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Performance Evaluation of Single Basin Solar Still

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***Abstract*—**In an attempt to investigate the performance of single basin solar still for climate conditions of Ludhiana a single basin solar still was designed, fabricated and tested. The energy balance equations for various parts of the still are solved by Gauss-Seidel iteration method. Computer model was made and experimentally validated. The validated computer model was used to estimate the annual distillation yield and performance ratio of the still for Ludhiana. The Theoretical and experimental distillation yield were 4318.79 ml and 3850 ml respectively for the typical day. The predicted distillation yield was 12.5% higher than the experimental yield. The annual distillation yield per square metre aperture area and annual performance ratio for single basin solar still is 1095 litres and 0.43 respectively. The payback period for micro-stepped solar still is 2.5 years.

***Keywords*—**Solar distillation, solar still, single basin, still.

I. Introduction

WATER is a basic necessity for all living beings along with food and air. Man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. However, use of water from such sources is not always possible or desirable because of the presence of large amount of salts and harmful organisms. The impact of many diseases affecting humankind can be drastically reduced if fresh hygienic water is provided for drinking. A diversity of approaches is used for separation of salts from saline water such as Reverse Osmosis, Electro Dialysis, Solvent Extraction, Flash Distillation etc. However, these methods are expensive for the production of small amount of fresh water. Solar energy can be used for distillation purpose where weather conditions are favorable and demand is not too large. Cooper [1] analyzed the solar still process with a digital simulation method and used it as a preliminary mathematical model to describe the system. Some of the common variables in single basin solar still such as water depth, wind velocity, still insulation, double glass cover and cover slope were investigated. Yadav and Parsad [2] conducted thermal analytical study on a single basin solar still based on the transient approach. Explicit expressions for glass cover temperature, water temperature; basin liner temperature, distillate output and the thermal efficiency of the still were developed. The effect of inlet water temperature, water mass in the basin, absorbivity of the basin liner etc. was studied. Porter et al. [3] reported a study on shallow single basin solar still having effective distillation area of 8.18 m^2 and mean water surface to glass cover height of 72 mm. The still produced an average of about 40 l/day of distilled water with initial water content of about 165 l and concluded that most of the thermal inertia delay in production occurs during the first hours in the morning. The largest part of distillate production was seen to take place between noon and sunset. After sunset, production was large when thermal inertia was large. As the thermal inertia increased, overall daily productivity decreased. In the present study, effort was made to investigate the performance of single basin solar still. For climate conditions of Ludhiana by developing computer model for single basin solar still to predict distillation yield, as a function of solar radiation, and ambient temperature for any place. To validate the results of computer model by conducting experiments on single basin solar still under environment conditions of Ludhiana to carry out economic analysis to calculate their payback period.

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II. Construction of Single Basin Solar Still

A schematic diagram of the single basin solar still is shown in Fig. 1. It is an airtight basin constructed of galvanized iron sheet with top cover of glass. The outer size of the base of the still is 58.5 × 233 cm. Back and front walls are 38 cm and 15 cm high respectively. So, the glass was inclined at 20^o with the base. A tray of galvanized iron sheet of rectangular shape of size 48 × 211 × 5 cm placed inside the still constitutes its basin. This tray was blackened with blackboard paint to absorb maximum solar radiation incident on it. A channel was provided along the lower end of glass cover to collect distilled water. The sides and bottom of the solar still were insulated with glass wool of thickness 5 cm.

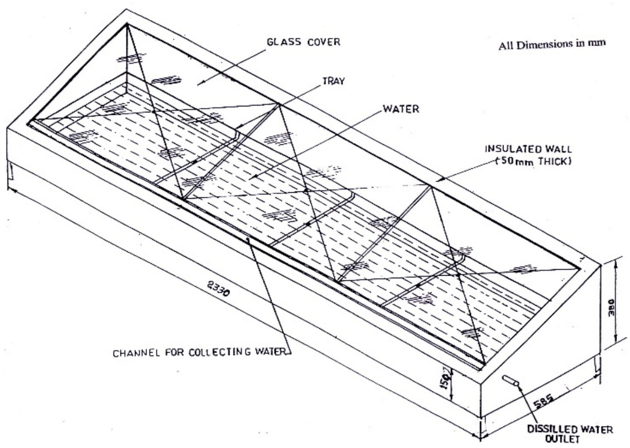

Fig. 1 Single Basin Solar Still

III. Mathematical Model

In order to write the energy balance equations for mathematical model for single basin solar still [4]-[6], the following assumption has been made:

(i) Absorptivity of solar radiation in the vapours between the glazing and water layer has been neglected.
(ii) Water mass in the basin liner is at uniform temperature.
(iii) Evaporating and condensing surfaces are assumed as parallel infinite plates.
(iv) The heat capacity of the glass cover, the absorbing material and the insulation is assumed negligible as compared to water.
(v) The solar radiation reflected from water surface to the glass cover is neglected.
(vi) The solar still is an airtight / vapour leakage proof.

The energy balance equations for the different elements are written as follows:

Heat balance on glass cover (per unit area):

Solar energy absorbed by glass	+	Energy received by glass from water surface by evaporation, convection and radiation	=	Energy loss from glass to ambient by convection and radiation

$$I_{ag} + h_{wg} \times (T_w - T_g) = h_{ga} \times (T_g - T_a) \quad (1)$$

Heat balance on basin liner (per unit area):

Solar energy absorbed by water	+	Energy received by water from basin liner by convection	=	Energy stored in water mass	+	Energy loss from water to glass by convection, evaporation and radiation

$$I_{aw} + h_{bw} \times (T_b - T_w) = m_w c_w \, dT_w/dt + Q_{w,2} \quad (2)$$

Heat balance on basin liner (per unit area):

Solar energy absorbed by basin liner	+	Energy loss from basin liner to water by convection	=	Energy loss from basin liner to ambient

$$I_{ab} + h_{bw} \times (T_b - T_w) = h_{ba} \times (T_b - T_a) \quad (3)$$

By solving the above three equations, Change in water temperature after time interval dt is:

$$dT_w = \{\alpha_w \times I_{\tau g} + [\, h_{bw}/(h_{bw} + h_{ba}) \times \alpha_b \times I_{\tau w} + [h_{wg}/(h_{wg} + h_{ga})] \times \alpha_g \times I - [h_{bw} \times h_{ba}/(h_{bw} + h_{ba}) + h_{wg} \times h_{ga}/(h_{wg} + h_{ga})] \times (T_w - T_a)\} \times dt/m_w c_w$$

Water temperature after time interval dt:

$$T_w = T_w + dT_w \, {}^{o}\mathrm{C} \quad (4)$$

Glass temperature after time interval dt:

$$T_g = \frac{\alpha_w \times I + h_{wg} \times T_w + h_{ga} \times T_a}{h_{wg} + h_{ga}} \, {}^{o}\mathrm{C} \quad (5)$$

Basin liner temperature after time interval dt:

$$T_b = \frac{\alpha_b \times I_{\tau w} + h_{bw} \times T_w + h_{ba} \times T_a}{h_{bw} + h_{ba}} \, {}^{o}\mathrm{C} \quad (6)$$

Distillation yield in time interval dt:

$$m = h_{ewg} \times (T_w - T_g) \ \mathrm{L/m^2hr} \quad (7)$$

IV. Numerical Computations

To predict theoretically the distillation yield of the still, a computer program was written in quick basic language for the solution of the energy balance equations of the still elements. The input parameters to the computer program include the climatic parameters (solar radiation, ambient temperature), thermo-physical parameters (Properties of air and water) and configurational parameters (dimensions of the stills). Initially, the temperatures of the different component of the still are assumed equal to the ambient air temperature at the sunrise time of the still. Using these initial values, different heat transfer coefficients are calculated. The obtained values of the different heat transfer coefficients along with climatic parameters are employed to calculate new values of the different temperatures from (4), (5) and (6) at time interval dt. The distillation yield of the still is then calculated from (7). This process is repeated with new values of the different temperatures for an additions time interval dt. For validation of the computer program, measured solar radiation and ambient temperature, data was used in the computer program. Hence, theoretically calculated different temperature of the still components and distillation yield on hourly basis is compared with experimental values. This validated computer model is used to calculate the yearly performance of the still. To predict yearly performance of the still, the computer program was run for the representative day of the each month to calculate distillation yield of the still. Hence, the total yearly distillation yield of the still is calculated assuming 300 clear days in a year.

V. Results and Discussions

The graph between solar radiation and ambient temperature vs. time (Fig. 2) shows that solar radiation increases in morning and decreases in evening. Ambient temperature follows the same trend. The maximum value of solar radiation at aperture 700 W/m^2 and maximum value of ambient temperature is 41.5^{o}C. The graph between theoretical and experimental water and glass temperature vs. time (Fig. 3) shows that water and glass (theoretical and experimental) temperature follows the same trend as that of solar radiation and ambient temperature. The theoretical predicted water temperatures are more than corresponding experimental values. This is possibly because in theoretical analysis, it has been assumed that there is no absorption of solar radiation in the air-vapour mixture present in the still. So theoretically, water will receives more solar radiation and will attain higher temperature. Experimental glass temperature is slightly lower than theoretically calculated temperature. This may be due to measuring error as thermocouple may give slightly lower temperature due to air gap between glass and junction of thermocouple in contact with it. Therefore, theoretically predicted water and glass temperature will be more than their respective experimental values.

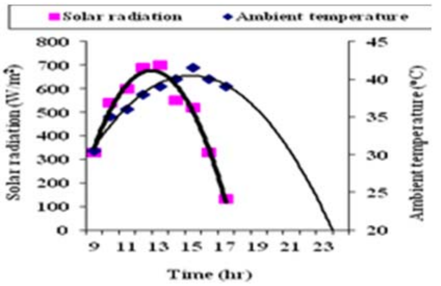

Fig. 2 Ambient temperature and solar radiation on aperture (inclined at 20° with horizontal) of single basin solar still as a function of time

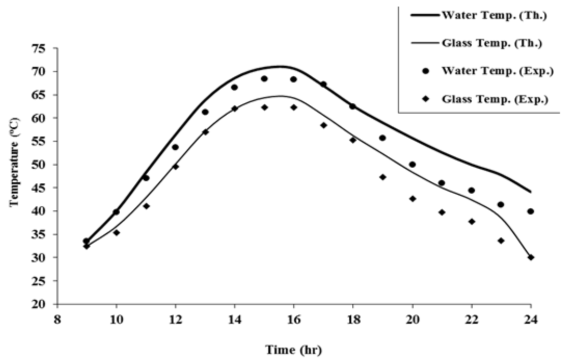

Fig. 3 Water and glass temperatures (Th. & Exp.) of single basin solar still as a function of time

The graph between evaporative, convective and radiative heat transfer coefficients (from water to glass) vs. time (Fig. 4) shows that convective and radiative heat transfer coefficients are almost constant during the operation of still. Radiative and convective heat transfer coefficients vary from 5.88 to 8.14 $W/m^{2o}C$ and 0.96 to 2.32 $W/m^{2o}C$ respectively during the day. On the other hand, evaporative heat transfer coefficient varies from 4.32 to 46.71 $W/m^{2o}C$ during the day. The value of convective heat transfer coefficient varies during the day but variation is small because temperature difference between two participating surfaces does not vary too much. In addition the variation in average temperature used for property evaluation of fluid between two participating surface is also small. On the other hand, for evaporation between water and glass cover, the net evaporation depended on temperature difference between water and glass cover because the vapour of the fluid between water and glass cover depends on this temperature difference. In addition, evaporation from water surface is strong function of water temperature. Since water, temperature varies a lot (34°C to 76°C) during the day and almost follows solar radiation input. Hence, evaporation heat transfer coefficient varies significantly while variation in convective heat transfer coefficient is insignificant.

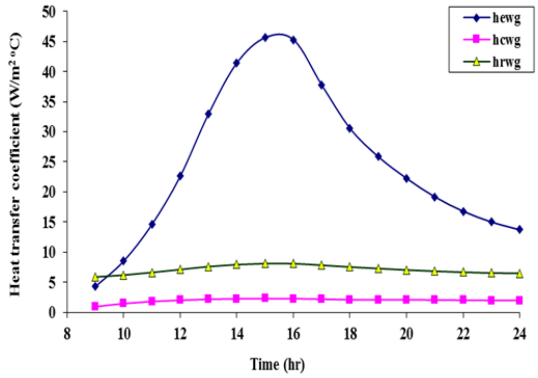

Fig. 4 Heat transfer coefficients (evaporative, convective and radiative) of single basin solar still as a function of time

The graph between distillation yield vs. time (Fig. 5) shows that theoretical and experimental distillation yield follows the same trend as that of solar radiation and ambient temperature. Theoretical and experimental distillation yield are 4318.79 ml and 3850 ml respectively for a typical day. The predicted distillation yield is 12.15% higher than the experimental yield. Higher theoretical distillation yield is due to higher theoretical water temperature (Fig. 3), which causes more evaporation of water from the basin and more condensation on the glass cover.

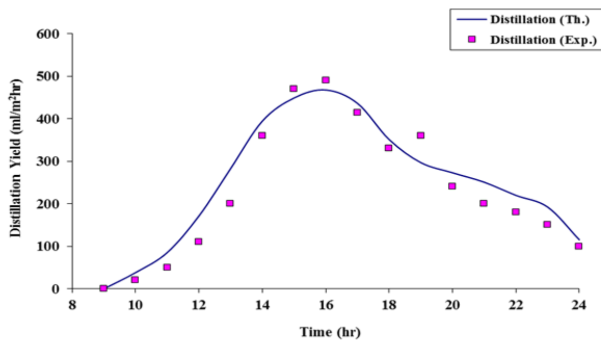

Fig. 5 Distillation yield (Th. and Exp.) of single basin solar still as a function of time

Annual yield was calculated for single basin solar still by computing yield for typical day (typical day represents the monthly average of global solar radiation and ambient temperature) of every month from their computer models. Yield of typical day of each month is shown in Fig. 6. Then annual yield at Ludhiana was calculated by multiplying 300 (assuming 300 clear days in a year) to the average distillation yield of typical day of each month calculated above. The result shows that annual distillation yields per square metre aperture area and annual performance ratio for single basin solar still are 1095 litres and 0.43 respectively. The payback period for single basin solar still is 2.5 years.

VI. Conclusion

The developed computer model predicts the performance of single basin solar still quit satisfactorily for Ludhiana hence can be used for predicting the system performance for any other place.

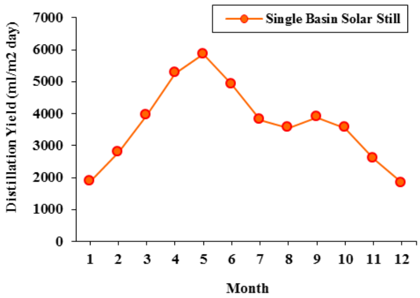

Fig. 6 Theoretically predicted distillation yield for single basin solar still for the climatic condition of Ludhiana on typical day of each month

APPENDIX

$$\delta(\text{degree}) = 23.45 \times \sin[360 \times \frac{(284+n)}{365}]$$

$$R_b = \frac{\sin(\delta)\sin(\phi-\beta) + \cos(\delta)\cos(\omega)\cos(\phi-\beta)}{\sin(\delta)\sin(\phi) + \cos(\delta)\cos(\omega)\cos(\phi)}$$

$$R_b = \frac{1+\cos(\beta)}{2}$$

$$R_r = \frac{\rho \times (1+\cos(\beta))}{2}$$

$$I_{ag} = I \times \alpha_g$$

$$I = (I_g - I_d) \times R_b + I_d \times R_d + I_g \times R_r$$

where, I_g= Global (total) radiation flux on horizontal surface, I_d = Diffuse radiation flux on horizontal surface.

$$\alpha_g = 1 - \tau_g - r_g$$

$$\theta = \cos^{-1}\{\sin(\delta)\sin(\phi-\beta) + \cos(\delta)\cos(\omega)\cos(\phi-\beta)\}$$

$$h_{cwg} = 0.884 \times [(T_w - T_g) + (P_w - P_g) \times (T_w + 273.15)/(268900 - P_w)]^{1/3} \text{ W/m}^{2\circ}\text{C}$$

$$h_{ewg} = \frac{16.273\times10^{-3}\times h_{cwg}\times(P_w - P_g)}{(T_w - T_g)} \text{ W/m}^{2\circ}\text{C}$$

$$P_g = \exp\left[\frac{25.317-5144}{T_g+273.15}\right] \text{ N/m}^2$$

$$P_w = \exp\left[\frac{25.317-5144}{T_w+273.15}\right] \text{ N/m}^2$$

$$h_{rwg} = \epsilon_{eff} \times \sigma \times [(T_w - 273.15)^2 + (T_g - 273.15)^2] \times [(T_w + 273.15) + (T_g + 273.15)] \text{ W/m}^{2\circ}\text{C}$$

$$\epsilon_{eff} = \frac{1}{\frac{1}{\epsilon_g} + \frac{1}{\epsilon_w} - 1}$$

$$h_{wg} = h_{cwg} + h_{ewg} + h_{rwg} \text{ W/m}^{2\circ}\text{C}$$

$$h_{cga} = \frac{0.86\times(Re_a)^{1/2}\times(Pr_a)^{1/3}\times K_a}{L_g} \text{ for } 2\times10^4 < Re_a < 9\times10^4$$

where $L_g = \frac{4\times A}{P}$ and $Re_a = \frac{\rho_a \times \text{WS} \times L_g}{\mu_a}$

$$h_{rga} = \frac{\epsilon_g\times\sigma\times[(T_w - 273.15)^4 + (T_{sky} - 273.15)^4]}{(T_g - T_a)} \text{ W/m}^{2\circ}\text{C}$$

$$T_{sky} = T_a - 6\ ^\circ\text{C}$$

$$h_{ga} = h_{cga} + h_{rga}$$

$$I_{aw} = \alpha_w \times I_{\tau g}$$

$$a_f = \sum \mu_j \times \exp(-\eta_j \times d_w)$$

$$I_{\tau w} = a_f \times (I_{\tau g} - I_{rw})$$

$$I_{rw} = I_{\tau g} \times R_w$$

$$I_{aw} = I_{\tau g} - I_{rw} - I_{\tau w}$$

$$\alpha_w = \frac{I_{aw}}{I_{\tau g}}$$

$$h_{bw} = \frac{0.54\times(Ra_w)^{1/4}\times K_w}{L_b} \quad \text{for } 10^5 \le Ra_w \le 10^7$$

$$h_{bw} = \frac{0.15\times(Ra_w)^{1/3}\times K_w}{L_b} \text{ for } 10^7 \le Ra_w \le 10^{10}$$

where $Ra_w = Gr_w \times Pr_w$.

$$Gr_w = \frac{\beta_w \times g \times \rho_w^{\ 2} \times (T_b - T_w) \times L_b^{\ 3}}{\mu_w^{\ 2}}$$

$$I_{ab} = I_{\tau w} \times \alpha_b$$

$$h_{ba} = \frac{1}{\left[\left(\frac{L_i}{K_i}\right) + \frac{1}{h_{cba}}\right]}$$

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