MATHEMATICAL MODELING FOR OUTPUT YIELD OBTAINED BY SINGLE SLOPE SOLAR STILL INTEGRATED WITH SAND TROUGHS

by

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The crisis for potable water is inevitable, due to increasing population. Solar desalination is apt technology to convert brack water and sea water into potable one. In the current work a mathematical modeling of a single slope solar still integrated with sand troughs is presented. The model is validated with the experimental results of a solar still with 3 cm of water level at the basin. The mathematical model findings and results obtained with the experimental investigations are within ±10% deviation. Capillary effect was proposed to obtain the yield daily basis and thermal effect model was integrated with the capillary effect model. From the results, it is understood that the yield obtained is more in the case of solar stills with sand troughs when compared to solar stills without sand troughs. Further the model is used for predicting yield for 1 cm and 2 cm of water levels at the basin. It is observed that the maximum yield was obtained for 1 cm water level at the basin. There is a good agreement between theoretical results and experimental results. It shows that the still produce better yield with the lower depth of water level at the basin, this may be because of the availability of more space in the sand for evaporation due to capillary effect in the troughs.

Keywords*: mathematical modeling, solar still, sand troughs, capillary effect model, yield, still efficiency*

Introduction

Nowadays, having good quality water for healthy living has become more complicated and costly. The shortage is increasing every day. Solar still is proven to be a successful technology to purify sea water and can cater the needs of safe drinking water. By using the same effect pool system, water is cheaper, safer and more environmentally friendly [1]. The 96% of the earth's water is seawater which is salty and we cannot use for many applications. It

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is good to address the problem of water scarcity with seawater purification. However, at present, a significant amount of energy that is detrimental to the environment produced by fossil fuels is involved in the separation of salts from sea water. It is also important to use an environmentally friendly energy source for the discharge of seawater. A wide variety of techniques are used to turn seawater into suitable water for daily use. One among them is desalination [2]. For desalination generally preferred system is solar still. In order to improve its performance, various successful modifications to conventional solar still play an important role. It can be achieved by the various methods and the suitability depends on various parameters like location, season and application [3, 4]. Single-basin solar modeling and performance analysis was carried out with double-glass glazing. The efficiency depends on the amount of insulation used [5]. The performance of solar pyramid still and the solar single slope still were compared by [6] in terms of efficiency and cost. Single slope solar still showed better performance than the pyramid still and it was also proven to be cost efficient. Single coverage flat plate collector reinforced with fiber was used to improve the evaporation of water from the base of the still [7]. Evaporation rate was observed to be increasing with the increase in insolation and wind speed. Reduction in relative humidity, concentration and mass-flow rate resulted in a higher evaporation rate. Integrated solar reservoir with built-in sandy heat reservoir has made with low investment. Integrated heat reservoir slightly improves efficiency and used without the sun also for some time [8].

The thermal energy present in the ground is tapped through energy piles technologies and then uses it for cooling and/or heating buildings. Due to the thermal gradients present within the soil mass, the heat transmits into/from the soil by conduction or convection. Thermal conductivity and thermal ability are the key thermal properties of the soil [9]. Hybrid energy, renewable, and non-renewable energy combination give an optimum solution for future energy needs [10]. Solar still efficiency relies on parameters such as basin depth, latitude angle, Sun rays during the year, thickness of the cover, its thermal conductivity, and still-basin material [11]. Two-stage desalination process, at cheaper cost and for any range of operation it is suitable [12].

An experimental study was recently conducted to validate the developed mathematical formulation in this study. Experiment was conducted on a single slope solar still integrated with sand troughs.

Experimental set-up

In this experimental set-up, basins are fabricated with a galvanized iron sheet and coated with mat finish black to absorb more amount of radiation. The dimensions of stills are with the aperture area of 1.67 m × 0.9 m. The back wall elevation is 0.36 m and the stature of the front wall is 0.1 m. The slope provided to the glass cover is 16.5° which is equivalent to the latitude of Koneru Lakshmaiah Education Foundation, Vaddeshwaram (Latitude:16.4419° N, Longitude: 80.6225° E, and altitude of 25 m above sea level), Vijayawada, Andhra Pradesh, India. Six numbers of sand troughs are fabricated and placed in the solar stills. The outer shell of sand trough made of mud pot material with an inner diameter of 0.075 m and fine sand particles with uniform size was filled in the troughs to increase the rate of evaporation within the still. The height of the troughs was adjusted in such a way that front troughs of height 0.085 m and back troughs with the height of 0.17 m to maintain the distance between troughs and glass cover as 0.03 m. Further reduction in this distance might result in a lesser temperature difference between water and glass which further decreases the production yield. Upon considering this fact, distance between trough and glass is taken as 0.03. The basin was

Figure 1. Photographic view of experimental set-up

insulated with 0.01 m layer of fly wood and 0.01 m layer of glass wool perfectly to avoid the escape of heat to the atmosphere from the still. Six number of *K*-type thermocouples were used in the each solar still to record the temperatures of outside glass, T_{go}, inside the glass, T_{gi}, basin liner, T_b, vapour, T_v, water, T_w, and ambient, T_a, for every 30 minutes of intervals. Solar radiation was measured by the use of solar power meter in W/m^2. Figure 1 displays the photographic view of the overall experimental set-up.

Mathematical modeling

After conducting experiments on single slope solar still integrated with sand troughs, it is observed that yield has been improved drastically. So it was decided that instead of conducting experiments several times to understand its performance, it is better to develop a mathematical model. Distillation gets done with the molecules escape from water surface to the surrounded gases. Sensible heat is required to cause the movement of molecules. Few prominent factors that influence the production rate of pure water, viz., climatic factors and thermal factors, are discussed before discussing theoretical analysis.

The amount of solar radiation that a solar still receives is the most important factor which affects its performance. If the amount of energy received is more, more quantity of water will be distilled. The amount of radiation available depends on various parameters such as day of the year, location (latitude and altitude), and diffuse radiation. Collector efficiency depends on design parameters viz. orientation, glass thickness, slope of the glass cover, *etc*. In the conventional solar still, surface temperature of the saline water place in the basin is increased utilizing solar energy. As a result of temperature rise of water, it gets evaporated from the surface which results in phase equilibrium between surface of water and the air just above it. Therefore, the air is in a saturate condition with the surface water temperature. Hence it can be stated that the yield of the solar still depends on the temperature of the saline water. Water vapour is diffused to the glass cover because of the differences in the partial pressure of water vapour between the saline water surface and the glass cover As the temperature at the bottom of the glass cover is lower than the saturation temperature of water vapour, water vapour starts to condense on the glass surface. So, the rate of evaporation and condensation of water not only depends on the temperature of saline water but also on the glass cover temperature. Mathematical equations that describe the performance of each component of the system for the conventional still are presented in this section. The method of solving these sets of equations to predict system performance is presented. The mathematical model is developed by considering each component separately and the energy balance equation was written for each component. Numerous mathematical models were available in the literature for various configurations of single slope solar still. But no mathematical model is available for single slope solar still integrated with sand troughs. For this development of theoretical model following procedure has been adapted:

– Selecting a suitable thermal model for the region which is not having sand troughs.

– Developing mathematical modelling for capillary action in sand troughs.
– Combining these two to get theoretical yield produced for single slope solar still integrated with sand troughs.
– Then validating this value with experimental value to understand the trend.
– After validation is overuse this equation to simulate for various combinations.
– Estimating the best combination which has better performance.

Mathematical modeling for capillary action

Capillary action is the vertically upward force to suck liquid at the bottom by porous medium under externally no applied pressure. Due to this action in sand troughs placed in the basin with saline water, some of the saline water raises through troughs. This is then converted into yield by thermal action, some part of the output yield is obtained directly by thermal action of solar radiation on saline water which is present in the region where sand troughs are not present. For determining the quantity of water raised (yield produced due to capillary action) following methodology has been adapted.

The capillary pressure difference obtained by Laplace equation is given:

$$P = 2\Upsilon_{LA}\cos\theta / r \tag{1}$$

$$r = d / 2n \tag{2}$$

where P is the capillary pressure, Υ_{LA} [Nm^{-1}] – the liquid surface tension, n [–] – the porosity, θ – the solid-liquid contact angle, and r – the capillary rise.

The rate at which the liquid is driven through the sand troughs is calculated by combining Lucas-Wash burn and Hagen-Poiseuille equations by neglecting inertial and gravitational forces:

$$\mathrm{d}h / \mathrm{d}t = r\Upsilon_{LA}\cos\theta / 4\eta h \tag{3}$$

$$\text{After obtaining the driven rate } v = \mathrm{d}h / \mathrm{d}t \tag{4}$$

There is a need to find a mass-flow rate of driven yield because of porosity ($\mathrm{d}m_p/\mathrm{d}t$) is obtained by:

$$\mathrm{d}m_p / \mathrm{d}t = vA_P\rho \tag{5}$$

where h is the height of the sand trough above liquid level of the base, A_P – the cross-sectional area of porous medium = πr^2, ρ [kgm^{-3}] – the density of saline water, and η [kgm^{-1}s^{-1}]– the dynamic viscosity of saline water.

– The properties of saline water

The n, ρ, Υ_{LA}, and η are to be obtained at an average of glass and base water temperature.

Yield for each time step (i) is obtained by integrating the differential equation both sides:

$$m_{pi} = vA_P\rho t_i \tag{6}$$

for getting total yield obtained due to porous action is obtained by:

$$m_p = \sum m_{pi} = \sum vA_P\rho t_i \tag{7}$$

Mathematical modelling for thermal action

For getting total yield obtained due to direct thermal action on saline water is obtained by an equation obtained by the following methodology.

The latent heat of evaporation, h_{fg}, corresponding to average temperature over an hour (57 °C) is extracted from steam table which is equal to 2366 kJ/kg. The P_d is the daily yield in kg/m^2 and the average solar intensity, I_{ave}, is 560 W/m^2 per day. The energy balance and absorption of solar radiation for different components (water mass, glass cover, and basin liner) of the conventional still without considering the heat capacity of basin and glass cover are given in fig. 2.

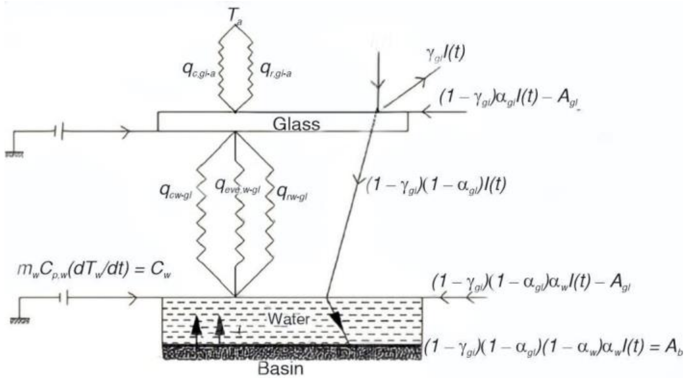

Figure 2. Thermal circuit diagram for the conventional still; L = latent heat of vaporization (kJ/kg), I = daily average radiation (W/m^2), A = area of glass cover (m^2), T_v = vapor temperature (°C)

Energy balance equations for the various components of a conventional still is given:

– For glass cover:

$$I(t)A_{gl} + U_{ow,gl}\left(T_w - T_{gl}\right) = \left(h_{c,gl\text{-}a} + h_{r,gl\text{-}a}\right)\left(T_{gl} - T_a\right) \tag{8}$$

$$U_{o,w\text{-}gl} = \left(h_{c,w\text{-}gl} + h_{eva,w\text{-}gl} + h_{r,w\text{-}gl}\right) \tag{9}$$

$$U_{o,gl\text{-}a} = \left(h_{c,gl\text{-}a} - h_{r,gl\text{-}a}\right) \tag{10}$$

– For water mass

$$I(t)A_w + h_{c,b\text{-}w}\left(T_b - T_w\right) = M_wC_{P,w}\frac{\mathrm{d}T_w}{\mathrm{d}t} + U_{o,w\text{-}gl}\left(T_w - T_{gl}\right) \tag{11}$$

– For basin liner

$$I(t)A_b = h_{c,b\text{-}w}\left(T_b - T_w\right) + U_{o,b\text{-}a}\left(T_b - T_a\right) \tag{12}$$

$$\frac{1}{U_{o,b\text{-}a}} = \frac{L_{\text{ins}}}{K_{\text{ins}}} + \frac{L_{\text{wood}}}{K_{\text{wood}}} + \frac{1}{h_{c,\text{wood-}a}} \tag{13}$$

Equation (8) can be arranged as:

$$T_{gl\,i} = \left(\frac{1}{U_{o,w\text{-}gl} + U_{o,gl\text{-}a}}\right)\left[I(t)A_{gl} + U_{o,w\text{-}gl}T_{wi} + U_{o,gl\text{-}a}T_a\right] \tag{14}$$

Equation (11) can be rearranged as:

$$\frac{\mathrm{d}T_w}{\mathrm{d}t}+\frac{\left(U_{o,w\text{-}gl}+h_{c,b\text{-}w}\right)}{M_w C_{P,w}}T_w=\frac{1}{M_w C_{P,w}}\left[I(t)A_w+h_{c,b\text{-}w}T_b+U_{o,w\text{-}gl}T_{gl}\right] \tag{15}$$

where

$$\frac{U_{o,w\text{-}gl}+h_{c,b\text{-}w}}{M_w C_{P,w}}=a_1 \tag{16}$$

$$\frac{1}{M_w C_{P,w}}\left[I(t)A_w+h_{c,b\text{-}w}T_b+U_{c,w\text{-}gl}T_{gl}\right]=C_1 \tag{17}$$

For differential equation in the form of $(\mathrm{d}T_w/\mathrm{d}t)+a_1T_w=C_1$ solution is:

$$T_{w,i+1}=\frac{C_1}{a_1}\left(1-\mathrm{e}^{-a_1t}\right)+T_{w,i}\mathrm{e}^{-a_1t} \tag{18}$$

Equation (12) can be rearranged as:

$$T_{b,i+1}=\frac{1}{h_{c,b\text{-}w}+U_{o,b\text{-}a}}\left[I(t)A_b+h_{c,b\text{-}w}T_{w,i}+U_{o,b\text{-}aa}\right] \tag{19}$$

Equations (14), (18), and (19) are the set of mathematical equations for the conventional solar still without assuming the heat capacity of the basin liner and the glass cover. The absorption capacity of the system components are known as absorptance given:

$$A_{gl}=(1-\gamma)\alpha_{gl} \tag{20}$$

$$A_w=(1-\gamma)\left(1-\alpha_{gl}\right)\alpha_w \tag{21}$$

$$A_b=(1-\gamma)\left(1-\alpha_{gl}\right)\left(1-\alpha_w\right)\alpha_b \tag{22}$$

The input parameters include climatic data and operational parameters are taken from the observed values and relevant thermophysical parameters for the conventional still are taken from tab.1. Using the known average value of observed temperatures of the basin, saline water and glass cover, internal and external heat transfer coefficients are calculated.

Table 1. Thermophysical and radiation parameters for conventional still

Design parameters	Design parameters
A = 1 m^2	M_w = 30 kg
M_{gl} = 4.65 kg	ρ_w = 1000 kg/m^3
$C_{P,gl}$ = 800 J/kgK	$C_{P,w}$ = 4186 J/kgK
ρ_{gl} = 0.0735	α_w = 0.05
α_{gl} = 0.0475	M_b = 8.95 kg
$h_{c,gl\text{-}a}$ = 8.8 W/m^{2}K	$C_{P,b}$ =381 J/kgK
$h_{r,gl\text{-}a}$ = 0.73 W/m^{2}K	$h_{c,w\text{-}gl}$ = 1.957 W/m^{2}K
$U_{o,gl\text{-}a}$ = 5.23 W/m^{2}K	$h_{evp,w\text{-}gl}$ = 27.71 W/m^{2}K
T_a = 35 °C	$h_{r,w\text{-}g\,l}$ = 7.4 W/m^{2}K
$(\alpha\tau)_{gl}$ = 0.8	$h_{c,b\text{-}w}$ = 332 W/m^{2}K
A_w = A_{gl} = 0.044	$U_{o,g\text{-}a}$ = 0.504 W/m^{2}K
A_b = 0.7126	T_{gi} = T_{wi} = 30 °C

The density of sand 1442 kg/m^3, sandy gravel, well-graded gravel with little or no fines have porosity 0.26 to 0.46.

By using these thermophysical parameters, equations (14), (18), and (19) are simplified as given:

$$T_{g,li+1} = 1.041\times10^{-3} I(t) + 0.874 T_{w,i} + 4.389 \tag{23}$$

$$T_{w,i+1} = 1.003\times10^{-4} I(t) + 0.745 T_{b,i} + 0.084 T_{gl\text{-}i} + 0.162 T_{w,i} \tag{24}$$

$$T_{b,i+1} = 2.143\times10^{-3} I(t) + 0.997 T_{w,i} + 0.053 \tag{25}$$

After evaluating T_b, T_w, and T_{gl} on hourly basis, hourly yield per unit area by thermal effect, m_{thi}, can be evaluated as:

$$m_{thi} = \frac{h_{eva,w\text{-}gl}\left(T_w - T_{gl}\right)\times 3600}{h_{fg}} \tag{26}$$

where T_b, T_w, and T_{gl} are calculated for additional time intervals and thus yiels can also be obtained for number of time intervals. For getting total yield due to thermal effect, m_{th}, is obtained by:

$$m_{th} = \sum m_{thi} \tag{27}$$

From eqs. (7) and (26) the total yield produced, m, can be obtained by:

$$m = m_p + m_{th} \tag{28}$$

Results and discussion

Observed the mathematical modeling results on single slope solar still integrated with sand troughs and without sand troughs as shown in fig. 3. It is observed that yield has been improved drastically when sand troughs used. In fig. 4 the comparison of a mathematical and experimental model for 3 cm water depth the mathematical model results and results obtained with the experimental investigation are compared. The results show that both the models showing the same trend but with deviation are more during midday. The reason may be more losses through sides of the still. In fig. 5 comparison of yield obtained for various depths such as 1 cm, 2 cm, and 3 cm using the mathematical model. The vapour temperature for higher water depths such as 2 cm and 3 cm decreases due to the increase in thermal inertia of the water in the higher water depth which further results in an increase in time to achieve maximum vapour temperature for 2 cm and 3cm water depth.

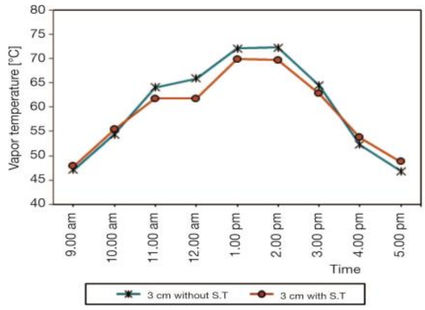

Figure 3. Comparison of yield with and without sand troughs

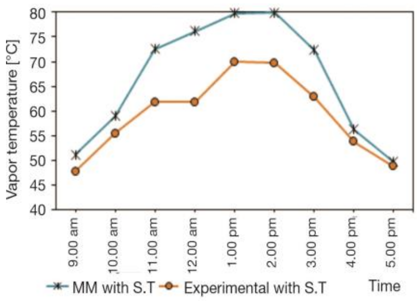

Figure 4. Comparison of mathematical and experimental models

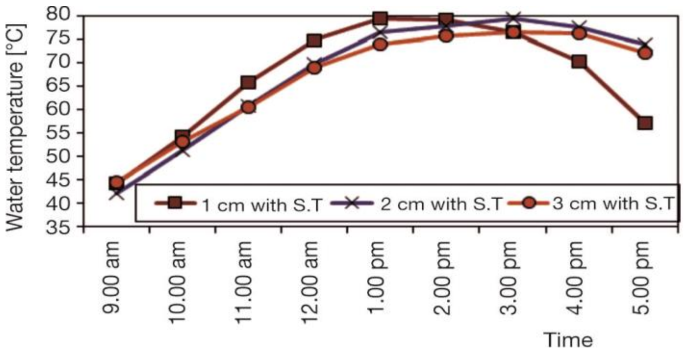

Figure 5. Comparison of yield obtained for various depths

Conclusions

- Though the trend in results is same in experimental and theoretical models, the magnitudes have deviation this may be because of various factors losses influenced during experimentation. In order to predict the capillary flow of liquid through sand troughs, a theoretical model was proposed.
- The model is based on the Lucas-Wash burn and Hagen-Poiseuille equations for capillary action and thermal circuit diagram for the solar still. A later model was used for predicting yield for 1 cm and 2 cm of water levels at the basin. It is observed that the maximum yield was obtained for 1 cm water level for the solar still with sand troughs means. Solar still produce better yield with low depth of water level when radiation is less comparatively, this is because of the availability of more space in sand, thereby more evaporation.
- The productivity and performance of the conventional solar still and the still with sand troughs were investigated for three different depths of normal and saline water of 1 cm, 2 cm, and 3 cm.
- The rate of yield increases with decrease in depth of the water at the basin and also the use of sand troughs increase the yield rate to an appreciable extent. The highest yield rate can be obtained by using sand troughs with less depth of water level. The maximum yield is obtained for 1cm water level at 2:00 p. m. The maximum yields of the case with and without sand troughs are 0.453 L/m^2 and 0.2 L/m^2 respectively. This is due to enhanced evaporation because of the deficiency in the thickness of the water layer.
- So the water level affects the evaporation rate and yield of the solar still. Solar still produce better yield on the experiment of still with 1 cm water level with troughs even though radiation is less than the data of experiment of still with 2 cm water level without troughs. Because sand troughs increased the evaporation rate further near to the glass surface in the solar still.

References

[1] Suneja, S., Tiwari, G. N., Effect of Water Depth on the Performance of an Inverted Absorber Double Basin Solar Still, *Energy Convers. Manag.*, *40* (1999), 17, pp. 1885-1897

[2] Kalogirou, S. A., Seawater Desalination Using Renewable Energy Sources, *Prog. Energy Combust. Sci.*, *31* (2005), 3C, pp. 242-281

[3] Arunkumar, T., *et al.*, A Review of Efficient High Productivity Solar Stills, *Renew. Sustain. Energy Rev.*, *101* (2019), Mar., pp. 197-220

[4] Schwartz, A. M., Capillarity - Theory and Practice, Industrial & Engineering Chemistry, *ACS*, *61* (1969) Jan., pp. 10-21
[5] Venkatesh, R., *et al.*, Performance Evaluation of Multipurpose Solar Heating System, *Mechanics and Mechanical Engineering*, *20* (2016), 4, pp. 359- 370
[6] Fath, H. E., *et al.*, Thermal-Economic Analysis and Comparison Between Pyramid-Shaped and Single-Slope Solar Still Configurations, *Desalination*, *159* (2003), 1, pp. 69-79
[7] Srithar, K., Mani, A., Analysis of a Single Cover FRP Flat Plate Collector for Treating Tannery Effluent, *Appl. Therm. Eng.*, *24* (2004), 5, pp. 873-883
[8] Tabrizi, F. F., Sharak, A. Z., Experimental Study of an Integrated Basin Solar Still with a Sandy Heat Reservoir, *Desalination*, *253* (2010), 1, pp. 195-199
[9] Suresh Isravel, R., *et al.*, Thermal Augmentation in Parabolic trough Collector Solar Water Heater Using Rings Attached Twisted Tapes, *Materials Today Proceeding, 21* (2020),1, pp. 127-129
[10] Gude, V. G., *et al.*, Renewable and Sustainable Approaches for Desalination, *Renew. Sustain. Energy Rev.*, *14* (2010), 9, pp. 2641-2654
[11] Kabeel, A. E., El-Agouz, S. A., Review of Researches and Developments on Solar Stills, *Desalination*, *276* (2011), 1, pp. 1-12
[12] Gude, V. G., *et al.*, Feasibility Study of a New Two-Stage Low Temperature Desalination Process, *Energy Convers. Manag.*, 56 (2012), Apr., pp. 192-198

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