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Research Paper

Effect of Inclination Angle & Water Temperature on Internal Heat Transfer Coefficients & Productivity of Single Slope Solar Still: An Indoor Simulation

Engineering

KEYWORDS : Solar Distillation, heat transfer coefficients, inclination angle, condensing cover

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ABSTRACT

In this communication, an effort has been made to investigate the effect of condensing cover inclination angle and water temperature on internal heat transfer coefficients and yield of single slope solar stills inclined at 15^0, 30^0 & 45^0.

For the purpose of accurate analysis inner glass cover temperature has been used instead of outer cover temperature. The construction of condensing cover consists of commonly used glass sheet to form top inclined cover and GRP sheets to make the side walls of the cover. Constant temperature water bath has been used for the experiment to maintain water temperatures ranging from 40^o C to 70^o C at steady state. The yield obtained at an interval of every 30 minutes has been used to determine the values of constants C and n and consequently convective & evaporative heat transfer coefficients.

The maximum value of heat transfer coefficients is for condensing cover with inclination angle of 150 and the minimum is for 300. The maximum temperature difference between evaporative surface and condensing surface is for condensing cover with inclination angle of 45^0 and the minimum is for 15^0. The maximum yield is obtained for condensing cover with inclination angle of 45^0.

1. INTRODUCTION

Drinking water, in adequate quantity and safe quality, is a basic requirement for life and a determinant of standard of living. The health burden of poor water quality is enormous. It is estimated that around 37.7 million Indians are affected by waterborne diseases annually, 1.5 million children are estimated to die of diarrhoea alone and 73 million working days are lost due to waterborne disease each year. The resulting economic burden is estimated at $600 million a year.

Over 97% of water available on the earth's surface is salty and environmental pollution caused predominantly by anthropogenic activities is also contributing to the degradation of fresh water. This has led to the intensification of the drinking water crisis in India. The problem of chemical contamination is also prevalent in India with 1,95,813 habitations in the country are affected by poor water quality. The major chemical parameters of concern are fluoride and arsenic. Iron is also emerging as a major problem with many habitations showing excess iron in the water samples.

A sustainable, green and cheap source of energy is required to provide fresh water to a large proportion of the Indian population. And for this matter renewable energy technologies are being seen as sustainable, green and cheap technologies for water distillation and desalination.

Amongst these, solar desalination is gaining more importance for obtaining potable water. The main advantage of this process is that, it does not utilize costly conventional fossil fuels, which create the problem. The solar energy is naturally and freely available. Though the solar desalination plants require skilled labour, its maintenance cost is low. In many areas of the world, the desalination of sea water is a common method for producing drinking water, which is currently increasing in importance [1] and solar desalination and distillation can be promising technology to meet the water need of these countries.

2. LITERATURE SURVEY

The operating temperatures of solar driven distillation unit range from 600 to 1200 [3] and their performance prediction mainly depends on accurate estimation of the basic internal heat and mass transfer relations. Many experimental and theoretical works have been conducted on single basin solar stills for testing the performance of different enhancement parameters. The oldest semi-empirical heat and mass transfer relation was given by Dunkle [2]. However, the relation developed by Dunkle has the following limitations:

a) It is valid for a low operating temperature range (45-500C).
b) It is independent of the cavity volume, i.e. the average spacing between the condensing and evaporative surfaces.
c) It is valid for cavities that have parallel condensing and evaporative surfaces.

Numerous empirical relations were developed later on to predict the hourly and daily distillate output for different designs of solar distillation units. Most of these relations are based on simulation studies. Kumar et al [5] has done thermal and computer modelling for determining the constants C and n and consequently heat and mass transfer coefficients for different types of solar still. Lof et. Al [6] have analysed heat and mass transfer of solar still in detail and studied the effect of various design parameters and climatic variables on the performance of a solar still. Numerical solution of the heat balance equations was then obtained with the aid of a digital computer. Sharma et al [7] developed a method for estimation of heat transfer coefficients for upward heat flow and evaporation in still and calculation of hourly output was done with this new approach. It was observed that the performance of solar still has an agreement with the result of an analysis based on Dunkle's relation with a factor of 0.65 to account for instauration. Shukla et al [8] has recently developed a model, based on regression analysis, to determine the values of constants C and n using the experimental data obtained from the stills. This method uses both inner and outer glass cover temperatures to determine the expressions for internal heat transfer coefficient and does not impose any limitations. Aboul-Enein et al. [9] presented a simple transient mathematical model for a single basin still through an analytical solution of the energy-balance equations for different parts of the still. The authors also investigated the thermal performance of the still both experimentally and theoretically, and the influence of cover slope on the daily productivity of the still. This transient mathematical model was used by El-Sebaii [10] for a vertical solar still to conduct parametric investigation. He found that the daily productivity of the still increases with the increase of the still length, width, and wind speed up to typical values. Akash et al. [4] examined the effect of using a solar still with various cover tilt angles of 15, 25, 35, 45 and 55 º in outdoor conditions and the optimum tilt angle for water production was found to be 35º.

3. EXPERIMENTAL SETUP

The experimental set-up includes a constant temperature water bath, condensing covers inclined at 15°, 30° & 45°, digital temperature indicators, well calibrated thermocouples (by Zeal Thermometer), two transparent pipes of small diameter and a measuring flask. The output from the still is collected through a channel. Two plastic pipes are connected to this channel to drain the distilled water to an external measuring jar. The total capacity of the constant temperature bath is 40 L, and its effective evaporative surface area is 0.3 m × 0.4 m. The water is heated by bath heating coils. Table 1, shows the detailed dimensions of condensing covers and Fig. 1 shows the picture of fabricated condensing cover.

TABLE 1: DETAILED DEMENSIONS OF CONDENSING COVERS

S. No	Parameter	Dimensions of 15° (mm)	Dimensions of 30°(mm)	Dimensions of 45° (mm)
1	Length	430	430	430
2	Width	330	330	330
3	Higher height	300	440	625
4	Lower height	64	69	75

FIGURE 1: CONDENSING COVERS

Condensing covers at three different inclination angles were fabricated in the lab with the help of common glass to make top inclined covers and 3 mm thick GRP (Glass Reinforced Plastic) sheets to make the side walls of the condensing covers. This glass reinforced plastic is manufactured by sticking many layers of corrugated sheets with special chemicals in such a manner that air is entrapped between its corrugated cavities, which provide a high degree of insulation for heat flow, which is a highly desired quality for the solar still material.

3.1 Procedure of Experiments

The experiments were conducted on different days in the month of June, 2012, on the campus of Sam Higginbottom Institute of Agriculture, Technology and sciences-Deemed to be University. The inclination angles of fabricated condensing covers are 15°, 30° & 45° and the operational temperature range is from 40^0 to 700 at intervals of 5°C. Constant temperature bath was started at 8:30 am an hour before commencing the experimental work to make sure that steady state has been reached. Continuous readings for every half an hour were then taken and recorded, i.e., 10:00, 10:30, 11:00, 11:30, 12:00, 12:30, 1:00, 1:30. 2:00, 2:30, 3:00, 3:30, 4:00, 4:30 and 5:00 under no fan conditions (natural mode). The same process was applied in temperatures 40°C, 45°C, 50°C, 55°C, 60°C, 65°C, 70°C for three inclination angles. Fig. 1 shows the experimental setup and ongoing experiment.

FIGURE 2: CONSTANT TEMPERATURE WATER BATH WITH CONDENSING COVER DURING THE EXPERIMENT

3.2 Thermal Model

The vapor, which consists of moisture and dry air, is freely convected above the water surface to the condensing cover by the action of pressure difference because of buoyancy force caused by density variation. This is due to the difference in temperatures between the water surface and condensing cover. This process within the unit always happens in natural mode. However, the external heat transfer from condensing cover to the atmosphere takes place outside the still and can either be under the natural mode, depending on ambient conditions, G.N. Tiwari, et al [11]

3.2.1 Determination of Characteristic Length

It is required to determine the characteristic length for the calculations of internal heat transfer coefficients and convective mass transfer. The Lower vertical height above the water surface is taken as lower characteristic length and higher vertical side as higher characteristic length. So we have taken half of the vertical height at the central axis of condensing cover, this is 120 mm for 15°, 30° & 45°.

Characteristic Length (LV) = Difference + Vertical Height of smaller end of the solar still (d_f)

Where,
Difference = Height of bath – Height of water

3.2.2 Determination of Temperature Dependent Physical Properties of Vapor

Various temperature dependent physical properties of vapor need to be determined, so as to determine constants C and n. The following expressions are used for the same.

1. Specific heat (C_p)

$$Cp=999.2+0.1434\times T_v+1.101\times10^{-4}\times T_v^2-6.7581\times10^{-8}\times T_v^3$$

2. Density (ρ)

$$\rho=\frac{353.44}{(T_v+273.15)}$$

3. Thermal Conductivity (K_v) $K_v=0.0244+0.7673\times10^{-4}\times T_v$

4. Viscosity (μ)

$$\mu=1.718\times10^{-5}+4.620\times10^{-8}\times T_v$$

5. Latent heat of vaporization of water (L)

when $T_v \le 70^\circ$ C

$$L=2.4935\times10^6\times[1-9.4779\times10^{-4}T_v+1.3132\times10^{-7}T_v^2-4.7974\times10^{-9}T_v^3]$$

when $T_v > 70^\circ$ C

$$L=3.1615\times10^6\left[1-\left(7.616\times10^{-4}\times T_v\right)\right]$$

6. Partial saturated vapor pressure at condensing cover temperature (P_g)

$$P_g = \exp\left[\left(\frac{25.317 - 5144}{T_g + 273}\right)\right]$$

7. Partial saturated vapor pressure at water temperature (P_w)

$$P_w = \exp\left[\left(\frac{25.317 - 5144}{T_w + 273}\right)\right]$$

8. Expansion factor (β)

$$\beta = \frac{1}{(T_v + 273.15)}$$

3.2.3 Determination of Internal Heat Transfer Coefficients and Convective Mass Transfer

In general for heat transfer the following equations may be applied the rate of convective heat transfer is described by the general equation,

$$Q = h_{cw} \times (T_w - T_g) = h_{cw} \times A \times \Delta T \quad \text{(eq. 1)}$$

The relation of the non dimensional Nusselt number carries the convective heat transfer coefficient as,

$$Nu = \frac{h_{cw}}{K_v} L_v = C(Gr.Pr)^n \quad \text{(eq.2)}$$

OR (eq.3)

$$h_{cw} = \frac{K_v}{L_V} C(Gr.Pr)^n$$

Where Gr & Pr are given as,

$$Gr = \frac{\beta g L_v^3 \rho^2 \Delta T}{\mu^2}$$

$$Pr = \frac{\mu \times C_p}{K_v}$$

The distillate output in (kg) from the unit can be obtained by the relation,

$$m_{ew} = \frac{q_{ew} \times A_w \times t}{L} \quad \text{(eq.4)}$$

Rate of evaporative heat transfer,

$$q_{ew} = h_{ew} \times (T_w - T_g) \quad \text{(eq.5)}$$

Evaporative heat transfer coefficient, W/m^2 °C,

$$h_{ew} = [(0.01623 \times h_{cw}) \times \frac{P_w - P_g}{T_w - T_g}] \quad \text{(eq.6)}$$

By substituting the expression for hcw from equation (3) into equation (6) we get,

$$h_{ew} = 0.01623 \times \frac{K_v}{L_v} \times C \times (Gr.Pr)^n \times \frac{(P_w - P_g)}{(T_w - T_g)} \quad \text{(eq.7)}$$

Substituting hew from equation (7) into equation (5) we get,

$$q_{ew} = 0.01623 \times \frac{K_v}{L_v} \times C \times (Gr.Pr)^n \times (P_w - P_g) \quad \text{(eq.8)}$$

Substituting qew from equation (8) into equation (4), we get

$$m_{ew} = \frac{0.01623}{L} \times \frac{K_v}{L_v} \times A_w \times t \times (P_w - P_g) \times C \times (Gr.Pr)^n \quad \text{(eq.9)}$$

Equation (9) can be rewritten as,

OR

$$m_{ew} = R \times C \times (Gr.Pr)^n$$

OR

$$\frac{m_{ew}}{R} = C \times (Gr.Pr)^n \quad \text{(eq.10)}$$

Where,

$$R = \frac{0.01623}{L} \times \frac{K_v}{L_v} \times A_w \times t \times (P_w - P_g) \quad \text{(eq.11)}$$

Taking the logarithm to both side of equation (10) & comparing it with the straight line equation.

$$y = mx + C \quad \text{(eq.12)}$$

We get

$$y = \ln\left(\frac{m_{ew}}{R}\right)$$

$$Co = \ln C$$

$$X = \ln\left(\frac{Gr}{Pr}\right)$$

$$m = n$$

By using linear regression analysis the coefficient in equation (12),

$$m = \frac{N(\Sigma xy) - (\Sigma x)(\Sigma y)}{(N)(\Sigma x^2) - (\Sigma x)^2} \quad \text{(eq.13)}$$

$$Co = \frac{(\Sigma y)(\Sigma x^2) - (\Sigma x)(\Sigma xy)}{(N)(\Sigma x^2) - (\Sigma x)^2} \quad \text{(eq.14)}$$

Where,
N = number of experiment observations

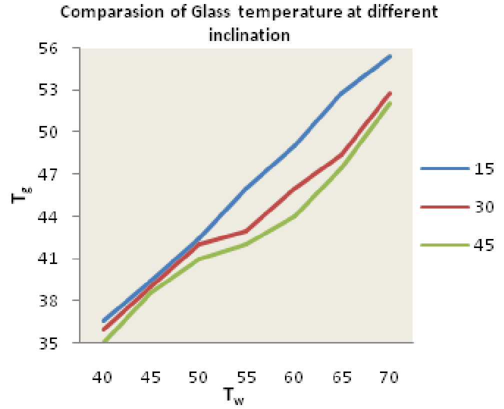
C = Exp (Co)
n = m

For the purpose of calculation of the above mentioned work, a computer program was developed in c.net.

4. RESULT & DISCUSSION

It can be clearly seen in Fig. 3 that inner glass temperature of the condensing cover increases with the decreasing inclination angle of the condensing cover at corresponding constant water temperature. It can also be seen that the minimum inner glass temperature is for condensing cover with 15° inclination angle and the maximum is for condensing cover with 45° inclination angle. This can be accounted by the fact that more heat is accumulated between the water surface and glass cover at lower inclination.

FIGURE 3: VARIATION OF INNER GLASS TEMPERATURE WITH RESPECT TO WATER TEMPERATURE AT DIFFERENT INCLINATIONS



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It's well known fact that in the field of distillation distillate output increases with the increase in temperature difference between evaporative surface and condensing surface. Fig. 4 shows the variation of temperature difference for three different inclination angles of the condensing cover at seven different temperatures. It can be clearly seen that temperature difference increases with the decreasing inclination angle of the condensing cover at corresponding constant water temperature. And also the temperature difference increases with increasing water temperature at all three inclinations. Here we are observing that the minimum inner glass temperature is for condensing cover with 15° inclination angle and the maximum is for condensing cover with 45° inclination angle.

FIGURE 4: VARIATION OF (T_w - T_g) AT DIFFERENT INCLINATION ANGLES WITH RESPECT OF TW

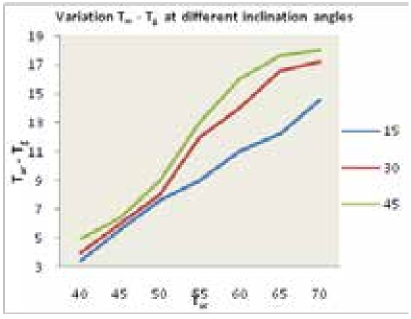


Fig. 5 and Fig. 6 shows the variation of the convective heat transfer coefficient and evaporative heat transfer coefficient with water temperature and inclination angle. It can be observed that the maximum convective heat transfer coefficient is for higher inclination angle whereas the minimum convective heat transfer coefficient is for 30^0 inclination angle. Also maximum evaporative heat transfer coefficient is for 15O inclination angle and the minimum evaporative heat transfer coefficient is for 30O inclination angle. Both convective and evaporative heat transfer coefficients increase with increase in water temperature.

FIGURE 5: VARIATION OF h_cW WITH RESPECT OF INCLINATION ANGLE AND WATER TEMPERATURE

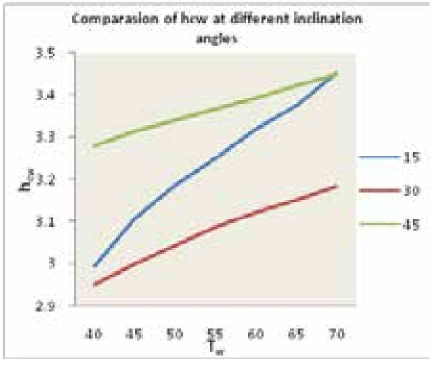


FIGURE 6: VARIATION OF h_ew WITH RESPECT OF INCLINATION ANGLE AND WATER TEMPERATURE

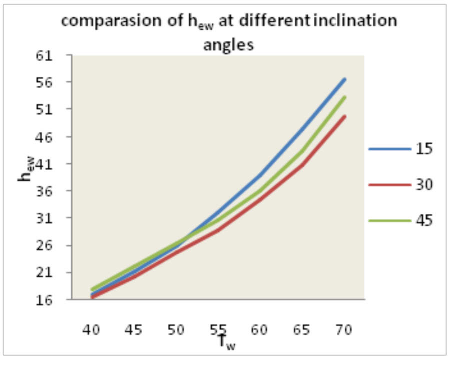


Fig. 7 shows the effect of inclination angle and water temperature on combined convective and evaporative heat transfer coefficients. It can be seen that the maximum combined heat transfer coefficient is for 15^0 inclination angle and the minimum is for 300 inclination angle.

FIGURE 7: EFFECT OF INCLINATION ANGLE AND WATER TEMPERATURE ON COMBINED HEAT TRANSFER COEFFICIENT

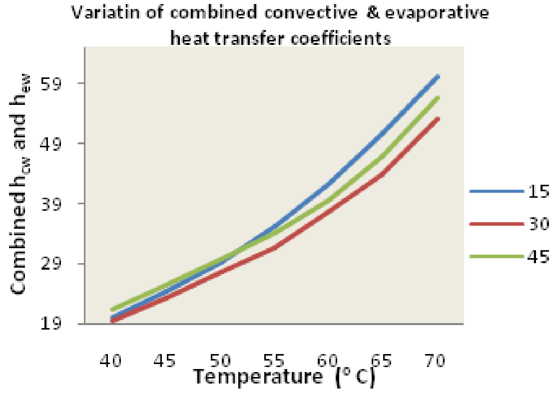
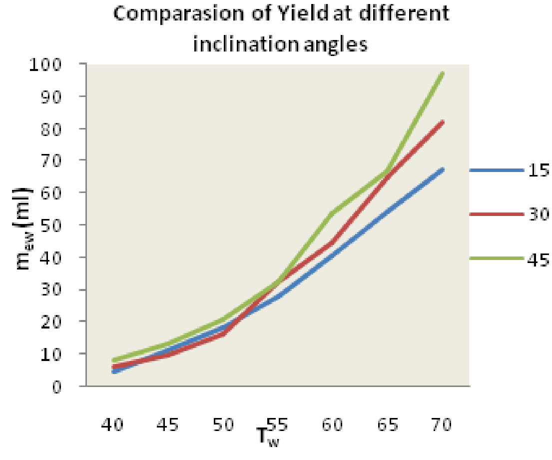


Fig. 8 shows that yield increases as the inclination angle of the condensing cover increases at corresponding constant water temperature. Also the yield increases as the temperature difference increases. It is because of the fact that yield is the product of heat transfer coefficient and temperature difference.

It can be seen from the figure that the maximum yield is obtained for condensing cover with inclination angle or 45^0 and the minimum yield is obtained for the condensing cover with inclination angle of 150. This is because of the fact that the temperature difference increases with increase in inclination angle of the condensing cover.

FIGURE 8: VARIATION OF PRODUCTIVITY WITH INCLINATION ANGLE AND WATER TEMPERATURE



CONCLUSIONS

In spite of the high value of combined heat transfer coefficient for condensing cover with 15^0 inclination angle, the maximum yield is obtained for condensing cover with the inclination angle of 450. This leads to the conclusion that the temperature difference between evaporative surface and condensing surface is a more dominant factor in contributing to the productivity of the solar still and also that the maximum distillate output is obtained at the combination of high inclination angle and high water temperature that is at 450 inclination and 700C water temperature.

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