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Performance enhancement of shallow solar pond by system modification

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ABSTRACT : In the present paper a relation for temperature rise of water in shallow solar ponds as a function of solar radiation available on the horizontal surface, depth and the top area of the pond has been developed. The relation is based on Hottel-Whillier-Bliss model and Garg & Prakash model of evaluating solar collection efficiency. Compensation of low density of solar radiation available on the horizontal surface of the solar pond by the use of planar reflector is incorporated. The calculations and experimentation has been done for the local climatic condition of Indore city, (Latitude 22.71° N, Longitude 75.91° E) in India. The results of calculation have been validated by performing experiments on prototype of shallow solar pond. Comparisons between experimental and theoretical results indicated that the theoretical model can be used for estimating the pond's performance with satisfactory accuracy. Overall a good agreement has been achieved.

Keywords : Shallow solar pond (SSP); solar radiation, pond depth, pond geometry, pond area

NOMENCLATURE

I	:	insolation, J/m^2
G	:	solar irradiance, W/m^2
G_b	:	beam radiation on horizontal surface, W/m^2
T_w	:	temperature of water
T_a	:	ambient temperature, K
T_c	:	temperature of glass cover, K
T_s	:	temperature of the sky, K
U	:	over all heat transfer coefficient, W/m^2 K
U_b	:	bottom loss coefficient, W/m^2 K
U_s	:	side loss coefficient, W/m^2 K
U_t	:	top loss coefficient, W/m^2 K
τ	:	transmitivity
τ_e	:	effective transmitivity
K_i	:	thermal conductivity of insulation, W/m K
K_g	:	thermal conductivity of glass cover, W/m K
t_g	:	thickness of glass cover, m
t_{ib}	:	thickness of insulation in the bottom, m
t_{is}	:	thickness of insulation in the sides, m
h_{ca}	:	convective heat transfer coefficient of the ambient air, W/m^2 K
$h_{r,\,ca}$	:	radiative heat transfer coefficient between cover and ambient, W/m^2 K
ρ	:	density of water / storage medium, Kg/m^3
σ	:	Stefan's Boltzmann constant
ε_w	:	emissivity of water surface
ε_c	:	emissivity glass cover
A	:	surface area exposed to solar radiation, m^2
m_f	:	mass of fluid/ storage medium, Kg
η_i	:	instantaneous collection efficiency
η_d	:	daily collection efficiency
η_m	:	monthly collection efficiency
η_a	:	annual collection efficiency
Q	:	total heat collected per unit area of solar pond, J/m^2
H	:	total daily insolation, J/m^2
m	:	air mass
δ	:	angle of declination
φ	:	latitude of the place
ω	:	hour angle
η_{mirror}	:	mirror's optical efficiency
θ_z	:	menith Angle.

I. INTRODUCTION

A shallow solar pond (SSP) is a solar collector that can be used for collecting and storing heat. In late 1970s a group of researchers at the Lawrence Livermore Laboratory conducted significant work to model and apply the technology of the SSP to industrial processes [1]. The depth of water in the SSP is relatively small, generally in the range of 4–15 cm. The temperature of the pond water is inversely proportional to the depth of the water, but the collected heat is directly proportional to the water depth.

There are three modes of operation that are possible with the SSP [2]. The first mode is called the batch heating mode in which the pond is filled in the early morning with water at an initial temperature Twi. In the afternoon, when the water temperature reaches its maximum value, the pond is emptied into an insulating reservoir. The second mode is called the closed cycle continuous flow heating mode. In this mode, the water is continuously circulated at a constant rate between the pond and the storage reservoir in which the heat may or may not be continuously removed by an appropriate heat exchanger. When the useful heat added to the pond water reaches zero, all of the pond water is emptied into the reservoir. The third mode is called the open cycle continuous flow heating mode in which the water at an initial temperature Twi is flowed continuously at a constant rate through the pond and then either to storage or to some end use.

The analytical study of the system consisting of a metallic rectangular tank with blackened bottom and side with transparent cover at the top was carried out by Sodha *et. al.* [3]. It was concluded that one dimensional analysis was adequate to predict the performance of shallow solar pond water heater and the daily efficiency would increase if water is continually withdrawn for consumption thereby reducing the pond water temperature and hence the rate of heat loss.

Typical peak temperatures achieved in a shallow solar pond ranges from approximately 60°C during summer and approximately 40°C during winter season. The annual efficiency of the shallow solar pond system is about 50% with a nominal operating depth of 7.5 to 10.0 cm [4].

II. MATERIAL AND METHODS

The main apparatus used for the experimentation includes the Shallow Solar Pond (as shown in the schematic with P.V.C. cover and glass glazing) with mirror, thermocouple temperature indicator- dimmerstat (with least count 1°C), solarimeter (with least count 20 mW/cm^2) (Make: CEL), whirling thermometer to measure wet bulb and dry bulb temperatures (with least count 0.1°C) (Make: Zeal-England).

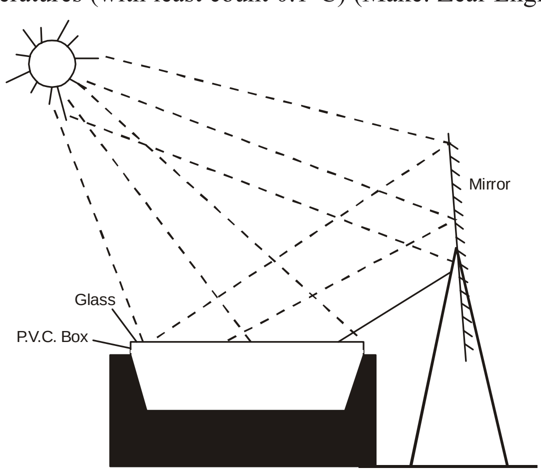

Fig.1. Schematic of shallow solar pond with plane reflector.

Dimensions of the pond :

Pond used in the experiment is a hollow truncated square pyramid,

Base area, $a = 0.365 \times 0.365$ m^2

Top area, $A = 0.46 \times 0.46$ m^2

Depth, h = 8 cm = 0.08 m

Glass thickness, t_g = 5 mm; P.V.C sheet thickness, t_p = 0.32 mm.

III. RESULTS AND DISCUSSIONS

A. Mathematical modelling

In this model Hottel Whillier's Bliss used which is very commonly applied for predicting the performance of flat plate collectors and can be satisfactorily used for evaluating performance of shallow solar ponds [5]. The two main parameters of the model are $\overline{\tau\alpha}$ (average over direct and diffuse radiation) and the overall heat transfer coefficient, U, that accounts for heat losses conducted downwards and convected and radiated in upward direction.

The instantaneous rate of heat collection per unit area of shallow solar pond covered with a single layer of top cover consisting of transparent insulating material, is expressed as

$$q = [(\tau)\, G - U(T_w - T_a)] \quad \text{...(1)}$$

Where,

$$U = U_b + U_s + U_t \quad \text{...(2)}$$

The heat loss through the rear side by convection and radiation is negligible compared to the heat loss by conduction, hence

$$U_b = \quad \text{...(3)}$$

The side loss will be mainly of conduction and convection

$$U_s = \quad \text{...(4)}$$

And the top loss include all the three modes of heat transfer, for a two glass cover it is expressed as

$$U_t = \frac{1}{R_1 + R_2} \quad \text{...(5)}$$

Where,

$$R_1 = \frac{t_g}{k_g} \quad \text{...(6)}$$

$$R_2 = \quad \text{...(7)}$$

For 0.5 m^2 area of plate convection coefficient is given by the dimensional equation

$$h_{ca} = 2.8 + 3.0\, V \quad \text{...(8)}$$

where, V is the wind speed in m/s and h_a is in W/m^2 K

And radiative heat transfer coefficient between top glass cover and ambient is given by

$$h_{r,\,ca} = \frac{\sigma\varepsilon_c (T_c + T_s)(T_c^2 + T_s^2)(T_c - T_s)}{(T_c - T_a)} \quad \text{...(9)}$$

Typical values of U for a shallow solar pond with single glazing vary from 6.2 W/m^{2}K in winter to 7.4 W/m^{2}K in summer [4].

The instantaneous or hourly collection efficiency is defined as :

$$\eta_i = \frac{q}{G} = (\tau) - U \qquad = (\tau) - U \frac{\Delta T}{G} \quad ...(10)$$

Hence daily collection efficiency can be evaluated as

$$\eta_d = \quad ...(11)$$

Similarly monthly average daily collection efficiency can be expressed as

$$\overline{\eta_m} = \quad ...(12)$$

And in the similar manner annual average collection efficiency $\overline{\eta_a}$ can also be expressed. In the above expressions Q represents the total daily collected heat per unit shallow solar pond area. H represents the total daily solar insolation, from sunrise to sunset. and represents the monthly average values of Q and H.

Total daily direct solar insolation, on average day of the month, for the given location of Indore (Latitude 22.71^{o} N, Longitude 75.91^{o} E) has been estimated by the author [6] using various methods. This can further be exploited to estimate the diffused component and hence the total solar radiation.

Now, if

$$q = \quad ...(13)$$

Where, A is the surface area of the pond, m is the mass of water, c_p is the specific heat and t is the time then the differential equation in T using above equations can be written as

$$[(\tau)G - U(T - T_a)] = \quad ...(14)$$

$$= \quad ...(15)$$

$$\frac{dT}{dt} = \quad ...(16)$$

$$\frac{dT}{dt} + \frac{AUT}{m_f c_p} = \frac{AG(\tau) + UAT_a}{m_f c_p} \quad ...(17)$$

$$\frac{dT}{dt} + \frac{AUT}{m_f c_p} = \frac{AS(t) + UAT_a}{m_f c_p} \quad ...(18)$$

Where, $S(t) = G_b(t).\tau$.

The contribution of beam radiation is only considered Assuming T_a to be constant over a given period of interest, the solution of equation for T_f at time t_f with an initial temperature of T_i at $t = t_i$ is

$$T = [T_a + (T_i - T_a) \exp(-AU(t_f - t_i)/m_f c_p)] + \frac{A}{m_f c_p} \quad ...(19)$$

The heat collected by a unit surface area of water between time $t = t_i$ and $t = t_f$ is then

$$Q(t_f) = \frac{m_f c_p}{A} [T_f - T_i] \quad ...(20)$$

And

$$Q(t_f) = [(T_a - T_i)(1 - \exp(-AU(t_f - t_i)/m_f c_p))] + \quad ...(21)$$

The pond depth, d as one of the parameters can be introduced by replacing

$$\frac{m_f c_p}{A} = c_p d\rho \quad ...(22)$$

Hence the above equation (21) becomes

$$Q(t_f) = c_p d\rho\, [(T_a - T_i)(1 - \exp(-U(t_f - t_i)/c_p d\rho))] + \quad ...(23)$$

The value of $G_b(t)$ has been calculated on the basis of model suggested by H.P. Garg and J. Prakash [2]. It is based on the air mass and is applicable for Indian condition. For Indian conditions a standard atmosphere (for clear days) has been defined as containing 15mm of perceptible water, 2.5 mm of ozone and 300 dust particles per cubic cm at 760mm of Hg pressure.

The final equation based on the transmission factor for instantaneous beam or direct radiation, under standard Indian atmosphere, is given as :

$$G_{bn} = 1246/(1 + (0.3135)\text{m}) \text{ W/m}^2 \quad ...(24)$$

Hence G_b *i.e.*, radiation on horizontal surface will be

$$G_b = G_{bn} \times \cos\theta_z \quad ...(25)$$

$$m = [\{(R/H_a)\cos\theta_z\}^2 + 2(R/H_a) + 1]^{1/2} - (R/H_a)\cos\theta_z \quad ...(26)$$

Where, R is the radius of earth and H_a is the thickness of the atmosphere.

The insolation collected over a period of time can be found by integrating G_{bn} over the required time period for which insolation is to be collected.

Hence in equation,

$$T = [T_a + (T_i - T_a)\exp(AUt_f / m_f c_p)] + \frac{A}{m_f c_p}$$

Since, planar reflector is also used here, hence irradiance, $S(t) = G_b(t) \times (\tau) \times (1 + \eta_{mirror})$

$$\tau_e = (\tau)_{glass} \times (\tau)_{P.V.C}$$
$$G_b = G_{bn} \times \cos\theta_z \ (W/m^2)$$
$$G_{bn} = 1246/(1 + 0.3135\ m)\ W/m^2\ [7]$$

Whereas zenith angle can be determined as [9]

$$\cos\theta_z = \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta \quad ...(27)$$

Therefore, mirror's optical efficiency

$$\eta_{mirror} = (\tau)_{mirror\ glass} \times \rho_{mirror} \times (\tau)_{mirror\ glass} \quad ...(28)$$
$$\eta_{mirror} = (\tau)_{mirror\ glass} \times \rho_{silvering} \times (\tau)_{mirror\ glass}$$
$$= \rho_{silvering} \times (\tau)^2_{mirror\ glass} \quad ...(29)$$

Till now most of these shallow solar Ponds have been with an integrated reflector [10] which limits the radiation to fall all the time on pond surface. The above planar reflector arrangement offset this limitation and also prevent the spillover of fluid if moved to track the sun else there will be loss of solar radiation. Once solar radiation is estimated than final temperature can be calculated using equation (21).

B. Experimentation on prototype

In order to validate the above model experiments have been conducted on prototype.

The Fig.2 and 3 show the variation of pond water temperature and irradiance during the day time as observed experimentally. The covering materials used on experimental days is also given alongside.

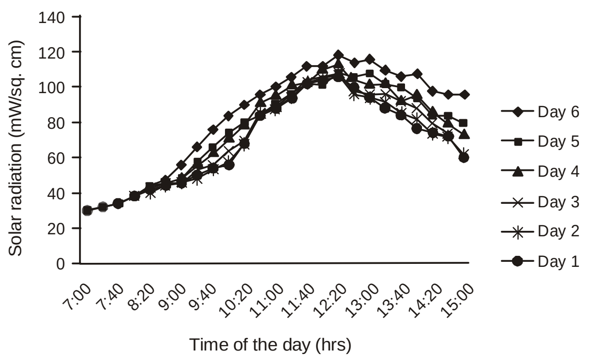

Fig.2. Variation of irradiance with time of the day observed during days of experiment.

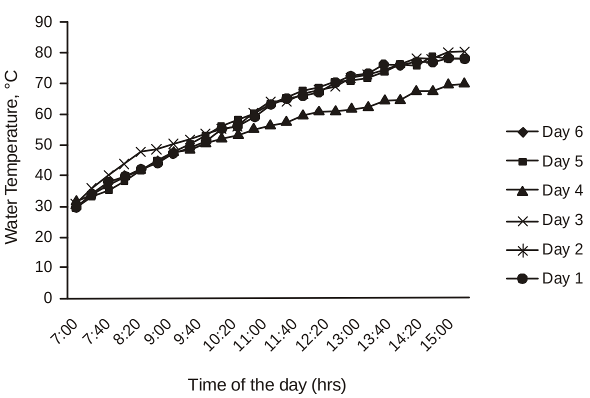

Fig.3. Variation of average temperature of water with time of the day observed during days of experiment.

The obseravation were taken from 7:00 to 15:00 hours on 27th Sept to 2nd October 2009. A number of observations of solar radiation received on horizontal surface, dry and wet bulb temperature and water temperature were recorded at an interval of 20 minutes and used for analysis. The variation of final temperature of water in pond was also checked with use of different covering materials and different time periods. The comparison of theoretical calculations and experimentally observed data are presented in graph below:

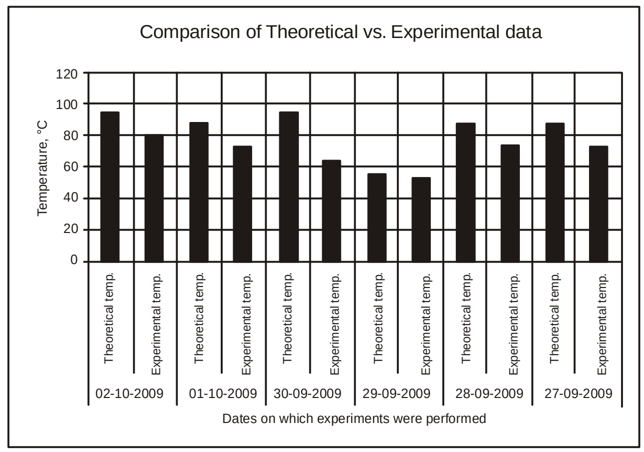

Fig.4. Comparison of actual temperature achieved versus theoretically calculated temperatures.

IV. CONCLUSION

The closeness of theoretical and experimental results indicates the validity of theoretical model. It also reveals that use of glass glazing along with the P.V.C. the final temperature rises to 79°C. This system modification of using combination of glass and PVC cover can enhance the pond performance in terms of storage water temperature.

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