Journal of Advances and Scholarly Researches in Allied Education
Vol. 16, Issue No. 9, June-2019, ISSN 2230-7540

Productivity Evaluation of a Double Slope Stepped Solar Still by Different Thermal Models

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Abstract – The present investigation was carried out with the objective to identify the most suitable thermal models in relation to evaluation of theoretical productivity of double slope stepped solar still. The productivity of double slope stepped solar still was estimated experimentally and compared with the theoretical productivity calculated with the help of existing thermal models. The highest similarity between experimental and theoretical productivity was achieved by the Dunkle model (1961) followed by the Tsilingiri model (2007) and Rahbar and Esfahani model (2013). It seems that the minimization of the gap between water surface and condensing surface in Double slope stepped solar still resulted in similarity in productivity with Dunkle model.

Key words Double Slope Stepped Solar Still, Thermal Model and Productivity

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1. INTRODUCTION

Solar distillation can partially support the human requirement for fresh water with an ecofriendly energy source. It exhibits a significant economic benefit over other purification processes due to cost-free resource and reduced operation and maintenance cost. The solar purification systems are used with a widespread variety of designs, configurations, geometry, and fabrication materials. The simple and independent operation of solar purification system is extremely appropriate for small scale and remote applications. It offers a chance for rural societies to prepare their individual potable water at noticeably lower prices. Among the existing solar purification systems, solar still is a very simple and easy to construct device that produces potable water from brackish water. It has many features, but the daily productivity from the solar still is not sufficient to meet the end users' requirements. Different solar still designs have been developed over the years and many investigational as well as theoretical research have been carried out by the researchers to enhance the performance. But the experimental research needs high investment cost and relatively longer period. Also, it does not provide any flexibility during the analysis of influencing parameters due to complexity in fabrication and its operation. Hence, the theoretical analysis is found more suitable to assess the critical parameters for the efficient operation of solar stills. Thermal modeling is amongst effective methods for theoretical investigations to predict the performance of thermal system. The thermal model, based on energy balances of its components, provide a clear understanding of the solar still behavior in actual climatic conditions.

2. EXPERIMENTAL SETUP

An improvised experiment was designed as passive solar distillation unit comprising a glazing glass cover inclined at an angle of 29^0 at geographical location of Amroha (28.9^0 in northern hemisphere). Such inclined glass cover at ensure maximum solar radiations. The tilted glass cover (5mm thick) serve as both the solar energy transmitter and condensing surface (for water vapors generated) in the basin of the still. The still basin comprised of galvanized iron having functional one m^2 area, had been fitted with ten stepped trays (dimension 80×13×1 cm each). These trays were black coated for the maximization of solar absorption (Figure 1). An output for distillate had been provided at the basin end, with help of plastic pipe fixed with Silica Gel. Also, both inlet- and outlet pipes were provided at top of still side wall in the channel hole. Similarly, the basin tray bottom was fitted with pipes for feeding saline water and drainage of water from still for cleaning purpose. Rubber gasket was fixed along all edges of the still to make the still airtight. The water evaporated and condensed at the inner surface of glass run downward along with lower edge which has been collected and measured quantitatively.

Figure 1. Photographic view of double slope stepped solar still

3. THERMAL MODELS

3.1 Dunkle model (1961)

Dunkle's model is the most popular model to evaluate various heat transfer coefficients following the empirical correlations to predict the performance of the single effect solar still. Dunkle used the following Nusselt–Rayleigh empirical correlation developed by Jakob (1957) for free convection of air in an enclosure

$$Nu = C\,.Ra^{\,n} \text{ with } C = 0.075 \text{ and } n = 1/3$$

Dunkle estimated the value of evaporative heat transfer coefficient ($h_{e,w-g}$) by using the following relations:

$$h_{ew} = 0.0163.h_{cw}.\left(\frac{P_w - P_g}{T_w - T_g}\right) \qquad 3.1.1$$

Convective heat transfer coefficient (h_{cw})

$$h_{cw} = 0.884\left[(T_w - T_g) + \frac{P_w - P_g}{268900 - P_w}(T_w + 273.15)\right]^{1/3} \qquad 3.1.2$$

Distillate output rate per unit area

$$m_{th} = \frac{h_{cw}R_a}{c_p R_w}\frac{P_o[P_w - P_g]}{[(P_o - P_w)(P_o - P_g)]} \qquad 3.1.3$$

3.2 Tsilingiri model (2007)

Tsilingiri has proposed a model based on the Chiltone-Colburn analogy. The convective heat transfer coefficient is evaluating by using thermo physical properties of saturated mixture.

Distillate output rate per unit area

$$m_{th} = \frac{h_{cw}}{\rho c_p Le^{2/3}}\left(\frac{P_O}{P_{LM}}\right)\left(\frac{M_w}{R}\right)\left(\frac{P_w}{T_w} - \frac{P_g}{T_g}\right) \qquad 3.2.1$$

Logarithmic mean pressure (Pa)

$$P_{LM} = \frac{[(P_o - P_w) - (P_o - P_g)]}{ln\frac{(P_o - P_w)}{(P_o - P_g)}} \qquad 3.2.2$$

Convective heat transfer coefficient

$$h_{cw} = 0.075\left(\frac{\rho.g.\beta}{\mu.\alpha}\right)^{1/3}\left[(T_w - T_g) + \frac{P_w - P_g}{268900 - P_w}(T_w + 273.15)\right]^{1/3} \qquad 3.3.3$$

3.3 Rahbar and Esfahani model (2013)

Based on Chiltone-Colburn analogy is proposed to estimate the productivity of a solar still. The rate of mass convection between water and glass-cover canbe expressed as

$$\dot{m} = h_m(\rho_w - \rho_g) \qquad 3.3.1$$

Based on Chiltone-Colburn analogy, the relation between heat and mass transfer coefficients for air - water vapor mixture can be expressed with a good accuracy as

$$h_{cw} = \rho c_p Le^{2/3} h_m \qquad 3.3.2$$

$$q_{ew} = h_{ew}\,(T_w - T_g) \qquad 3.3.3$$

Moreover, from the ideal gas law, there is:

$$P = \frac{P}{RT}$$

$$q_{ew} = \dot{m}_{ew}\,.h_{fg} \qquad 3.3.4$$

$$h_{ew} = \frac{h_{fg}\left(\frac{P_w}{T_w} - \frac{P_g}{T_g}\right) h_{cw}}{R_{vap}\, \rho c_p \; Le^{\frac{2}{3}} \left(T_w - T_g\right)} \qquad 3.3.5$$

$R_{vap} = 461.5$ J/kg. K

Evaporative mass can be expressed as follows:

$$\dot{m_{ew}} = \frac{h_{ew}(T_w - T_g)}{h_{fg}} \qquad 3.3.6$$

Putting the value of h_{ew} from above equation

Distillate output rate per unit area $(\dot{m_{ew}})$

$$\dot{m_{ew}} = \frac{\left(\frac{P_w}{T_w} - \frac{P_g}{T_g}\right)}{R_{vap}\, \rho c_p \; Le^{\frac{2}{3}}} h_{cw} \qquad 3.3.7$$

4. RESULTS AND DISCUSSION

Figure 2 shows water and glass temperature at different positions of solar still. East and west side water temperature follow the equation $-0.2098\ x^2 + 3.63\ x + 49.19$, $R^2 = 0.8976$, $-0.243\ x^2 + 4.76\ x + 45.57$, $R^2 = 0.8946$, respectively. East and west side glass temperature follow the equation $-0.2436\ x^2 + 4.18\ x + 44.854$, $R^2 = 0.9631$, $-0.2186\ x^2 + 4.63\ x + 38.94$, $R^2 = 0.8854$, respectively.

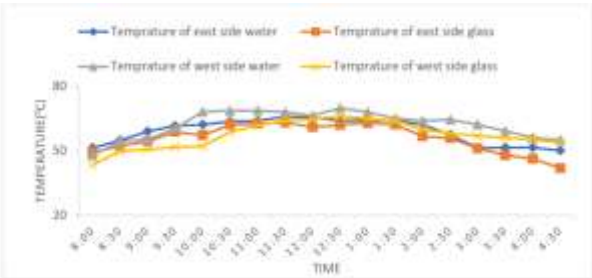

Figure 2. Variation in water and glass temperature with time of a day.

Figure 3 shows the variation of convective heat transfer with time. convective heat transfer calculated by different thermal models. Convective heat transfer coefficient depends on water and glass temperature**.**

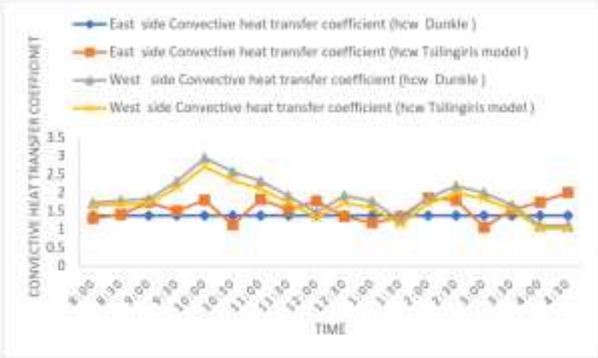

Figure 3. Variation in convective heat transfer coefficient with time of a day.

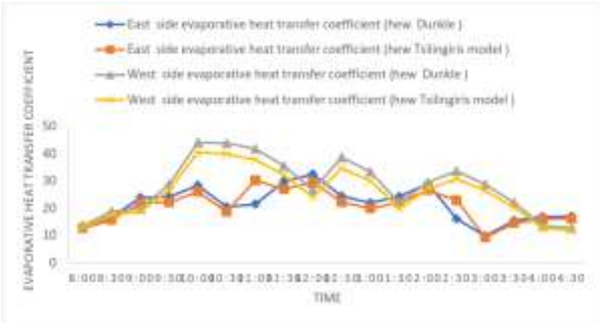

Figure 4. Variation of evaporative heat transfer coefficient with time of a day.

The productivity calculated by Rahbar and Esfahani model is higher than experimental productivity (Figure 5). However, the productivity calculated by Tsilingiri model and Dunkle model is lower than the experimental productivity. Productivity calculated by Dukle's model is closely resembles with the experimental productivity, thus, Dunkle's model is most suitable for the productivity evaluation.

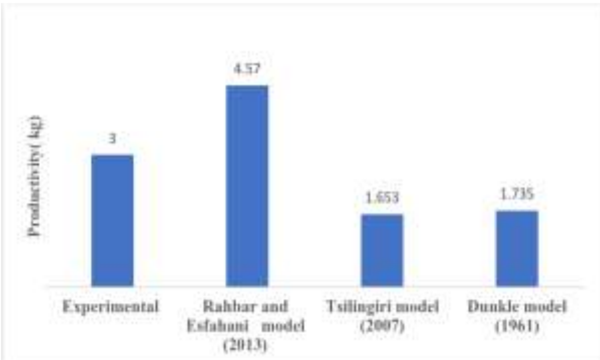

Figure 5. Experimental and thermal models based productivity.

5. CONCLUSION

The present study suggest that various thermal models have varying productivity estimates. Comparison of experimental productivity with thermal model's productivity showed wide variations which implies that each model may not serve the purpose of prediction of productivity. Productivity calculated by Dunkle's model is most appropriate. Moreover, the value of h_{ew}/h_{cw} is a function of glass and water temperatures. The tendency of productivity is always similar to the tendency of convective heat transfer coefficient.

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