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SOME INVESTIGATIONS ON FLAT-PLATE SOLAR WATER HEATER

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PREFACE

This dissertation entitled "Some Investigations on Flat-Plate Solar Water Heater" has been carried out in the school of Theoretical and Environmental Science, Jawaharlal Nehru University, New Delhi-110057. The work is original and has not been submitted in part or in full for any degree or diploma of any University.

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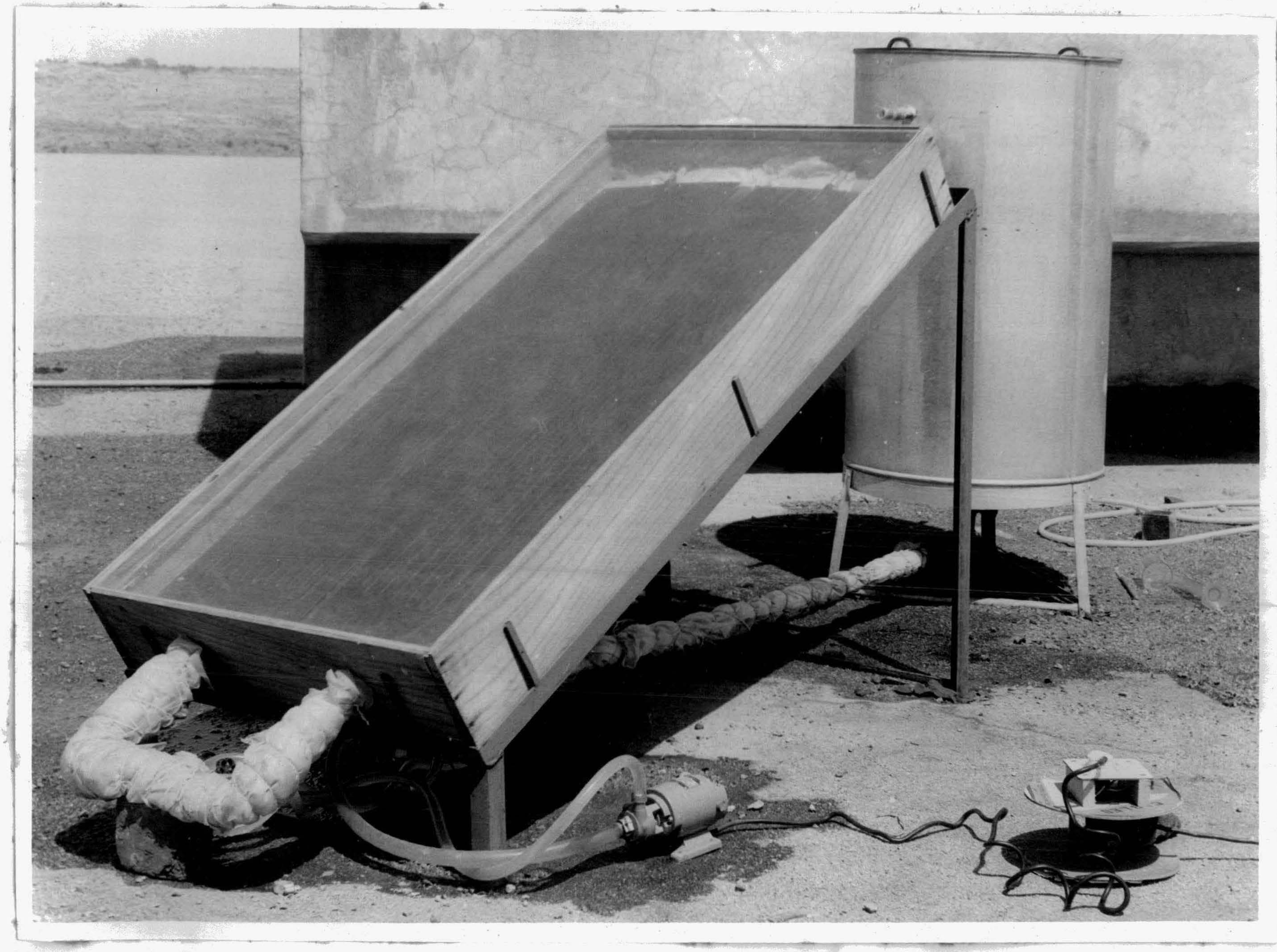

Fig.(i): CONSTRUCTED FLAT PLATE SOLAR WATER HEATER

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CHAPTER ONE

INTRODUCTION

In view of ever increasing energy needs, fast depleting fossil fuels and the pollution hazards associated with the burning of fossil and nuclear fuels, a renewed interest has come in the research and development works for the utilization of solar energy. The solar energy is the primary source of energy from which fossil fuels, wind energy, tidal energy, hydropower etc., are derived. This itself is derived from thermonuclear reactions taking place inside the sun. It comes from the sun in the form of electromagnetic radiation. Above the earth's atmosphere, its spectral distribution is close to that of a blackbody at $6000^{o}K$ and has average intensity equal to 1.3 KW/m^2. The intensity of these radiations as received on earth's surface is reduced and spectral distribution modified depending upon the nature and distribution of particulate matter, clouds etc., and the length of the path traversed by these radiations in the atmosphere. In addition, there are seasonal and diurnal variations of the intensity as received at any location. It happens that our country is blessed with a tremendous amount of solar energy. (e.g., the integrated daily average intensity received on a horizontal surface in Southern and Central India is about 4.5 $\frac{KWh}{m^2}$ with daily incidence exceeding $\frac{7\ KWh}{m^2}$ at times) and therefore efforts are needed for its harnessing.

There are essentially three approaches that have been followed for converting the solar energy into usable energy. These are 1) utilizing the thermal energy of these radiations 2) converting solar energy directly into electrical energy using solid state devices and 3) using photosynthesis and biological conversion process. The thermal devices have better cost benefit ratio than others and have already been developed for providing hot water for household purposes, heating and cooling of buildings, drying of agricultural produce, solar distillation, solar pumps for lifting water from deep wells for irrigation purposes etc. The central part of these devices are solar energy collectors. The flat plate type solar energy collector is the most commonly used collector and has been the subject of study for several years. Still efforts are needed to enhance its efficiency and reduce its cost so that it becomes commercially acceptable.

The flat plate solar energy water heater essentially consist of 1) solar energy absorbing surface, usually metal surface coated with selective coating 2) channels or tubes attached to absorbing surface so that the collected heat could be extracted by the flowing fluid (usually water) 3) insulation at the back of absorber surface to reduce conductive loss from the absorber and 4) cover at the top of the absorbing surface to reduce convective and radiative losses from the absorber. The essential parts of flat plate solar energy collector is shown in fig (I). The principle involved for energy collection optimization is straight forward. The heat absorbed by the collector plate should be maximized while the heat dissipated from it must be minimized. Selective surfaces have been developed (see tableA1) for absorbing most of incident solar radiations and emitting (or radiating) small amount of energy. This is possible since the wavelength region of the two properties do not overlap. Several cheep insulating materials are available which can be used for supporting the absorber so that the conduction losses are minimum. Convective and radiative losses can be minimized by various methods. Among these the most notables are i) use of selective surfaces that possesshigh ratio of solar absorptivity to infrared emissivity (6,10,20), ii) employment of diurnal tracking to minimize high reflection loss due to large incidence angles on glass covers (18) iii) suppression of natural convection that can be accomplished by evacuation (15), partition of air space into cells or even restraining air flow by addition of radiation transmission materials (4,8), and iv) use of multiglass covers and high solar transmission glasses (17). However, there have been some inherent difficulties in achieving optimization. e.g., use of cellular structures or multiglass covers not only reduce convective losses but also reduce the incident radiation energy on the absorber, these are technical difficulties in having flat plate collector with glass or plastic cover even partially evacuated etc.

Several kind of absorber plate has been used in the fabrication of solar water heaters. The following are the major types: 1) Bonded sheet type, 2) Soldered tube type, 3) Clamped tube type, 4) Rectangle tube type, 5) Corrugated sheet with flat plate, 6) Corrugated sheet with corrugated sheet coupled at opposite crests, 7) Corrugated sheet with corrugated sheet coupled at like crests and 8) Built in storage type absorber.

It may be mentioned that the absorber panel must permit effective transfer of heat from the absorber surface to the heat transfer fluid (water). It should be of low cost, corrosion resistant suitable for application of selective coating and permit ready connections to external pipings. These requirements are met by aluminium roll bonded panels which have become available (from A.J. Electronics, Poona) in the country only recently (1974). Using these panesls of appropriate sizes so that we have i) uniform flow distribution throughout the panel and 2) high efficiency for transferring the absorbed heat to the flowing fluid, a solar water heater has been fabricated. This is shown in fig. (i). Studies on these have been conducted by measuring the amount of heat collected at different flow rates. In particular the effect of variation of cover spacing and number of covers have been stuided and analysed.

The plan of presentation is the following. In Chapter II we discuss various processes which enter in the solar energy collection phenomena. In particular, we describe nature and availability of radiant energy, various processes which affects its intensity and spectral distribution. Moon's classical model has been outlined which can be used for a rough estimate of incident energy. Solar radiation data is usually recorded on horizontal surfaces by various metereological stations. We have described, how it can be used to calculate intensity at inclined surfaces. Transmission and reflection from glass and plastic covers for various angles of incidence are described. Mechanism of heat loss in one cover and two cover collector system is described and empirical formulas are given which can be used to compute theoretical values of various loss coefficients. Summary of principles involved in reducing heat losses by the use of honey-comb structures, partial vacuum and selective coatings is given.

In Chapter III we derive Hottel - Whillier - Bliss equation which governs the energy collection when the collector operates under steady state condition. The efficiency of heat collection then depends upon three factors namely F_R - the heat removal factor, U_L - the overall heat loss coefficient and $(\tau\alpha)_e$ - the transmission absorption product. We describe a methods of measuring these parameters alongwith their dependences. We also include a discussion of limitations of HWB equation and a comment on the Takor's method of testing of solar collectors.

In Chapter IV, we describe the construction details of flat plate collector and give experimental results of various studies which we have made on it. In particular, we have given experimental results of the amount of heat collected at two different flow rates of water through the collector for collector having three different cover systems namely (1) one glass cover separated by 6 cms from the absorber, (2) one glass cover separated by 9 cms from the absorber, and (3) two glass covers separated by 6 cms and 9 cms from the absorber. Our results has shown very clearly that the efficiency of collection increases considerably if the flow rate through the collector is increased from say 6 litres/hour to 10 litres/hour. Finally, we have given the cost break up of the fabricated collector and have calculated the average value of the cost of heat collected by it.

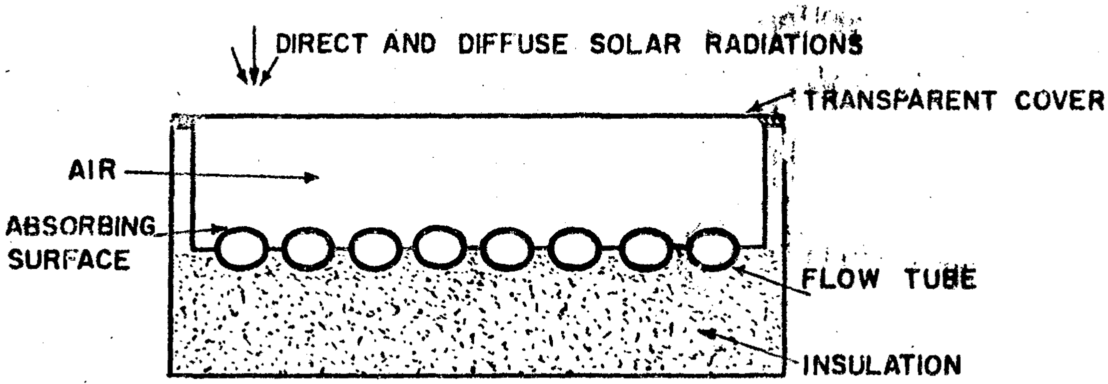


FIG. BASIC FLATE PLATE SOLAR COLLECTOR

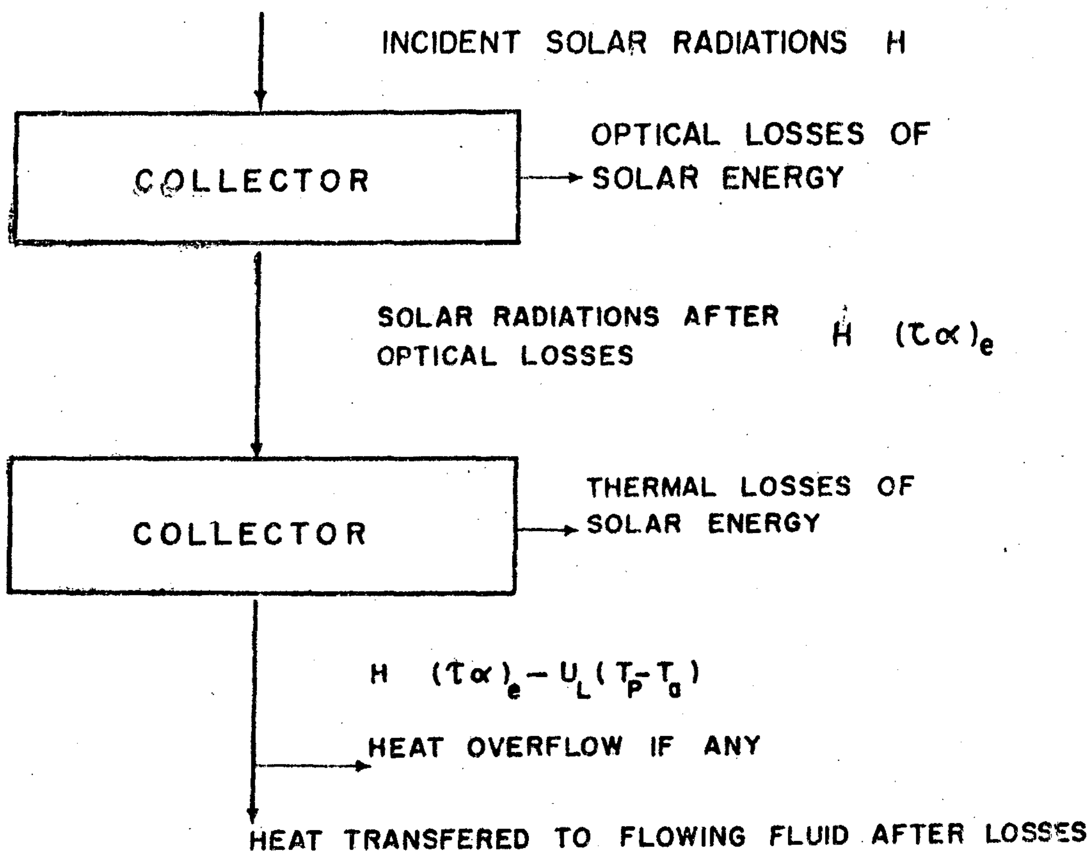


FIG. I SCHEMATICS OF SOLAR ENERGY PROCESSES OF FLAT PLATE COLLECTOR

CHAPTER TWO

SOLAR ENERGY COLLECTION PHENOMENON

The schematics of solar energy collection phenomenon for a solar water heater operating under steady state condition is shown in figure (I). At any instant of time out of the incident radiant energy, a part is lost due to various optical and thermal losses. The remaining is collected as heat which is a measure of its thermal efficiency.

2.1 Incident Solar Radiations

Before making any attempt to harness solar energy as a source of power, it is necessary to have an accurate knowledge of its availability and characteristics e.g., intensity, spectral distribution, diurnal and seasonal variations. The incident radiant energy called insolation, above the earth's atmosphere (about 150 km from earth's surface) has a wavelength spectrum close to that of a black body at 6000°k. (as shown in fig 2.1.1) and its intensity is 1.94 cal/sq.cm/min. or equivalently 1358 watts/sq.m. This remains uniform throughout the year, the only variation is due to the slight ellipticity of the earth's orbit.

The solar energy reaching the earth's surface varies with latitude, season, time of the day and may change rapidly and discontinuously due to changes in local metereological conditions.

During the passage downwards through the atmosphere a part of the solar beam is reflected back into space mainly by clouds, another is scattered in all directions by molecules of dry air, water vapor and dust particles, some is absorbed by various molecules while the remainder is transmitted through the atmosphere which is received at the ground as beam or direct radiation. Some of the reflected and scattered radiation also reaches the earth as diffuse or sky radiation. Specifically, the x-rays and other very short wave radiations (ultraviolet radiations) of the solar spectrum are absorbed high in the ionosphere by atomic nitrogen and oxygen. The ozone layer about 25 km. from the earth surface plays a significant role in eliminating ultraviolet radiations and converting them into visible and infrared radiations.

At wavelengths longer than 2.5 μm due to strong absorption by CO_2 and water vapor, very little energy reaches the ground. Thus most of the incident energy reaching the earth surface has wavelengths between 0.29 μm and 2.5 μm.

The approximate model set up by Moon is very helpful in analyzing the attenuation in the atmosphere and in understanding and using solar energy data. Moon's model consists of the following. Scattering of solar radiation by air molecules occurs in accordance with the theory of Rayleigh which indicates that the scattering coefficient would vary approximately as λ^{-4} where 'λ' is the wavelength of the radiation. This has been experimentally verified and monochromatic transmission factor associated with atmospheric scattering can be written,

$$\tau_{a\lambda} = 10^{-0.0039\,\lambda^{-4}} \qquad (2.1.1)$$

where 'λ' is in μm, m = 1, and the barometric pressure is 760 mm.

For dust scattering, from particles that are much larger than air molecules and that vary in size and concentration from location to location, height and from time to time, Moon developed a transmission factor,

$$\tau_{d\lambda} = 10^{-0.00389\ \lambda^{-4}} \qquad (2.1.2)$$

where m = 1 and the average concentration of dust particles is 800/cm^3 at the ground.

Water vapor scattering for zenith sun and 20 m.m. of preciptiable water (the amount of water vapor in the air column above the observer) can be written as,

$$\tau_{w\lambda} = 10^{-0.0075\ \lambda^{-2}} \qquad (2.1.3)$$

The total effect of scattering on the beam radiation can be written as an approximation,

$$\tau_{\lambda s} = \left[(\tau_{a\lambda})^{P/760}(\tau_{d\lambda})^{d/800}(\tau_{w\lambda})^{W/20}\right]^{m} \qquad (2.1.4)$$

The transmission factor resulting from absorption is primarily dependent on ozone (at short wavelengths) and water vapor and CO_2 (at long wavelengths). Thus,

$$\tau_{a\lambda} = \tau(O_3)^{e/3.8}\ \tau(H_2O, CO_2)^{Wm/20} \qquad (2.1.5)$$

Therefore monochromatic transmittance for beam radiation is

$$\tau_{\lambda} = \tau_{\lambda}(s)\ \tau_{\lambda}(abs) \qquad (2.1.6)$$

It is seen that most of the incident energy on earth's surface has wavelength spectrum lying in the range $0.25\,\mu m \leq \lambda \leq 2.5\,\mu m$ about half being in the visible and the other half in the infrared region. Further the incident energy can be considered as made up of two parts a) beam component or direct radiations from the sun b) diffuse component. From the knowledge of the relative position of sun (which depends upon hour angle H, altitude 'A' and azimuth angle 'Z' of the sun) it is possible to determine precisely the angle of incidence of direct-beam component on any surface. For a given time and location the altitude and azimuth of the sun are given by the following expressions,

$$\sin A = \cos L \cos \delta \cos H + \sin L \sin \delta \quad (2.1.7)$$

$$\sin z = \frac{\cos \delta \sin H}{\cos A}$$

$$\text{or} \quad \cot z = \frac{\sin L \cos H - \cos L \tan \delta}{\sin H} \quad (2.1.8)$$

The angle of incidence on a horizontal surface would be $i_h = (90-A)$. Since surfaces sloped either north or south have the same angular relations with the sun, the angle of incidence i_b on a south or north facing surface is obtained by substituting (L-b) in place of 'L' in the relation where 'b' is the angle of slope of a surface kept in northern hámisphere. Thus,

$$\cos i_b = \cos (L-b) \cos \delta \cos H + \sin (L-b) \sin \delta \quad (2.1.9)$$

The angle of incidence on any sloped surface is given by,

$$\cos i_{b,\phi} = \sin b \cos A \cos (z-\phi) + \cos b \sin A \quad (2.1.10)$$

where 'b' is the zenith angle of the perpendicular to the slope and 'ϕ' is the azimuth angle from the south of the perpendicular. Note that $\phi = 0$ refers to a surface facing south.

Solar radiation on horizontal surface is being recorded by various metereological stations. For purposes of solar process design, it is often necessary to convert this data to that on a tilted surface. This can be done exactly for the beam component as below. Since

$$I_h(D,H) = I_n(H) \cos i_h \quad (2.1.11)$$

$$I_{b,\phi}(D,H) = I_n(H) \cos i_{b,\phi} \quad (2.1.12)$$

$$\frac{I_{b,\phi}(D,H)}{I_h(D,H)} = \frac{\cos i_{b,\phi}}{\cos i_h} \quad (2.1.13)$$

For a surface facing south R_b, is simplified and is given by,

$$R_b = \frac{\cos(L-b)\cos\delta\cos H + \sin(L-b)\sin\delta}{\cos L\cos\delta\cos H + \sin L\sin\delta} \qquad (2.1.14)$$

It is interesting to note that the ratio of the beam component received on the tilted surface to that on horizontal surface can be larger than one. In Appendix II we have calculated these for latitude 30°N for various values of declination (which refers to various times of the year) for surfaces facing south and inclined at angles 20°, 30° and 40°.

Although direct-beam sunshine is the major useful radiation, the brightness of the whole sky (diffuse component of intensity) adds a significant fraction. For example, for cloudless skies, this fraction arises from the radiation scattered by dry air and haze aerosols. Its magnitude varies considerably throughout the day. On an average cloudless day it amounts to about one sixth of the total insolation at noon and more than one third the total when the sun is at low altitudes. For a cloudless day sometimes, it is a good approximation to assume that diffuse radiations are distributed uniformly over a hemisphere. Then from the data of the intensity received on the horizontal surface, one can obtain the magnitude of diffuse component on any inclined surface using the following relation;

$$I_{b,\phi}(d,H) = I_h(d,H)\,\frac{(1+\cos b)}{2} \qquad (2.1.15)$$

where I_h (d, H) is the intensity of diffuse component on a horizontal surface. Thus the total intensity received on an inclined surface on a cloudless day can be obtained from the knowledge of direct and diffuse components on the horizontal surface.

$$I_{b,\phi}(H) = I_h(D,H)\,R_{b,\phi} + I_h(d,H)\,\frac{1+\cos b}{2} \qquad (2.1.16)$$

Here it may be mentioned that clouds exert a powerful influence in reducing the amount of radiations of both categories received at ground. Empirical equations for estimating solar radiations have been developed by various investigators by they yield very approximate values. Therefore it is always desirable to make use of measurements with suitably designed and well calibrated instruments to get the information about incident solar energy.

Energy received by a flat plate collector is maximum when its surface is normal to the sun's rays. As a result the loss of intensity caused by the radiation arriving at the horizontal surface at an angle can be reduced by tilting the receiver. Thus the collector surface should be tilted to such an angle that it is always normal to sun rays. But this cannot be achieved with a fixed installation because the altitude of the sun varies throughout the day and the declination varies over the year. To keep collector surface moving according to the movement of sun is highly inconvenient and not economical. Hence one has to choose some value for the tilt of the collector which permit maximum amount of energy interception over the period for which the collector is intended to be used.

One can determine the optimum tilt in the following way. Incident radiation on a horizontal and tilted surface is shown in fig (2.1.2). Total amount of hourly solar radiation incident upon any surface on a cloudless day is,

$$I_{b,\phi}(T,H) = I_h(D,H)\,\frac{\cos i_{b,\phi}}{\cos i_h} + I_h(d,H)\,\frac{1+\cos b}{2}$$

Total energy incident on the collector surface, in a given day is

$$E_T = 2\int_0^{H_0} I_{b,\phi}\,(T,H)\,dH \qquad (2.1.17)$$

From this one can obtain the optimum value of the tilt of the collector for receiving the maximum amount of energy. For example for a collector surface facing south this is given by,

$$b_{opt} = \tan^{-1} \frac{\int_0^{H_0} I_h(D,H)\,dH\;\frac{(\operatorname{Sin} L \operatorname{Cos}\delta \operatorname{Cos} H - \operatorname{Cos} L \operatorname{Sin}\delta)}{(\operatorname{Cos} L \operatorname{Cos}\delta \operatorname{Cos} H + \operatorname{Sin} L \operatorname{Sin}\delta)}}{\left[\int_0^{H_0} \frac{I_h}{2}(d,H)\,dH + \int_0^{H_0} I_h(D,H)\,dH\right]} \qquad (2.1.18)$$

Knowing the values of direct and diffuse solar radiation incident on a horizontal surface for the period of operation one can get the optimum angle of tilt for receiving maximum amount of radiant energy from equation(2.1.18)

(2.2) Optical Losses

Now let us consider what happens to the radiation that is incident on the solar collector. A part of it is reflected back from the surface of the cover. The coefficient of reflection is related to the refractive index of the material of the cover. The transmitted fraction (τ) of solar radiations through cover or covers of the flat plate collector depends upon 1) the angle of incidence of solar radiations 2) the wavelength of solar radiations 3) the number and thickness of covers of the collector unit. The fraction ($1-\tau$) of the incident solar radiations are thus lost through reflections from the covers and absorption by the covers. These losses are referred to as optical losses. The transmitted fraction of solar radiation through 'n' cover system can be approximated to the product of $\tau^{\lambda}_{r,n}(\theta)$ - the fraction transmitted because of loss due to reflection in the covers, and $\tau_{a,n}(\theta)$, the fraction transmitted because of loss due to absorption in the covers. i.e $\tau^{\lambda}_{n}(\theta) = \tau^{\lambda}_{r,n}(\theta)\,\tau^{\lambda}_{a,n}(\theta)$ (2.2.1)

The transmittance τ_ρ due to reflection for a single sheet is given by

$$\tau_\rho = \frac{1-\rho}{1+\rho} \qquad (2.2.2)$$

For a beam incident at an angle θ, the reflection coefficient 'ρ' becomes,

$$\rho = \frac{1}{2}\left[\frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} + \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \right] \qquad (2.2.3)$$

$\mu = \dfrac{\sin\theta_1}{\sin\theta_2}$ where θ_1 and θ_2 are the angles of incidence and refraction.

In addition to the reflection at glass air interface one has to reck with absorption by the glass covers also. If the length of path through the sheet is 'L' intensity of light I, and extinction coefficient 'K',

$$-dI = I\,K\,dL$$

The transmittance τ_a due to absorption alone becomes,

$$\tau_a = e^{-KL} \qquad (2.2.4)$$

For the combined effects of reflection and absorption by one sheet only, (for normal incidence)

$$\tau_1 = \frac{(1-\rho_\lambda)^2 e^{-KL}}{1-\rho_\lambda^2 (e^{-KL})^2} \qquad (2.2.5)$$

For small values of K and P

$$\tau_1 = \frac{1-\rho}{1+\rho} e^{-KL} = \tau_{1\rho}\,\tau_{1a} \qquad (2.2.6)$$

Considering 'n' covers and an angle of incidence 'θ'.

$$\tau_n^\lambda(\theta) = \tau_{\rho,n}^\lambda(\theta)\;\tau_{a,n}^\lambda(\theta) \qquad (2.2.7)$$

where,

and

$$\tau_{\rho,n}^\lambda(\theta) = \frac{1-\rho_\lambda(\theta)}{1+(2n-1)\rho_\lambda(\theta)} \qquad (2.2.8)$$

$$\tau_{a,n}^\lambda(\theta) = \exp(-n K_\lambda L \sec\theta) \qquad (2.2.9)$$

If $\theta = o$, u for normal incidence,

$$\tau_n(\lambda, 0) = \frac{1 - \rho_\lambda}{1 + (2n-1)\rho_\lambda} e^{-nK_\lambda L} \qquad (2.2.10)$$

The transmittance depends on the properties of materials used for transmitting solar radiations and the angle of incidence.

Materials capable of transmitting radiant energy are termed as diathermanous materials. The material most commonly used as a cover is glass. Transparent plastics are also used sometimes. Iron content (Fe_2O_3) in glass is of particular importance in its effect upon spectral transmittance. Figs. (2.2.3) shows this effect for four different percentages of Fe_2O_3. For the lowest percentage the transmittance rises to more than 90% in the near ultraviolet region, remains high and uniform throughout the visible and well into infrared region. As the Fe_2O_3 content rises to 0.15 percent, the overall transmittance is decreased, but it remains at a high level in the visible region. For maximum solar energy collection it is desirable to have the highest possible transmittance throughout the spectrum of incident radiations ie 0.3 μm to 2.5 μm. and it should be opaque to the radiations outward.

The effect of increased thickness of glass is shown in figure (2.2.3). In each instance increased thickness results in diminished transmittance with remarkable effect in the infrared and ultraviolet region. For low-iron glass increased thickness has an almost negligible effect. As the iron content increases, the effect of thickness also increases.

Angle of incidence also affect the transmittance of glass. Curves of calculated transmittances of systems of glass plates allowing for reflection and absorption losses are shown in figure (2.2.4)

Transparent plastics can also be used as cover plates instead of glass. They have some advantages over glass due to their toughness and flexibility relative to glass, the availability of many types in the form of thin sheets and films. Disadvantages are their relatively low resistance to scratching and abrasion, softening at high temperatures, turning yellow upon exposure to sunlight which make their long time durability uncertain. Spectral transmittance of some transparent plastics versus wavelengths are shown in figure (2.2.5).

Optical losses can be minimized by suitably selecting the materials for cover plates. Another method to reduce it is the use of V - corrugated inner cover instead of plane covers. The mechanism of achieving this is sketched in figure (2.2.2). In ease of flat surface inner cover, solar rays reflected from inner surface are reflected away from the absorber plate and hence are lost. In the V - corrugated inner cover reflected rays are reflected back towards the absorber plate and are therefore not lost. Studies made by the Waterloo research group (26) shows that thin teflon sheet can give the best performance in this regard.

2.3. Thermal Losses

The radiant energy absorbed by the absorber raises its temperature and consequently the absorber loses heat in various forms like radiation and convection of heat outward to the atmosphere and by conduction through the backside of the absorber into adjacent materials. In figure (2.3.1) we have indicated possible mode of heat transfer for one and two cover systems.

Amount of instantaneous heat lost from the absorber at temperature T_p, per unit area is given by, U_L (Tp - Ta) where U_L is the overall thermal loss coefficient given by $U_L = Ub+Ut$ (2.3.1)

Here the first term represents the backward heat loss and the second term accounts for the upward heat loss. For one cover system

$$U_b = \frac{Kin}{L} \quad (2.3.2)$$

and

$$U_t = \left\{ \frac{1}{kg} + \frac{1}{h^c_{p-c} + h^r_{p-c}} + \frac{1}{h^c_{c-s} + h^r_{c-s}} \right\}^{-1} \quad (2.3.3)$$

For two cover system,

$$U_t = \left\{ \frac{l_1}{kg} + \frac{l_2}{kg} + \frac{1}{h^c_{p-c_1} + h^r_{p-c_1}} + \frac{1}{h^c_{c_1-c_2} + h^r_{c_1-c_2}} + \frac{1}{h^c_{c_2-s} + h^r_{c_2-s}} \right\}^{-1} \quad (2.3.4)$$

In most of the collector designs backward heat loss coefficient is very small. The convective part of upward heat loss coefficient from pate to cover is due to natural convection currents. It is a complicated function of various factors such as 1) difference of temperature between plate and cover 2) Distance between the plate and the cover 3) Viscosity of air 4) Pressure of air in the space between the absorber and the cover 5) slope of the collector to the horizontal etc. Similar is true for the convective heat loss coefficient from one cover to another cover. Empirical relations determining the magnitude of various convective and radiative losses are given below.

For a collector inclined at an angle of 30^o to the horizontal, the convective loss coefficient from absorber tocover separated by 'd' cms is given by (11),

$$h^c_{p-c} = 1.14 \frac{(Tp - Tc)^{0.31}}{d^{0.007}} \left(1-0.0018 \frac{(Tp+Tc-10)}{2}\right) \quad w/m^2\,^oc \qquad (2.3.5)$$

where temperatures are expressed in ^oc.

The radiative heat transfer between absorber and cover (two infinite parallel plates) is given by

$$h^r_{p-c} = \sigma \left\{ \frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1 \right\}^{-1} (T_p^2 + T_c^2)(T_p + T_c) \qquad (2.3.6)$$

At the outermost cover the upward rate of energy transfer is,

$$q_u = h_w\,(T_cn - TA) + h^r_{cn-s}\,(T_{cn} - T_s) \qquad (2.3.7)$$

Where $h_w = 5.7 + 3.8v \frac{W}{m^2\,^oc}$ (2.3.8)

Here 'v' is wind velocity expressed in $\frac{m}{sec}$. and

$$h^r_{cn-s} = \sigma\,\varepsilon_{g_n}\,(T_{cn}^2 + T_s^2)\,(T_{cn} + Ts) \qquad (2.3.9)$$

where Ts is the sky temperature. It depends upon the humidity and ambient air temperature. It is given by (11)

$$T_{sky} = 0.0552\,T_{air}^{1.5} \qquad (2.3.10)$$

where T_{sky} and T_{air} are both in ^oK.

At thermal equilibrium, for one cover system, the upward heat losses from the absorber in to the cover is equal to that from the top surface to the atmosphere, i.e.,

$$h^c_{p-c_1}\,(T_p - T_{c_1}) + h^r_{p-c_1}\,(T_p - T_{c_1}) = h_w\,(T_{cn} - Ta) + h^r_{cn-s}\,(T_{cn} - T_s) \qquad (2.3.11)$$

For any given absorber-plate temperature, the upward heat loss can be decreased with the addition of more cover sheets. But this also reduces the solar energy input to the absorber plate.

Therefore, a suitable choice of the number of covers has to be made in designing collector.

The overall heat loss coefficient, can be determined theoretically from the knowledge of properties of materials used various operating temperatures at thermal equilibrium.

The convective heat loss between surfaces can be decreased by evacuating the space between them. Evacuating a flat plate collector to a pressure of 1.25 torr results in elimination of natural convection heat loss from the absorber. This mode of heat transfer then reduces to pure conduction through the air space between the absorber and the cover. The effect of the vaccum environment is especially pronounced when it is used in a collector having selective absorber surface, as combined radiative and convective losses is reduced.

Another method to minimize convection losses is to place a properly designed cellular structure (honeycomb structure) over a solar absorber. This can suppress thermal instabilities in the air space and achieve wavefront and wavelength selectivity. In a honeycomb structure, a large number of thin glass tubes are mounted on the collector. The mechanism of their action is as follows. Solar radiation incident upon the collector suffers reflection and a small amount of absorption losses from transmission through the cover glass and then they enters the honeycomb array. Depending upon the angle of incidence, the radiant energy encounters many times with cell walls on its passage to the absorber plate. At each encounter a portion of energy is transmitted essentially undeviated from the original direction, a smaller portion is reflected specularly and continues down toward the absorber, a small fraction is scattered by surface imperfections into upward and downward directions and a small fraction is absorbed. Thus the incident energy reaching the absorber is absorbed.

The honeycomb acts to suppress convection by confining the fluid (air) motion to walled cells. In a tilted array heated from the bottom, upward flowing hot air in the honeycomb is retarded by viscous shear on the cell walls and thermal energy in the air is drained by conduction to the cell walls. Lateral conduction through the cell walls and radiation exchange across the cell walls distribute this energy to the colder regions, and hence to the colder downflowing air, which lessens the buoyancey difference between the hot and cold air. Viscous shear also acts to slow the downflowing colder air.

Thermal radiation transfer from the hot absorber plate to the relatively cold cover glass is also reduced considerably by the presence of cell walls. Emitted photons from the absorber plate which encounter the cell walls are absorbed strongly because of their infrared wavelengths. The radiation from the cell walls is directed both upwards and downwards. The downward directed infrared radiant fluxes at the absorber plate and so reduces the net infrared radiation loss.

Cell walls create a path for heat conduction from the absorber to the cover glass and therefore should be made as thin as practicable. Thin walls also favor maximum transmission of incident solar radiation and minimize the volume of honeycomb material used. For a specified cell wall thickness it is advantageous to make the cell diameter large so as to maximize the transmission of solar radiation and minimize wall conduction. An extensive study has been carried by K.G.T. Holland etal (8) in this regard.

Radiative heat transfer can also be reduced by employing spectrally selective surfaces - reducing ε_p and ε_g by selectively coating the absorber surface and the glass surface with a coating which reflects for infrared radiation. ($\lambda \geq 3 \mu m$) An efficient coating is defined as having a high absorptance over the solar spectrum, but in addition having a low emittance to reduce thermal radiative heat losses. There are a variaty of techniques for separating solar selective coatings. 1) a coating which is absorbing over the solar spectrum, but which is transparent in the infrared. In this case the emittance is mainly controlled by the emittance of the substrate, which can be made very low by using a polished metal surface. 2) A careful control of surface roughness so that solar radiation suffers multiple reflection and is absorbed, while for longer wavelength radiation, the surface appears smooth and takes on the emittance of the base material. Properties of some selective surfaces for solar energy application are given in Appendix I

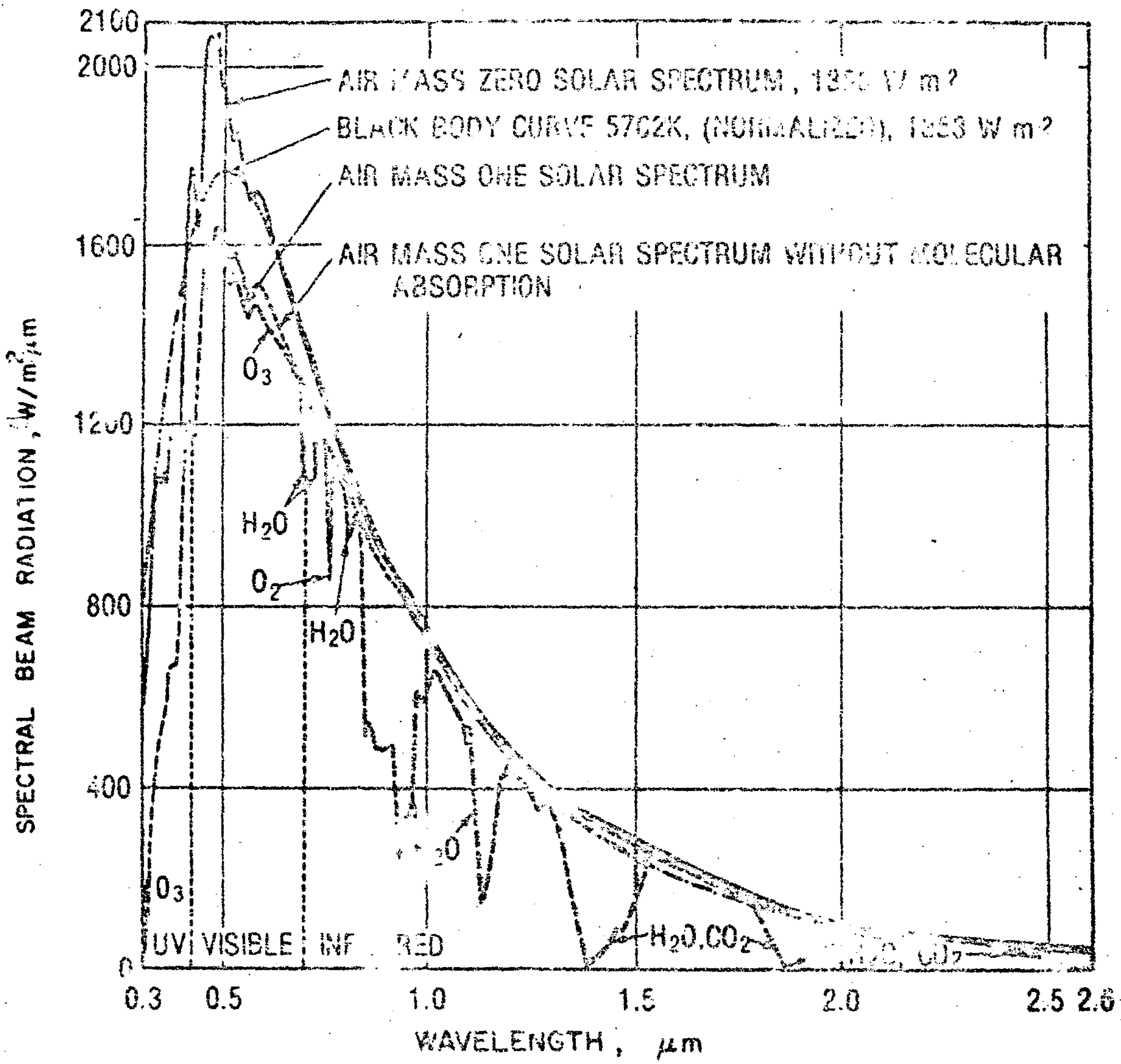


Figure 2.1.1 Solar spectral intensity for air mass zero and one.

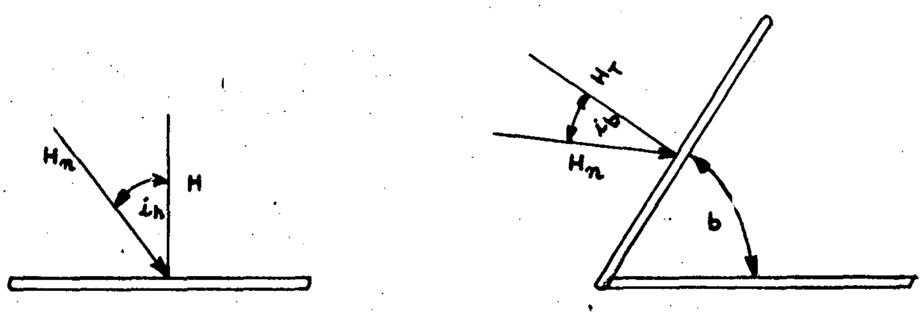


FIG. 2.1.2. RADIATION ON HORIZONTAL AND TILTED SURFACES.

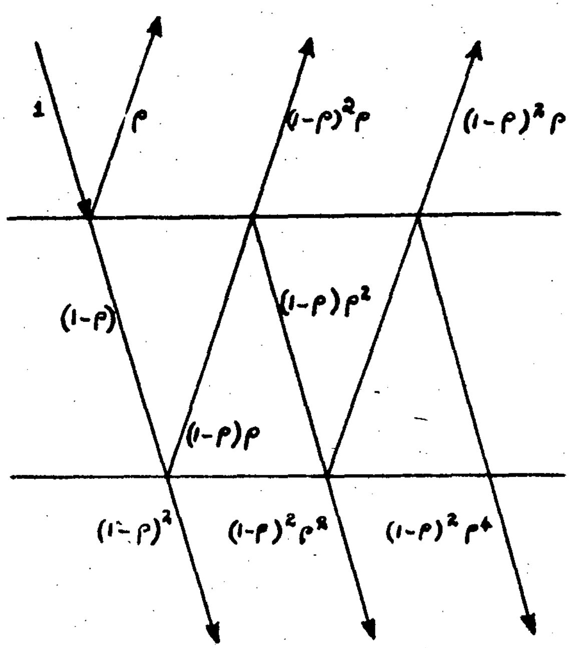


FIG. 2.2.1. ABSORPTION OF SOLAR RADIATION BY ABSORBER PLATE.

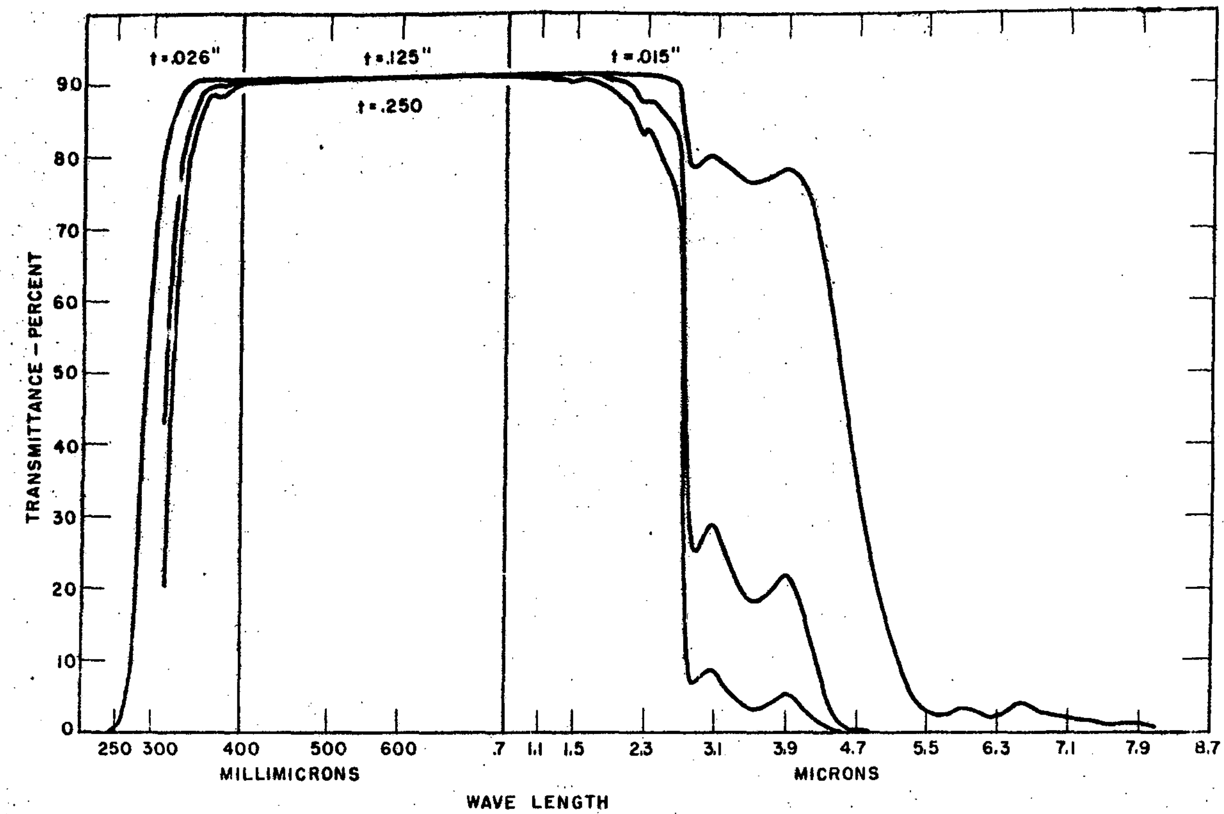


Figure 2.2a Spectral Transmittance of Glass Containing 0.02 Fe_2O_3.

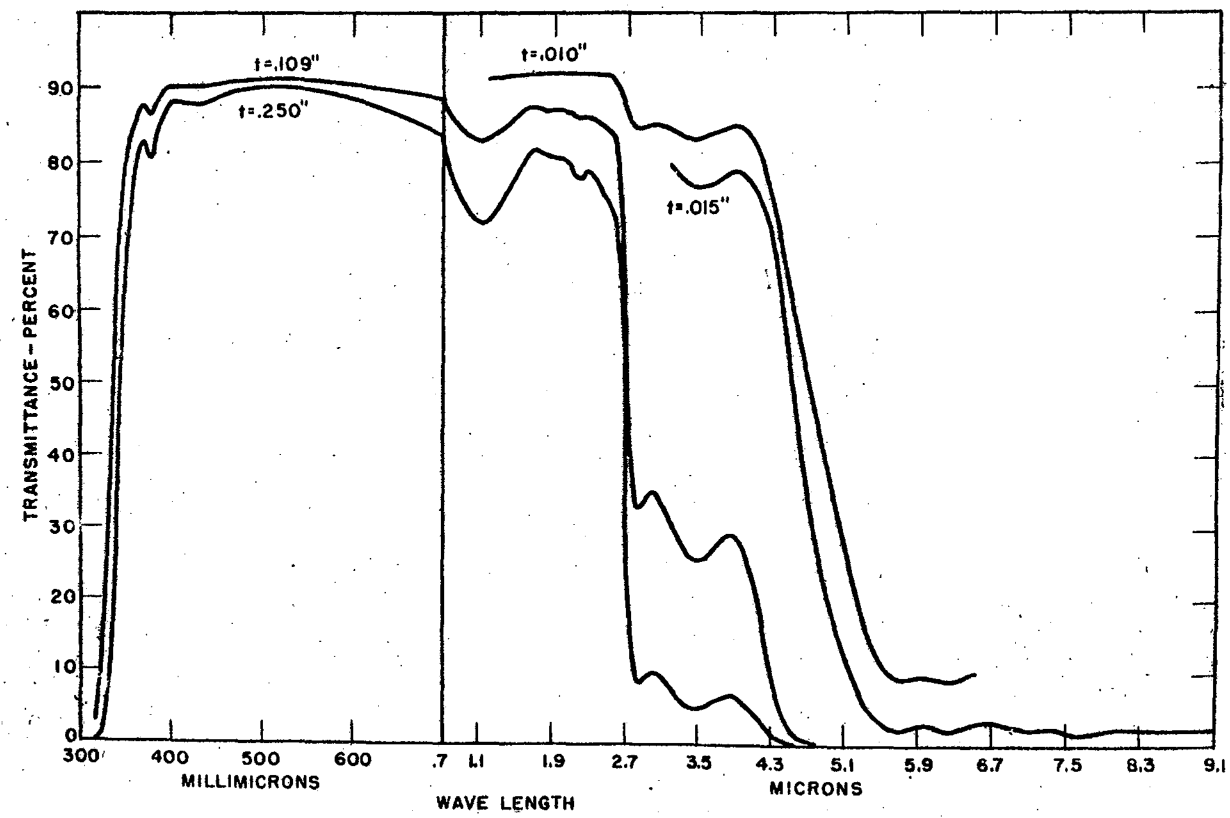


Figure 2.2b Spectral Transmittance of Glass Containing 0.10 Fe_2O_3.

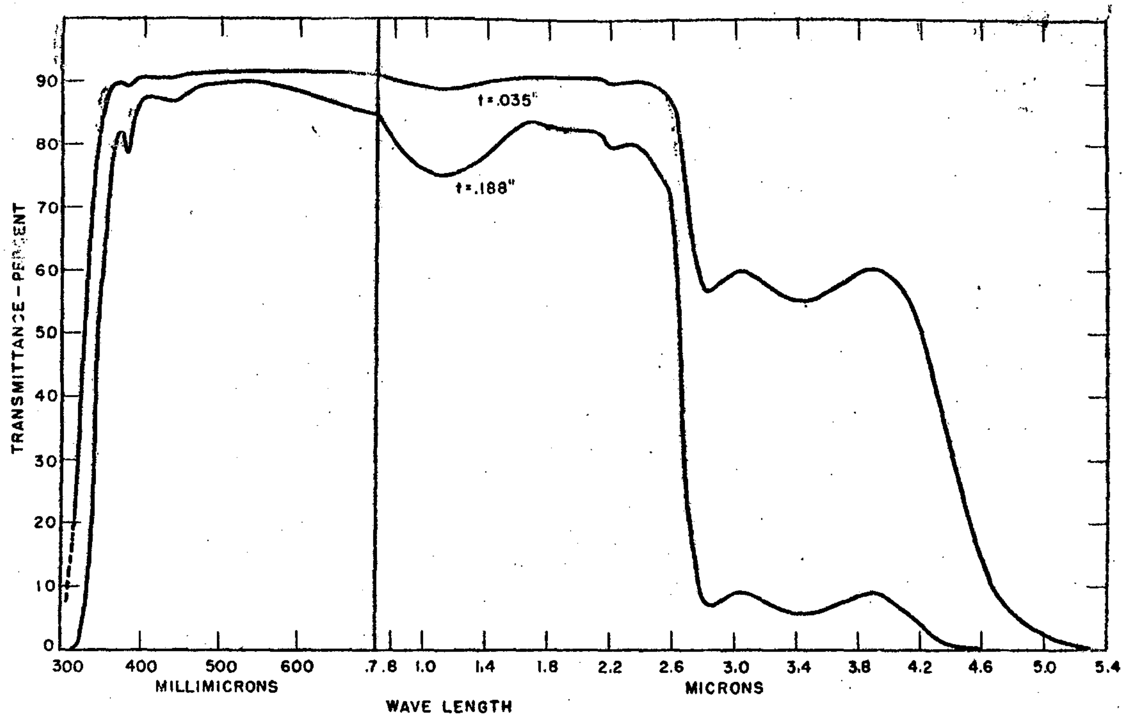


Figure 22c Spectral Transmittance of Glass Containing 0.15 Fe_2O_3.

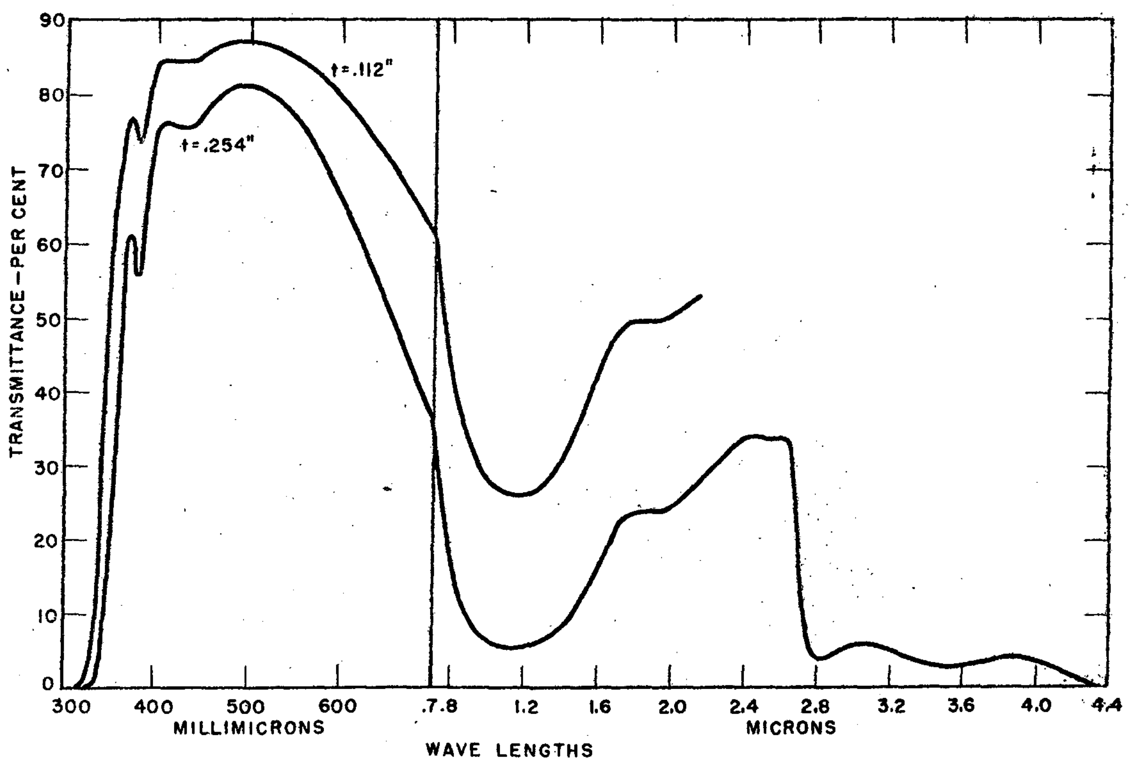


Figure 22d Spectral Transmittance of Glass Containing 0.50 Fe_2O_3.

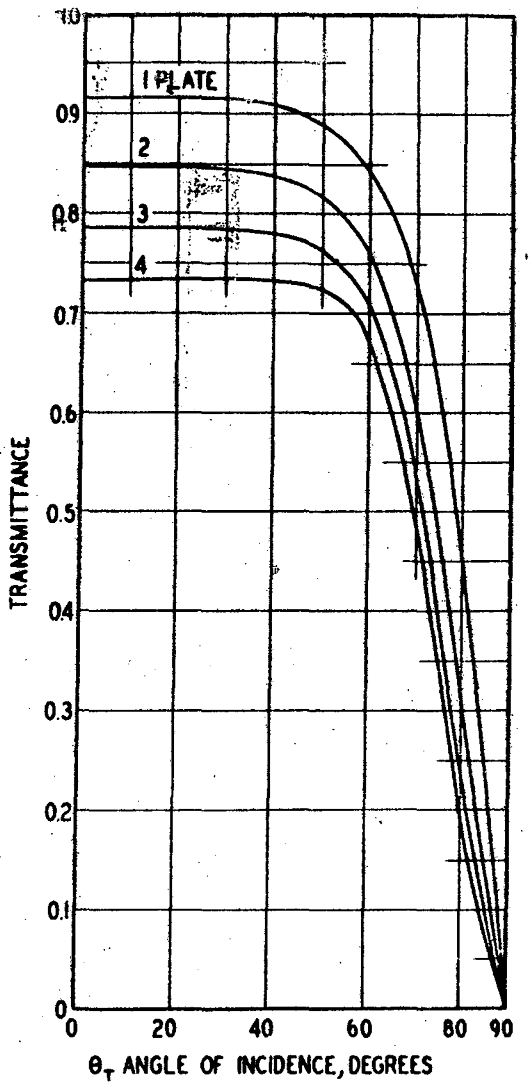


Figure 2.2.3a Curves of Calculated Transmission Versus Angle of Incidence, Taking into Account Reflection Losses Only (Refractive Index = 1.526, Hottel and Woertz).

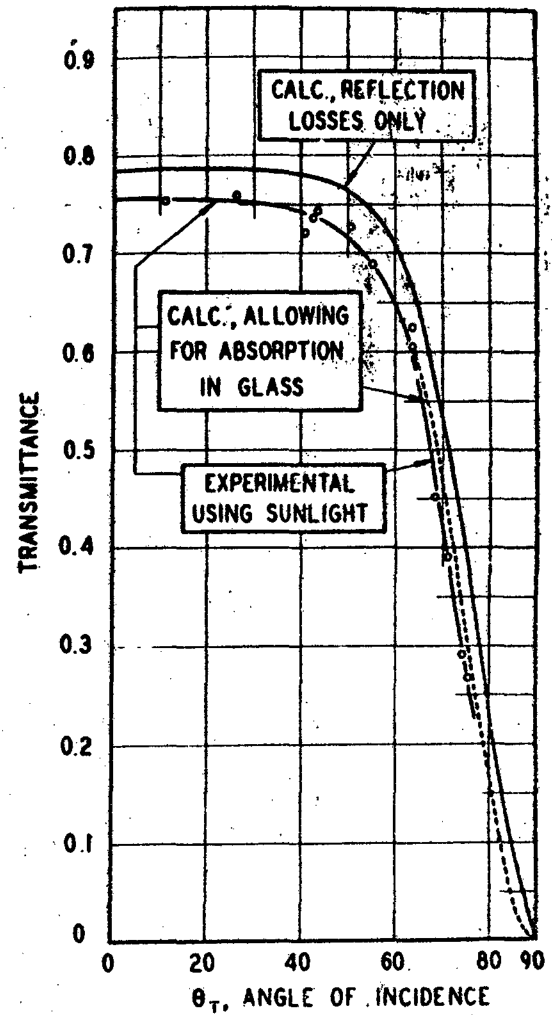


Figure 2.2.3b Curves of Calculated Transmission Versus Angle of Incidence, Taking into Account Reflection and Absorption Losses. Top, Middle, and Bottom Families, KL per sheet = 0.0125, 0.0370, and 0.0524, Respectively. (Hottel and Woertz)

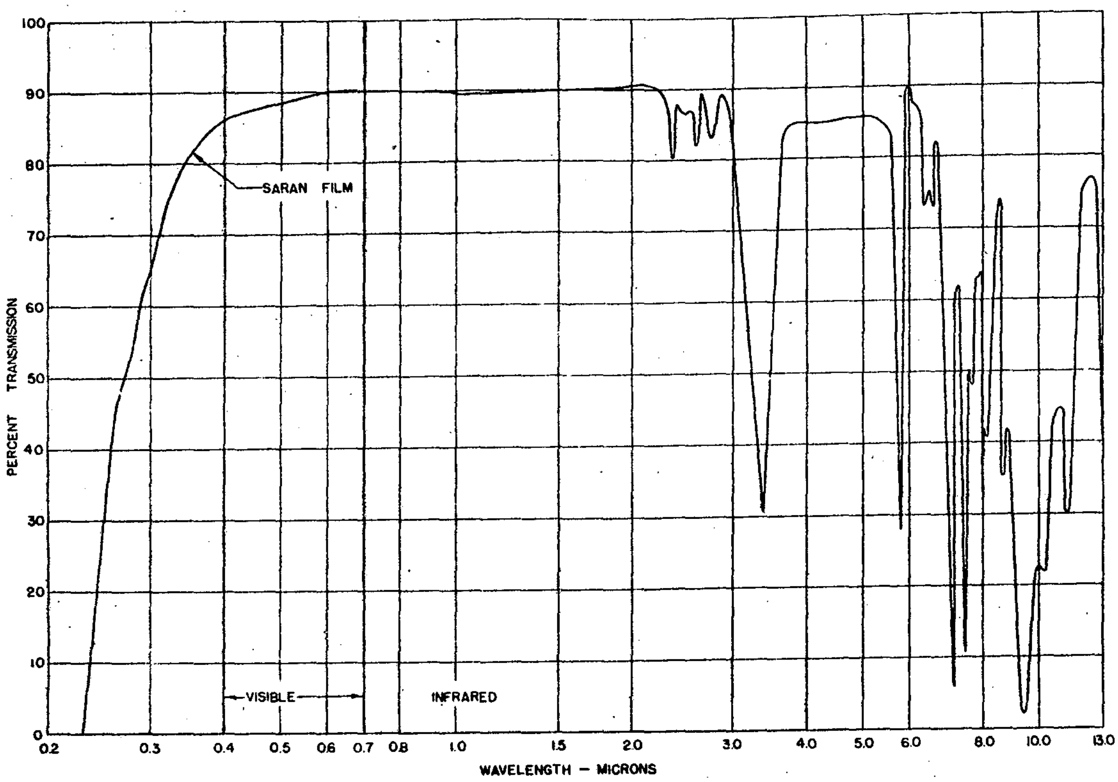


Figure 23. Spectral Transmittance of Polyvinylidene Chloride Film 0.0014 in. Thick.

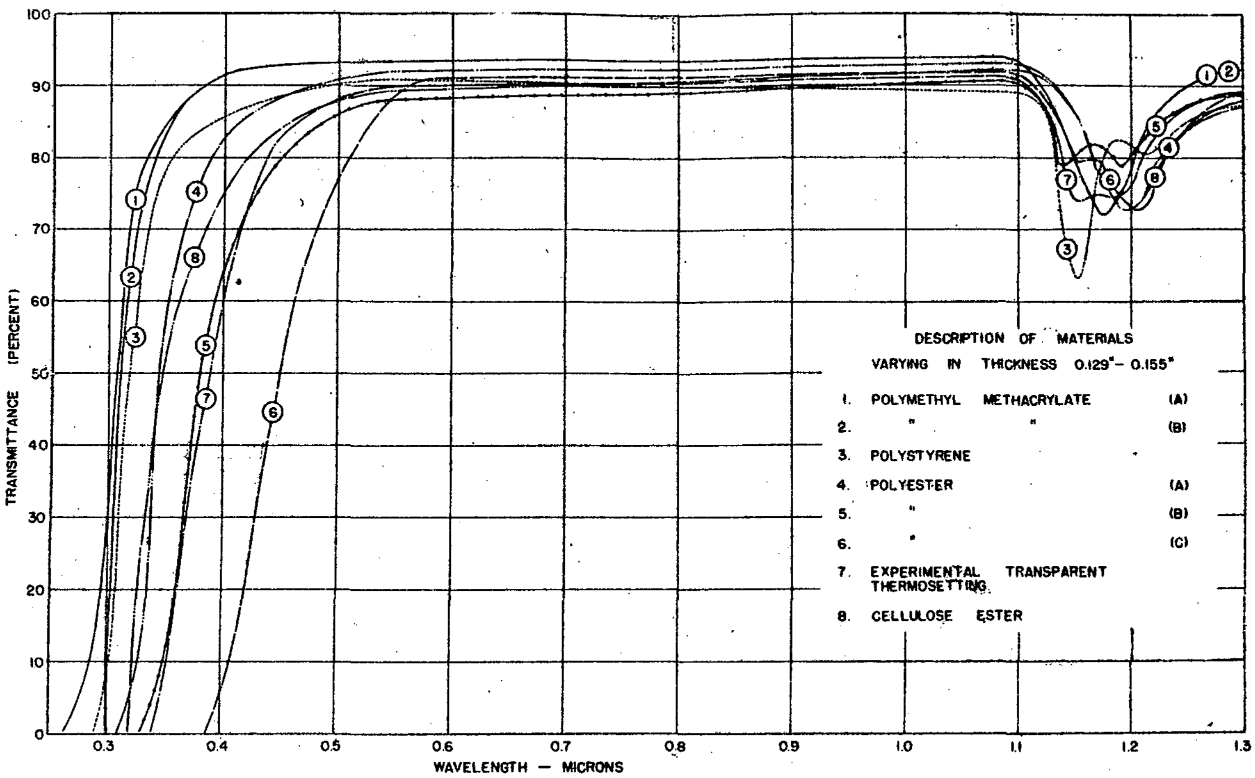
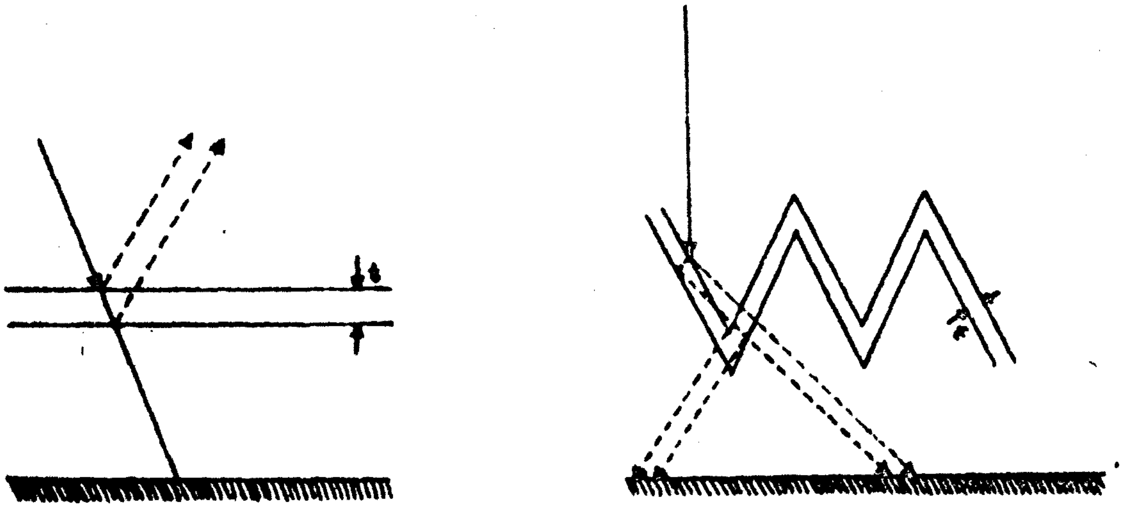
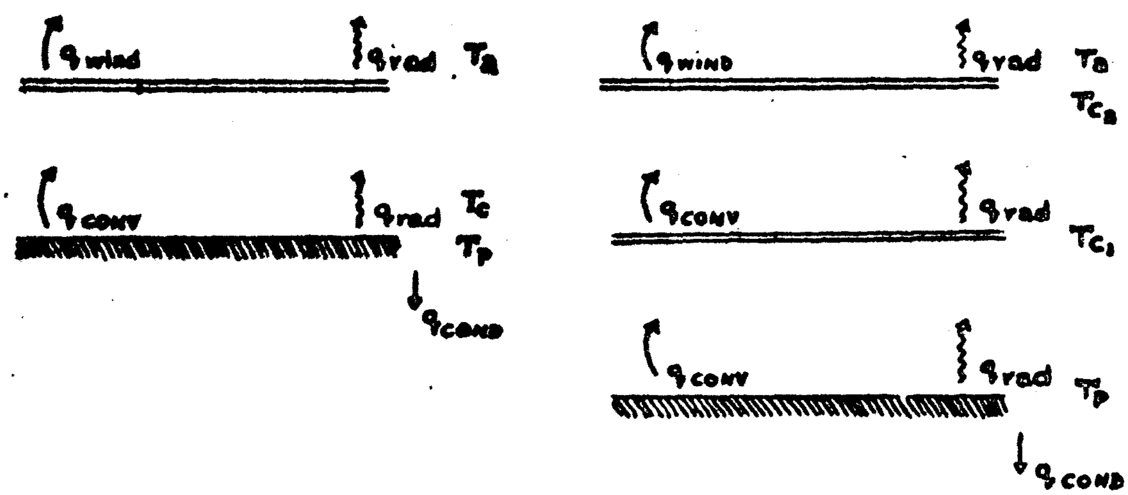


FIG. 2.2.4 b : SPECTRAL TRANSMITTANCE OF PLASTIC MATERIALS.



FIG·2·2·2 STANDARD INNER COVER V-CORRUGATED INNER COVER



FIG·2·3·1 TEMPERATURE DISTRIBUTION AND HEAT LOSS TERMS

CHAPTER THREE

HOTTEL - WHILLIER - BLISS EQUATION

3.1 Derivation of Hottel - Willier Bliss equation:

The behaviour of a solar flat plate collector can be described by Hottel - Whillier - Bliss equation (25) under the following conditions:

1) Collector operates in a steady state condition.
2) Loss coefficient is constant over the operating temperature range of the absorber.

Here we give the derivation of the HWB equation for a solar collector having bonded sheet as absorber. When the collector operates under steady state conditions, a part of heat energy collected by the collector will be transferred to the fluid and the rest will be lost through various mechanisms of heat losses.

Consider an element 'dx' of the collector (see fig. 3.1.1)
Rate of heat energy collected by the element 'dx' is given by,

$$Q_i \, dx = dx \, (\tau\alpha)_e \, H \, [(W-D) F+D] \quad (3.1.1)$$

Rate of heat lost by the element 'dx' is

$$q_f' \, dx = dx \, [(W-D) F+D] \, U_L \, (Tp - Ta) \quad (3.1.2)$$

Rate of energy collected by the fluid through the element 'dx' is

$$q_f \, dx = h_f \, n\pi \, D \, dx \, (Tp-Tf) \quad (3.1.3)$$

or

$$\frac{q_f \, dx}{nh_f \, \pi \, D \, dx} + T_f = T_p \quad (3.1.4)$$

We have from the energy balance,

$$q_f' \, dx + q_f dx = Q_i \, dx \quad (3.1.5)$$

From these equations, we can rearrange various terms like temperatures etc. and integrate over the length of the collector. We get,

$$\int_{T_{f,i}}^{T_{f,o}} \frac{\dot{m} C_p \, dT_f}{U_L \left[\frac{H(\tau\alpha)_e}{U_L} - (T_f - T_a) \right]} = nwF' \int_0^l dx \qquad (3.1.6)$$

where $F' = \dfrac{1}{\dfrac{nw}{(W-D)F+D} + \dfrac{nW\,U_L}{nh\,D}}$

Integrating equation (3.1.6) and rearranging terms we get

$$1 - \frac{H_f - (T_{f,o} - T_a)}{H_f - (T_{f,i} - T_a)} = 1 - \exp\left(-\frac{U_L A F'}{\dot{m} C_p}\right) \qquad (3.1.7)$$

(Here we have substituted H_f for $\frac{H(\tau\alpha)_e}{U_L}$

or we can write equation (3.1.7) as,

$$\dot{m}C_p\,(T_{f,o} - T_{f,i}) = F_R A \left[H\,(\tau\alpha)_e - U_L\,(T_{f,i} - T_a) \right] \qquad (3.1.8)$$

which is the HWB equation, where

$F_R = \dfrac{\dot{m}C_p}{U_L} \left[1 - \exp\left(\dfrac{-U_L AF'}{\dot{m}C_p} \right) \right]$ is the heat removal factor.

The instantaneous efficiency $= \dfrac{q_u}{HA}$

$$= F_R \;(\tau\alpha)_e - \frac{U_L}{H}\,(T_{f,i} - T_a) \qquad (3.1.9)$$

HWB equation expresses heat delivery from a collector in terms of three operating variables F_R, U_L, $(\tau\alpha)_e$ and the incident energy. This equation states that useful heat collected per unit area equals solar energy absorbed by the absorber $(\tau\alpha)_e H$ minus the heat loss, $U_L\,(T_{f,i} - T_a)$ and then multiplied by a factor related to the effectiveness of transferring the heat absorbed by the absorber plate to the heat removal fluid, F_R.

The efficiency of a flat plate solar water heater depends upon several factors like its design parameters, its orientation, temperature and mass flow rate and the distribution of the fluid through the collector, incident radiant energy and environmental conditions (e.g., wind velocity, ambient air and effective sky temperature etc.,) apart from transient heat transfer processes. The incident radiant energy and environmental conditions change even through out the day which makes the characterization of solar collector difficult. However, on a cloudless day, the above changes are slow so that the collector can be regarded as operating under nearly steady state conditions over small periods of time. Then its instantaneous efficiency is essentially determined by the three factors namely 1) heat removal factor F_R 2) overall heat loss coefficient, U_L and 3) effective transmittance absorptance product $(\tau\alpha)_e$ in terms of the operating variables of temperature and insolation. All these parameters enter in the equation governing the thermal performance namely HWB equation,

$$\dot{m}C_p \, (T_{f,o} - T_{f,i}) = F_R A \left[(\tau\alpha)_e H - U_L \, (T_{f,i} - T_a) \right]$$

This equation is of course, valid when U_L can be regarded as constant over the operating temperature range of the absorber. For most collectors U_L is a slowly varying function of absorber temperature and hence the above equation is a reasonable approximation over the usual temperature range of operation. Thus the information about the parameters of HWB equation is useful and can be used for the characterization of collector, improvement of its design and computer simulation of heating processes.

The effective transmittance - absorptance product, $(\tau\alpha)_e$ represents the complex interaction of optical properties in the solar radiation wavelengths. This is somewhat larger than the direct product of the cover transmittance and absorber absorptance because some of the radiation reflected from the absorber is returned to the absorber due to cover reflectance. The effective transmittance-absorptance product is influenced by cover transmittance, number of covers and absorption of the absorber plate.

The heat removal factor F_R, is influenced by the heat transfer resistance between the heated absorber surface and collector fluid which in turn would be affected by the design of the absorber plate and by the properties and flow rate of the fluid through the collector.

The heat loss coefficient U_L is influenced by the number and spacing of covers and by conditions within the spaces such as honeycomb cells or evacuation. The heat loss coefficient is also influenced by the radiation properties of the absorber and covers.

3.2 Parameter determination:-

Here we describe an experimental method for determination of various parameters of HWB equation.

a) Effective transmission - absorptance product:

This term depends on the nature of the radiation. For radiation having wavelength between 0.29μ m and 3μm, the coefficient of transmission through clear white glass covers and the coefficient of absorption for most of the coatings used in making flat plate type collectors is almost a constant. We can write,

$$(\tau\alpha)_e = (\tau\alpha)_s + (\tau\alpha)_l \qquad (3.2.1)$$

For a given design, $(\tau\alpha)_s$ depends upon angular distribution of incident radiant energy. The radiant energy can be considered to be made up of two parts, 1) the direct beam component, whose angle of incidence change in a known manner throughout the day and 2) the remaining called the diffuse component, which to a good approximation can be regarded as distributed uniformly on a cloudess day. The experimental procedure requires a series of pyranometer measurements as described below to determine $(\tau\alpha)_s$ for beam component and global radiations (total of beam and diffuse components) separately. From this data, $(\tau\alpha)_s$ for any incident radiant energy can be computed easily.

For a one cover system or any kind of cover system or any kind of cover systems having transmittance and reflectance ρ, it is easily seen that

$$(\tau\alpha)_s = \tau - \frac{1}{\tau}\left[\frac{H_r}{H} - \rho\right] \qquad (3.2.2)$$

The incident energy H can be measured by keeping pyranometer parallel to the collector's cover facing upwards. The reflected insolation, H_r can be measured by the pyranometer - by measuring the transmitted energy H through a similar cover system, kept parallel to collector. Then equation (3.2.2) can be used for evaluating $(\tau\alpha)_s$ for various angles of incidence of beam component and for diffuse radiations.

Sometimes, two similar covers having transmittance 'τ' and reflectance 'ρ' are used then in place of equation (3.2.2), the following equation can be used

$$(\tau\alpha)_s = \left[\tau - \frac{1}{\tau}\left(\frac{H_r}{H} - \rho\right)\right]\left[\frac{H_r'}{H} - \rho(1+\tau^2)\right]\frac{H}{\tau H_r} \qquad (3.2.3)$$

where H_r and H_r' are the reflected insolation from one cover and two cover respectively. Here we have neglected ρ^2 compared to one.

The $(\tau\alpha)_1$ depends upon the amount of incident energy absorbed by the cover system and various loss coefficients. All of the solar radiation that is absorbed by a cover system is not lost since this absorbed energy can increase the cover temperature and consequently reduce the losses from the plate. The solar energy absorbed by the cover is $H\left[1 - (\tau\alpha)_s - \frac{Hr}{H}\right]$. Heat loss from the absorber to cover system without absorption is $U_1\,(T_p - T_c)$ and the loss with absorption is $U_1\,(T_p - T_c')$. Here we have assumed that the small amount of absorption in the cover and consequent increased cover temperature does not change the magnitude of U_1 and U_2. The difference 'D' in two loss terms is,

$$D = U_1 \quad (T_p - T_c) - (T_p - T_c') \qquad (3.2.4)$$

The temperature difference $(T_p - T_c)$ can be expressed as

$$(T_p - T_c) = (T_p - T_a)\,\frac{U_L}{U_1} \qquad (3.2.5)$$

where U_L is the overall loss coefficient and is equal to $\frac{U_1U_2}{U_1+U_2}$

The temperature difference $(T_p - T_c')$ can be expressed as

$$(T_p - T_c') = U_2(T_p - T_a) - H\left[1 - (\tau\alpha)_s - \frac{H_r}{H}\right] \qquad (3.2.6)$$

Therefore,

$$D = (T_p - T_a)U_L - \frac{U_1U_2}{U_1+U_2}(T_p - T_a) + \frac{H\left[1-(\tau\alpha)_s - \frac{H_r}{H}\right]U_1}{U_1 + U_2}$$

$$\text{or} \quad D = H\left[1 - (\tau\alpha)_s - \frac{H_r}{H}\right]\frac{U_L}{U_2} \qquad (3.2.7)$$

The quantity 'D' represents the reduction in collector losses due to absorption in the cover but can be considered an additional input to the effective value of transmission absorption product. Thus,

$$(\tau\alpha)_I = \left[1 - (\tau\alpha)_S - \frac{H_r}{H}\right]\frac{U_L}{U_2} \qquad (3.2.8)$$

Its magnitude is usually a few percent of $(\tau\alpha)_S$. It can be reasonably determined by using either computed values of loss coefficients or by using the approximate relation,

$$\frac{U_2}{U_1} = \frac{T_p - T_c}{T_c - T_a} \qquad (3.2.9)$$

b. Heat removal factor F_R

For a given design it depends on the heat extraction efficiency of the fluid flowing through the collector and the overall heat loss coefficient U_L. It is possible to determine F_R as a function of mass flow rate by conducting experiments with initial temperature of water same as the ambient air temperature and measuring the amount of heat collected over small periods. Then HWB equation can be used to determine F_R as a function of mass flow rate. Here heat loss term in HWB equation is not precisely zero because the plate temperature is non-uniform and unequal to $T_{f,i}$. However, for good heat transfer design this disparity is not large. It may be mentioned that for most collector designs F_R is essentially independent of U_L.

c. The overall heat loss coefficient.

For a given design, UL depends upon environmental conditions (wind velocity, ambient air and effective sky temperature), mean absorber temperature and the inclination of the collecting system. For the existing environmental conditions and the inclination of the collecting system, it can be determined as a function of mean absorber temperature using HWB equation by conducting experiments with different initial temperatures of water.

Here, we have described an experimental method for determination of various parameters of HWB equation along with their dependences. This can permit proper characterization of solar water heater.

3.3 Design Considerations :

Efficiency of a collector is the ratio of the useful energy collected to the insolation incident on the collector surface (see eqn 3.1.9). From this equation it is clear that efficiency is governed by various factors like F_R, $(\tau\alpha)_e$, U_L, H and operating temperatures. In order to attain maximum efficiency insolation reaching the absorber should be maximized and the loss term should be minimized. Obviously the heat removal factor is also important.

In this context some factors concerning collector performance are worth mentioning.

If energy is to be withdrawn from the collector at a temperature only slightly above the ambient air temperature, the outward heat loss are small, and therefore concentrating the radiation on the collector increases the useful energy collection by the factor equivalent to concentration factor.

Ifa collector is operating with only one cover plate and a collector temperature close to atmospheric the outward loss is low. Putting on a second plate will approximately halve the losses, but they were already small and at the same time the insolation reaching the absorber plate will be cut by some percent due to reflection and transmission losses by the additional glass cover. On the other hand if the collector is operating at a high temperature, the saving in outward losses by adding one or more glass plates can offset the added optical losses. Thus, in general the optimum number of glass covers is larger when it is desired to collect energy at higher temperatures.

The fin efficiency factor enters in the heat removal factor term. So the diameter and the spacing between the channels should be chosen to give a fin efficiency nearly equal to one. An increase in its value can result in better heat transfer to the flowing fluid and hence the overall efficiency of the collector can be improved.

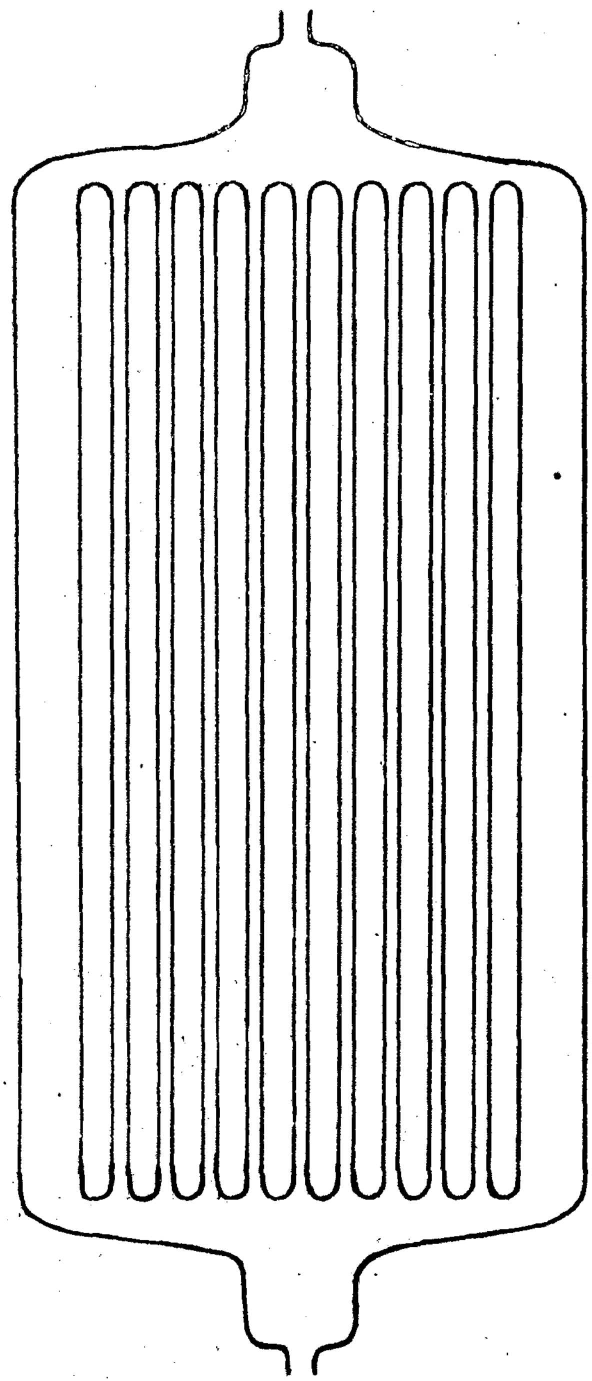
By using selective surfaces transmission of solar radiation can be increased and longwave radiative losses can be minimized. The reduction in the rear and edge heat losses can further improve the efficiency of the collector.

3.4 Limitations of HWB equation

The assumptions made for the derivation of HWB equation are not satisfied at all times. In fact, the efficiency of the collector cannot be described by this equation, when 1) collector does not operate under steady state condition and 2) the overall heat loss coefficient cannot be regarded as constant over the temperature range of operation of the collector. The former situation prevails at several times of the day due to the heat capacity effects of the collector. The operation of flat plate collector is inherently transient since the driving forces e.g. incident radiant energy and environmental conditions are changing continuously. These are particularly important during early morning hours and at times of sudden changes of driving forces.

The overall heat loss coefficient has been assumed constant over the operating temperature range of the collector for the derivation of HWB equation. This is not correct. For most collectors, one finds that it is a slowly changing function of absorber temperature. Our equation (3.1.1) can still explain the behaviour of the collector. It is possible to integrate this equation if the functional dependence of U_L on temperature is known. Tabor (22) has suggested that we can represent U_L as,

$U_L = U_o \Delta T^p$ where U_o is a constant and 'p' is usually in the range 1 to 1.3 for flat plate collectors. Using this form of U_L, integration in Eq. (3.1.1) can be carried out. Incorporating the variation of U_L, Tabor (22) has suggested an alternate method for characterizing the collector by the use of parametric form for efficiency of the collector. This parametric form can be restricted to hold true over certain temperature range as demanded by the integrated equation (3.1.1) Thus the efficiency of the collector under any conditions can be established. However his method requires the use of two or more collectors and restricted temperature range of operation.



ELEVATION OF ABSORBER PLATE.

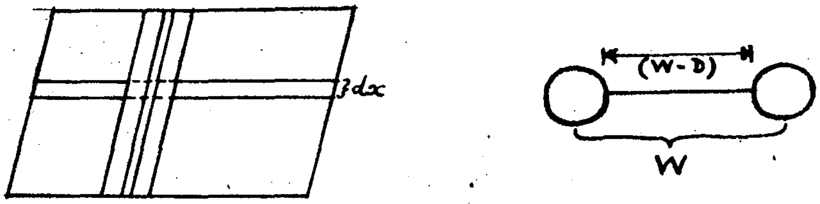


FIG. 3.1.1 SHEET AND TUBE DIMENSIONS

CHAPTER FOUR

CONSTRUCTION AND STUDIES ON THE FLAT PLATE COLLECTOR

4.1 CONSTRUCTION

The complete solar water heater comprises of the following:-

(a) Solar energy absorber,

(b) Storage tank for water and

(c) Circulation system.

(a) Solar energy absorber:

For solar energy absorber, we have constructed the flat plate type solar energy collector. Its essential parts are,

the absorber panels with channels for the flow of water, back insulation for reducing the heat loss from the absorber and box with suitable cover for allowing solar radiation to transmit through it on the absorber plate.

(1) Absorber panel:- The solar energy absorber panel should have a selective surface for absorbing most of the radiant energy and should permit effective transfer of heat to the heat exchanging fluid. For practical purposes it should be of low cost, corrosion resistant and permit ready connections to external pipings. 'Bonduct' aluminium panel satisfy these requirements. We have chosen the 'bonduct' panel which has flow passages (built in channels) suitable for uniform flow distribution in the panel. The chosen panels has ten channels. Outer size of each channel is 1.8 cms in width and 0.5 cms in

height. These channels are arranged in parallel and separated by 2.8 cms (centre to centre distance). All these channels are provided with a common inlet and outlet tube for water circulation. The size of the absorber panel is 140" x 35" x 0.05". We have applied a thin layer of black paint after degreasing its surface.

ii) Backside insulation:- Four inches of glass wool has been kept at the backside of the solar absorber in the wooden box to reduce heat loss from the back of the absorber plate. The wooden box is made of ½" commercial plywood and has outer dimensions of 152" x 78" x 24". The density of glass wood used is $\frac{48\ kg}{m^3}$ and its thermal conductivity is 0.04 Keal/m.hr.^{o}c at the mean temperature of 60^{o}c.

iii) Cover panes:- Cover panes should be transparent to solar radiation and opaque to re-radiated infrared radiation. It should be of low cost, easy to install require little or low maintenance and be resistant to breakage and degradation. Glass or plastics can be used as the cover panes. Gass cover has better transmittivity for solar radiations compared to plastic covers and glass covers does not deteriorate with time, while most available plastics in the country turn yellowish with time. Therefore we have chosen clear white glass cover.

(b) Storage tank:

It is normally necessary to have a storage tank for storing hot water because of the intermittent nature of solar energy. A double walled storage tank of capacity 140 litres is used for this purpose. Suitable inlets and outlets have been provided for incoming and outgoing water.

(c) Circulation system:- For water circulation, ½ inch. dia tubing is used for connections between the absorber and the tank. The pipes are insulated with glass wool (1 inch) to prevent the heat losses. Water circulation is maintained with the help of a booster pump. Control valves have been provided for adjusting the rate of flow through the collector.

We have used two similar absorber panels arranged side by side, fitted in the box. The whole unit is mounted over a stand, which we have fixed on the top of the roof of our school; facing south and its surface inclined at an angle of 30° to the horizontal. Storage tank is placed nearby the collector unit. A photograp of this constructed collector is shown.

4.2 Experimental Results and Analysis:-

We have recorded the amount of the useful energy collected by the collector by 1) varying the space between the absorber and the glass cover and 2) the use of one and two glass covers. This has been done for different flow rates of water through the collector. The analysis of our observations can help in determining the conditions under which the efficiency of the constructed flat plate type solar water heater is large.

Experimentally, record has been made of the outgoing temperature of the water when the collector operates in nearly steady state conditions. Hourly observations have been made between 9 A.M. to 4 P.M. during the month of May and June.

Representative results are presented in the tables from 1 to 6 and graphs from 1a to 6a. These results are for different flow rates of water through the collector (namely 3.6 litres/hr, 6 litres/hr and 10 litres/hour) and for three different cover system, namely

1) One glass cover separated by 6 cms. from the absorber
2) One glass cover separated by 9 cms. from the absorber
3) Two glass covers separated by 6cms and 9 cms respectively from the absorber.

From the rate of flow of the fluid through the collector and its rise in temperature one can calculate the amount of useful heat collected. $\dot{m}C_p (T_{f,o} - T_{f,i})$

To determine the efficiency of the collector, we need data for the incident radiant energy on the collector surface. We did not have any instrument to record this at the site of the installed collector. Therefore we have taken recorded data by Indian Metereological department at the New Delhi station. They are recording data for global radiant energy and the diffuse radiant energy. As discussed in Chapter II we can approximately calculate the intensity of radiant energy on any inclined surface. For this we need information about the amount of direct component of the incident energy and the diffuse component and its angular distribution on any surface. From the available data the direct component (I_D^h) and diffuse component (I_d^h) of intensity on the horizontal surface can be easily obtained. We assume that the angular distribution of the diffuse radiations is uniform over a hemisphere. Then the total incident energy on the inclined surface at an angle i_b to the horizontal and facing south is given by (see eqn 2.1.17)

$$I_T = I_D^h R_b + I_d^h \frac{1+\cos b}{2}$$

where R_b is defined in the eqn (2.1.14) and is dependent on the latitude of the place L, time of the day (hour angle ω) and the declination of the sun (δ). Its value for various times of days of reported observations have been calculated and tabulated in table (II) In the same table, we have given the calculated values of the incident radiant energy on the collector surface. The ratio of the useful energy collected to the incident energy gives the efficiency of the collector at the time of operation. We have calculated the efficiency at various times of days of reported observation and plotted it in graphs from 1b to 6b, along with the outgoing temperature of the fluid and wind velocities.

4.3 Cost - benefit analysis

The preceding discussion was concerned with the thermal performance of solar heating systems. The designing of systems must be performed with due consideration of their cost.

The annual cost of a solar heating system includes the annual cost of owning the collector, storage unit and associated controls, pumps, piping operating the system, and maintenance.

The annual cost of ownership includes interest on the investment and depreciation. The operating cost is primarily for power requirements for pumping water. The maintenance cost includes repairs, replacement of glass covers in collectors or any other costs of keeping the system in operating condition.

The annual cost of delivering solar heat can be estimated as follows :

$$C_s, a = (C_c A_c + C_{ST} + C_E) + PCp + C_{MM} + C_{ML} \quad (4.3.1)$$

where $I = \frac{1}{y} + \frac{R}{100}$

A break-up of the production cost of the constructed solar water heater is given below :

Materials of construction	Size and number	Cost in Rupees
'Bonduct' panels	35 x 145 cm^2 (two)	240
Wooden box	78 x 152 x 21 cm^3 (one)	80
Glass cover	152 x 78 cm^2 (two)	100
Double walled m.5 tank with 1" thick insulation	Capacity 140 litres	250
m.5 angle iron stand	one	80
Booster pump	200 watts (one)	350
Glass wool insulation, pipes, plastic tubes, paint etc., and installation charges		100

Total cost of the unit is = Rs.1200

In equation (4.3.1) C_{MM} and C_{ML} i.e., maintenance and labor cost is very small compared to ownership costs. So C_s, a becomes,

$$C_s, a = (C_c A_c + C_{ST} + C_E) I + P_{cp}$$

For our constructed solar water heater assuming a life span of 20 years, C_s, a will be

$$= 156.00 + PCp.$$

Cost of energy delivered : For example considering the pefformance on June 2, 1976, the total useful energy collected on that day

= 2751 Kcal

= 3.2 KWh

$$\text{Cost per unit energy delivered} = \frac{C_s,\ a/360}{3.2}$$

$$= \underline{24 \text{ Paise}}$$

Cost per unit energy delivered is 24 Paise, which is less than that of the conventional energy sources. This is the case for summer season. Similarly one can estimate the cost of energy delivered for the winter months.

4.4 Conclusions:

There are number of parameters which can effect the instantaneous efficiency of the flat plate solar energy collector as discussed in Chapter III. Number of othese parameters, namely environmental conditions and incident energy have varied during the days of experimental observations. This has made it difficult to separate the effect of one parameter over the other. Still we have made an attempt to arrive at some general conclusions from the results of certain selective days on which some of these parameters were constant.

A general trend of our experimental results shows that the efficiency of the collector increases with the increase of flow rate of water through the collector. Theoretically this was expected as discussed and now we have verified it experimentally. Another observation is the following. By reducing the distance between glass cover and the absorber amount of convective heat loss from the absorber to cover increases. This increase is small to compensate the heat loss from the cover by a small increase in wind velocities (say from 6m/sec to 7m/sec). This is clearly seen by comparing results of our observation on 30th May and 2nd June 1976. In fact wind velocity affects the efficiency of the collecting system considerably. This is also supported from the results of 4th June which shows that the efficiency is considerably increased when wind velocities were smaller. Another interesting result follows by comparing data of June 2 and June 4, 1976 at 9 A.M. and 10 A.M. The use of two covers reduces the amount of energy received by the absorber compared to that by one cover system. However the heat losses in the former case is also reduced. Our results indicate that at wind velocities of about 6m/sec and at intensity of incident energy equal to about 60 cal/cm^2/hr the one cover system has a higher efficiency.

Our cost-benefit analysis shows that the cost of energy delivered is competitive with that from the conventional energy sources. Anyhow further research on flat plate type solar collector is needed especially to bring down its initial investment and increase its cost-benefit ratio so as to make it economically viable for commercial utilization.

Table 1: Data of incident radiant energy from Indian Metereological Department, New Delhi

Date	Time of the day	Total radiation incident on a horizontal surface (cal/cm^2/hr)	Diffuse radiation incident on a horizontal surface (cal/cm^2/hr)
28.5.1976	9 A.M.	56.9	17.3
	10 A.M.	69.8	19.0
	11 A.M.	78.7	19.4
	12 A.M.	82.8	21.8
	1 P.M.	83.1	22.4
	2 P.M.	79.9	25.1
	3 P.M.	67.9	22.3
	4 P.M.	55.5	17.5
30.5.1976	9 A.M.	54.6	19.9
	10 A.M.	68.3	23.3
	11 A.M.	77.5	25.1
	12 A.M.	81.2	28.0
	1 P.M.	80.8	28.8
	2 P.M.	76.1	28.8
	3 P.M.	65.7	26.5
	4 P.M.	50.4	24.2
2.6.1976	9 A.M.	55.0	18.1
	10 A.M.	64.9	20.9
	11 A.M.	78.6	21.7
	12 A.M.	83.5	22.7
	1 P.M.	82.6	23.2
	2 P.M.	76.4	35.1

(Continued)

Table 1: (Continued)

Date	Time of the day	Total radiation incident on a horizontal surface (cal/cm^2/hr)	Diffuse radiation incident on a horizontal surface (cal/cm^2/hr)
	3 P.M.	65.4	25.0
	4 P.M.	50.5	20.5
3.6.1976	9 A.M.	57.2	16.7
	10 A.M.	70.5	17.9
	11 A.M.	81.3	19.3
	12 A.M.	84.2	20.7
	1 P.M.	82.3	22.7
	2 P.M.	77.2	21.8
	3 P.M.	67.6	19.3
	4 P.M.	53.5	16.7
4.6.1976	9 A.M.	52.8	15.4
	10 A.M.	68.0	17.6
	11 A.M.	77.1	19.4
	12 A.M.	82.0	20.0
	1 P.M.	81.1	18.8
	2 P.M.	74.4	19.7
	3 P.M.	66.2	19.1
	4 P.M.	57.4	16.8
5.6.1976	9 A.M.	47.5	24.4
	10 A.M.	21.0	20.0
	11 A.M.	29.8	28.8
	12 A.M.	60.1	41.6

(Continued)

Table 1: (Continued)

Date	Time of the day	Total radiation incident on a horizontal surface ($cal/cm^2/hr$)	Diffuse radiation incident on a horizontal surface ($cal/cm^2/hr$
	1 P.M.	40.5	38.7
	2 P.M.	57.1	38.5
	3 P.M.	58.7	28.8
	4 P.M.	42.6	33.2

Time of the day	Calculated value of R_D	Direct component of incident Radiation on a horizontal surface (Cal/cm^2/hr)	Direct Component of incident Radiation on the collector surface (cal/cm^2/hr)	Diffuse Radiation incident on a horizontal surface (from Table) (cal/cm^2/hr)	Diffuse Radiation on the collector surface (cal/cm^2/hr)	Calculated value of the total incident radiant energy on the collector surface (cal/sec)
9 A.M.	0.8837	39.6	35.0	17.3	16.2	142.4
10 A.M.	0.9128	50.8	46.3	19.0	18.9	181.7
11 A.M.	0.9253	59.3	54.9	19.4	19.2	206.4
12 A.M.	0.9253	61.1	56.5	21.8	21.6	217.7
1 P.M.	0.9128	60.7	55.4	22.4	22.2	215.7
2 P.M.	0.8837	54.2	47.9	25.1	25.5	204.5
3 P.M.	0.8269	45.6	37.7	22.3	22.1	166.6
4 P.M.	0.7092	38.0	27.0	17.5	17.4	123.4

Table 2a : Conversion of the incident radiant energy data on the horizontal surface to that on the collector surface (Date : 28.5.1976; Declination = 21°35')

Time of the day	Calculated value of R_b	Direct component of incident Radiation on a horizontal surface $cal/cm^2/hr$	Direct Component of incident Radiation on the collector surface $(cal/cm^2/hr)$	Diffuse Radiation incident on a horizontal surface (from Table I) $cal/cm^2/hr$	Diffuse Radiation on the collector surface $cal/cm^2/hr$	Calculated value of the total incident radiant energy on the collector surface (cal/sec)
9 A.M.	0.8810	34.7	30.6	19.9	18.6	136.7
10 A.M.	0.8939	45.1	41.1	23.3	21.7	175.0
11 A.M.	0.9223	52.4	48.3	25.1	24.9	204.0
12 A.M.	0.9223	53.2	49.1	28.0	27.8	214.0
1 P.M.	0.8939	52.0	46.5	28.8	28.6	209.1
2 P.M.	0.8810	47.3	41.7	28.8	28.6	195.6
3 P.M.	0.8422	39.2	33.0	26.5	26.3	165.1
4 P.M.	0.7046	26.2	18.4	24.2	24.1	118.4

Table 2b Conversion of the incident radiant energy data on the horizontal surface to that on the collector surface (Date : 30.5.1976; Declination $21^{\circ}54'$

Time of the day	Calculated value of R_b	Direct component of incident radiation on a horizontal surface cal/cm^2/hr	Directo component of incident radiation on the collector surface (cal/cm^2/hr)	Diffuse radiation incident on a horizontal surface (from Table I) cal/cm^2/hr	Diffuse Radiation on the collector surface (cal/cm^2/hr)	Calculated value of the total incident radiant energy on the collector surface (cal/sec)
9 A.M.	0.8760	36.9	32.3	18.1	18.0	139.4
10 A.M.	0.9059	44.0	39.8	20.9	20.8	168.9
11 A.M.	0.9189	56.9	52.3	21.7	21.5	205.7
12 A.M.	0.9189	60.8	55.9	22.7	22.5	218.4
1 P.M.	0.9059	59.4	53.8	23.2	23.0	209.1
2 P.M.	0.8760	41.3	36.2	35.1	34.8	197.8
3 P.M.	0.8183	40.4	33.0	25.0	24.8	161.2
4 P.M.	0.6986	30.1	21.0	20.5	20.3	115.2

Table 2c: Conversion of the incident radiant energy data on the horizontal surface to that on the collector surface (Date 2.6.1976; Declination = 22°18)

Time of the day	Calculation of R_b	Direct component of incident radiation on a horizontal surface cal/cm^2/hr	Direct component of incident radiation on the collector surface (cal/cm^2/hr)	Diffuse radiation incident on a horizontal surface (from Table I) (cal/cm^2/hr)	Diffuse radiation on the collector surface (cal/cm^2/hr)	Calculated value of the total incident energy on the collector surface (cal/sec)
9 A.M.	0.8752	40.5	35.5	16.7	16.6	144.9
10 A.M.	0.9048	52.6	47.6	17.9	17.8	182.0
11 A.M.	0.9177	62.0	56.9	19.3	19.2	211.9
12 A.M.	0.9177	63.4	58.2	20.7	20.6	219.6
1 P.M.	0.9048	59.6	53.9	22.7	22.5	212.9
2 P.M.	0.8752	55.5	48.6	21.8	21.6	195.4
3 P.M.	0.8168	48.2	39.4	19.3	19.2	163.1
4 P.M.	0.6974	36.8	25.7	16.7	16.6	117.6

Table 2d: Conversion of the incident radiant energy data on the horizontal surface to that on the collector surface (Date : 3.6.1976; Declination = 22°25')

Time of the day	Calculation of R_D	Direct component of incident radiation on a horizontal surface $cal/cm^2/hr$	Direct component of incident radiation on the collector surface $(cal/cm^2/hr)$	Diffuse radiation incident on a horizontal surface (from Table I) $(cal/cm^2/hr)$	Diffuse radiation on the collector surface $(cal/cm^2/hr)$	Calculated value of the total incident energy on the collector surface (cal/sec)
9 A.M.	0.8740	37.4	32.7	15.4	14.4	131.1
10 A.M.	0.9057	50.5	45.7	17.6	17.5	175.9
11 A.M.	0.9168	57.7	52.9	19.4	19.3	201.1
12 A.M.	0.9168	62.0	56.8	20.0	19.9	213.6
1 P.M.	0.9057	62.4	56.5	18.8	18.6	209.2
2 P.M.	0.8740	54.7	47.8	19.7	19.6	187.6
3 P.M.	0.8155	47.0	38.4	19.1	19.0	159.9
4 P.M.	0.6958	34.6	24.1	16.8	16.6	113.4

Table 2e: Conversion of the incident energy data on the horizontal surface to that on the collector surface. (Date : 4.6.1976; Declination = $22^{\circ}32'$; Latitude = 28.5°

Time of the day	Calculation of R_D	Direct component of incident radiation on a horizontal surface (cal/cm^2/hr)	Direct component of incident radiation on the collector surface (cal/cm^2/hr)	Diffuse radiation incident on a horizontal surface (from table I) (cal/cm^2/hr)	Diffuse radiation on the collector surface (cal/cm^2/hr)	Calculated value of the total incident energy on the collector surface (cal/sec)
9 A.M.	0.8728	23.1	20.2	24.4	24.2	123.7
10 A.M.	0.9028	1.0	0.9	20.0	19.9	57.8
11 A.M.	0.9160	0.9	0.8	28.8	28.6	22.1
12 A.M.	0.9160	18.4	16.9	41.6	41.4	161.2
1 P.M.	0.9028	1.8	1.6	38.7	38.4	108.7
2 P.M.	0.8728	12.6	11.0	38.5	38.2	137.2
3 P.M.	0.8130	29.9	24.3	28.8	28.6	147.4
4 P.M.	0.6960	9.4	6.5	33.2	33.0	151.0

Table 2f: Conversion of the incident energy data on the horizontal surface to that on the collector surface (Date : 5.6.1976; Declination 22°38'

Time of the day	Ambient air temperature in degree centigrade	Average wind speed in meters/sec	Calculated incident energy on the collector surface in (cal/sec)	Temperature of the outgoing water in degree centigrade	Useful energy collected in cal/sec	Percentage Efficiency of Collector
9 A.M.	36.0	3.89	142.4	61.0	29.0	20.0
10 A.M.	36.5	4.45	181.7	65.0	32.5	18.0
11 A.M.	37.5	4.45	206.4	72.0	39.5	19.0
12 A.M.	39.0	2.78	217.7	76.0	43.5	20.0
1 P.M.	38.0	5.56	215.7	74.5	42.0	20.0
2 P.M.	40.5	7.22	204.5	71.5	30.0	19.0
3 P.M.	39.0	4.45	166.6	70.0	37.5	23.0
4 P.M.	38.0	6.11	123.4	62.0	29.5	24.0

Table III a Collector with one outer cover. Morning hours very slightly cloudy.
Rate of flow of water through the collector 3.6 litre/hour and water temperature at the inlet of the collector = 32.5 $^{\circ}$c (Date of experiment 28.5.1976)

Time of the day	Ambient air temperature in degree centigrade	Average wind speed in meters/sec	Calculated incident energy on the collector surface in cal/sec	Temperature of the outgoing water in degree centigrade	Useful energy collected in cal/sec	Percentage Efficiency of collector
9 A.M.	35.0	7.22	136.7	57.0	68.1	50.0
10 A.M.	37.0	8.33	175.0	69.0	101.4	65.0
11 A.M.	39.5	7.78	204.0	70.5	105.5	52.0
12 A.M.	41.0	8.33	214.0	76.5	122.0	57.0
1 P.M.	41.5	7.22	209.1	67.0	95.8	46.0
2 P.M.	42.0	7.22	195.6	64.0	87.5	45.0
3 P.M.	41.5	7.22	165.1	59.0	73.6	45.0
4 P.M.	41.5	6.11	118.4	53.0	57.0	49.0

Table III b: Collector with one outer cover. Cloudless day. Rate of flow of water through the collector 10 litres/hour and water temperature at the inlet of the collector = 32.5°c (Date of experiment 30.5.1976)

Time of the day	Ambient air temperature in degree centigrade	Average wind speed in meteres/sec	Calculated incident energy on the collector surface in cal/sec	Temperature of the outgoing water in degree centigrade	Useful energy collected in cal/sec	Percentage Efficiency of collector
9 A.M.	37.0	5.01	139.4	55.0	62.5	45.0
10 A.M.	38.0	6.11	168.9	66.0	93.1	55.0
11 A.M.	41.0	6.11	205.7	68.0	97.2	47.0
12 A.M.	43.0	6.11	218.4	89.0	151.5	69.0
1 P.M.	43.5	5.56	209.1	86.0	143.1	68.0
2 P.M.	44.0	5.56	197.8	82.0	131.8	67.0
3 P.M.	43.5	5.56	161.2	67.0	90.3	56.0
4 P.M.	43.5	4.45	115.2	55.5	59.7	52.0

Table III c: Collector with one inner cover. Cloudless day Rate of flow of water 10 litres/hour and the water temperature at the inlet of the collector = 32.5^{o}c (upto 11 A.M.); 34.5^{o}c (11.30 onwards). (Date of experiment 2.6.1976)

Time of the day	Ambient air temperature in degree centigrade	Average wind speed in meteres/sec	Calculated incident energy on the collector surface in cal/sec	Temperature of the outgoing water in degree centigrade	Useful energy collected in cal/sec	Percentage Efficiency of collector
9 A.M.	36.5	6.67	144.9	64.0°c	52.5	36.0
10 A.M.	37.5	8.33	182.0	72.0°c	65.9	36.0
11 A.M.	39.5	8.33	211.9	75.0°c	70.8	34.0
12 A.M.	42.0	8.89	219.6	90.0°c	95.9	44.0
1 P.M.	42.5	7.22	212.9	88.0°c	92.5	43.0
2 P.M.	43.0	6.94	195.4	86.5°c	90.0	46.0
3 P.M.	42.5	5.56	163.1	72.5°c	66.7	41.0
4 P.M.	42.5	4.45	117.6	63.0°c	50.8	43.0

Table IIId: Collector with one inner cover. Cloudless day; dusty. Rate of flow of water through the collector 6 litres/hour, and the water temperature at the inlet of the collector = 32.5°c. Date of the experiment (3.6.1976)

Time of the day	Ambient air temperature in degree centigrade	Average wind speed in meters/sec	Calculated incident energy on the collector surface in cal/sec	Temperature of the out-going water in degree centigrade	Useful energy collected in cal/sec	Percentage Efficiency of Collector
9 A.M.	35.0	5.56	131.1	51.0	45.8	35.0
10 A.M.	37.5	6.11	175.9	59.0	68.1	39.0
11 A.M.	41.0	3.89	201.1	78.0	120.9	60.0
12 A.M.	42.5	1.11	213.6	89.0	151.4	73.0
1 P.M.	43.0	0.56	209.2	79.5	125.0	60.0
2 P.M.	43.5	1.11	187.6	77.5	119.5	64.0
3 P.M.	42.5	0.56	159.9	70.0	98.6	62.0
4 P.M.	42.5	0.56	113.4	66.0	87.5	77.0

Table IIIe: Collector with both covers. Afternoon slightly cloudy. Rate of flow of water through the collector 10 litres/hour, and the water temperature at the inlet of the collector 34.5°c (Date of the experiment 4.6.1976)

Time of the day	Ambient air temperature in degree centigrade	Average wind speed in meteres/sec	Calculated incident energy on the collector surface in cal/sec	Temperature of the outgoing water in degree centigrade	Useful energy collected in cal/sec	Percentage Efficiency of collector
9 A.M.	34.0	0.28	123.7	57.0	39.2	32.0
10 A.M.	35.0	3.33	57.8	59.0	42.5	74.0
11 A.M.	35.0	3.89	82.1	63.0	49.2	60.0
12 A.M.	35.0	4.45	161.2	55.0	35.8	22.0
1 P.M.	36.0	0.56	108.7	90.0	94.2	87.0
2 P.M.	37.0	3.89	137.2	85.0	85.8	63.0
3 P.M.	37.0	1.11	147.4	76.0	70.8	49.0
4 P.M.	37.5	3.33	151.0	66.0	54.2	26.0

Table III f: Collector with both covers. Cloudy in the forenoon; clear sky in the afternoon. Rate of flow of water through the collector 6 litres/hour, and the water temperature at the inlet of the collector 33.5^{o}c. (Date of experiment 5.6.1976)

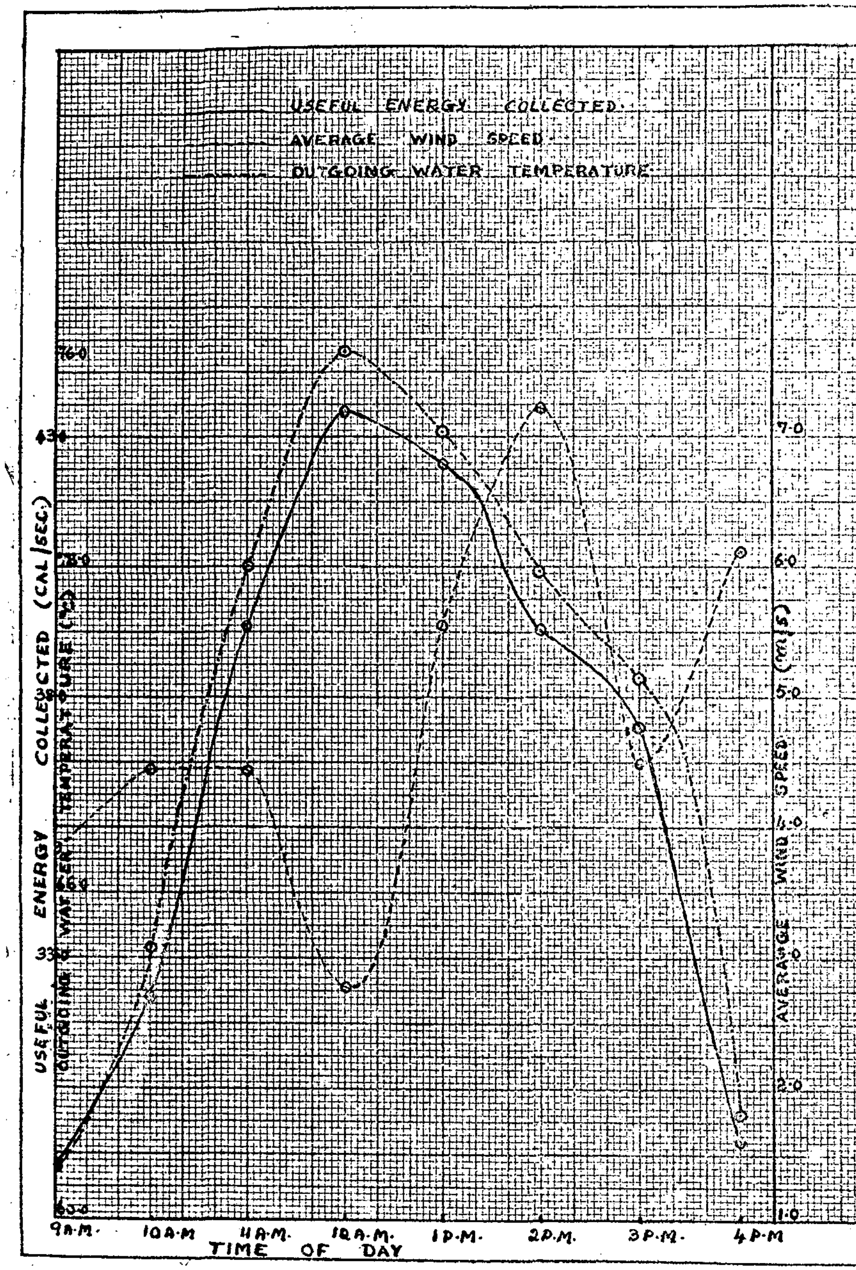


FIGURE 1a

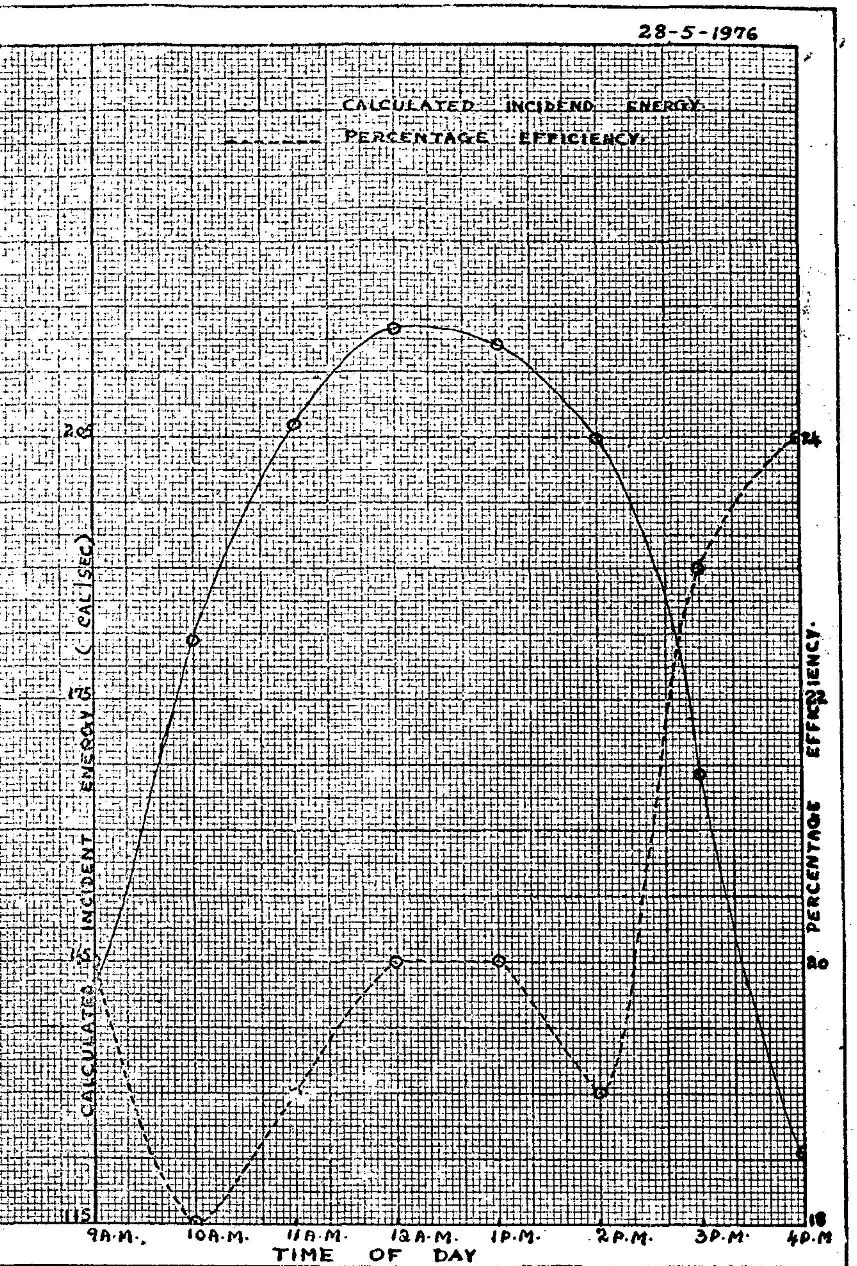


FIGURE 1b

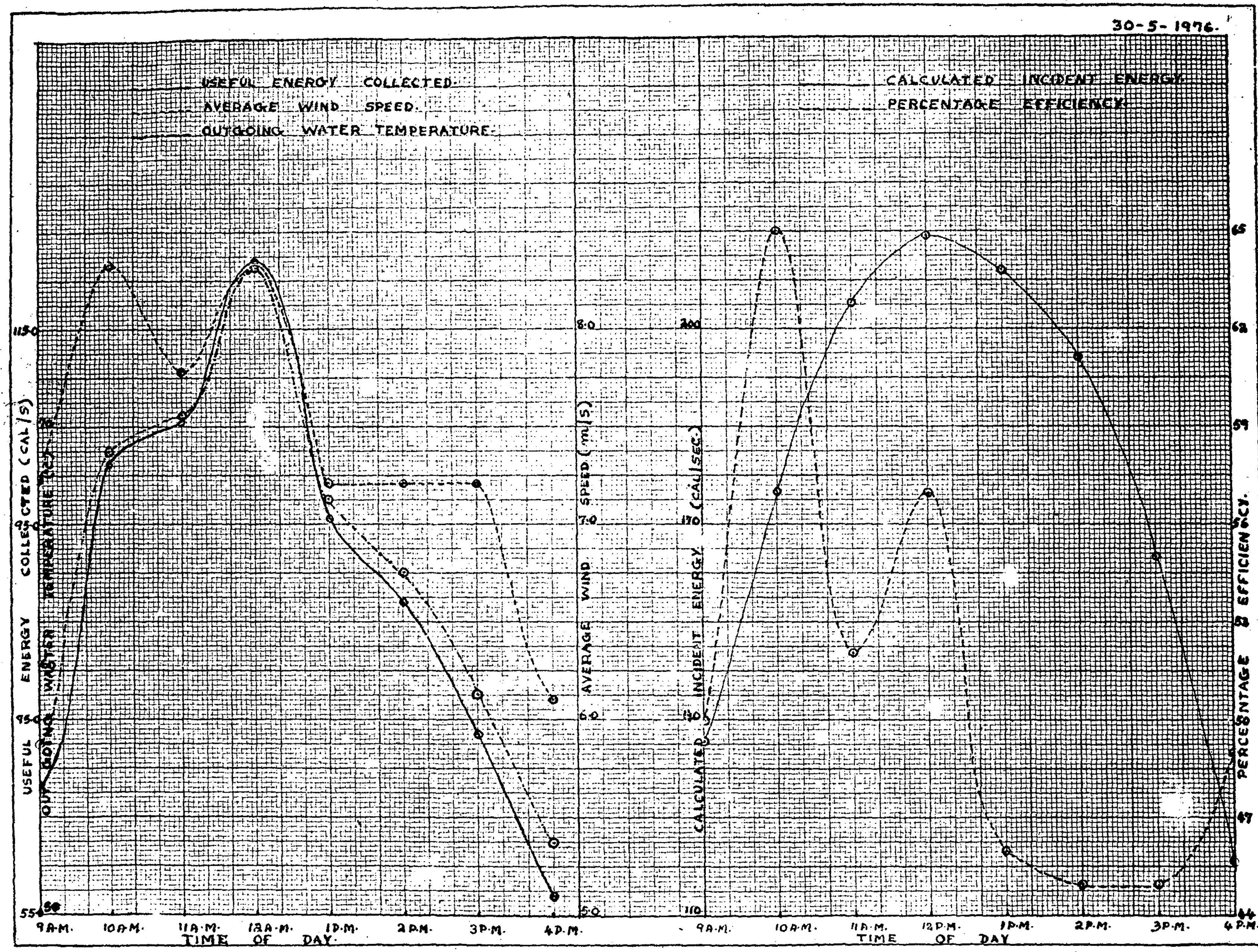


FIGURE 2a

FIGURE 2b

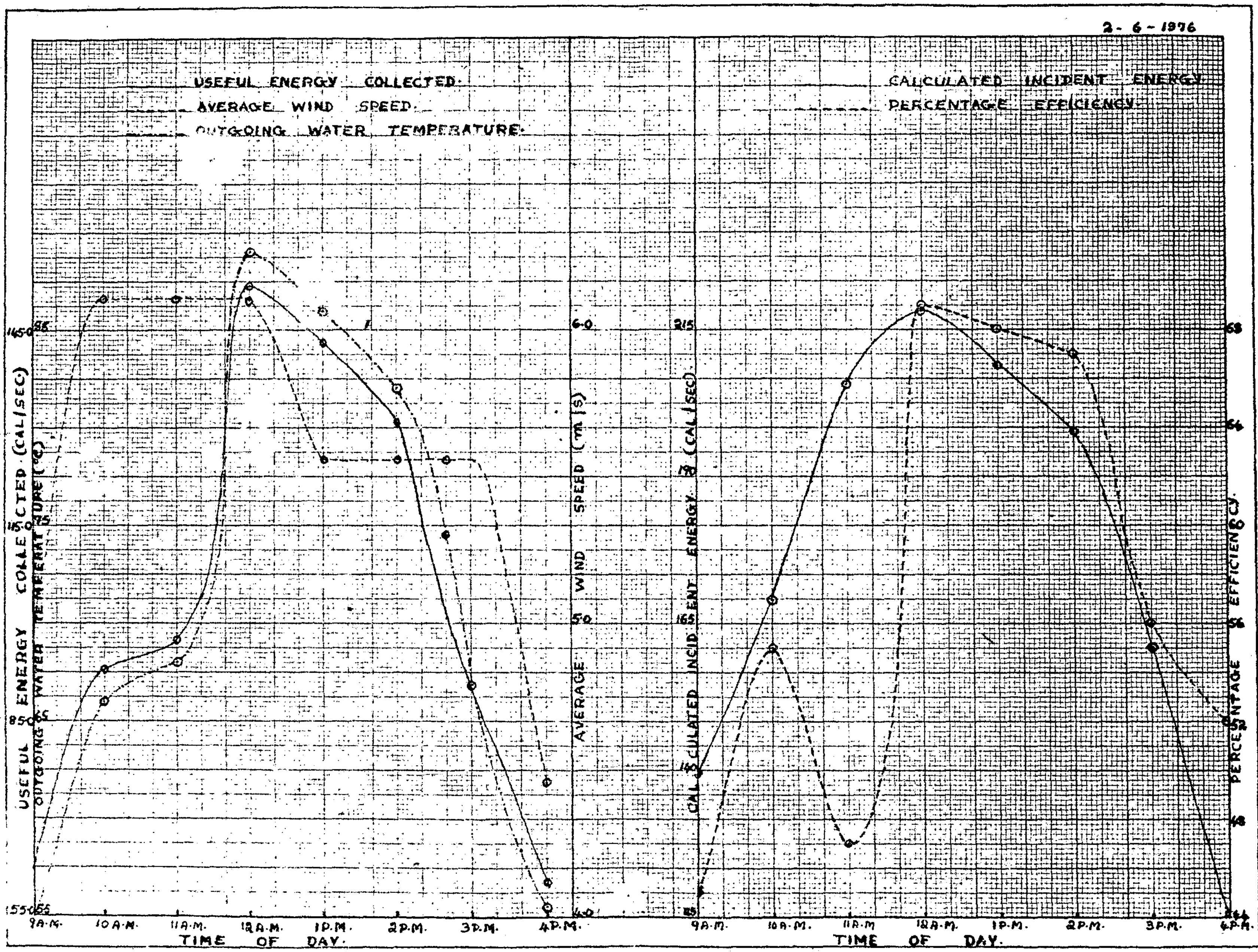


FIGURE 3a FIGURE 3b

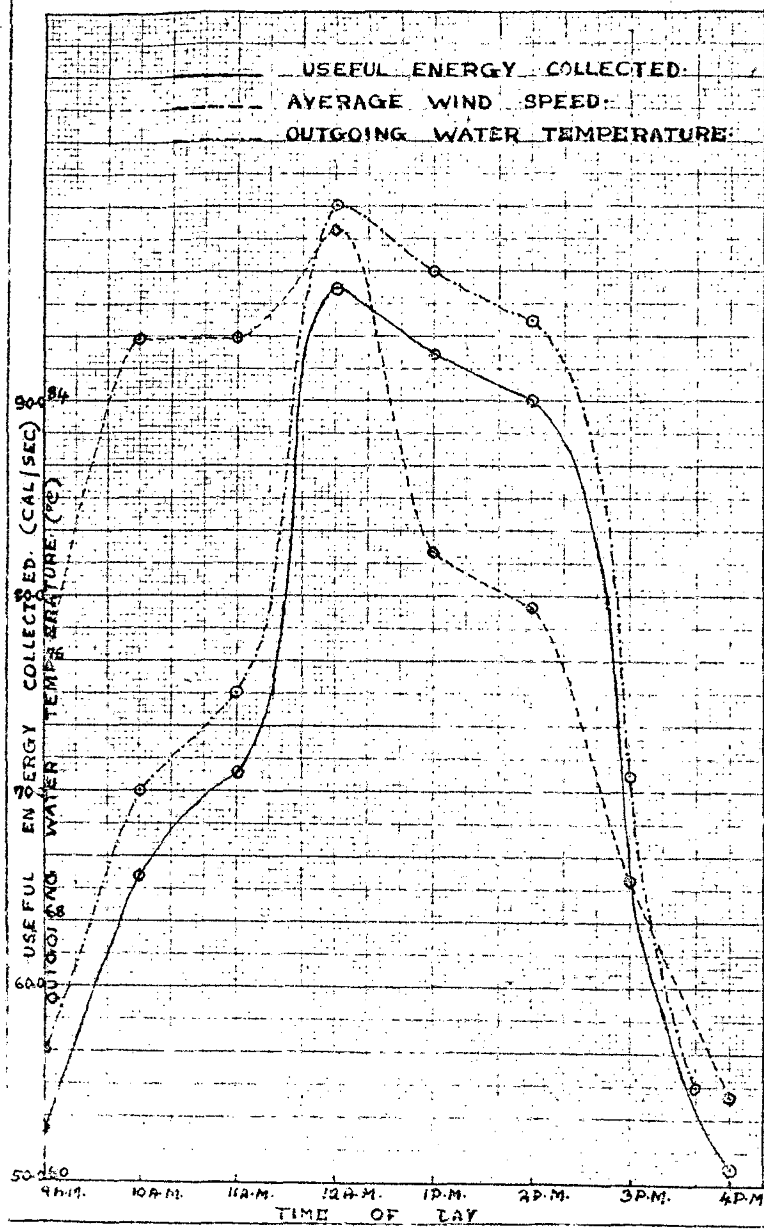


FIGURE 4 a.

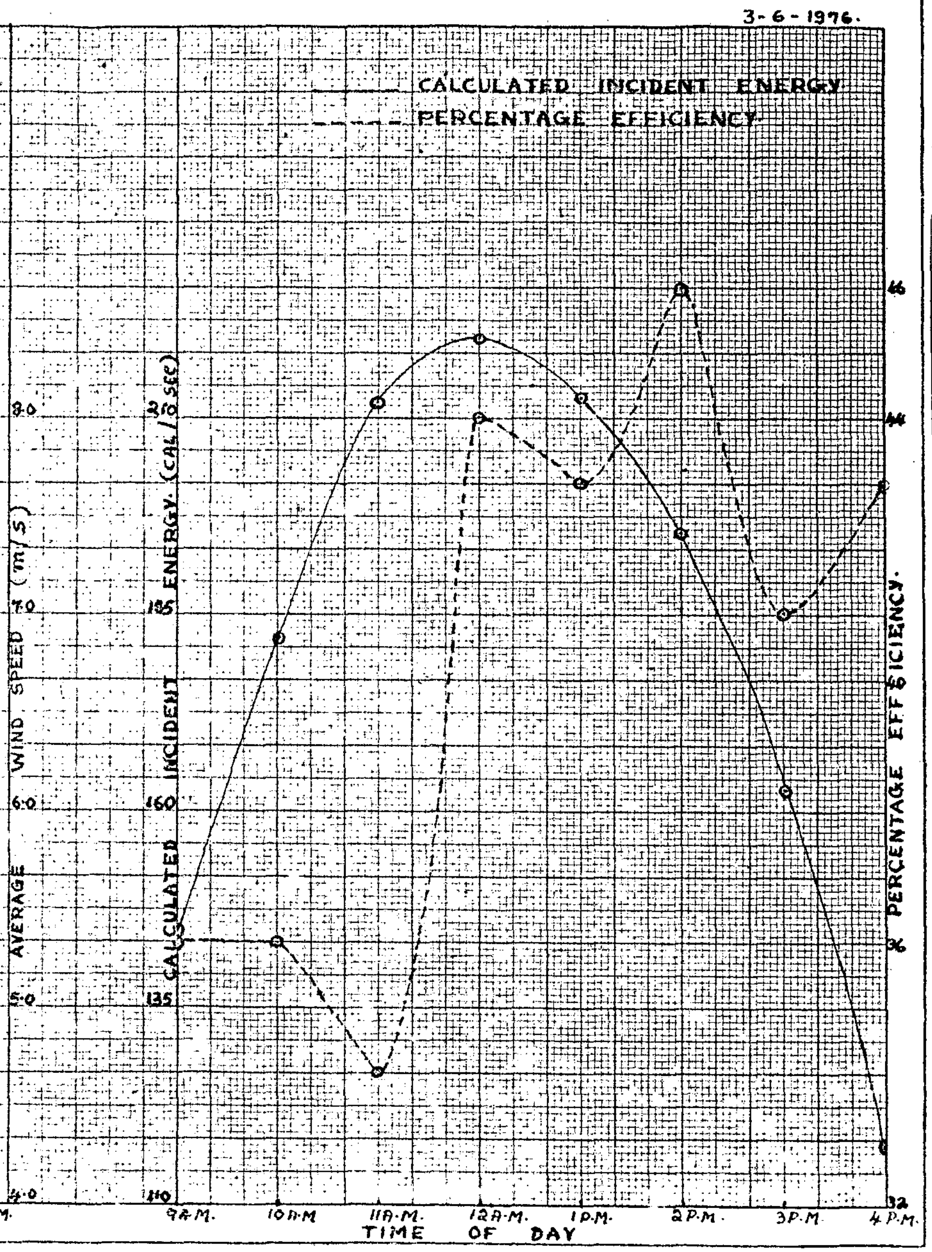


FIGURE 4 b

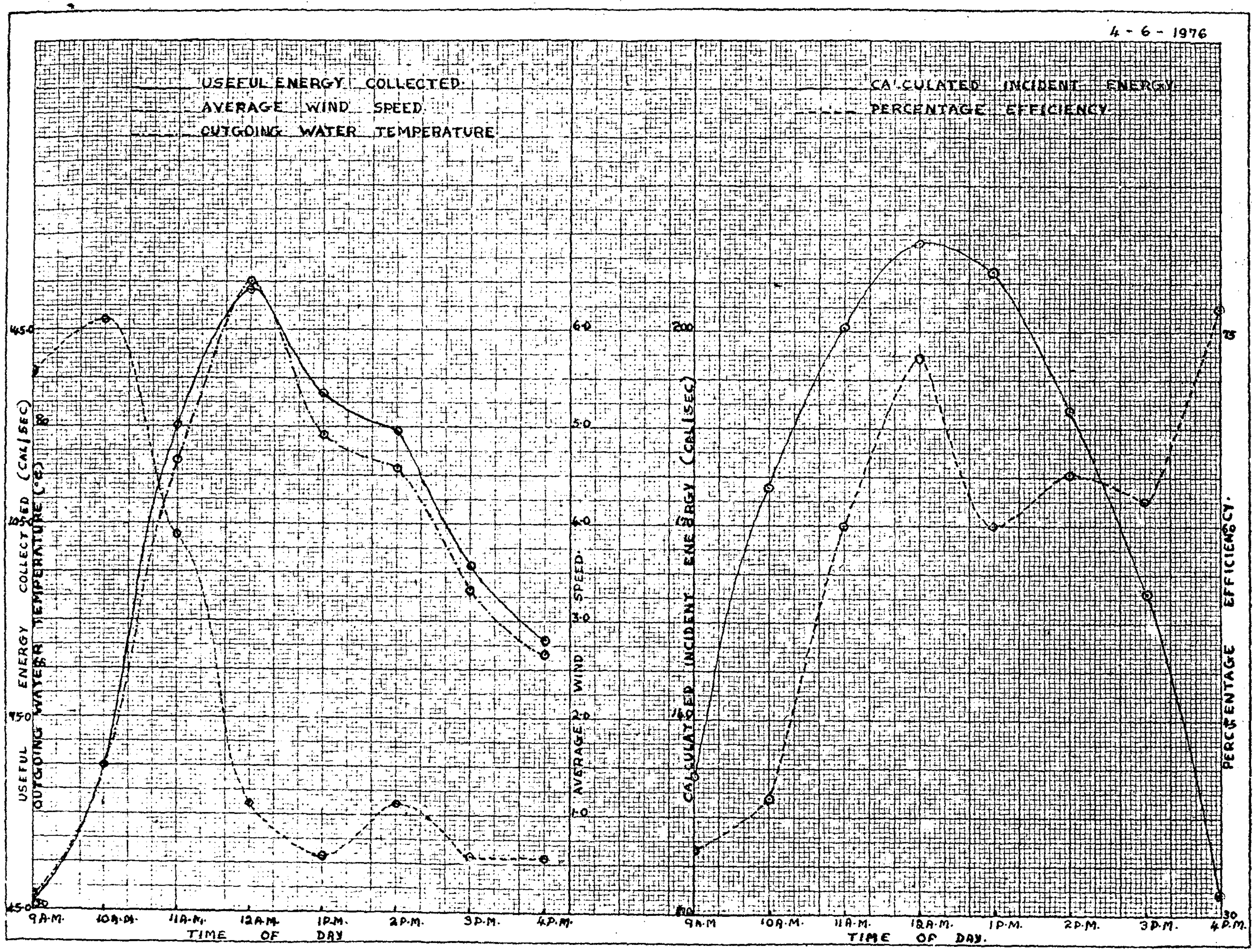


FIGURE 5a

FIGURE 5b

APPENDIX I

TABLE - 1: PROPERTIES OF SOME SELECTIVE SURFACES FOR SOLAR ENERGY APPLICATION

Surface	α^*	ε^*
"Nickel Black"; containing oxides and Sulfides of Ni and Zn on polished Ni	0.91 - 0.94	0.11
"Nickel Black" on galvanized iron (experimental)	0.89	0.12
Same process (commercial)		0.16-0.18
"Nickel Black", 2 layers on electroplated Ni on mild steel (and after 6 hr immersion in boiling water)	0.94	0.07
Cuo on Ni; made by electrode position of Cu and subsequent oxidation	0.81	0.17
Co_3O_4 on silver by deposition and oxidation	0.90	0.27
CuO on Al; by spraying dilute $Cu(No_3)_2$ solution on hot Al plate and baking	0.93	0.11
"Cu Black" on Cu, by treating Cu with solution of NaOH and $NaClO_2$ (commercial process)	0.89	0.17
Ebanol C on Cu; commercial Cu blackening treatment giving coatings largely CuO(Commercial process)	0.90	0.16

Surface	α^*	ε^*
CuO on anodized Al; treat Al with hot $Cu(NO_3)_2$- KM_nO4 solution and bake.	0.85	0.11
Al_2O_3- Mo - Al_2O_3- Mo-Al_2O_3Mo-Al_2O_3 interference layers on Mo (measured at 500°F)	0.91	0.085
PbS crystals on Al	0.89	0.20

From 'Solar Energy Thermal Process' - Duffie and Beckman

* = absorptance for solar energy

* = emittance for long wave radiation at temperatures typical of flat-plate solar collectors.

APPENDIX II

Calculation of conversion factor (R_D) for converting beam radiation on a horizontal surface to that on a tilted surface

Table (2a) : (Declination = 10^o, Latitude = 30^o)

Angle of inclination in degrees	Hour angle in degrees	Angle of incidence on a horizontal surface in degrees, ih	Angle of incidence on the tilted surface in degrees i_b	$R_D = \frac{\cos i_b}{\cos i_h}$
20	0	20.0	0	1.066
	10	22.1	9.7	1.064
	20	27.4	19.8	1.056
	30	34.4	29.5	1.054
	40	42.0	39.3	1.041
30	0	20.0	10.0	1.048
	10	22.1	14.0	1.047
	20	27.4	22.4	1.042
	30	34.4	41.5	1.033
	40	42.0	41.0	1.015
40	0	20.0	0	1.066
	10	22.1	9.7	1.064
	20	27.4	19.8	1.056
	30	34.4	29.5	1.054
	40	42.0	39.3	1.041

Table (2b) : (Declination = -10°; Latitude = 30°)

Angle of inclination in degrees	Hour angle in degrees	Angle of incidence on a horizontal surface in degrees, i_h	Angle of incidence on the tilted surface in degrees, i_b	$R_D = \frac{\cos i_b}{\cos i_h}$
20	0	40.0	20.0	1.227
	10	41.3	22.3	1.229
	20	44.4	28.2	1.256
	30	49.3	36.1	1.242
	40	55.2	44.7	1.246
30	0	40.0	10.0	1.285
	10	41.3	14.0	1.287
	20	44.4	22.7	1.295
	30	49.3	31.5	1.308
	40	55.2	41.0	1.322
40	0	40.0	0	1.305
	10	41.3	9.7	1.308
	20	44.4	19.8	1.317
	30	49.3	29.5	1.335
	40	55.2	39.3	1.356

Table (2c) : (Declination = 0°; Latitude = 30°)

Angle of inclination in degrees	Hour angle in degrees	Angle of incidence on a horizontal surface in degrees, i_h	Angle of incidence on the tilted surface in degrees, i_b	$R_D = \frac{\cos i_b}{\cos i_h}$
20	0	30.0	10.0	1.137
	10	31.5	14.0	1.137
	20	35.7	22.4	1.137
	30	41.4	31.5	1.137
	40	48.4	41.0	1.137
30	0	30.0	0	1.154
	10	31.5	10.0	1.154
	20	35.7	20.0	1.154
	30	41.4	30.0	1.154
	40	48.4	40.0	1.154
40	0	30.0	10.0	1.137
	10	31.5	14.0	1.137
	20	35.7	22.4	1.137
	30	41.4	31.5	1.137
	40	48.4	41.0	1.137

NOMENCLATURE

A	Solar Altitude
A_c	Area of the collector
b	Slope of plane from horizontal
C_c	the capital cost per unit of collector
C_E	The capital cost of equipment, pumps, pipings etc.
C_{ML}	the annual cost of maintenance labor
C_{MM}	the annual cost of maintenance materials
C_p	Specific heat, the unit cost of power
$C_{s,a}$	the annual cost of solar energy system
$C_{s,T}$	the capital cost of storage
D, d	Diameter, dust factor (defined locally)
E	Energy
F'	Collector efficiency factor
F_R	Collector heat removal factor
H	total solar energy incident on the plane of measurement (usually horizontal)
H_D	beam component of solar energy incident on the plane of measurement (often horizontal but may be normal)
H_d	diffuse component of solar energy incident on plane of measurement (usually horizontal)
H_n	Solar energy incident on surface normal to beam component
H_T	Solar radiation on a tilted surface
h	heat transfer coefficient
I	radiation intensity, interest and depreciation

i_b	angle between surface normal and beam radiation (Tilted surface)
i_h	angle between surface normal and beam radiation (horizontal surface)
K	length extinction coefficient
k	thermal conductivity
L	Latitude
l	length
m	air mass
m	mass flow rate of water
n	number of covers
N_f, N_Q	true and approximate retention efficiency
P	the annual power requirements of the solar energy system
p	pressure
Q	energy per unit time
q_u	useful energy collected in unit time
R	ratio of total radiation on tilted surface to that on plane of measurement
R_b	ratio of beam radiation on tilted surface to that on plane of measurement
R_d	ratio of diffuse radiation on tilted surface to that on plane of measurement
T	Temperature
T_a	Ambient air temperature
$T_{f,i}$	Inlet water temperature
$T_{f,o}$	Outlet water temperature
U	Overall heat transfer coefficient

W	distance between tubes

Greek

α	absorptance
δ	declination angle, thickness
ε	emittance
η	efficiency
λ	wavelength
ρ	reflectance
τ	transmittance
Φ	angle (defined locally)
ω	hour angle

Subscripts

a	air, absorbed
b	beam, back
c	collector, cover
d	diffuse
f	fin, fluid
g	glass
i	incident, inlet
L	loss
n	normal
p	plate
r	radiation
s	scattered
T	tilt
t	top
u	useful
w	wind
λ	wavelength

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