 0.5 cm. to 4 cm. diameter were blackened using black board paint. These stones were then packed properly in the tray around the food boxes. The heating and cooling time constant for the above modification were determined (Table 2.6) to be:

Heating time constant = 90 min. ...(2.42)
Cooling time constant = 140 min. ...(2.43)

It can be seen that even though there is not much increase in the heating time constant, the cooling time constant has increased tremendously.

Effect of tracking

From the heating time constants for both tracking and nontracking modes it is evident that the difference is not much (about 20 min. only). This small increase in time can be tolerated, because for the advantage gained in terms of

Table 2.6(a) Heating Time Constant with blackened stones.

18/11

TIME	TEMP. ^0C		ENERGY (MW/cm^2)
hr. min.	AMB.	TRAY	
10.00	22.6	32	82
10.15	23.8	46	84
10.30	25.2	50	86
10.45	27.0	58	90
11.00	27.6	62	92
11.15	28.2	68	94
11.30	29.4	74	100
11.45	30.6	80	100
12.00	31.0	84	102
12.15	30.6	88	100
12.30	31.2	92	100
12.45	32.8	94	100
1.00	31.2	96	100
1.15*	32.2	96	96
1.30	32.4	90	96
1.45	32.2	92	96

* Tray was opened for 2.5 min. to see its effect on the tray temperature.

Table 2.6(b). Cooling Time Constant with blackened stones

Date : 18/11

TIME hr min	TEMP. °C AMB.	 TRAY
1.46	26.4	92
1.48		88
1.52		84
1.57		80
2.04		76
2.12		72
2.21		68
2.32		64
2.44	26.4	60
2.58		56
3.14		52
3.30		48
3.55		44
4.20	26.4	42

nontracking is much more. Once the food is kept it requires no further attention. Of course where time is important one can take the trouble of tracking it once in a while. It will not require more than two or three changes in orientations during the whole day.

Theory

Starting from the basic energy balance equations, the expression for tray temperature is obtained. The basic energy balance equations are:

For tray

$$m_{tr} s_{tr} \frac{dT_{tr}}{dt} = I C A_g \tau_g \alpha_{tr} - A_g U_1 (T_{tr} - T_g) \quad \ldots(2.44)$$

For glass

$$m_g s_g \frac{U_L}{U_2} \frac{dT_g}{dt} = A_g U_1 (T_{tr} - T_g) - U_2 A_g (T_g - T_a) \quad \ldots(2.45)$$

where $U_L = U_1 U_2/(U_1 + U_2)$ is the overall heat transfer coefficient and

$U_1 = h_c + h_r$ (heat transfer coeff. from tray to glass)
$U_2 = h_w + h_r$ (heat transfer coeff. from glass to ambient)
h_c = heat transfer coeff. for convection
h_w = heat transfer coeff. for wind
h_r = heat transfer coeff. for radiation
T_{tr}, T_g = Temp. of tray and glass
s_{tr}, s_g = specific heat of tray and glass
I = Insolation incident on the glasscover
m_{tr}, m_g = Specific heat of tray and glass
A_g = area of glass,
C = concentration factor,
τ_g = Transmittance of glass
α_{tr} = Absorbitivity of tray.

Starting from those equations it can be shown that the tray temperature equation comes out to be:

$$T_{tr} = (T_{amb} + (S/U_L)) - (S/U_L)\, e^{-tY}$$

where $S = IC\, A_g\, \tau_g\, \alpha_{tr}$

and the time constant is :

$$1/Y = \left[m_g\, s_g\, (U_L/U_2) + m_{tr}\, s_{tr} \right] / A_g U_L \qquad \ldots(2.46)$$

In order to evaluate the heat transfer coefficients U_1 and U_2 an experiment was conducted. The temperatures of water, tray, glass were noted. The temperature of the outside wood surface was also noted to get an idea of the losses through the sides. Thermocouples of copper constantan were used to sense the temperatures and a Honeywell potentiometer was used to read the temperature. From this data and (see Table 2.7) using standard methods, the values of the heat transfer coefficients h_c, h_r and h_w were determined as follows:

$h_c = 1.9\ W/m^2\ {}^oK$

$h_w = 24.9\ W/m^2\ {}^oK$

and h_r came out be very very small as compared to h_c and h_w and so was neglected.

So $U_1 = 1.9\ W/m^2\ {}^oK$

$U_2 = 24.9\ W/m^2\ {}^oK$

and $U_L = 1.765\ W/m^2\ {}^oK$

Table 2.7. Evaluation of heat transfer cofficient

Date : 15/8

TIME (min.)	AMB.	TRAY	OIL	GLASS	WOOD	ENERGY (mW/cm^2)
	Temperature °C					
0	31.4	31.4	39.4	42.4	42.4	74
15	31.5	42.2	47.5	51.5	51.5	80
20	31.6	52.6	50.6	55.6	58.6	80
30	32.0	59.0	58.0	58.0	58.0	80
40	32.0	67.0	61.0	63.0	63.0	82
50	33.0	78.0	73.0	73.0	73.0	86
70	34.0	85.0	80.0	84.0	77.0	88
80	34.2	86.2	100.2	85.2	79.2	88
100	34.4	86.4	106.4	86.4	79.4	90
110	35.0	89.0	108.0	88.0	80.0	90
130	35.4	95.4	108.4	90.4	82.4	96
150	36.0	89.0	111.0	92.0	62.0	96
170	36.4	90.4	118.4	88.4	62.4	100
275	35.0	93.0	112.0	88.0	74.0	92
275	38.4	87.4	107.4	89.4	82.4	98
295	37.2	70.2	103.2	83.2	67.2	88
315	37.2	70.2	101.2	76.2	67.2	88
335	37.2	60.2	99.2	71.2	60.2	80

Design - III

Another box type solar cooker was designed and fabricated incorporating the following modifications[49] :

(i) To achieve better reflectivity, mirror strips were put on the two parabolic reflectors.

(ii) For keeping or taking out the utensil there was drawer type of arrangement and this was causing enormous heat losses so the drawer type of arrangement was changed to flapping door arrangement to keep or remove the cooking utensils.

With these modifications, observations have been taken in box type solar cooker. This box type solar cooker with reflectors can work for two hours without tracking. First the solar cooker is kept facing the sun in such a way that the indicator shows that sun beam is symmetrical with respect to two reflectors. When the temperature of the cooker rises to 90°C - 100°C , the cooking vessels (black coated aluminium boxes) are kept inside the box. Depending upon the food material the cooking time may vary. The chart in Table 2.8 gives cooking time of various food materials. The general performance of the box type solar cooker is studied by

Table 2.8. Food material cooked and the corresponding cooking time

Food Cooked	Time Taken (hrs.)
Rice	1
Masoor Ki dal	1
Potato	$1\frac{1}{2}$
Mung Ki dal	1
Palak	1
Brinjal	1
Gheeya	$1\frac{1}{2}$
Tinda	1
Khichari	1

keeping solar cooker box in the sun throughout the day so that the solar radiations falls directly on the the glass surface and the cooker requires only three independent positions throughout the day. The inside temperature of the solar cooker, the atmospheric temperature as well as the intensity of solar radition are recorded throughout the operating period of the cooker. The data observed are recorded in Table 2.9. The variation of above data for a typical day is given in Table 2.10 and is shown in Fig. 2.17.

Table 2.9.

Date	11/2 Temp(°C)		20/2		8/3		29/3	
Time (hrs.)	Amb.	Tray-Amb.	Amb.	Tray-Amb.	Amb.	Tray-Amb.	Amb.	Tray-Amb.
9.30	25.2	4.8	23.6	8.4	-	-	35.0	27.0
10.00	26.2	11.8	24.0	16.0	30.0	0.0	35.5	56.5
10.30	27.0	29.0	25.2	36.8	30.5	4.5	40.0	68.0*
11.00	27.2	52.8	26.2	49.8	31.0	14.0	43.0	47.0
11.30	28.0	64.0	26.8	57.2	33.5	41.5	43.0	53.0
12.00	28.4	71.6	27.6	64.4	33.5	60.5	44.0	56.0
12.30	-	-	-	-	35.0	65.0 *	44.0	66.0
13.00	28.8	73.2*	28.6	71.4	35.0	55.0	-	-
13.30	29.0	71.0	28.2	71.8*	-	-	-	-
14.00	30.2	57.8	27.4	66.6	34.5	45.5	43.5	57.0
14.30	30.0	46.0	26.8	49.2	34.5	45.5	43.0	53.0
15.00	28.2	37.8	26.4	37.6	34.5	45.5	42.0	48.0
15.30	28.0	33.8	26.4	35.6	34.0	42.0	41.5	38.5
16.00	28.0	28.0	26.2	33.8	32.0	42.0	40.0	35.0
16.30	28.2	21.8	26.2	29.8	30.0	40.0	35.0	35.0

* Maximum difference from ambient

Table 2.10. Cooling time constant

Date : 7/4

Time hrs. min.	Amb. Temp °C	Tray	Energy (mW/CM^2)
9.00	30.5	60	60
9.15	30.5	70	64
9.30	31.5	78	68
9.45	33.5	82	70
10.0	33.5	88	68
10.15	31.5	96	74
10.30	35.5	98	74
10.45	35.0	98	80
11.00	35.5	100	82
11.15	36.5	100	82
11.30	37.0	100	88
11.45	38.5	76	80
12.00	38.0	62	84
12.15	40.0	56	85
12.30	40.0	46	86
12.45	40.0	36	88

To get an idea of the heat storage capability of the cooker, the cooling time constant is determined. For this purpose the cooker was allowed to attain the maximum temperature and then was brought inside a room. The fall of temperature against

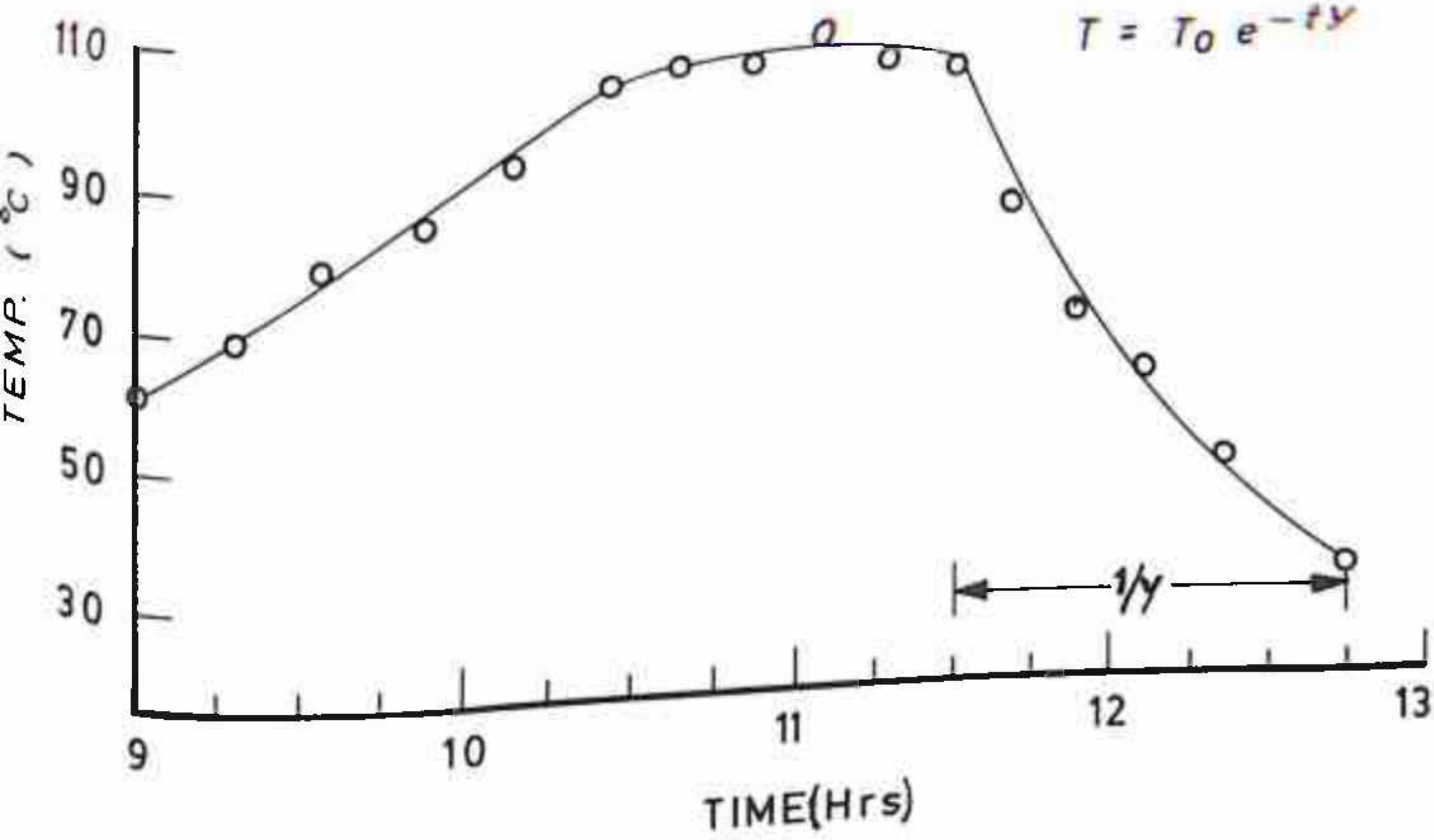

Date: 7/4

Fig. 2.17 TEMPERATURE V/S TIME CURVE.

time was noted (see Table 2.10). From this data the cooling time constant was determined.

$T = T_o e^{-t\gamma}$ where T_o is the maximum temperature (see Fig. 2.5). Here T_o is 100°C. When $t = 1/\gamma$ where $1/\gamma$ is the time constant then $T = T_o e^{-1} = 36.9 \simeq 37^{\circ}C$

Using this value of $T = 37^{\circ}C$, cooling time constant is found to be 75 minutes. This heat storage capability of the cooker is quite satisfactory. The heating time constant depends upon the atmospheric temperature and in general on weather conditions. The temperature rise of the empty cooker box is linear with time i.e. it does not follow exponential curve as that of cooling process. It has been observed experimentally that the heating time constant varies from half an hour to one hour (See Table 2.9).

The cooking efficiency of the cooker η is quite a good indicator of its performance. The conversion efficiency of the solar cooker can be expressed as

$$\eta = \frac{\text{(thermal capacity of the aluminium box + water) x rise in temp.}}{\text{Solar insolation during the period x area of the entrance aperture of box.}} \quad \ldots(2.47)$$

From the experimental data (Table 2.11) the efficiency is calculated to be 42.89%

TABLE 2.11

Date: 27/2

Time Hrs.Min.	Amb.	Temp.^{0}C Tray	Energy (mW/cm^2)
10.00	29	30	50
10.30	30	70	60
11.00	31	90	70
11.30	30	80	60
12.00	29	67	50
12.30	29	75	60
13.00	29	75	70
14.00	29	75	70
14.30	29	74	60
15.00	29	75	60
15.30	29	74	60

Date: 5/4

Time Hrs. Min	Amb.	Temp.^{0}C Tray	Energy (mW/cm^2)
11.00	33	32	96
11.15	34	59	96
11.30	34	87	88
11.45	36	97	104
12.00	36	97	104
12.15	36	92	108
12.30	36	84	110
		114	

TABLE 2.11

Date: 27/2

Time	Amb.	Tray	Energy (mW/cm^2)
Hrs.Min.	Temp °C		
10.00	29	30	50
10.30	30	70	60
11.00	31	90	70
11.30	30	80	60
12.00	29	67	50
12.30	29	75	60
13.00	29	75	70
14.00	29	75	70
14.30	29	74	60
15.00	29	75	60
15.30	29	74	60

Date: 5/4

Time	Amb.	Tray	Energy (mW/cm^2)
Hrs. Min	Temp °C		
11.00	33	32	96
11.15	34	59	96
11.30	34	87	88
11.45	36	97	104
12.00	36	97	104
12.15	36	92	108
12.30	36	84	110

Date: 29/3

Time	Amb.	Tray	Energy (mW/cm^2)
Hrs. Min	Temp °C		
9.30	35	43	56
9.45	35	70	60
10.00	36	87	64
10.30	40	89	74
11.00	43	65	78
11.30	43	97	82
12.00	44	96	92
12.30	44	104	100
14.00	43	82	72
14.30	43	90	82
15.00	42	74	58
15.30	42	67	45
16.00	40	60	40
16.30	35	57	37

2.5 PARABOLOID SOLAR COOKER

The reflecting surfaces of paraboloid cooker are made of aluminium sheet which acts as a reflector. The diameter of the paraboloid is chosen to be 100 cm and the depth is 25 cm. The upper rim perimeter is divided into convenient number of divisions which is chosen to be 16 here. Thus 16 triangular strips of an aluminium sheet are cut. The shape of the above strip is calculated in the following way:

(i) The parabola of 25 cm. focal length is drawn Fig. 2.18(a), from the equation $y^2 = 4ax$, a being 25 cm.

(ii) From Fig. 2.18(a) at each value of x, curve length l as well as fraction of perimeter b i.e., $\frac{1}{2} \times 2\pi y \times 1/16$ is calculated.

(iii) The shape of the strip of aluminium is found out by plotting l verses b for each value of x (Fig. 2.18(b)

First the paraboloid is placed facing the sun in such a way that it gives the maximum temperature at the focus. The utensil is painted black and it is kept with an air tight cover. The utensil is then kept at the focus, Fig. 2.18(c). Initial temperature is noted. It takes one hour to one and a half hours to cook the food. The final temperature is also noted.

In this cooker the temperature rises very quickly and also falls very quickly i.e., the heating and cooling time constants are appreciably less as compared to box type solar cooker. But the main problem of this design is in its focusing i.e., it takes sometime to focus it properly and once it is focussed properly it gives sufficient temperature for cooking. The rise in temperature of the solar cooker, the atmospheric temperature as well as intensity of solar radiations are recorded through out the operating period of the cooker. Cooking time for various food materials using this cooker is given in Table 2.12.

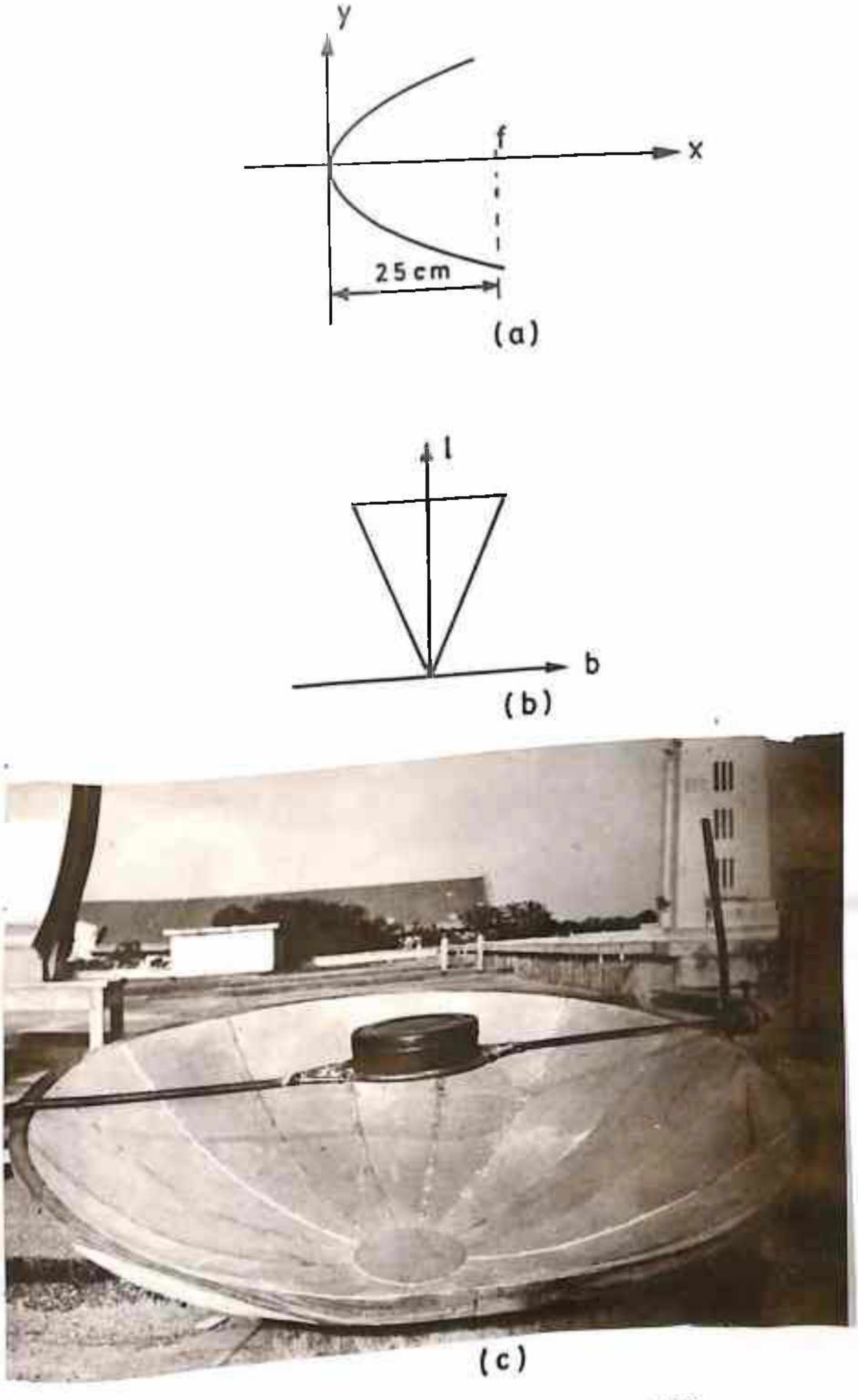


Fig. 2.18 PARABOLOID SOLAR COOKER.

Table 2.12 Observation Table

Food Cooked	Time Taken
Rice	1 hour
Dal	1 hour
Potato	1 hour
Tea	20 minutes

2.6 SUNBASKET COOKER

This cooker has a parabolic reflector which concentrates solar rays at the focus of the parabola. The cooking pot is kept in the basket at its hottest point which is the focus. The parabolic surface is made of papier mache reinforced by a layer of jute fabric.

Equation of parabola is $y^2 = 4ax$ where a is the distance of the focus from the bottom of parabola. Thus $a = 10$ gives $y^2 = 40x$. The paraboloid framework consists of 12 wooden pieces and a ring at the bottom, Fig. 2.19 . It is then completely covered from outside to form a mould. Inside lining is of silver paper which are pasted to the shell. The cooker surface tends to be rough and hence the inner lining is not smooth. Uniform basket surface would improve the efficiency. A wooden block of 10 cm. height is placed at the bottom of the parabola and the vessel is kept over it, Fig. 2.20.

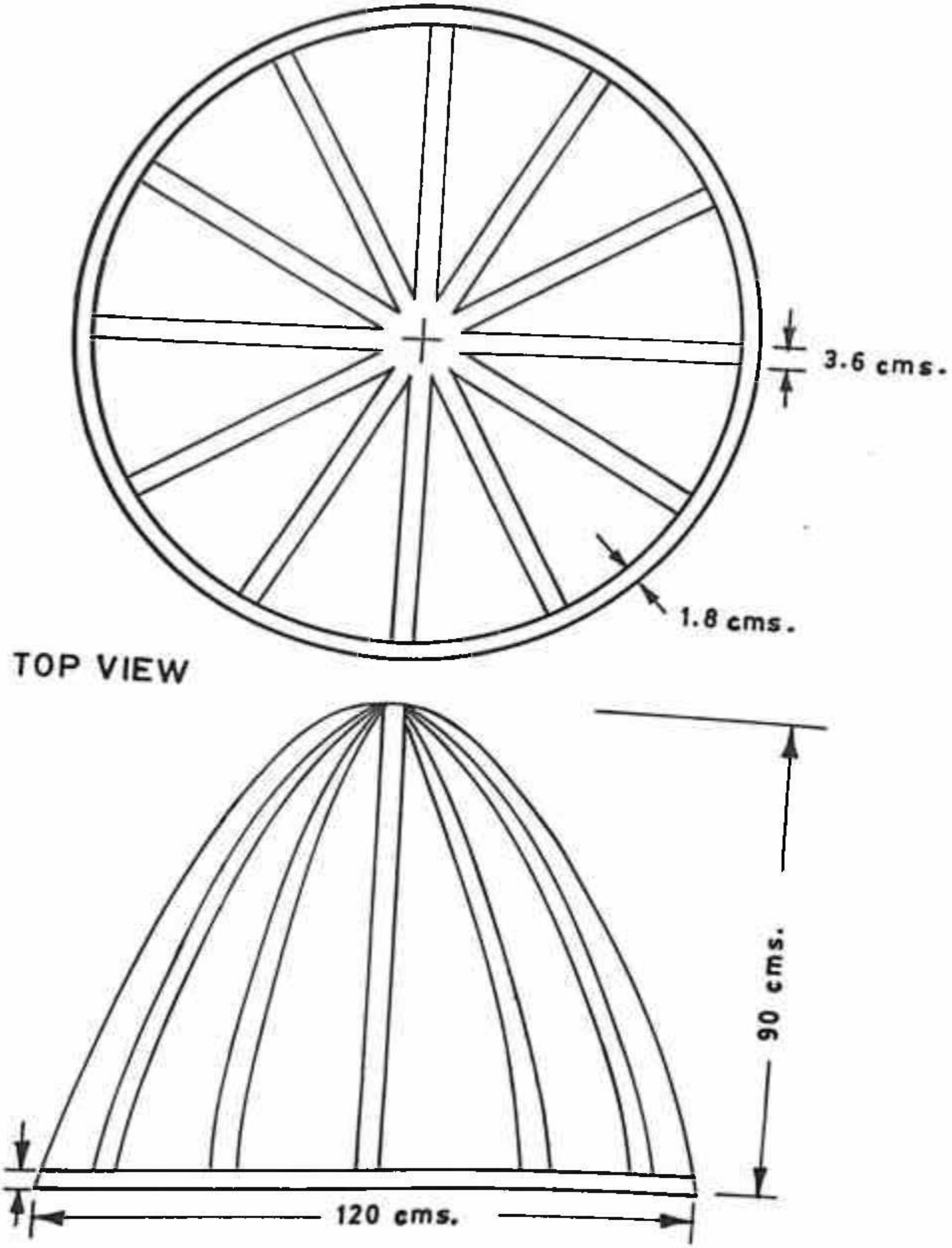


Fig.2.19 WOODEN FRAME WORK.

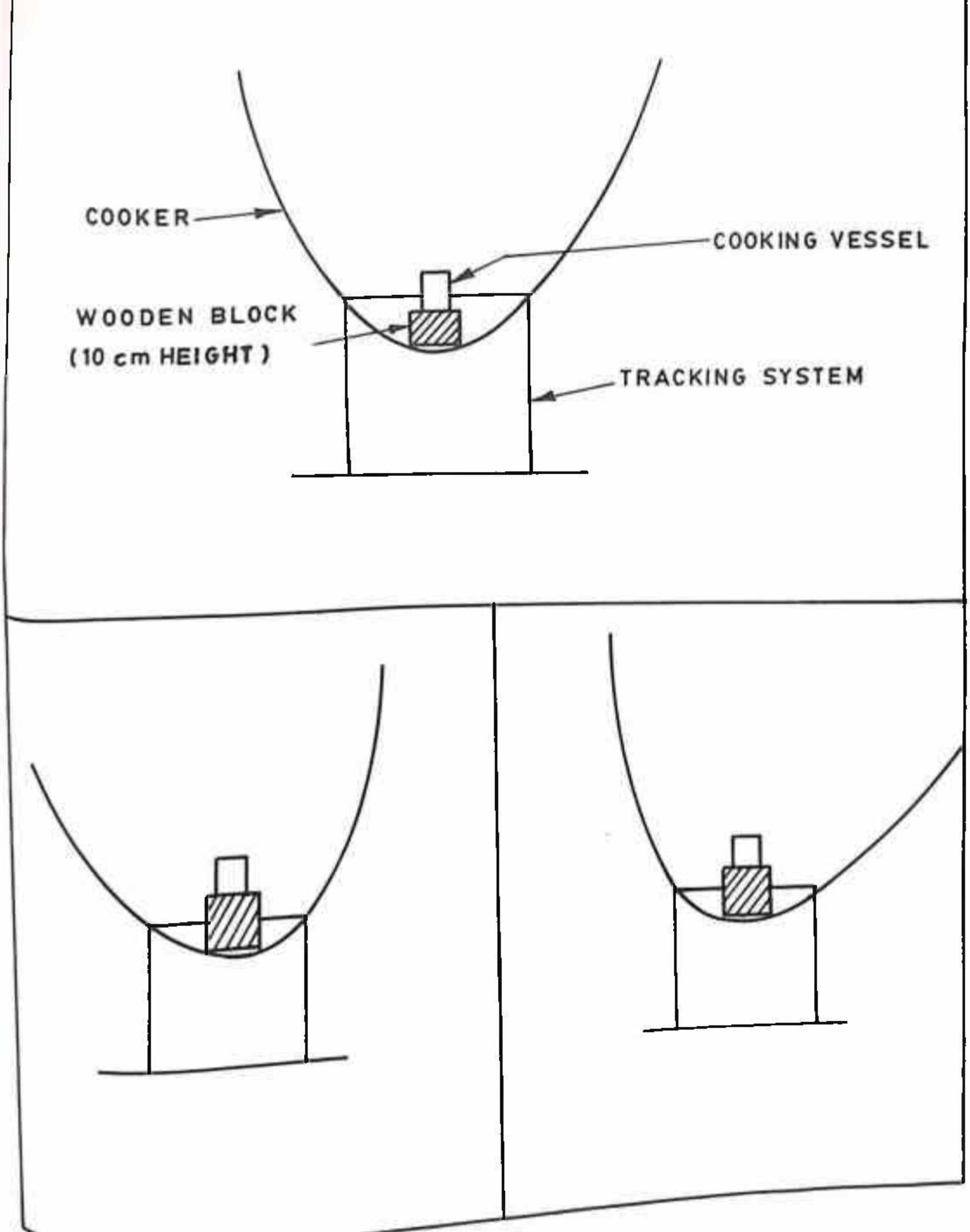


Fig. 2.20 SETTING OF THE SUNBASKET ON THE WOODEN BLOCK.

Design of tracking system

The design of a manually adjustable tracking system for this cooker has been completed. The parabola is supported by a wooden frame and it requires adjustments after every hour. The tracking is achieved by varying the heights of the supports for different legs of the tracking system. The advantages of this kind of tracking system are its low cost, ease of fabrication, light weight and easy adjustments.

With the above listed modifications test readings were taken with one litre of water in mild steel pot painted black. The solar insulation was recorded using solarimeter, Table 2.13. These results are shown in Fig. 2.21. To calculate efficiency the ambient temperature, the inside water temperature and solar insulation readings are required. After every hour the direction of cooker has to be aligned with that of the solar rays. The efficiency of the cooker is defined as:

$$\text{Efficiency} = \frac{\text{Thermal capacity of water x rise in temperature above ambient}}{\text{Intensity of solar insolation x effective area}} \quad \ldots(2.48)$$

and is calculated as follows:

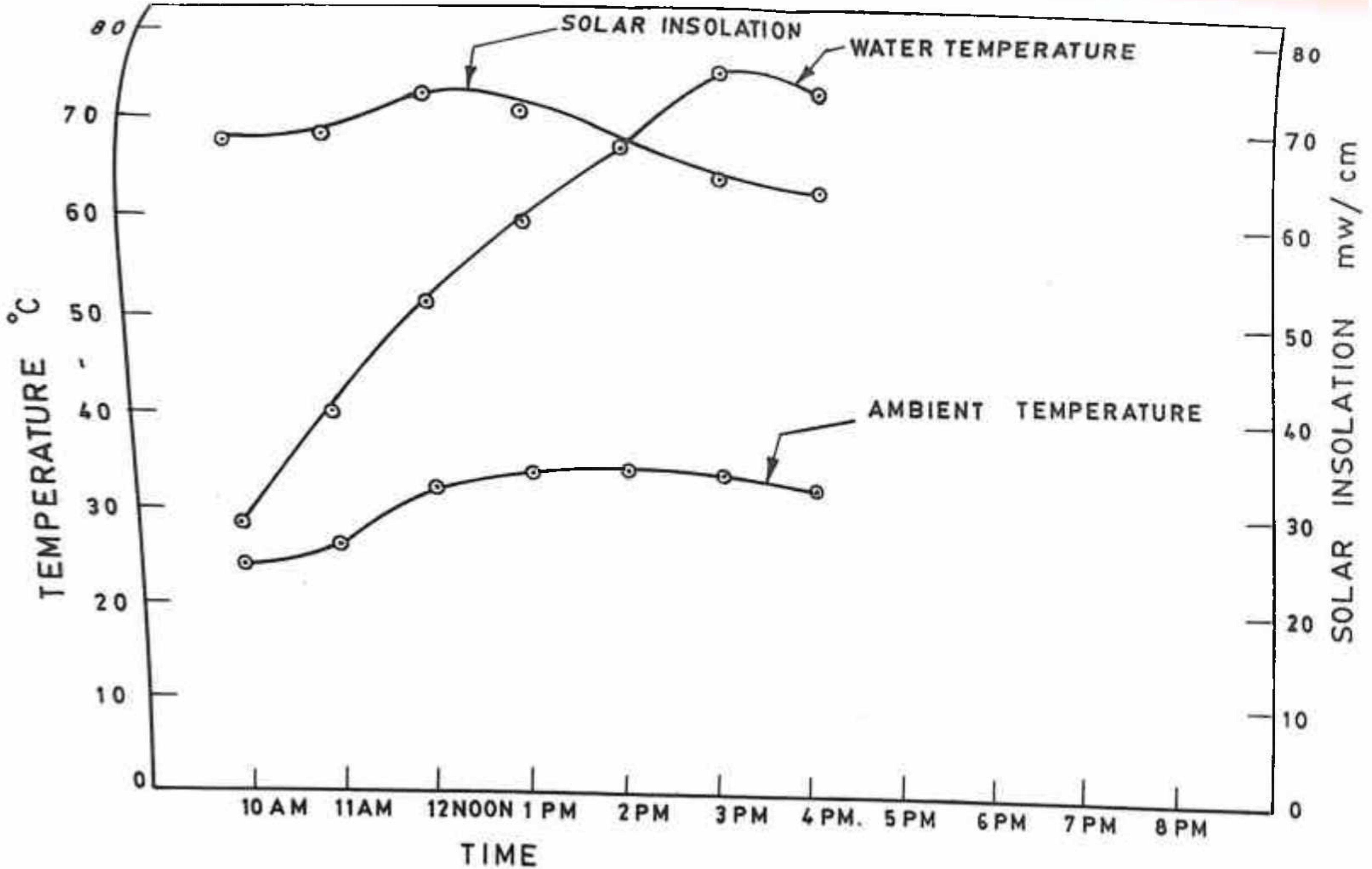


Fig. 2.21 TEMPERATURE Vs TIME CURVE.

Table 2.13 Performance studies on sun basket cooker

Date :	2/3			18/11		
Time	Ambient	Water	Intensity of solar rad	Ambient	Water	Intensity of solar rad
(Hrs.)	temp (^{o}C)		(mW/cm^2)	temp (^{o}C)		(mW/cm^2)
10.00	28.5	29.5	67	24.0	28.5	68
11.00	30.5	40.0	69	26.0	40.0	69
12.00	33.0	63.0	69	32.0	51.5	73
13.00	33.5	65.0	71	33.5	60.0	70
14.00	33.5	68.5	70	33.5	68.0	68
15.00	33.5	73.5	69	33.0	76.0	65
16.00	31.5	71.5	67	32.0	74.0	64

Mass of water = 1 Kg.

Specific heat of water = 1.00 Kcal/Kg. ^{o}C

Thermal Capacity of water = 1 Kcal/^{o}C = 4186 J/^{o}C

Rise in temperature above ambient = (76-33) ^{o}C = 43 ^{o}C

Area of reflecting surface = 0.196 m^2

Mean intensity of solar radiation = 69.3mW/cm^2 = 693J/m^2-s

$$\eta = \frac{43 \times 4186 \times 100}{693 \times 5 \times 3600 \times 0.196} = 7.36\% \qquad ..(2.49)$$

2.7 SOLAR OVEN

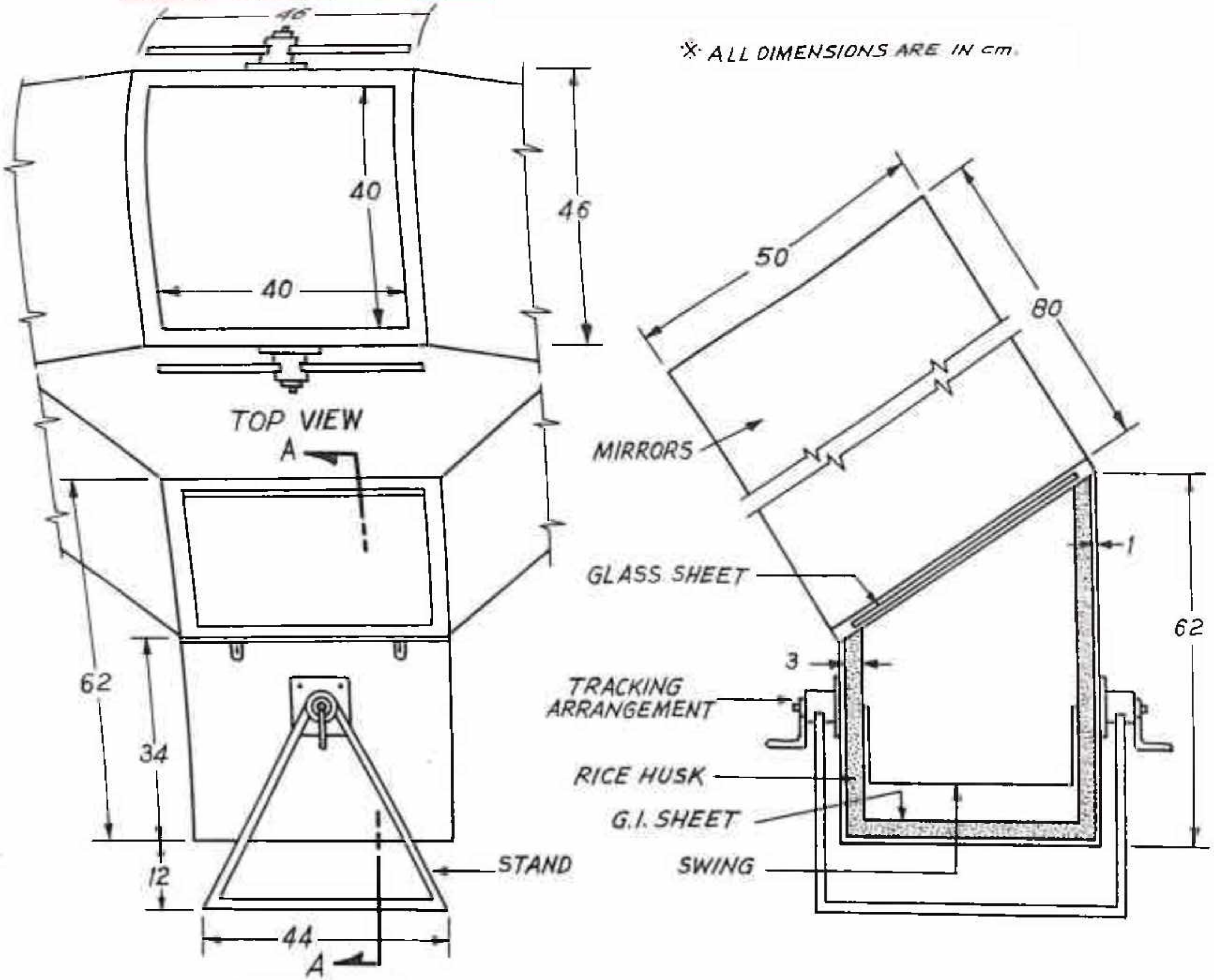
The oven design, Fig. 2.22 consists of a double - walled box with galvanized iron as inside lining and an outer casing of wood. In between two layers rice husk is filled in as insulator. The top of box is covered by a glass sheet to have a greenhouse effect. The side of the box facing south is smaller than the side facing north to have the glass surface inclined at an angle equal to latitude of the place so that after constant tracking the glass surface receives nearly perpendicular rays of the sun.

A low cost and simple tracking arrangement is provided to make it a tracking type of solar oven, the total cost being about Rs. 500/-. A swing platform for the cooking vessel is designed so that the liquid food stuff does not spill when the oven is tilted for tracking.

Moderate concentration with flat side mirrors can be achieved to improve collector performance without tracking. While the incorporation of curved mirrors into the design and tracking can improve collector performance to a greater degree, there are many situations where these sophistications are not required.

Design of the Reflector

Flat mirror design associated with stationary collectors produces only concentration of nearly 2. However, with periodic tilt adjustments higher concentration can be obtained.



FRONT VIEW

SECTIONAL SIDE VIEW AT 'AA'

Fig. 2.22 SOLAR OVEN.

The two mirrors are required to fulfil the condition that the extreme incident ray reaches the opposite corner of the base. This ensures that all other rays incident at this angle or at smaller angles will strike the base with one or more reflections. From Fig. 2.23 it follows that the ray striking at the extreme corner S comes to the target and strikes at Q. Let the dimension of base be B and dimension of aperture be A. Let R be the length of mirror. Let the ray makes an angle δ to the normal, 2δ is acceptance angle and the reflecting surface makes an angle α to the normal. Therefore, we get:

$$R/B = \cos\,(2\alpha + \delta)\;/\;\sin\,(\alpha + \delta) \qquad \ldots(2.50)$$

$$R/D = 1/\cos \qquad \ldots(2.51)$$

$$R/A = \cos\,(\alpha+\delta)/\sin\,(3\alpha + \delta) \qquad \ldots(2.52)$$

From (2.50) and (2.52) we get

$$\frac{A}{B} = \frac{\sin\,(3\alpha + \delta)}{\sin\,(\alpha + \delta)}\;\frac{\cos(2\alpha + \delta)}{\cos\,(\alpha + \delta)} \qquad \ldots.(2.53)$$

Now assuming to be tracking $\delta = 0$

$$\frac{A}{B} = \frac{\sin 3\alpha}{\sin\alpha} \cdot \frac{\cos 2\alpha}{\cos\alpha}\;; \qquad \ldots.\;(2.54)$$

and

$$\frac{R}{B} = \frac{\cos\,2\alpha}{\sin\alpha} \qquad \ldots(2.55)$$

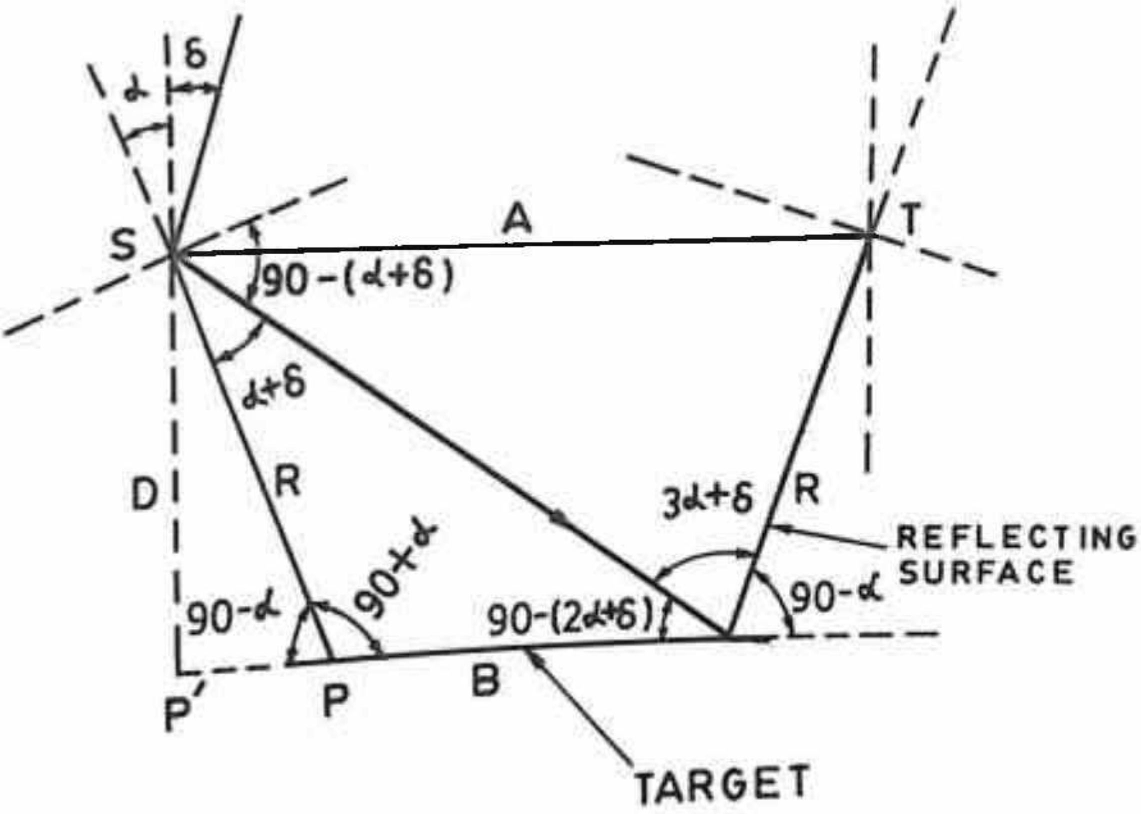


FIG. 2.23 RAY DIAGRAM.

Therefore the ratio of base to the reflecting surface can be calculated. For concentration = 2 we get:

$$2 = \frac{\text{Sin } 3\alpha}{\text{Sin}\alpha} \quad \frac{\text{Cos}2\alpha}{\text{Cos}\alpha} \qquad \ldots(2.56)$$

$$\tan 2\alpha = \sin 3\alpha$$

or

$$\alpha = 20^0\ 45' \qquad \ldots(2.57)$$

This gives $A = 2.0B$, $R = 2.1B$

In this way we obtain the design parameters of the cooker for a given concentration factor.

The principal observations made and the results obtained are as follows:

Table 2.14. Cooking Observations

Name of food stuff	Quantity (gm.)	Time taken (mts.)
1. Rice	100	45
2. Potato	250	60
3. Coffee	750	45

Table 2.15. Temperature inside the oven with aluminium foil.

Time	Temperature	
(hrs.)	Ambient (^0C)	Inside (^0C)
10.00	27.0	40.0
11.00	27.8	51.8
12.00	28.4	58.2
13.00	29.4	63.4
14.00	29.4	67.2
15.00	28.2	70.0
16.00	27.5	64.2

These data are shown in Fig. 2.24.

Table 2.16 Temperature inside the oven with plane mirrors.

Time	Temperature (^0C)	
(hrs)	Ambient	Inside
10.00	23.8	36.5
11.00	24.5	44.8
12.00	26.8	58.5
13.00	27.8	66.2
14.00	27.2	78.8
15.00	26.5	78.8
16.00	25.0	71.2

These data are shown in Fig. 2.25. The insolation data are shown in Fig. 2.26.

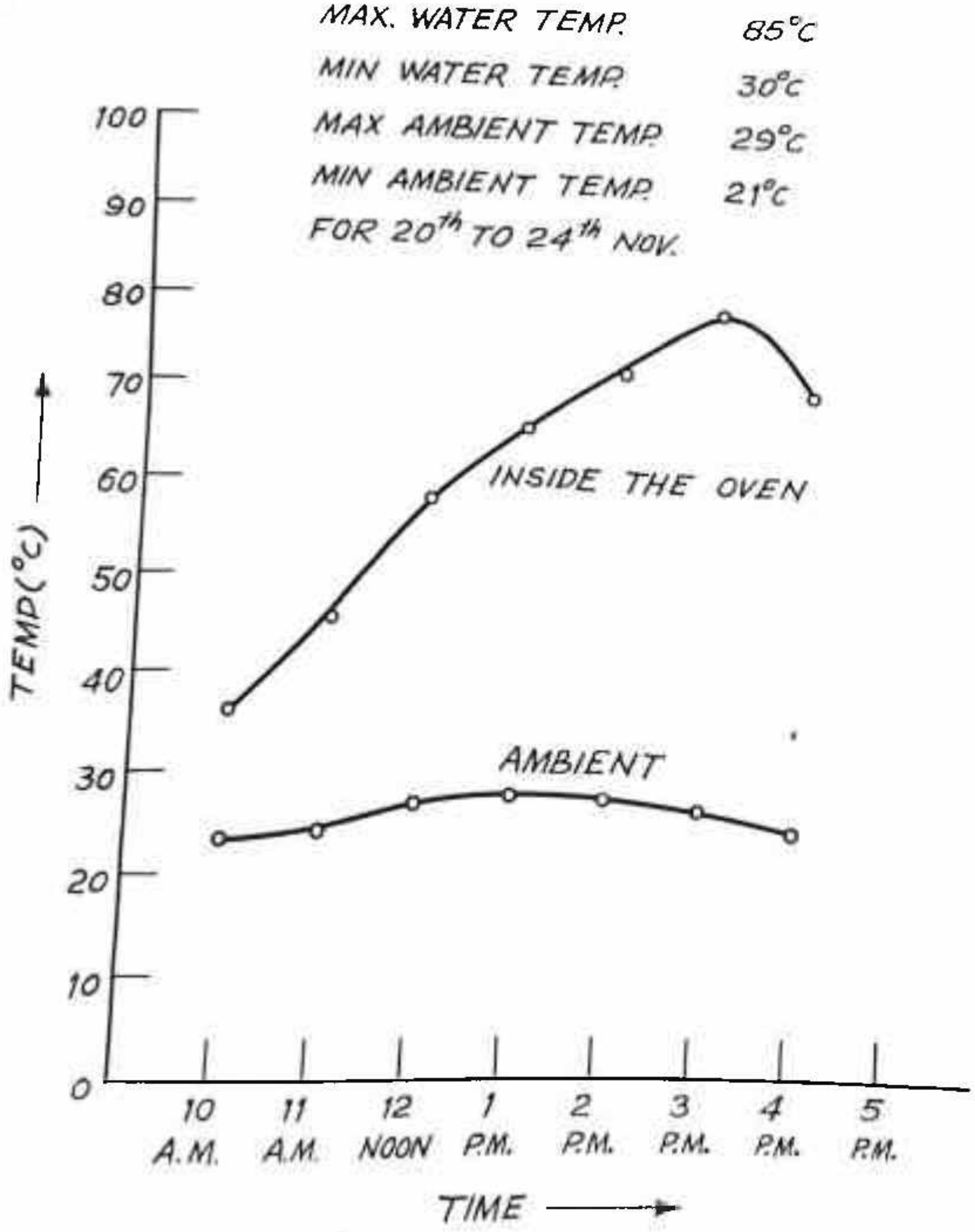


Fig. 2.24 AVERAGE TEMP.-TIME CURVE (WITH MIRRORS).

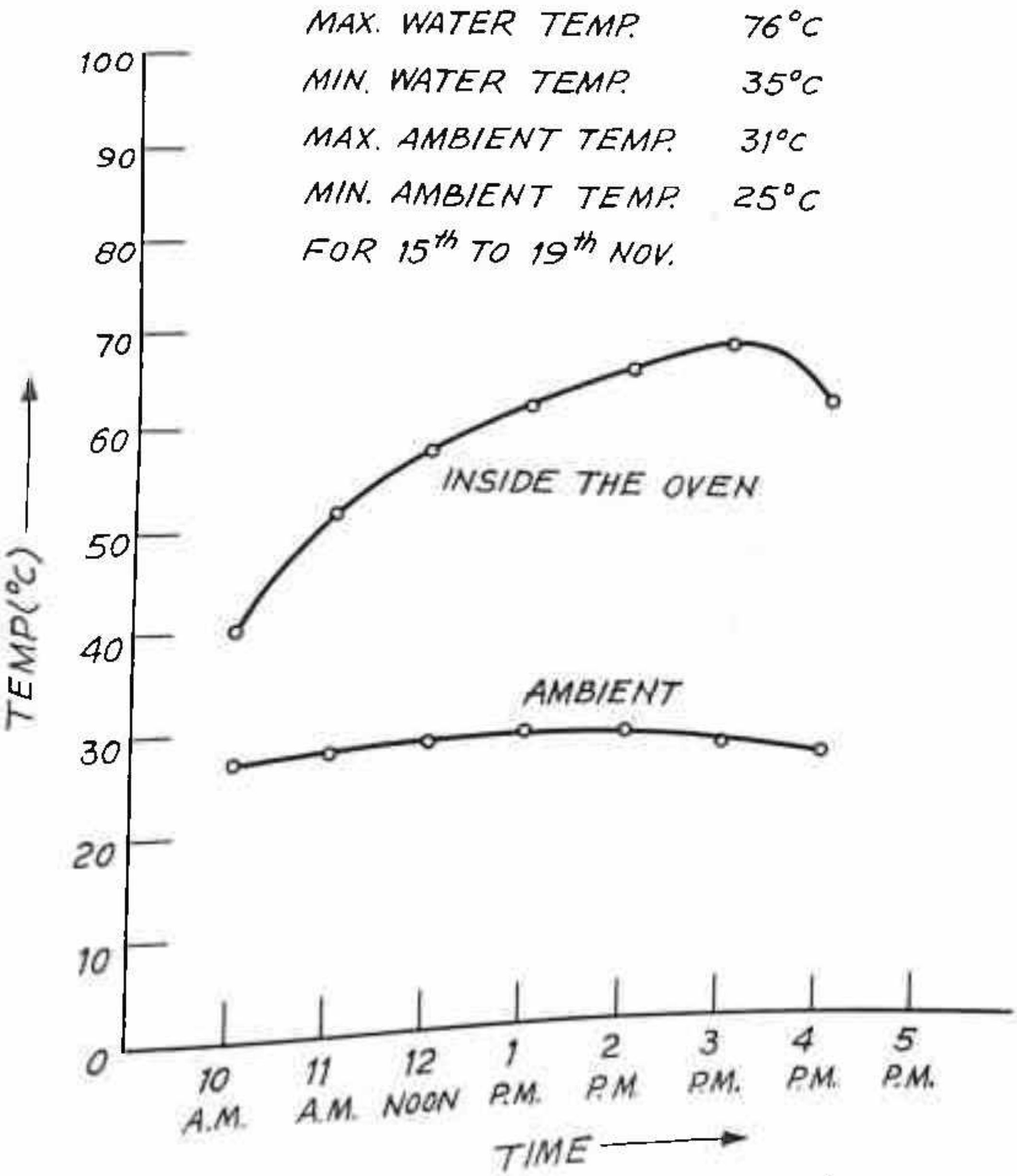


Fig. 2.25 AVERAGE TEMP.-TIME CURVE (WITH ALUMINIUM FOIL REFLECTORS).

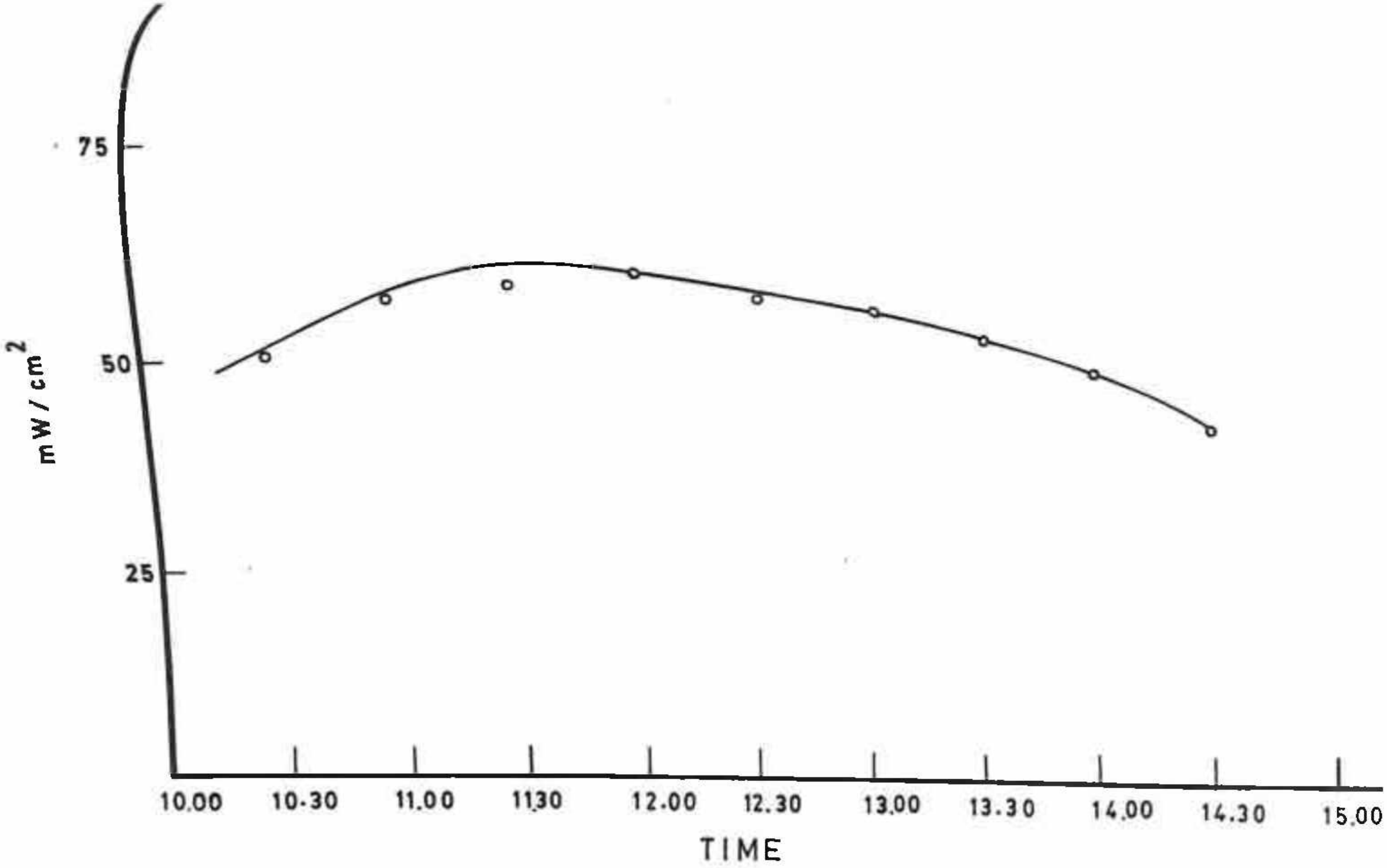


FIG. 2.26 INSOLATION CURVE.

Efficiency calculations

Area of glass = $0.16\ m^2$

Concentration Factor = 2

Amount of water = 10 Kg

Number of squares under the curve = 33

Maximum rise in temperature inside the oven = 39.5 °C

Area under the insolation curve = $33 \times 0.2 \times 30 = 198$

Total incident insolation = $198 \times 1600 \times 2 \times 4.186J$

Energy used in heating water = $10 \times 39.5 \times 1000 \times 4.186J$

$$\eta = \frac{39.5 \times 10000}{198 \times 1600 \times 2}$$

$$= 62.3\% \qquad \ldots(2.58)$$

2.8 SOLAR STILLS

A solar still[50-54] consists of glass roof, basin to hold impure water and channels to collect the distilled water. The solar radiations are absorbed by a black plastic covered basin through the glass cover to heat up the impure water. The rate of evaporation becomes considerable when it reaches 5 - 6 °C above the ambient atmospheric temperature. The resulting mixture of water vapour and air circulates inside the enclosure and the thin film of water condenses as the vapour comes into contact with the cooler inner surface of the cover. The heat of condensation is given up to the cover and is dissipated to the atmosphere by radiation and convection. The condensate flows through the channels to a suitable storage system.

Following the absorption of solar radiation in the saline water and basin liner, part of the energy is transferred to the cover by the simultaneous mechanism of evaporation, radiation and convection and partly by conduction of heat through the sides and base. The loss through the sides and base can be avoided by using suitable insulation which increases initial cost but this is more than offset by a greater per cent increase in the output for a given radiation level.

Solar stills fabricated at BITS

The following two types of solar stills have been fabricated and studied:

(a) Roof type solar still

(b) Tent type solar still

(a) Roof type solar still

The design of this type of still was a variation of the one used in Australia[50-51], with suitable modifications in the sealing material and inclination of the glass plates, Fig. 2.27.

The underground water at Pilani is at a depth of about 150 ft. from the ground level and after pumping, it is stored first in a tank and then passed through the solar still. This water has dissolved salt content of 1000 ppm and its

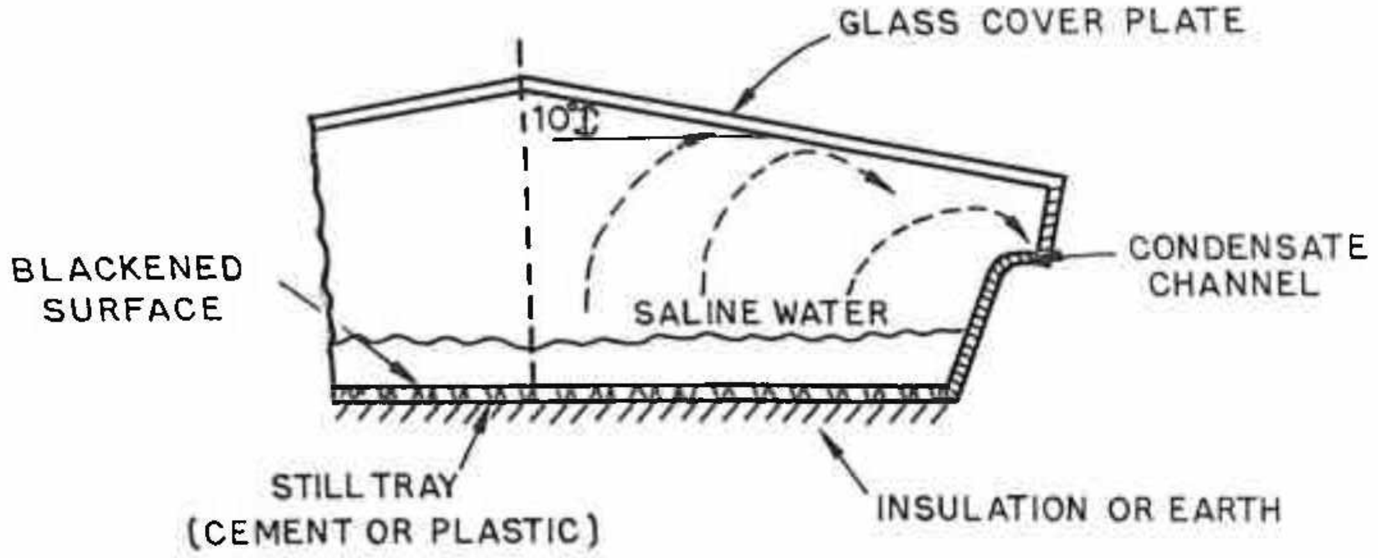


Fig. 2.27 SKETCH OF ROOF-TYPE SOLAR STILL.

hardness is temporary. During the period of observation, saline water was continuously flowing through the still in order to maintain the total amount of water in the still constant at 82065cc level. The flow of water in the overflow tube is adjusted to a drop per 2 to 3 seconds, thus ensuring that the quality of saline water in the still remaining unchanged. A sample of the saline water was analyzed and its composition was found to be as follows:

Total dissolved solids	...	1000 ppm
Total alkalinity	...	460 ppm as $CaCO_3$
Total hardness	...	86 ppm as $CaCO_3$
Mg hardness	...	63 ppm as $MgCO_3$
Sulphate	...	72 ppm as SO_4
Chloride	...	200 ppm as Cl

Hourly observations of solar intensity, ambient and saline water temperatures and distilled water temperatures and distilled water yield have been carried out during the month of october as shown in Figs. 2.28 and 2.29. The curves showing the variation of these quantities with time of day on these days have a remarkable similarity.

It was observed that the ambient temperature and saline water temperature reach maximum of 35.7°C and 59.3°C, respectively, at about 2 P.M. whereas the yield of distilled water is maximum between 2.30 P.M. to 3.00 P.M., Fig. 2.28.

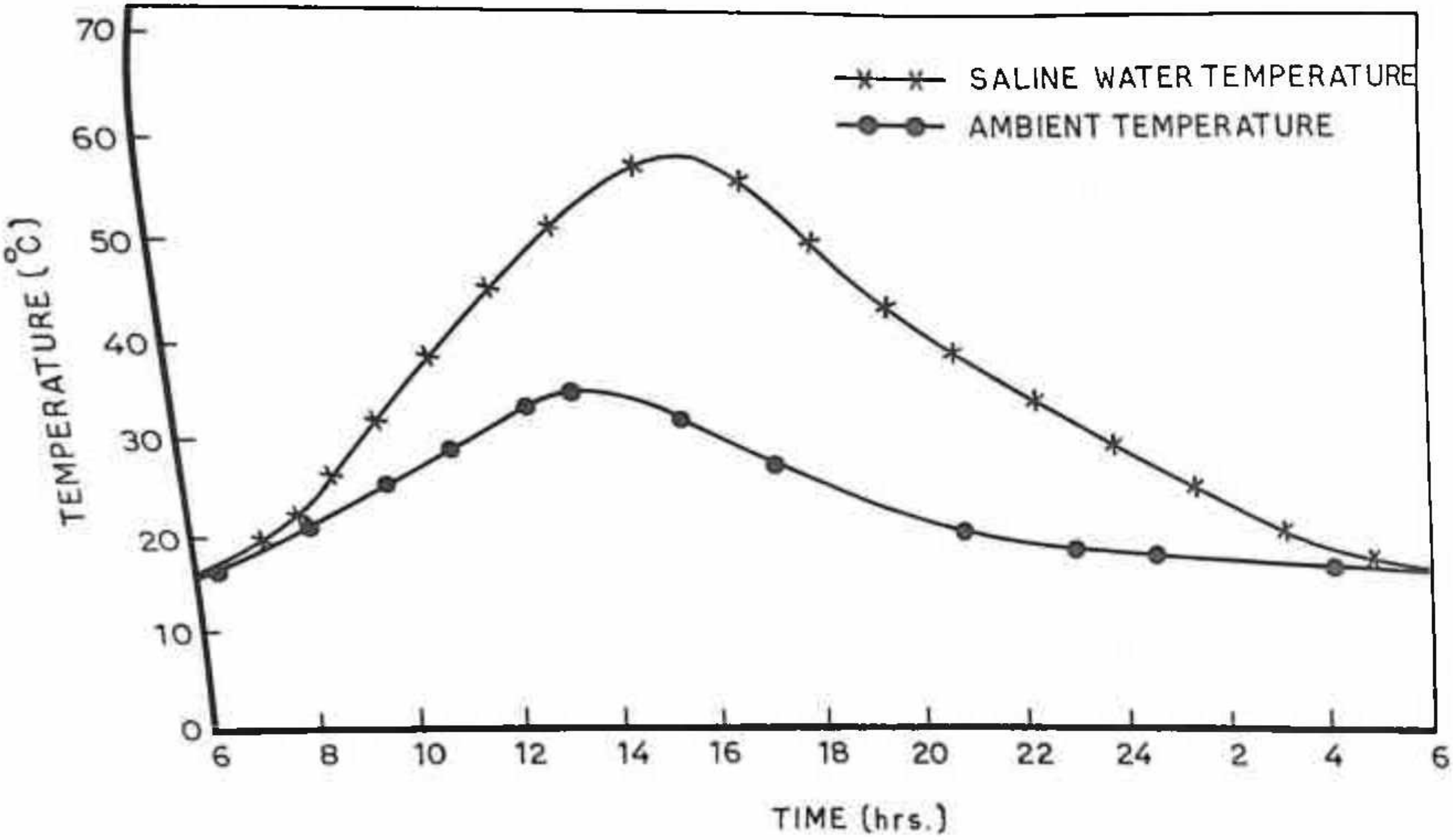


Fig. 2.28 VARIATION OF THE AMBIENT TEMPERATURE AND OF THE SALINE WATER TEMPERATURE IN THE MONTH OF OCTOBER.

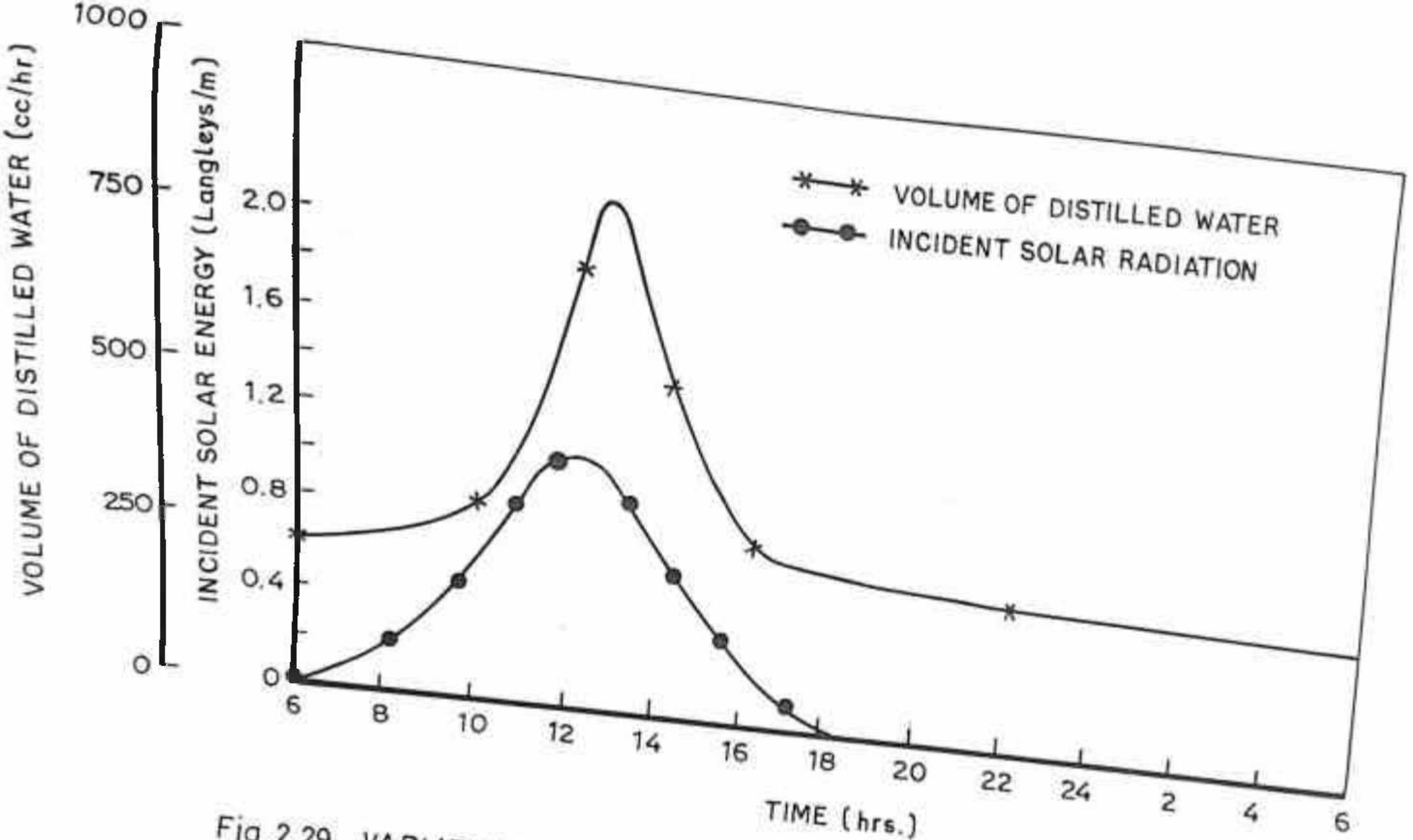


Fig. 2.29 VARIATION OF INCIDENT SOLAR RADIATION AND VOLUME OF DISTILLED WATER PRODUCED.

The time lag between the two is due to the time involved in the transfer of heat from the solar energy first by the absorbing surface, then to the saline water and subsequent distillation. Distillation is seen to be a continuous process i.e. it goes on all the 24 hours a day, the maximum and minimum rates being 818 cc and 220 cc per hour, respectively[55] (Fig. 2.29). As the volume of water is increased in the still, the maximum rate of distillation decreases and the minimum rate increases and the efficiency goes up as the heat losses decrease.

Another interesting feature is that the saline water temperature goes below the ambient temperature for an interval of about 1.5 hours between 6 A.M. and 8 A.M. in the morning whereas at all other times, it is above the ambient temperature.

The electrical conductivity of distilled water was measured by Phillips conductivity bridge and was found to be 1.02×10^{-5} mhos which is sufficiently low. The quality of the distilled water is good and it is useful for all laboratory work.

Efficiency η of the solar still is calculted as follows:

Area exposed to saline water = $2.36\ m^2$

Total solar energy incident = 439.6 langleys

Amount of watr distilled = 5.454 l/day

Taking $50^{\circ}C$ as the mean temperature at which distillation takes place, we have:

Latent-heat of vaporisation of water = 568.5 Cal

$$\therefore \quad \eta = \frac{5.454 \times 10^{3} \times 568.5}{439.6 \times 2.36 \times 10^{4}} = 0.299 \qquad \ldots(2.59)$$

or

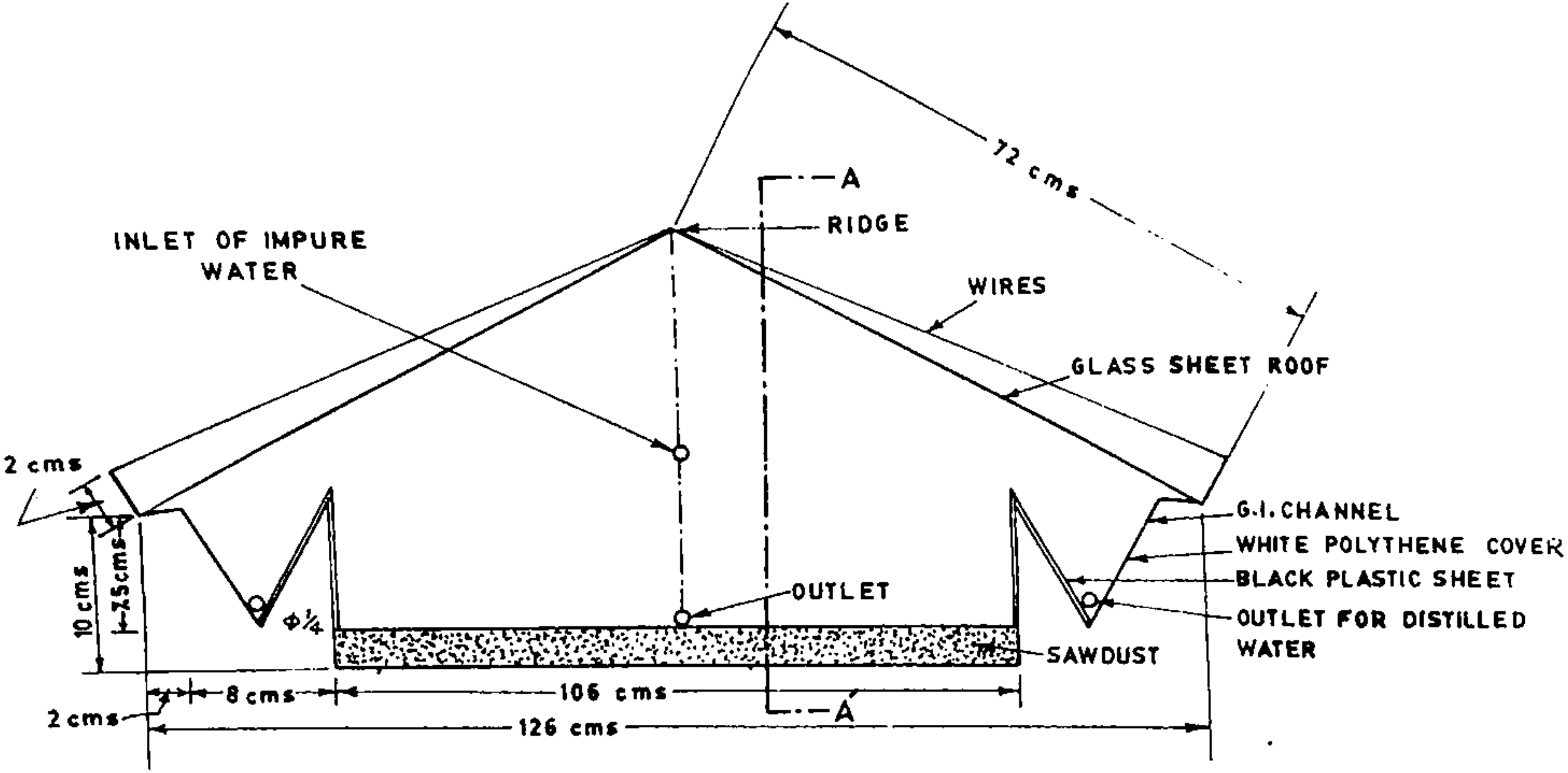
$$\eta = 29.9\% \qquad \ldots(2.60)$$

Thus the efficiency of the still is 29.9% and its production is 2.31 litres/sq.m/day of distilled water.

A separation plate type solar still gives about 15-20% more distilled water than the one described above, the atmospheric conditions and water depth remaining same. In this still a separation plate, covered with small pebbles, is placed in the middle of the water dividing the water into two layers for suppressing the convectional movement of water. This results in absorption of most of the heat in the upper layer. The separation plate also prevents loss of heat from the base, thus increasing the efficiency.

(b) Tent-type Solar Still

The basin in this still is 1.22m long and 1.07m wide, Fig. 2.30. The main framework is made up of channels of G.I. sheet located along both sides of the still and held in place by inverted metal sheet angle at interval of 0.61m.The frame is placed on a wooden platform with an inclination of 1:100



ELEVATION

Fig. 2.30 SOLAR STILL.

in order to facilitate the flow of both saline and distilled water.

The end faces of the still were also made of G.I. sheet with the two top sides at an inclination of 15^0 to facilitate the glass cover inclination at 15^0. Both the side channels were blinded with copper tubes to achieve the outflow of distilled water. Window glass panes of 3 mm thickness have to be mounted on the edges of the distilled water channels and interlocked at the centre. The glass roof is made vapour proof by a rubber lining on its four edges.

The effect of various atmospheric variables on the working of the still is given below:

a) Solar insolation

It is obvious that the productivity of a solar still depends mostly on the solar insolation. Therefore, solar stills are usually very advantageous in regions of the world having a high average solar insolation.

b) Wind velocity

The wind velocity increases over a solar still, heat is removed from the cover by convection more rapidly. This lowers the cover temperature which may temporarily increase the rate of condensation inside the still. However, as the cover temperature decreases, the rate of heat transfer from the brine to the cover by means of radiation and convection also increases. The brine temperature is reduced. As the rate of evaporation decreases exponentially with the temperature of the brine, the net effect of increased wind velocity is a slight decrease in productivity. If a still is well sealed to prevent vapour leakage, increased wind velocity has only minor negative effects on productivity. However, when poorly sealed joints exist, the negative effects are pronounced.

c) Ambient temperature

For each 5 - 6 °C rise in ambient temperature the output is about 5% .

The following design factors have an appreciable effect on productivity of a still:

a) Effect of brine depth

The still depth should be as shallow as possible so that the still reaches high brine temperature with minimum thermal lag resulting in exponential increase of the evaporation rate. If there is too much water, the thermal inertia of the still increases, but if the amount of water is too little, then after evaporation has continued for sometime, a layer of salt forms on the water surface and the reflection from the water surface increases resulting in a decrease of the efficiency. Periodic flushing of the still with fresh water can prevent the deposit of salt.

b) Effect of condensate leakage

Even very small holes or cracks in collection channels reduce output because the flow rate in a single channel is so small that entire stream can be easily lost due to such leakage. Only completely corrosion - resistant one - piece channels are found satisfactory.

c) Effect of vapour leakage

Solar stills should be designed so that air and vapour leakage can be kept to a minimum. Nearly every solar still has shown some deterioration in productivity, part of which is due to vapour leakage. Silicon rubber is a very good sealant except for its high cost.

d) Effect of basin insulation

The bottom and sides of solar still basins have to be well insulated to reduce heat losses. Since heat losses are proportional to the perimeter, insulation benefits smaller stills more than bigger stills.

e) Effect of cover design

A symmetrical double sloped set at an angle of 10^o - 20^o with the horizontal is most suitable for large installation to receive maximum solar radiations and might permit adequate film condensation of the moisture. Cover glass sheet about 3 mm thick is found to be the most suitable choice for transmission and least absorption.

f) Effect of construction materials

Cement blocks, which are able to withstand weather conditions and the effects of salt water can be used for commercial purpose stills. For the absorbing black surface, concrete with bituminous paint can be used. Butyl rubber sheet about 1 mm thick may give better results.

The efficiency of a solar still is the ratio of the amount of heat energy required for the evaporation of the liquid to the total amount of heat energy introduced into the system. The still produces about 5-6 l/m^2/day. The efficiency varies between 40 - 50%.

2.9 SOLAR DRYER

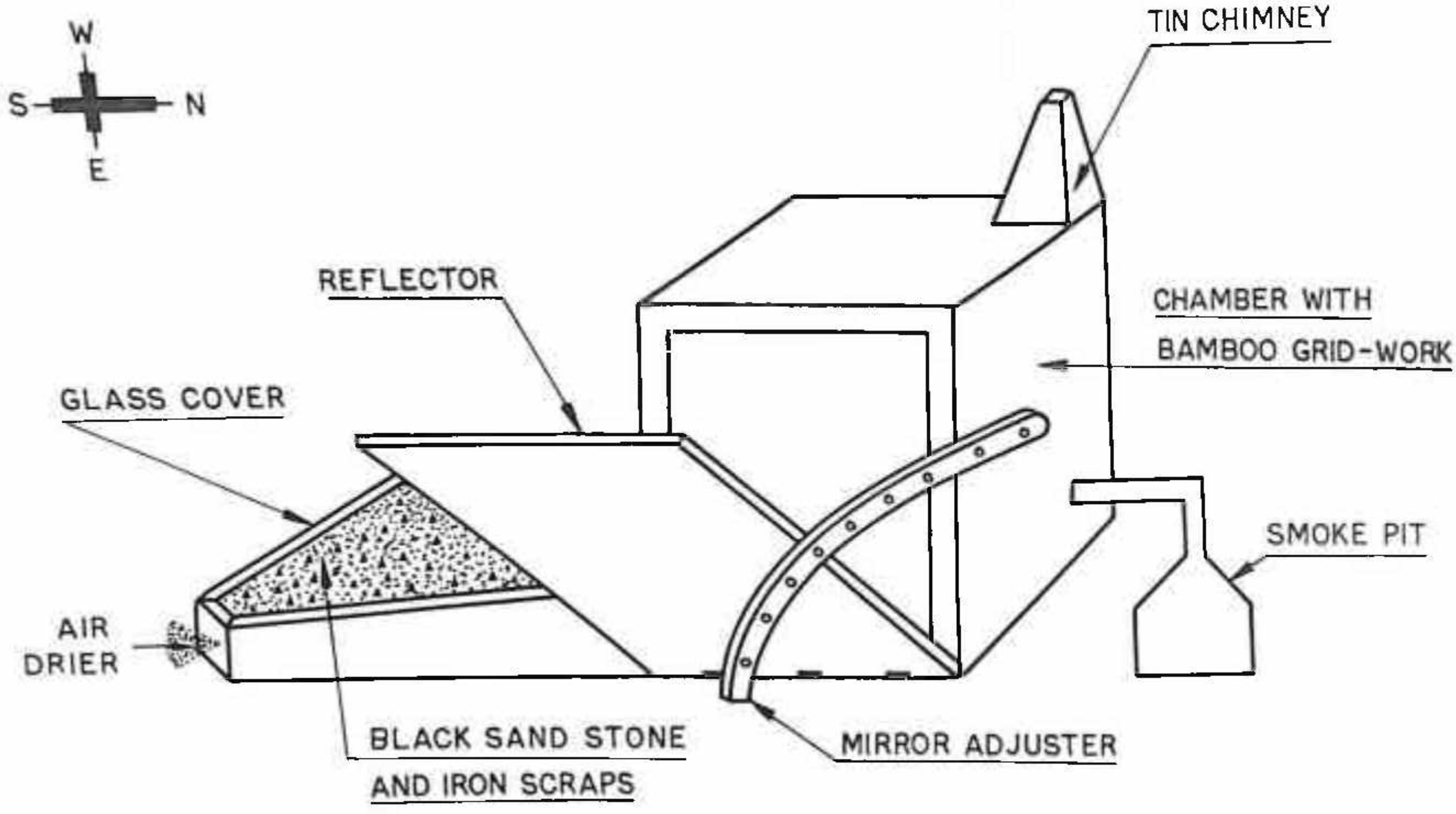
Drying means removal of moisture to a level acceptable for commercial use. While assessing the price of the product in the market, moisture content is an important factor. For example, market grade tobacco should contain only 14% moisture. Overdrying as well as underdrying are harmful. Controlled solar drying in the dryer permits early harvesting and reducing field loss of product from storms and hot dusty loo which scorches the tobacco leaves. Hot blasts have to be avoided to keep the leaf in proper shape. However, open sun drying is a big loss by way of flavour and aroma, devoid of which the tobacco is sold very cheaply in the market. Also control of humidity is a big factor during sunshine. A solar dryer solves all these problems by ensuring optimum moisture, proper flavour, aroma and flat lustrous shape. It consists of the following components:

Air Heater

Air heater is attached to the south wall of the dryer. The structure is made of wood 2.5 cm. thickness. The dimensions of the heater are 0.9 m. in length and at the entrance of the air, the dimensions are 0.6m x 0.3 m. This is covered with glass. The inside space is filled with mixture of black stone and iron scrap. The heater is connected to the drying chamber through an adjustable slit.

Drying Chamber

This is a box type structure having dimension 1.5m x 1.5m x 1.8m, Fig. 2.31. The whole structure is made of wood which is available locally and is cheap and strong. Thickness of the wood is 7.5cm. East and west walls are reflectors which are adjustable according to the incident angle of the solar radiation in the forenoon and in the afternoon. The reflectors have wooden base having planks of thickness 2.5cm. and MS sheet over it painted with aluminium oxide to boost radiation inside the chamber. In case there is need to close the chamber completely, the reflectors act as lids. The north and south walls are made of bamboo and stuffed with rice husk for insulation. On top of this structure is a chimney for outlet of air and moisture. The chimney is made of MS sheet. The dimensions of the chimney are 0.45m x 0.45m at the



Not to the scale

Fig.2.31 THE SOLAR DRIER.

base and 0.15m x 0.15m at the top. The height of the chimney is 0.75 m.

Roof

Roof is made of grid of bamboo sticks and the top has a lining of unbaked bricks. The roof is thus semipermeable to moisture.

Bamboo matrix

In order to suspend the tobacco plant inside the chamber for drying, a three dimensional bamboo network in the form of matrix is made and put inside the chamber. The ripe plants are suspended inside the whole volume of the matrix. This allows free air current throughout the volume.

Wind mill structure for air stirrer

Air stirrer is to stir and ensure uniform distribution of air inside the structure. The stirrer is connected to the wind mill for this purpose. The wind mill rotors are made of aluminium sheet with highest curvature towards the tip so as to obtain a higher torque. The sweep diameter is 0.9m and the length of the rotor is 1.07m. The rotor torque is transferred to the stirrer through belts.

Smoke pit

Smoke pit is a structure having dimensions 0.6m x 0.6m x 0.6m with conical head. The smoke pit is attached to the north side of the structure for curing of the tobacco. Tobacco having high chlorine content sweats and unless moisture is removed from the leaves they get bacterial growth and get out of shape. Dense smoke is passed from the pit to give uniform colour to the leaves.

After 2-3 days of solar drying, curling of the leaves at the edge begins which indicates overdrying and faster rate of evaporation than needed. At this stage, the humidity in the chamber is to be increased. To ensure this, the reflectors should be closed and water sprinkled over the roof of the dryer. Ceiling gets moist since the roof is semipermeable to moisture and stirrer also works injecting more humidity inside. The dry leaves become tender and can be packed.

In order to test the moisture content of leaves, a roll of leaves is put into a bamboo tube through which gases from the tractor exhaust are passed. The temperature of the exhausts is 140 °C. If the leaves get dried in 6 minutes, the moisture content is 12 - 14%. If it takes more time, then solar drying is to be continued.

Solar cabinet dryer

It is a hot box wherein vegetable matter can be dehydrated. It consists of a rectangular container insulated at its base and covered with a double layer transparent roof.

Solar radiation passing through this roof is absorbed on the blackened interior surfaces and raises the internal temperature.

The principal components are transparent roof of plastic film or glass sheets, framework, panels, etc. of wood or metal for portable models and of brick, rock or concrete for permanent structures and insulation of wood shavings, coconut fibre, glass wool, etc. The dryer as constructed was 1.93m x 0.66m with a tray area of 1.1 m^2.

To provide ventilation, holes are drilled through the base to induce fresh air into the box. Outlet ports are located on the upper sections of the side and rear panels of the cabinet frame. As the cabinet temperature increases, warm air passes out of these upper apertures by natural convection creating a partial vacuum and inducing fresh air up through the base. As a result, there is a constant perceptible flow of air over the drying product, which is placed on perforated drying trays to facilitate air circulation.

2.10 SPACE HEATING AND COOLING

A passive system with a possibility of providing some comfort in village houses has been studied. The experimental set up for space heating (Fig. 2.32) consists of an insulated chamber 120 cm x 120 cm x 60 cm fitted with a water wall 10cm. thick on the 120 cm x 120 cm face. The water wall is

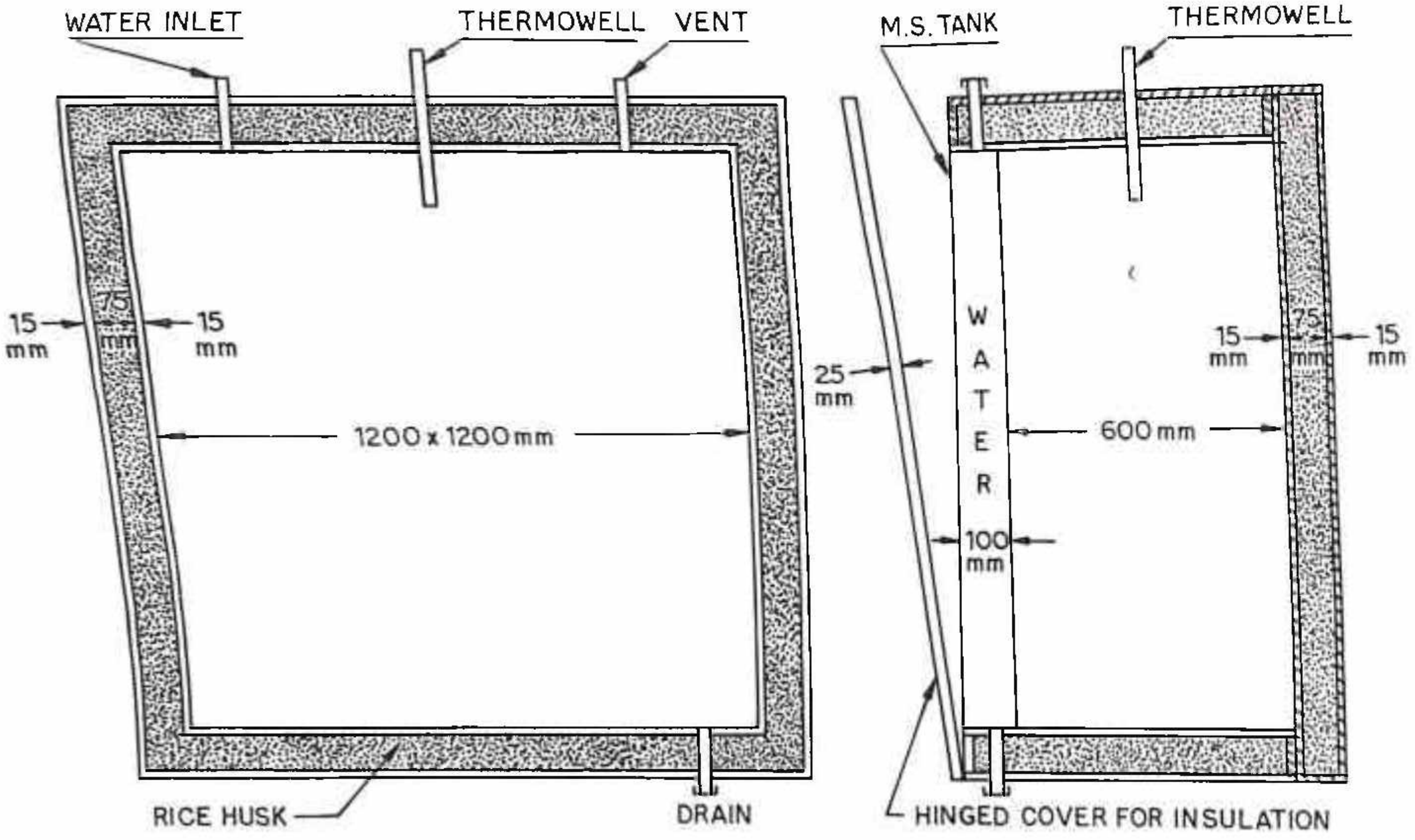
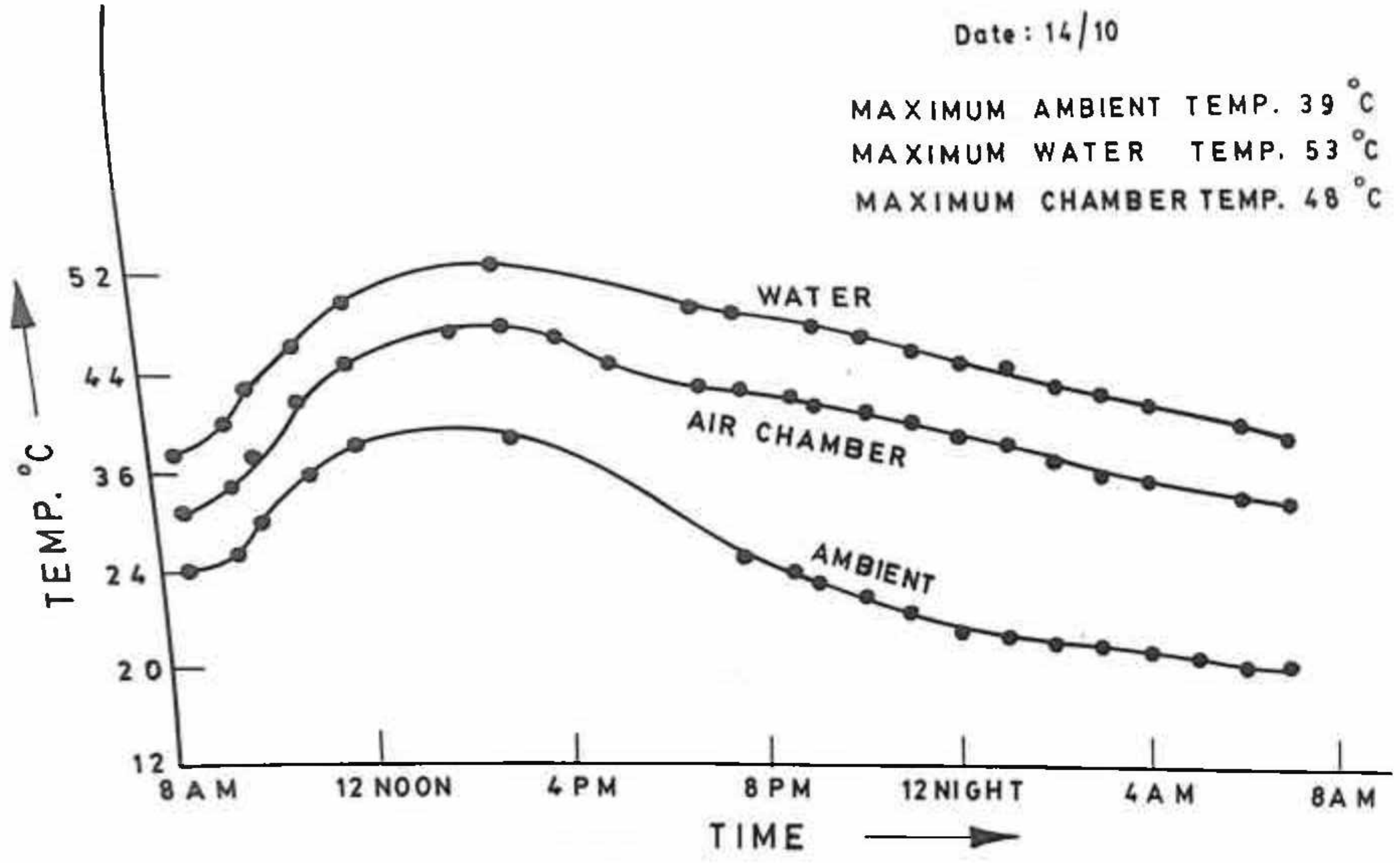


Fig. 2.32 EXPERIMENTAL SETUP FOR SPACE HEATING.

enclosed in a mildsteel box. The heat collected by the water wall during the day is dissipated into the chamber during night. Observations taken on a number of days in different months show that the night temperature in the chamber is about 10 °C above the ambient temperature. A typical round the clock data of temperature is shown in Fig. 2.33. A lot more work is to be done to extend the results of this experiment to space heating in houses.

For space cooling the attempt is to take advantage of the evaporative cooling in the night to keep the room cool during the day. A set of experiments conducted show that the temperature of water, in an open tray exposed to the night sky, falls appreciably below the ambient temperature (Fig. 2.34). The experimental set up consists of a chamber and a steel tray as shown in Fig. 2.35. The water in the tray is exposed to the night sky and closed with an insulating lid during the day. The recorded data on a number of days show the chamber temperature to be about 10oC below the ambient temperature. A typical temperature data is shown in Fig. 2.36. The set up in its present form can be used as a cold storage in village houses.



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MAXIMUM AMBIENT TEMP. 39 °C
MAXIMUM WATER TEMP. 53 °C
MAXIMUM CHAMBER TEMP. 48 °C

Fig. 2.33 SPACE HEATING - VARIATION OF TEMPERATURE WITH TIME.

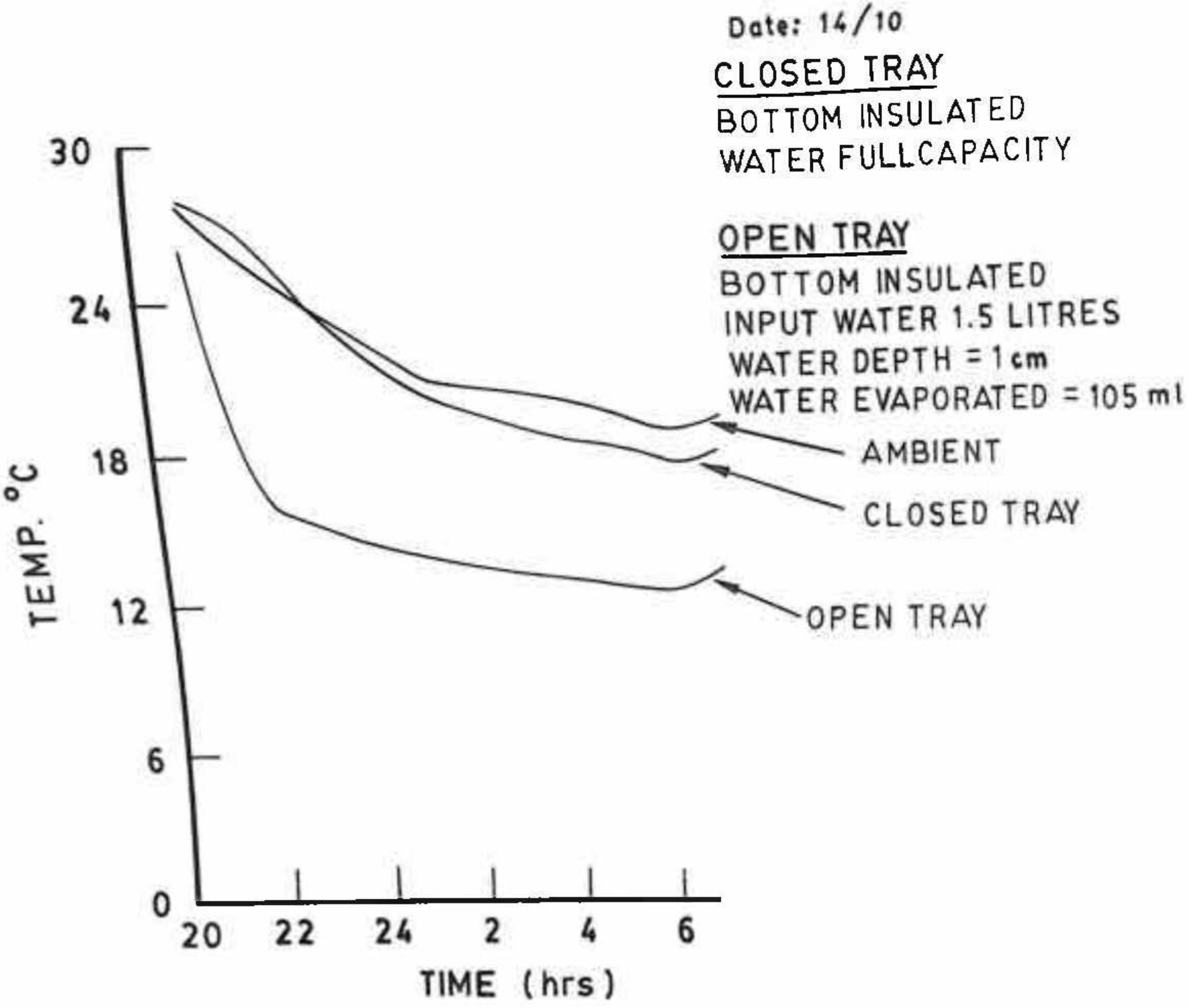

FIG.2.34 NIGHT COOLING VARIATION OF TEMP. WITH TIME.

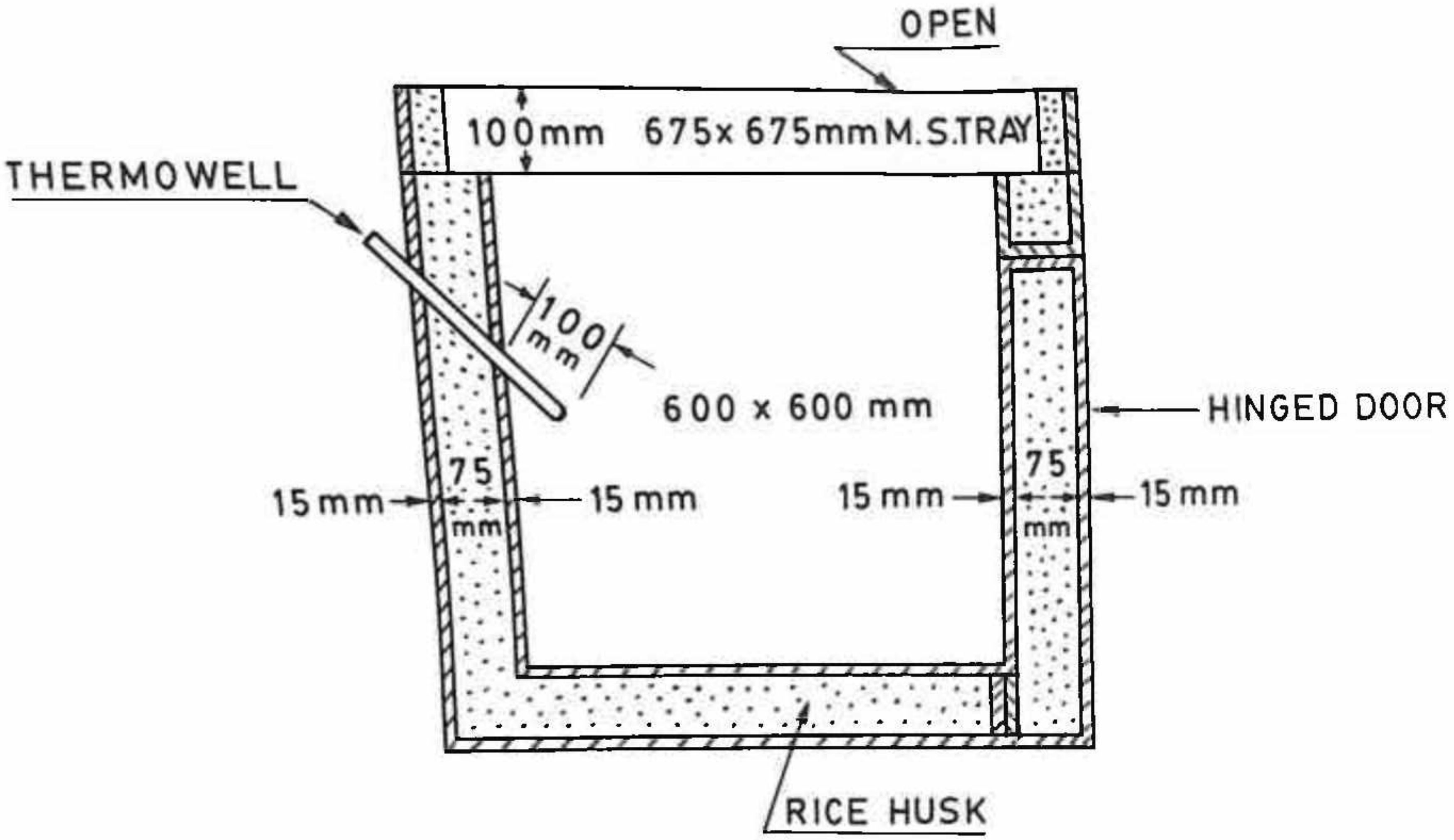

Fig. 2.35 SETUP FOR SPACE COOLING.

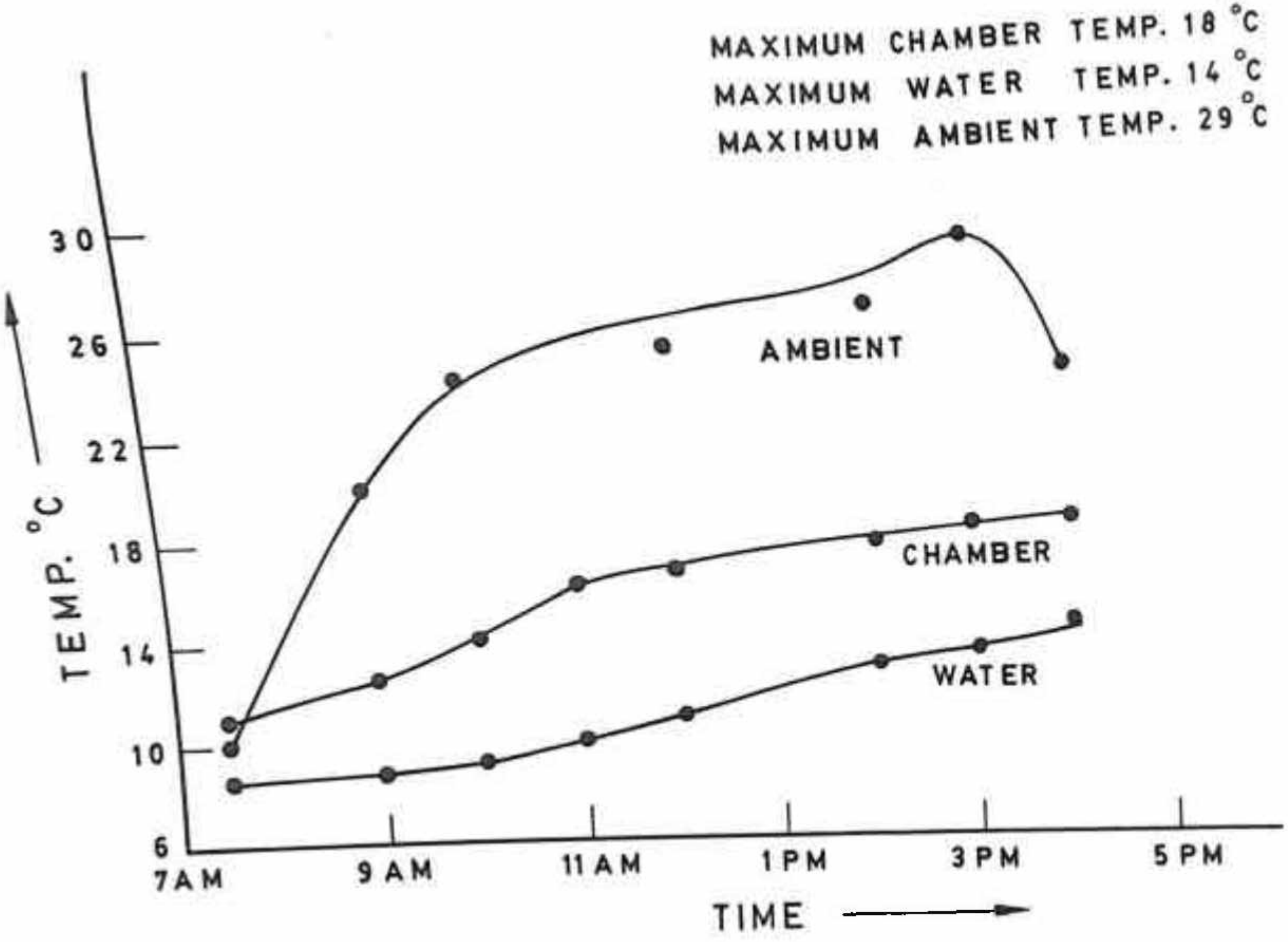

Fig. 2.36 SPACE COOLING – VARIATION OF TEMPERATURE WITH TIME.

CHAPTER III

ECONOMIC ANALYSIS

CHAPTER III

ECONOMIC ANALYSIS

In the economic analysis of solar energy, we seek to minimize net costs of the energy component of a building or facility by optimizing the trade offs between the owning and operating costs of a solar energy system vis-a-vis conventional energy system. First we discuss the basic concepts and methods of economic analysis and then the major components of costs and savings associated with various solar energy systems.

3.1 METHODS OF ECONOMIC ANALYSIS

When investment costs are high and resulting benefits are distributed and changing in amount overtime - as they are for most applications of solar energy - it is reasonable to make thorough comparisons of lifetime costs and savings before undertaking an investment. "Life-cycle costing" is a method of economic evaluation that is generally appropriate for evaluating an investment whose principal benefits occur in the form of cost savings. This is done by measuring relevant period of time, taking into account the time value of money. This method means the summing of acquisition, maintenance, repair, replacement and energy costs over the life-time of the investment. The investment that has the lowest total life-cycle cost while meeting the investor's objectives and constraints is the preferred investment.

Another widely used method of evaluation, the payback method, does not take into account costs and savings over the entire life of an investment. Even though the payback method gives an incomplete evaluation, it is relevant because of its widespread use. This method finds the period of time that is expected to elapse before cumulative savings from an investment in solar energy will offset the investment costs. In the cases, where a fast turnaround on an investment is required, the payback method may provide useful information.

(i) Life-Cycle Costing Method

This method calculates the total present value (PrV) or the annual values of the life-time rupee costs associated with each alternative energy system under consideration. The alternative with the lowest PrV is more economical, provided it meets other requirements and fulfils other constraints of the investor.

Following is a formula for calculating, the total life-cycle costs associated with owning and operating any energy system (in terms of present value rupee):

$$PrV = I - (V_n a^n) + \sum_{j=1}^{n} a^j (M_j + R_j) + \sum_{k=1}^{H} \sum_{j=1}^{n} P_k Q_k b^j \qquad \text{......(3.1)}$$

where PrV - total present value, life-cycle costs, associated with a given energy system

I - total initial costs associated with the energy system, including design, purchase, installation, building modification, and the value of useful building space lost

V_n - residual or salvage value at year n, the last year in the evaluation.

a^j - present value formula computed for a designated year from j=1 to n, interest rate r and discount rate d; i.e., $a^j = [(1+r)/(1+d)]^j$

M_j - maintenance costs in j-th year

R_j - repair and replacement costs in j-th year

P_k - the initial price of the kth type of conventional energy for energy types k = 1 to H

Q_k - the required quantity of the kth type of conventional energy (taking equipment efficiencies into account).

b^j - present value of an amount in the jth year, escalated at a rate e_k, where k denotes the kth type of energy, and discounted at a rate d i.e. $b^j = [(1 + e_k)/(1 +d)]^j$

The life-cycle costing method is effective for determining whether a solar energy system is expected to reduce the total life-cycle costs of the energy components. As long as life cycle costs continue to decline as the size of the solar energy system is increased, it pays to increase the size of the system, other things being equal. The life-cycle costing method, however, is not always effective, because the method does not lend itself to ranking competing investments in terms of their economic efficiency and return on the investment.

(ii) Payback Method

This evaluation method measures the elapsed time between the point of an initial investment and the point at which accumulated savings, net of post-investment accumulated costs, are sufficient to offset the initial investment. The algebraic expression for determining discounted payback is the following:

$$\sum_{j=1}^{Y_r} a^{j} = I/S \qquad \ldots. \quad (3.2)$$

where Y_r = number of years to pay back when cash flows are discounted,

S = net savings per year

and other variables are as previously defined.

The payback method has the principal advantages of being easy to understand and familiar to a wide audience. Its appeal also lies in the fact that it allows emphasis to be given to the recovery of investment funds which is important if financial resources are available for only a short period of time or if there is considerable doubt as to the expected life or resale value of the major components of the investment. Often however, too much emphasis input on the length of the payback period, and not enough on overall expected profitability of the investment.

A principal disadvantage of the payback method is that, it does not provide a comprehensive evaluation of the profitability of an investment because it does not include those cash flows which occur after the point payback is reached. This shortcoming can be overcome to some extent by comparing the expected life of the major components of an investment with the estimated payback period to determine how long savings are expected to continue beyond the point that costs are recovered. On the whole the payback method provides no clear and reliable measure of overall economic performance for comparing alternative investments because an investment with a longer payback may be more profitable than an investment with a shorter payback.

(iii) Converting Cost and Savings to a Common Time and Common Measure

A necessary step in the economic evaluation method is the adjustment of the various cost items to an equivalent time basis. This adjustment is necessary because an investment in solar energy results in expenditures and savings that occur both in the present and in the future, and there is a difference between the value of a rupee today and its value at some future time. This time dependency of value reflects not only inflation but also the real earning potential of money. Removing inflation means measuring cash amounts in terms of the value of the rupee in a base year, usually the time at which the investment decision is made. There are several alternative ways of removing inflation from cash flows. Briefly, these are the following:

(1) Exclude inflation from the analysis at the outset by assuming that all cash flows are fully and evenly

responsive to inflation and therefore, remain constant in terms of base-year.

(2) Include expected price change in cash flow estimates and then remove inflation prior to discounting by the use of a constant price deflator based on past inflation rates or predicted ones,

(3) Include expected price changes in cash flow estimates and discount the cash flows with a discount rate that includes the expected rate of inflation, in addition to the investor's real potential earning rate.

The choice depends in part on the expected pattern of price change. Future prices of goods and services relevant to the investment may not respond fully and evenly to inflation in such a way that they remain fixed in constant rupee value. The future value of an item may rise at a rate faster than general price inflation. For example, forces of demand and supply are widely expected to increase the price of non-renewable energy sources faster than most other prices.

If future prices are fixed at current levels, or for some other reason, these prices are not expected to respond fully to inflation, we should follow the second or the third approach and discount the future annual payments with a discount rate that includes inflation. If future prices are expected to rise faster than general price inflation, the adjustment to constant rupees is usually made by the third approach. To discount cash flows to equivalent values at a common time, an appropriate interest formula, with properly chosen discount rate, is applied to each cash amount. The discount rate stipulates a minimum rate of return which must be recovered on an investment over and above other investment costs. A nominal discount rate is appropriate to use only in combination with cash flow which also includes inflation. Market rates of interest, such as the mortgage rate on building loans, are nominal rates.

Energy prices are widely expected to escalate faster than the rate of increase in the general price level. Hence energy prices are usually escalated in evaluating the economic performance of solar energy. The economic performance of the solar energy system tends to be quite sensitive to the choice of a fuel price escalation rate. Because of the considerable uncertainty about energy prices in the distant future, caution is advisable in specifying a long term rate of price escalation.

In evaluating the economic performance and life expectancy of a solar energy system there is little past experience on which we can base our estimates of an uncertain future,and the appropriateness of key assumptions is often questionable. Yet the results of an economic evaluation are dependent on the particular parameteric values and assumptions specified by the analyst. In many economic studies that have been made of solar energy, the simplifying assumption is made that the timing and values of most or all of the cash flows are known with certainty, that is deterministic life cycle cost models are used and decisions are based on single-value estimates of the parameters.

Now we specify the parameters using which we have carried the economic analysis of various low grade solar energy devices. Basically we have to specify the three parameters i.e., the inflation rate, the interest rate and the discount rate. While specifying these parameters we should try to be as realistic as possible and should also keep in mind that any change in these parameters would result in suitable changes in the analysis, method of analysis remaining same. While fixing the inflation rate we take the averaged out inflation rate for the last fifteen years. The wholesale price index for all commodities (Base 1981 - 82 as 100) stood at 300.6 during the week ending April 28, 96. This means a price increase by a factor of 3 in 15 years or an averaged out inflation rate of 7.6%. We, therefore, take the averaged out inflation rate to be 8% per annum by rounding off the inflation rate obtained above. The interest rate is taken to be 8%, which is the average value of the interest rates corresponding to 'Savings Account' and to 'Term Deposits' in a bank. The discount rate we take to be 10% per annum. When we take these factors into account, the present value (PrV) of Rs. 100/- to be spent / received after n years will be

$$\left[\frac{1 + 0.08}{1 + 0.10}\right]^{n} \text{x } 100 \qquad \ldots(3.3)$$

This obviously implies that if we have to spend Rs. 100/- every years for N years, PrV works out to be

$$100 \sum_{n=1}^{N} \{(1+0.8)/(1+0.10)\}^{n} \qquad ...(3.4)$$

As we need to do the economic analysis for a number of devices and for different periods of time, it will be useful to tabulate these factors for various values of n and N. This is done in Table 3.1 for periods upto 25 years. This table also gives the coefficients a^{j}, Eq. (3.1).

Table 3.1. Factors used in economic analysis. Here

$a = (1.08/1.10) = 0.9818$

n (yrs)	a^{n}	N (yrs)	$\sum_{n=1}^{N} a^{n}$
1	0.982	1	0.982
2	0.964	2	1.946
3	0.946	3	2.892
4	0.929	4	3.821
5	0.912	5	4.734
6	0.896	6	5.630
7	0.879	7	6.509
8	0.863	8	7.372
9	0.848	9	8.220
10	0.832	10	9.053
11	0.817	11	9.870
12	0.802	12	10.672
13	0.788	13	11.460
14	0.773	14	12.233
15	0.759	15	12.993
16	0.746	16	13.738
17	0.732	17	14.470
18	0.719	18	15.189
19	0.706	19	15.895
20	0.693	20	16.588
21	0.680	21	17.268
22	0.668	22	17.936
23	0.656	23	18.591
24	0.644	24	19.235
25	0.632	25	19.867

With this back ground we shall present the economic analysis of various low grade solar energy devices in the remaining sections of this chapter.

3.2 DRUM WATER HEATER

Drum Water heaters have been discussed in See 2.1. The finned type costs Rs. 1100/- while the unfinned type costs Rs. 1000/-. The installation cost is Rs. 150/-. As seen in Table 2.1, both these varieties produce 80 litres per day of hot water at a temperature which is nearly 30°C more than the ambient temperature. In terms of energy this is equal to:

$$80,000 \times 30 = 2400 \text{ Kcal} \qquad \ldots(3.5)$$

which comes to 2.79 KWH per day and means an energy saving of Rs. 1528/- per year. The economic analysis of the drum water heater is presented in Table 3.2 taking the drum water heater to be an add-on system resulting in 80% of

Table 3.2 Economic Analysis of a finned drum water heater (Add-on)

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 10 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
Drum Water Heater + Geyser	6250	306	50	3223	2500	2080	7393	1
Geyser	5000	1528	25	14059	2250	1872	17187	-

energy saving, there being nearly 300 sunny days in a year and the analysis is done over a period of 10 years, assumed to be the life of the drum water heater.

3.3 SOLAR WATER HEATING SYSTEM AT BITS

The solar water heating system installed at BITS to supply hot water to hostels, messes and the guest house has been discussed earlier (See 2.3 and App. II). In this section we shall take up the economic analysis of this system. This will be done separately for the case of hostels where the system is a stand-alone system and for the messes and guest house where it is an add-on system. The system consists of 85 units at a total cost of Rs. 38,17,000/- and provides 53,800 litres of hot water per day. The maintenance cost of the system is Rs. 1,25,000/- per year and it results in energy saving to the tune of Rs. 5,00,000/- per year and has a salvage value of Rs. 7,57,000/- after 15 years. For the purpose of economic analysis we prefer using all these costs per unit on an averaged out basis i.e.,

Total cost = Rs. 44,906/-

Maintenance Expenditure = Rs. 1,470/- per year.

Energy Saving = Rs. 5,882/- per year

Amount of hot water produced = 633 lit/day

Salvage value after 15 year = Rs. 8,906/-

(a) A stand-alone SWH unit

A stand alone SWH unit may be suitable for the hostels where hot water is needed only for taking bath. Each unit of the SWH system serves on an average 30 students in two wings of hostel. Normally, there are 3 bath rooms in each wing and hence we need 6 geysers, each costing Rs. 5000/- approximately, to supply hot water in all the bath rooms of the two wings using electricity. Table 3.3 gives a comparison between the two systems. From this analysis it follows that in spite of the higher installation cost,the stand-alone SWH unit pays from itself in 11 years and gives a net saving of Rs. 44,297/- (PrV) over an estimated 15 years life span.

(b) An add-on SWH unit

In messes and in guest house the SWH unit can only be used as an add-on unit because at times we may not be able to get hot water from SWH unit. Same is the situation in a house where we want to ensure regular supply of hot water for taking bath, cleaning utensils and washing clothes. Before carrying out the economic analysis we have to work out the

Table 3.3 Economic Analysis of a stand alone SWH unit

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 10 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
SWH Unit	44,906	-	1470	19,100	8,906	6,760	57246	11
Geyser	30,000	5,882	150	78,374	9,000	6,831	101,543	--

extent we have to depend on the geyser system for our hot water needs. Here we do a typical calculation of this type.

Let us take a household of 4 members. It is assumed that the need of hot water per day is

60 litres at 60 °C

and 20 litres at 90 °C

and that the average ambient temperature is

15 °C for 6 months (Oct - Mar)

and 30 °C for 6 months (Apr - Sept.)

Thus our energy requirement per day will be

60,000 x 45 + 20,000 x 75 = 4200 Kcal ...(3.6)

Taking the efficiency of the process to be 0.8 we shall need 5250 Kcal/day, which is equal to 21,945 kJ or 6.1 KWH per day during Oct - Mar period and

60,000 x 30 + 20,00 x 60 = 3000 Kcal ...(3.7)

which comes to 4.4 KWh per day during Apr. - Sept. period. Thus, the average out energy requirement is 5.25 KWh per day throughout the year which means an annual bill of Rs. 2879/- @ Rs. 1.50 per KWH, if we use the geyser system alone.

When we use an SWH unit as add-on to geyser it will be reasonable to assume that all the requirement of water at 60 °C will be met by the SWH throughout the year and during the Apr. - Sept. period we can get even the hot water supply at 90 °C from the SWH unit. However, during Oct. - Mar. period we shall, in all likelihood, need the geyser for 90°C supply i.e., we would use

20,000 x 75 = 1500 Kcal

which comes to only 2.17 KWH per day i.e. an energy bill of Rs. 592/- in an year. This results in a saving of Rs. 2287/- in the electricity bill per year due to the add-on SWH unit.

Also in making a comparison, it will be proper to take the installation cost to be notionally 1/6th of the one given in Table 3.3 because we are presently talking of a single flat plate collector whereas there are 6 such collectors in an SWH unit. The economic analysis for this case is represented in Table 3.4.

3.4 BOX TYPE SOLAR COOKER

In this section we shall present the economic analysis of the box type solar cooker . While doing this it will be relevant to take into account the subsidies extended by the government to the LPG users, who reside mainly in urban areas, and to solar cooker users. Also it will be meaningful to compare the box type cooker with fire wood or kerosene ovens for the rural user.

(a) Box type Solar Cooker Vs. LPG (Subsidised)

An LPG user has to initially spend about Rs. 2000/-, including Rs. 900/- paid as the security deposit which carries no interest, and on an average uses one cylinder, costing Rs. 105/-, per month. In case a user wants to use a

Table 3.4 Economic analysis of an add-on SWH unit.

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 15 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
Flat Plate Collector+ geyser	12484	592	270	11200	2984	2265	21419	4
Geyser	5000	2875	25	37680	1500	1139	41541	-

box type cooker as add-on he can certainly do so and hope to do most of lunch cooking by the use of solar energy i.e., one can hope to save about 1/3rd of LPG usage making the gas cylinder last 1.5 months. Now the cost of a typical box type solar cooker costs Rs. 800/- making use of the subsidies offered by government. Table 3.5 gives this economic analysis.

Table 3.5. Economic analysis of box-type solar cooker & LPG (Subsidised)

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 15 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
Box type Solar Cooker & LPG Stove	2800*	840	100	12213	1400*	1063	13950	2-3
LPG Stove	2000*	1260	50	16938	1200*	911	18027	--

* Includes Rs. 900/- paid as the security deposit. This amount does not carry any interest.

(b) Box type Solar Cooker Vs LPG (unsubsidised)

Here we repeat the analysis given in Table 3.5 for the case when a solar cooker costs Rs. 1400/- and an LPG cylinder costs Rs. 175/- assuming that the government is neither providing an incentive (of Rs. 600/-) to buy a cooker and is also not subsiding the LPG cylinder purchase, other conditions remaining same. This analysis is presented in Table 3.6.

(c) Box type Solar Cooker Vs fire wood or Kerosene

In rural sector, people use either firewood or kerosene for cooking. An average house hold uses about 10 litres of kerosene every month on cooking which comes to about Rs. 500/- per year. As regards fire wood, sometimes it is purchased and at other times it is 'free' in the sense that it is cut from nearby trees. Thus, usage of firewood leads to large scale deforestation also which can be avoided by switching over to solar cooker. However, we are not considering this aspect in our economic analysis. Table 3.7 gives economic analysis of solar cooker Vs kerosene stove.

Table 3.6 Economic analysis of box type solar cooker & LPG (unsubsidised) .rm75

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 15 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
Box-type Solar Cooker + LPG Stove	3400*	1575	100	21763	1400*	1063	24100	3-4
LPG Stove	2000*	2100	50	27935	1200*	911	29024	--

Table 3.7 Economic analysis of box type solar cooker Vs Kerosene Stove.

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 15 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
Box-type Solar Cooker + Kerosene Stove	100	33	75	3694	250	208	4486	7 - 8
Kerosene Stove	200	500	25	4753	50	42	4911	--

It should be noticed here that a longer payback period, in fact more than double of the earlier values, does not necessarily mean that it is less useful in rural context. The longer payback period is simply because of the rural energy needs (Rs. 500/- p.a.) being much lesser than the urban needs (Rs. 1275/- p.a.) and therefore the resultant savings are lesser as it is taken to be 1/3rd of the total energy consumed for cooking in each case.

3.5 SUNBASKET & SOLAR OVEN

The sunbasket and the solar oven are essentially used for cooking only and hence their economic analysis is similar to that of the box type solar cooker, except that we have to take the cost of these devices, which works out to be Rs. 500/- and Rs. 700/-, respectively, instead of that of the cooker which was Rs. 800/- (subsidised). All other considerations being same, we shall simply present the economic analysis of these devices in Table 3.8 on the lines of that presented in Table 3.5 earlier.

Table 3.8 Economic analysis of solar basket & oven.

System	Installation cost (Rs.)	Energy Exp. per year (Rs.)	Maint Cost per year (Rs.)	PrV of Energy Exp & Maint. (Rs.)	Salvage Value after 15 yrs (Rs.)	PrV of Salvage value (Rs.)	Net PrV (Rs.)	Pay back period (yrs)
Solar basket + LPG Stove	2600*	840	100	12213	1300*	987	13826	1-2
Solar Oven + LPG Stove	2800*	840	100	12213	1300*	987	14026	2
LPG Stove	2100*	1250	50	16938	1200*	911	18127	--

3.6 SOLAR STILL

A typical solar still, as described in Sec. 2.8, produces 5 - 6 lit of distilled water per square meter of surface area per day. In case we want to use a solar still to produce potable water for domestic use, it can be easily done by having a solar still of about 6 m^2 area as a typical household will need 30 - 35 lit of potable water per day. Therefore, if someone is residing in an area where potable water is not available easily, a solar still is really useful and no economic analysis need be done in this sort of situation.

On the other hand, if we consider the use of a solar still to produce distilled water for medicinal purposes, it can be easily seen that the solar still is extremely economical. A litre of distilled water costs Rs. 7/- or so and therefore a solar still, of 1 m^2 area, produces distilled water of Rs. 35/- worth every day i.e., about Rs. 10,500/- per year, taking 300 sunny days in a year. The cost of solar still being very less, it pays for itself within a few months.

No economic analysis is presented here for the coil type solar collector, solar dryer and the arrangement for space heating and cooling, because in all these cases the set ups have not gone through enough field trials and therefore there is not enough basis for making such analysis.

CHAPTER IV

DISCUSSIONS AND CONCLUSIONS

CHAPTER - IV

DISCUSSIONS AND CONCLUSIONS

We shall now attempt to draw certain conclusions having discussed various low grade thermal devices. Performance studies of these devices have been presented in Chapter II and the economic analysis for most of these has already been given in Chapter III. First we shall have rather general discussion on various factors affecting market penetration of solar energy devices and then come to the specific devices dealt with in this thesis.

As time passes, more and more people agree that solar energy does not soil the atmosphere and does not boil the hydrosphere, but they are anxious to know what it does to their energy bill . Now the only way to find out in a decisive way is to try it and to build various solar systems and see if these work to our advantage. When one looks around, one realizes that though once in a while you do find a solar water heater unit on the roof top of a house or a hotel or a solar cooker in the lawn of a house, yet these devices have not got wide spread acceptance. Some of the possible reasons behind this are:

(i) In quite a few applications we can use the solar energy device as add-on and not as a stand-alone unit. In photovoltaic applications this need arises because of the difficulties in sufficient storage of the energy. In solar water heating this need arises because all days are never sunny days and there may be even a spell of cloudy days, whereas in solar cooking this need is there because food will have to be prepared at times when there is no sun e.g. early mornings, night etc. This feature implies that an additional investment is involved in using solar energy devices most of the times.

(ii) A change in work habit is required before we can have more acceptability of solar devices. Thus, the housewife will have to go to the courtyard or roof, where the solar cooker may be kept, a number of times while the cooking is in progress. This may be thought to be rather inconvenient.

(iii) Some modifications in the existing buildings may be required so that solar energy can be effectively utilized. The houseowners may be reluctant to make the additional investment needed for these modifications.

(iv) The warnings about continued future availability of conventional energy sources are not taken seriously by most of the people as they tend to believe that these are exaggerated a lot. In the meanwhile large scale deforestation and depletion of natural oil and coal reserves continues to meet the ever growing energy needs of our society.

(v) Many times economic viability of a solar device is justified taking only the initial investment into account without taking inflation rate and discount rate into consideration.

(vi) People generally tend to depend much on the government and governmental agencies for bringing out any change whereas this change can only come when people become more aware of their individual responsibilities in bringing out such a change.

Out of the above factors, we have tried to eliminate at least one i.e. carrying out of economic analysis properly in Chapter III for specific set of values of interest rate, inflation rate and discount rate. One can easily do the numerical calculations for different inflation and discount rates by making tables similar to Table 3.1. As regards the other factors, we can only hope that with time more favourable circumstances will be created for better acceptability of solar energy devices. We should remember that we have not inherited this planet (the earth). We have only got it from our forefathers for passing on to the next generations in as much environmentally and ecologically balanced condition as possible. Now we shall try to discuss and draw specific conclusions about various solar energy devices discussed in Chapter II and III.

As mentioned earlier, BITS has gone in a big way to install solar water heaters for constant supply of hot water to students' hostels, messes and to the Institute guest house. The specifications of this system are given in App-II, the maintenance aspects were discussed in Chapter II and in Tables 3.3 and 3.4 we showed that the system will pay back for itself in a period of about 11 years for add-on units and in 4 years for stand-alone units. Thereafter, the system will result in substantial savings. What makes the whole system extremely useful are certain other reasons as given below:

(i) Using geysers in houses or guest houses or hotels may be practicable, but not in hostels. There is, on an average, one bathroom for 5-6 students and therefore for about 2500 students we need nearly 400-450 geysers, one for each bath room, which if used simultaneously will load the power lines to an extent for which these are not designed.

(ii) Another problem is how to ensure safety of the geysers installed in hostel bathrooms which are open day and night.

As a testimony to the above it may be mentioned that BITS hostels were built about 40 years back and students could get hot water in bathrooms only after the SWH system was installed some years back. Therefore, it follows that the comparison in Table 3.3 is valid only when both the alternative systems are feasible. From this discussion it is concluded that for certain applications the solar water heating system is to be preferred over the geyser system as it results in substantial savings. However, in other situations there is no alternative to it and we have to use SWH system if we want regular hot water supply.

As regards solar cooker, performance studies were presented in Chapter II and the economic feasibility has been established well beyond doubt in Chapter III through Tables 3.5 - 3.8. Inspite of this we really do not find solar cooker becoming increasingly popular. Rather there seems to be a decrease in its popularity. The reason for this is basically the inconvenience resulting from the fact that solar cooking is possible generally in the open. This is also compounded by the fact that with more and more women joining the workforce, there is an increasing need for cooking to be done rather quickly in the mornings and the poor sun takes a beating in the process.

Solar still is certainly very useful if we have no potable water around and brackish water is to be made potable. Also if we want distilled water regularly, solar still presents a very viable and attractive alternative. However, both these needs arise in a rather limited way and hence the limited advantages we get using this device.

Space and comfort conditioning normally will need structural changes in buildings. Hence if we design and construct new buildings in a way so as to get maximum advantages from solar energy, we can certainly decrease the energy consumption a lot. For this it is necessary that this technology passes on right from solar energy scientists and engineers to the common mason so that the new buildings can be cheaper as well as energy efficient but at the same time

APPENDICES

APPENDIX - I

LIST OF INSTITUTIONS/RESEARCH LABORATORIES

List of Institutions/Research Laboratories in India where solar energy research is being carried out:

S.No.	Institute/Lab.	Solar Devices *
1.	Alagappa University, Karaikudi	COLL
2.	Annamalai University, Annamalai Nagar	CONCOL(N),PUMP,STILL DRYER, HEATCOOL
3.	Bangalore Inst. of Tech., Bangalore	SOLPOND
4.	Bengal Engg. College, Howrah	COLL,HEATCOOL,CELL
5.	B.H.E.L., Delhi	PUMP
6.	B.H.E.L., Hyderabad	CONCOL (N) HEATCOOL
7.	B.I.T.S., Pilani	CELL, CONCOL (N,T), PUMP,STILL,DRYER,HEATCOOL, WATHEAT
8.	C.A.Z.R.I., Jodhpur	CELL,CONCOL (N) HEATCOOL,STILL,DRYER, WATHEAT COOKER, HEATCOOL, WATHEAT
9.	C.E.E.R.I., Pilani	CELL
10.	C.E.L., Sahibabad	CELL
11.	C.E.R.I., Karaikudi	STILL, COLL, COOKER
12.	Ch. Charan Singh Haryana Agri. Univ. Hisar	AIRHEAT
13.	C.G.C.R.I., Calcutta	CELL

* Legend is given at the end of the appendix.

S.No.	Institute/Lab.	Solar Devices
14.	C.M.E.R.I., Durgapur	PUMP, DRYER
15.	C.S.M.C.R.I., Bhavnagar	STILL, COOKER, PUMP, COLL
16.	Hindustan Brown Bovery, Baroda	PUMP, WATHEAT
17.	I.A.C.S., Calcutta	STILL, COOKER, CELL
18.	I.I.Sc., Bangalore.	FRELENS, WIMILL
19.	I.I.T., Bombay	CELL, COLL, CONCOL (N,T) DRYER, HEATCOOL
20.	I.I.T., Delhi	CELL, CONCOL(N), PUMP, STILL, FRELENS WATHEAT, AIRHEAT, HEATCOOL, COOKER, SIPH
21.	I.I.T., Kanpur	CELL, PUMP, DRYER, HEAT COOL
22.	I.I.T., Kharagpur	STILL, HEAT COOL, CELL
23.	I.I.T., Madras	CELL, CONCOL(N), HEAT COOL
24.	Inst. of Tech. B.H.U., Varanasi	CELL
25.	Jadavpur Univ., Calcutta	COLL, CELL, HEAT COOL
26.	Jawahar Lal Nehru Agri. Engg. Univ., Jabalpur	DRYER, HEATCOOL
27.	Jyoti Ltd., Baroda	WATHEAT, HEAT COOL, CONCOL(N,T)
28.	Kakatiya Inst. of Tech. & Sci., Warrangal	INSOL, COLL
29.	L.D. Engg. College, Ahmedabad	WATHEAT
30.	Madurai Kamraj Univ., Madurai	COOKER, HEATCOOL

S.No.	Institute/Lab.	Solar Devices
31.	Maland College of Engg., Hasan	STILL, HEATCOOL
32	Maharashtra Energy Dev. Agency, Bombay	CELL
33.	National Instruments Ltd. Calcutta	INSOL
34.	N.P.L., Delhi	CELL, COOKER
35.	Punjab Agriculture Univ., Ludhiana	CONCOL(N), COOKER, HEATCOOL
36.	Rabindra Mahavidyalaya Hooghly	CELL
37.	Raj. Agri. Univ., Udaypur, (Bikaner Campus)	CELL
38.	Raja's Govt. Arts College, Pudukottai, (TN)	COOKER
39.	R.E.C., Warrangal	INSOL, COLL
40.	Sah Industrial Research Inst. Varanasi	CELL
41.	S.P.R.E.R.I., Vidyanagar	STERIL, HEATCOOL
42.	Solar Energy Centre, DNES, New Delhi	CONCOL(N), FRELENS
43.	S.S.P.L., Delhi	CELL
43.	Sri Ramakrishna Missian Vidyalaya Arts & Sc. College, Coimbatore	CELL, COOKER
44.	Sri Venkateswara Univ., Tirupati	CELL
45.	T.E.R.I., Pondicharry	SOLPOND, HEATCOOL
46.	Univ. of Kalyani, Kalyani	CELL
47.	Univ. of Poona, Pune	CELL
48.	University of Roorkee, Roorkee	WATHEAT, HEATCOOL, AIRHEAT
49.	Visvesvaraya R.E.C., Nagpur	HEATCOOL

Legend:

AIRHEAT - Air Heater

CELL - Solar Cell (PV Applications)

COLL - Solar Thermal Collectors

CONCOL(N),(T) - Solar concentrators and Collectors (Nontracking), (Tracking)

COOKER - Solar Cooker

DRYER - Solar Dryer

FRELENS - Fresnel's Lens

HEATCOOL - Heating and Cooling (Including Refrigeration) and Air Conditioning.

INSOL - Solar Insolation Measurments

PUMP - Solar Pump

SIPH - Solar industrial Process Heat

SOLPOND - Solar Pond

STILL - Solar Still

WATHEAT - Solar Water Heater

WIMILL - Wind Mills

APPENDIX - II

SOLAR WATER HEATER SYSTEM AT BITS

A massive project was undertakes by BITS to install a solar water heater system with an overall capacity to supply 50,500 litres of water at 60°C and 3300 litres of water at 90°C per day to BITS hostels, guest house and messes which works out to be about 20 litres of hot water /student/day, sec. 2.3. This system was preferred over the forced flow system because it does not require any kind of fuel. However, in such a system it is necessary to keep the cold water tank at about 8′ height from the surface level. Table A-1 gives other technical specifications of such SWH units. The system is found to give hot water having temperature in the range of 50 - 70°C during different months of the year.

The economics of the system is given in Table A-2, the life span of the system being 15 years and the pay back period being 6 to 7 years only. The system results in annual energy saving to the tune of Rs. 5,00,000/-. Annual maintenance cost of the system is only Rs. 1,25,000/-which arises mainly because of descaling, as discussed in See 2.3.

TABLE A-1

Technical Specification of the Solar Water Heating System

Collector Specifications

a) Overall collector dimensions : 1.014m x 2.116m

b) Effective absorber area : 1.94 Sq.m.

c) Collector housing (material & thickness : FRP 3mm

d) Glazing material & thickness : Tempered Glass, 4mm

e) Transmitivity of glazing : 85%

f) Absorber material & thickness : Copper, 0.21mm

g) Type of absorber & absorptivity : Selective, 95%

h) Absorber emmissivity : 20%

i) Riser material, size, thickness & Nos. : Copper, 12.5mm, 26 SWG, 9 Nos.

j) Header material, size & thickness : Copper 25 mm, 22SWG

k) Method of bonding : Soldering

l) Sealing of collector : Neoprene Rubber pasted

m) Bottom/side insulation material & thickness : Resin Bonded pads/Spintex 300/P.U. Foam (Al.foil to cover insulation)

n) Hydraulic test pressure : 3.5 Kg/Sq. cm.

o) Collector support material : M.S.

STORAGE TANK

a) Material of construction & thickness : M.S. 3mm thick (For mess where systems to be used for cooking purposes, S.S. tank of 19 to 12 SWG).

b) Details of corrosion protection : Epoxy Coating inside the tank

c) Insulation material & thickness : 100mm thick Resin Bonded Pads/Spintex 300

d) Cladding material & thickness : 28 SWG G.I. Sheet upto 250 lpd & A1.24 SWG for more than 500 lpd systems.

INSTRUMENTATION

a) Water meter : Appropriate size (Paramount Dashmesh)

b) Strainer : Appropriate size (Paramount Dashmesh)

c) Temperature gauges : One dial type

d) Non-return valve : Appropriate size.

INTERNAL PIPING

a) Material : G.I.B Class as per IS-1239

b) Insulation material & thickness : P.U. Pipe Sections/ Resin bonded pads

c) Cladding material & thickness : A1., 26 SWG

TABLE A-2

The economics of the SWH systems installed at BITS.

BASIC DATA

1) Litres of hot water delivered per day (average) : 1) 50,500 at 60°C
2) 3,300 at 90°C

2) Average rise in temperature : 1) 35°C
2) 65°C

3) Approximate no. of days of operation (excluding vacation/monsoon days) : 210 days/year

4) Total cost : Rs. 38,17,100/-

5) Life of the systems : 15 years

6) Salvage value after 15 years : Rs. 7,57,000/-

7) Annual maintenance : Rs. 1,25,000/-

8) Annual energy generation/saving : Rs. 5,00,000/-

9) Interest rate of discounting the cost of the project : 10%

ECONOMIC PARAMETERS

1) Pay back period : 6-7 years

2) Net present value : Rs. 25,87,278/-

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