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Effect of sponge liner on the internal heat transfer coefficients in a simple solar still

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ABSTRACT

In the present study, an attempt has been made to enhance the productivity of a solar still by increasing temperature difference between water and glass, using sponge liners at the inner wall surfaces. Two conventional basin still units were fabricated with the same design parameters. The experimental studies were conducted on the simple solar still with various thicknesses of sponge liners like 3, 5, 7, 10 and 12 mm. To evaluate the convection heat transfer correlation C and n, a thermal model is developed in the present work by using the experimental observations. The regression analysis is used to develop thermal model. Also a mathematical model has been developed to predict the water, glass temperature and mass of distilled output. The values of convection and evaporation heat transfer coefficients obtained in thermal model have been used in the mathematical model. From the experimental and analytical studies, it is concluded that, (i) sponge liner stills works towards increasing the temperature difference between water and glass by reducing the temperature of glass, (ii) The values of convection heat transfer coefficient and evaporation heat transfer coefficient differ for a particular condition and a particular model of solar still, (iii) The present studies have proved that there is a definite need to modify the values of C and n to predict the exact performance of solar stills, (iv) The internal heat transfer coefficients which are evaluated by thermal model have been found best suitable for theoretical model to get good agreement with experimental results.

Keywords: Solar still; Sponge liner; Heat transfer coefficients; Thermal model; Thickness

1. Introduction

Distillation process is considered as one of the simplest and widely adopted techniques for converting seawater into fresh water. One of the main advantages of the distillation process is that it requires heating only up to 120°C, which can be supplied from solar energy or other cheap fuels. The distillation processes such as multistage flash evaporation, reverse osmosis, electro dialysis, ion-exchange, phase change and solvent extraction are energy intensive, expensive and uneconomical for small quantities of fresh water. On the other hand, the use of conventional energy sources (hydrocarbon fuels) to drive these technologies has a negative impact on the environment. The solar stills are particularly suitable for the developing countries and especially for the remote rural areas in such countries because they have great economic advantage over other distillation processes with reduced operating

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and maintenance costs. Also their daily operation and routine maintenance is simple, and above all the solar energy is abundant, everlasting, and available on site, free of cost and pollution free. Because of the simplicity of the apparatus design, requirement of fresh water, and free thermal energy, work in the field of solar distillation is in progress for more than one hundred years.

Yeh and Chen [1] investigated the effects of climatic, design and operational parameters on the output of wick type solar stills. Abu-Hijleh and Rababa'h [2] have proposed modifications to enhance the distillate production by placing the sponge cubes over the water surface. The sponge cubes increased the surface area over which evaporation of water occurs, and caused the increase in output by 18%. Sodha et al [3] have presented a design and performance analysis of a multiple-wick solar still, in which the wet surface was created by a series of jute cloth pieces of increased length, separated by thin plastic liners. Akash et al. [4] have studied the effect of using different absorbing materials like black rubber mat, black dye and black ink to enhance the still output by 30–40%. Tiwari et al. [5] have studied the performance of a double condensing multiple-wick solar still. In this still, the area of the condensing surface had been increased by introducing an additional galvanized iron sheet just below the blackened wet jute cloth. Frick and Sommerfeld [6] proposed a wick-type solar still, in which blackened wet jute cloth formed the liquid surface, which could be oriented to intercept maximum solar radiation and attain a high temperature on account of low thermal capacity. Moustafa et al. [7] studied the solar stills with different types of configurations. They found that (i) the major design factors affecting energy utilization are basin temperature, condensing surface temperature and ambient air temperature and (ii) basic reflection and thermal radiation from the evaporating surface and transparent cover are the major sources of heat energy loss in a solar still.

The main objective of this study is (i) to enhance the performance of a simple solar still by increasing temperature difference between water and glass, using sponge liners at the inner wall surfaces and optimizing sponge liner thicknesses, (ii) to develop a thermal model using simple linear regression analysis for evaluating the convection heat transfer coefficient correlations C and n, and find the convection and evaporation heat transfer coefficients using the new modified C and n values, and (iii) to develop a mathematical model to predict the performance of solar distillation system using the new calculated value of convection and evaporation heat transfer coefficients, which are obtained in the thermal model.

2. Solar still with a sponge liner

In a conventional still, a part of the radiation is reflected by the inner wall surfaces to the still components like water, basin liner, vapour etc and the remaining part of the energy is stored by the inner wall surfaces, which is lost to the environment. The proposed modification on a conventional solar still is that the entire inner wall surfaces are fully covered with sponge liners for utilizing the maximum available energy inside the still to convert saline water into fresh water. The following points are considered while introducing the sponge liner: (i) by capillarity effect the basin water raises through sponge liner and absorbs heat from inner wall surfaces and vapour region inside cavity, and contributes additional evaporation thus increasing the productivity apart from the effect of basin liner surface, (ii) the productivity of the solar still is mainly dependent on temperature differences between water and glass; in this modification this difference increases because of the temperature reduction in vapour and inner wall surface, (iii) the sponge liners also reduce the basin water depth by extracting water from basin liner during the operation, (iv) the sponge liner materials reduce the heat losses from inner wall surfaces to the other components, thus reducing the operating temperatures of the still components when compared with conventional still, and (v) the sponge materials are readily available in the market at low cost.

The schematic arrangement of solar still with sponge liner on the inner wall surfaces is shown in Fig. 1, and the pictorial view of sponge liner arrangement on the still is shown in Fig. 2. These experiments were carried out during January 2009–February 2009 under the same climatic conditions with sponge liners of various thicknesses like 3, 5, 7, 10, 12 mm. The water transport of the sponge liners are measured by vertical strip wicking test. It is observed that there is rise in water about 10 mm in ten minutes interval for all the sponge liners irrespective of thickness. The sponge liners are placed on the inner wall surface and the bottom end is in contact with basin water for rising water through it by the capillary effect. The water depth of these experiments is considered as 20 mm [8].

3. Experimental setup

Two single slope single basin-type solar still units are fabricated with same design parameters, and tested at the testing field of the Mechanical Engineering Department, Adhiyamaan College of Engineering, Hosur, Tamilnadu, India (Latitude: 12° 43′ 0 N, Longitude: 77° 49′ 0 E). The photographic view of single slope single basin solar distillation units are shown in Fig. 3. The experimental setup consists of a passive solar distillation unit with condensing cover inclination 10°. The bottom surface of the still was painted black for greater absorptivity. The basin is designed for a maximum depth of 150 mm. Moreover, to avoid the spilling of basin water into the distillate channel and to prevent the contact of distillate channel with the glass cover as well as with the water depth, the height of the lower vertical side (front wall) of still is kept at

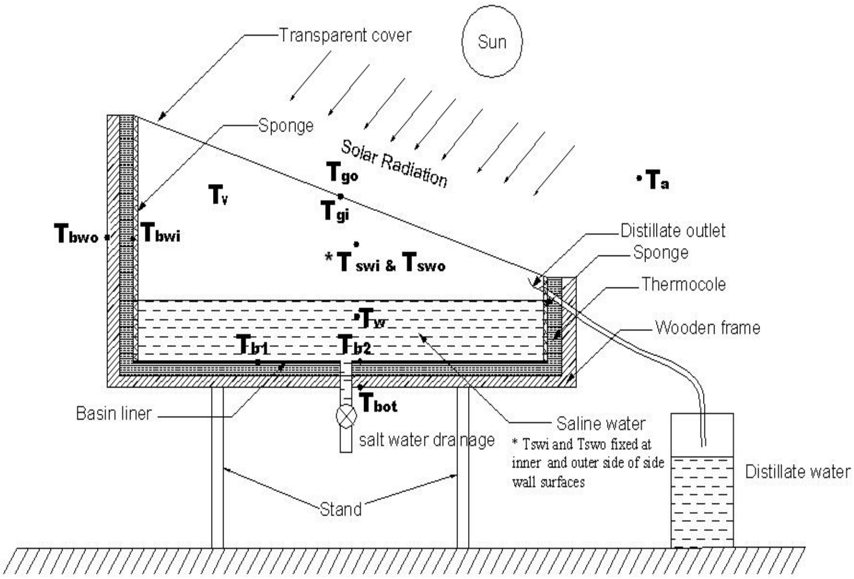

Fig. 1. Schematic diagram of the single slope solar still with sponge liner at inner wall surfaces.

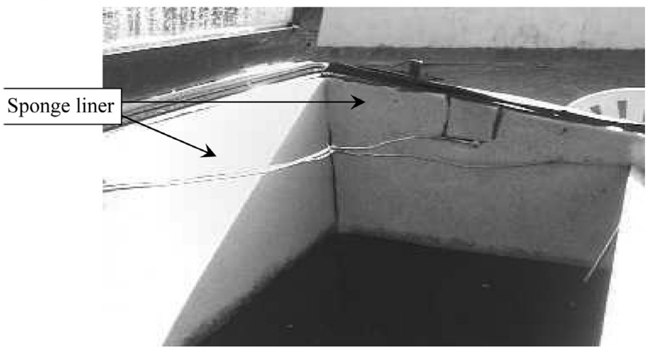

Fig. 2. The sponge liner arrangement at the inner wall surfaces.

Fig. 3. Pictorial view of the experimental setups.

200 mm, whereas the height of higher vertical side (back wall) is kept at 288 mm. The effective basin area of each still is kept 1000 mm × 500 mm (0.5 m^2) and it is made of galvanized iron (G.I.) sheet of 1.4 mm thickness. Condensing cover is made of plane glass 4 mm thick, fixed to the top of the vertical wall of the stills using rubber gasket on bottom sides. Glass cover has been framed with wood and sealed with silicon rubber, which plays an important role to promote efficient operation as it can accommodate the expansion and contraction between dissimilar materials. To ensure the non-leakage of vapour to the atmosphere, eight numbers of bolt and nuts are used on still. The output from the still is collected through a channel, fixed at the end of the smaller vertical side (front wall) of the basin. A steel rule is fixed on inner back wall surfaces to measure the water level in the basin. A plastic hose is connected to this channel to drain the distilled water into an external measuring jar. The technical specifications of the solar still are given in Table 1.

The experiments were started at 9:00 o'clock local time and lasted till 17:00 o'clock and the daily productivity is obtained as a summation of day and night. The night productivity is the total collection from the end of test to start of test in the next day. The following parameters were measured every 60 min for a period of investigations glass temperature (inside and outside), basin liner temperature, vapour temperature, back and side wall surface temperature (inside and outside), bottom side temperature, water temperature, ambient temperature, wind velocity and solar intensity. The hourly variations of all the above mentioned parameters were used to evaluate average values of each for further numerical computations. The data selected for discussion was based on similar solar intensity pattern for getting concurrent results. The averages hourly solar intensity and wind velocity was observed during the experiments are 556 W/m^2 and 0.3 m/s respectively (Fig. 4).

Table 1
Technical specification of the solar still

Specification	Dimension
Basin area (A_b), m^2	0.5
Glass area (A_g), m^2	0.508
Area of back wall (A_{bw}), m^2	0.488
Area of side wall (A_{sw}), m^2	0.234
Steffan Boltzmann constant (σ), W/m^2 K^4	5.67×10^{-8}
Latent heat vapourization of water (h_{fg}), kJ/kg	2382.9
Emissivity of glass (ε_g)	0.88
Emissivity of water (ε_w)	0.96
Average depth of air–vapour mixture (d_f), m	0.144
Thickness of thermocol (L_{th}), mm	25.4
Thermal conductivity of thermocol (K_{th}), W/mK	0.015
Thickness of wood (L_{wood}), mm	12.5
Thermal conductivity of wood (K_{wood}), W/mK	0.055

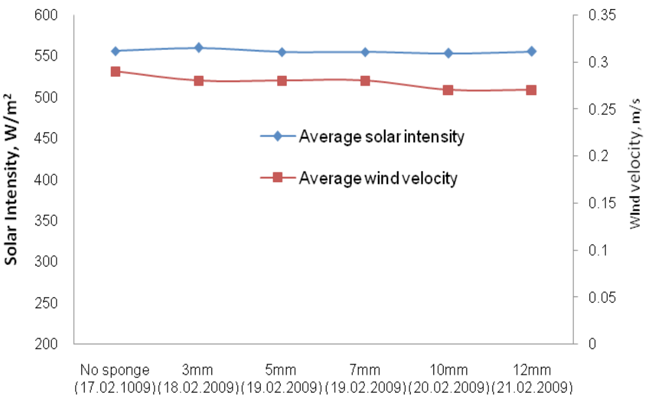

Fig. 4. Average hourly solar intensity and wind velocity for the experimental days.

The measuring devices used in the system are as follows:

1. Twelve thermocouples (type k) coupled to digital thermometer with a range from 0 to 99.9°C with ±1°C accuracy are used to measure the temperatures of the various components of the still system.
2. The solar intensity was measured with the help of a calibrated pyranometer of least count of 2 mW/cm^2 (1 mW/cm^2 = 10 W/m^2). It is generally measured as the total solar radiation.
3. A 30 mm steel rule is fixed inside wall used to measure water level inside basin is with least count of 0.5 mm.
4. The distillate output was recorded with the help of a measuring cylindrical jar of least count 1 ml.
5. The ambient air velocity was measured with an electronic digital anemometer model of Lutron AM-4201. It had a least count of 0.1 m/s with 2% accuracy on the full-scale range of 0.2–40.0 m/s.

4. Evaluation of convection and evaporation heat transfer coefficients

In a solar distillation process, solar energy in the form of short electromagnetic waves passes through a clear glazing surface such as glass. Upon striking a darkened surface, this light changes wavelength, becoming long waves of heat, which is added to the water in a shallow basin below the glazing. As the water heats up, it begins to evaporate. The warm vapor rises to a cooler area. Almost all impurities are left behind in the basin. The vapor condenses onto the underside of the cooler glazing and accumulates into water droplets or sheets of water. The combination of gravity and the tilted glazing surfaces allows the water to run down the cover into a collection trough, where it is channeled in to storage.

The performance prediction of a solar still mainly depends on an accurate estimation of the basic internal heat and mass transfer relations. Heat transfer between the evaporating surface and the glass cover is controlled by free convection, evaporation and radiation. Convection heat transfer occurs among the different layers of water inside the still. From the water surface to the condensing glass cover, heat is accompanied by transport of water formed above the water surface through the air–vapour mixture. Both convection and evaporation heat transfers occur simultaneously and are independent of radiative heat transfer. Hence understanding of these modes of heat transfer is essential.

Even though the use of basin type solar still was suggested more than hundred year ago, the first theoretical treatment of this subject appeared in 1961. Dunkle derived a common semi-empirical relation for simple solar still. Based on the Dunkle's relation, number of solar stills with different geometry and modification has been analysed by various investigators. On the basis of experimental data, Dunkle found the values of constants 'C' and 'n' as C = 0.075 and n = 1/3 with the following limitations [9]:

- It is valid for a mean operating temperature range of 50°C and an equivalent temperature difference of 2°C.
- It is independent of average distance between the condensing and evaporating surfaces and
- It holds good for heat flow upwards in horizontally enclosed air space.

Hence it is required to examine the validity of the above mentioned Dunkle's relationship with and without the limitations. Linear regression analysis is a simple tool to evaluate C and n which is free from various limitations followed in the Dunckle model. In the proposed thermal model, the values C and n are to be modified by regression analysis using experimental hourly yield (m_w), water temperature (T_w) and glass temperature (T_g).

Heat transfer occurs in the humid air inside the solar still by free convection which is caused by the buoyancy force formed due to density variation in the humid area. Density variation is caused by a temperature gradient in the fluid. Hence the rate of heat transfer from the water surface to the glass (Q_{cw}) by convection through humid air in the upward direction is given by

$$Q_{cw} = h_{cw} A_w \left(T_w - T_g\right) \tag{1}$$

where h_{cw} is convection heat transfer coefficient and it is dependent on the operating range of temperature and physical properties of the fluid.

The relation of non dimensional Nusselt number carry convection heat transfer coefficient as

$$\mathrm{Nu} = \frac{h_{cw} d_f}{k_f} = C\left(Gr\,\mathrm{Pr}\right)^n \tag{2}$$

where C and n are constants depending upon the range of Grashof number (Gr) and Prandtl number (Pr) on the temperature dependent physical properties of water vapour, volume of the enclosure and the temperature difference between the water and glass cover, d_f is average vertical distance of glass and basin water surface, m.

The expression for the temperature-dependent physical properties of humid air as given in Table 2, where T_f is the film temperature, it is equal to

$$T_f = \frac{\left(T_w + T_g\right)}{2} \tag{3}$$

where P_w and P_g are the partial vapor pressures at water and glass temperatures, respectively, and they can be expressed by the following equation respectively [10]

$$P_g = e^{\left(25.317 - \frac{5144}{T_g}\right)} \tag{4}$$

The rate of heat loss due to evaporation can be determined by the expression given below:

$$Q_{ew} = h_{ew} A_w \left(T_w - T_g\right) = 0.01623\, h_{cw} \left(P_w - P_g\right) \tag{5}$$

The convection and evaporation losses are strongly dependent on each other. The evaporation heat transfer coefficient is determined by expression given below:

$$h_{ew} = \frac{0.01623.h_{cw}\left(P_w - P_g\right)}{\left(T_w - T_g\right)} \tag{6}$$

The hourly distillate output from the solar still can be evaluated by using the expression

$$m_w = \frac{A_w.Q_{ew}.3600}{h_{fg}} \tag{7}$$

where m_w – mass of hourly distilled output, kg, h_{fg} – latent heat of evaporation, J/kg.

From Eqs. (2) and (5), Eq. (7) can be rewritten as given below

$$m_w = 0.01623\left(P_w - P_g\right)\left(\frac{k_f}{d_f}\right)\left(\frac{3600}{h_{fg}}\right)C(Ra)^n \tag{8}$$

and rewritten as

$$\frac{m_w}{R} = C(Ra)^n \tag{9}$$

where

$$R = 0.01623\left(P_w - P_g\right)\left(\frac{k_f}{d_f}\right)\left(\frac{3600}{h_{fg}}\right) \tag{10}$$

Taking the logarithm of Eq. (9), it reduces into an equation of straight line:

$$\ln\left(\frac{m_w}{R}\right) = \ln C + n\ln(Ra) \tag{11}$$

Eq. (11) has an analogy of a straight line represented by $Y = aX + b$ where

$$Y = \ln\left(\frac{m_w}{R}\right); a = n; X = \ln(Ra) \text{ and } b = \ln C \tag{12}$$

Eq. (11) has been solved for different sets of experimental observation using a linear regression technique as mentioned below:

$$a = \frac{N\Sigma XY - \Sigma X\Sigma Y}{N\Sigma X^2 - (\Sigma X)^2} \tag{13}$$

$$b = \frac{\Sigma Y\Sigma X^2 - \Sigma X\Sigma XY}{N\Sigma X^2 - (\Sigma X)^2} \tag{14}$$

where N is the number of experimental observations.

After knowing the values constants 'a' and 'b' from Eqs. (13) and (14), the values of C and n will be obtained from Eq. (12). For the above-mentioned work, macro was developed in EXCEL sheet. This models takes the value of system design parameters e.g. d_f (spacing between the condensing and evaporating surfaces of the still), A_b (area of still) and experimental data of water and glass temperature and distilled output as its input parameters. After giving input data, it moves to evaluation of physical properties of humid fluid inside the distiller unit.

5. Mathematical modeling of solar distillation system

In the proposed mathematical model all the climatic, design and operational parameters affecting the performance of solar stills appear explicitly in energy balance equations. The analytical expressions have been derived for hourly water glass and basin liner temperatures as a function of design and climatic parameters. These expressions are based on energy balance equations for each

Table 2
Temperature dependent physical properties of vapor [9]

Property	Expression
Specific heat capacity, C_p	$999.2 + 0.1434\,T_f + 1.101\times10^{-4}\,T_f^2 - 6.758\times10^{-8}\,T_f^3$
Thermal conductivity, k_f	$0.244 + 0.7673\times10^{-4}\,T_f$
Dynamic viscosity, μ	$1.718\times10^{-5} + 4.62\times10^{-8}\,T_f$
Density, ρ	$353.44 / (T_f + 273.15)$
Expansion factor, β	$1 / (T_f + 273.15)$

component of solar stills. This model predicts the theoretical values of water temperature, glass temperature and basin liner temperature at every hour and compares the same with experimental results.

In order to write the energy balance equations, the following assumptions were made:

- The level of water in the basin is maintained constant level
- The condensation that occurs at the glass trough is a film type
- The heat capacity of the glass cover, the absorbing material, and the insulation material are negligible
- No vapor leakage in the still
- No temperature gradient along the glass cover thickness and in water depth
- The system is in a quasi steady-state condition
- The heat capacity of the insulator (bottom and side of the still) is negligible

5.1. Energy balance for the water mass in the still

Referring to Fig. 5, the heat balance equation on basin water can be written as

$$C_w \frac{dT_w}{dt} = \alpha_w I_1 + Q_b - Q_{cw} - Q_{rw} - Q_{ew} \tag{15}$$

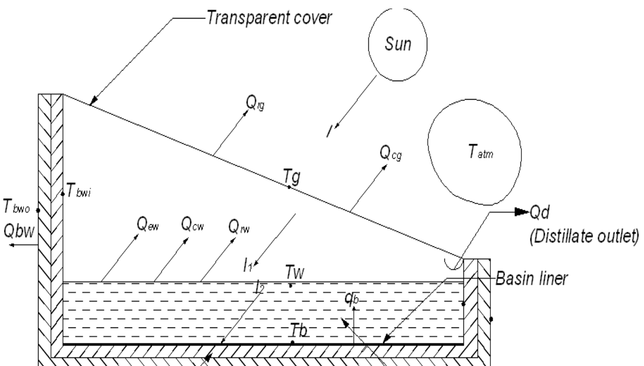

Fig. 5. Various components of a conventional single slope solar still.

where Q_b is the convection heat transfer from basin to water, C_w — heat capacity of basin water (mass × specific heat), T_w — basin water temperature, Q_{ew} — evaporation heat transfer from water to glass, Q_{rw} — radiative heat transfer from water to glass, Q_{cw} — convection heat transfer from water to glass, I_1 is the radiation falling on to the water surface after transmitting through glass, and I_2 is the solar intensity falling on the basin liner after passing through the water mass, I_1 and I_2 can be expressed,

$$I_1 = (1-\alpha_g)I \tag{16}$$

$$I_2 = (1-\alpha_g)(1-\alpha_w)I \tag{17}$$

where α_g is the radiation absorptivity of glass and α_w is the radiation absorptivity of the water and I is solar intensity available on site, W. Radiation heat transfer occurs between water surface and glass cover due to temperature difference, according to Steffan–Boltzman's law

$$Q_{rw} = h_{rw} A_w \left(T_w - T_g\right) = \varepsilon_{eff} A_w \sigma \left(T_w^4 - T_g^4\right) \tag{18}$$

$$h_{rw} = \varepsilon_{eff}\sigma\left[\left(T_w^2 + T_g^2\right)\left(T_w + T_g\right)\right] \tag{19}$$

where h_{rw} — radiative heat transfer coefficient between water and glass, A_w — cross section area of the basin water, T_g — temperature of glass, σ — Steffan–Boltzmaan constant, 5.67×10^{-8} W/m^2 K^{-4}, ε_{eff} is the effective emittance between the water surface and the glass cover.

The rate of heat transfer from the water surface to the glass (Q_{cw}) by convection through humid air in the upward direction is given by

$$Q_{cw} = h_{cw} A_w \left(T_w - T_g\right) \tag{20}$$

The rate of heat loss due to evaporation can be determined by the expression given below:

$$Q_{ew} = h_{ew} A_w \left(T_w - T_g\right) \tag{21}$$

where h_{cw} and h_{ew} are convection heat transfer coefficient and evaporation heat transfer coefficient respectively and these values obtained for each case have been used in this model.

5.2. Energy balance for the glass cover

The heat balance equation on glass cover

$$Q_{rg} + Q_{cg} = \alpha_g I + Q_{ew} + Q_{rw} + Q_{cw} \quad (22)$$

where Q_{cg} — convection heat transfer from glass to atmosphere, I — solar radiation falling on the still and Q_{rg} is the radiative heat transfer from glass to atmosphere equal to

$$Q_{rg} = \varepsilon_g A_g \sigma\left(T_g^4 - T_s^4\right) = h_{rg} A_g \left(T_g - T_a\right) \quad (23)$$

where A_g — surface area of glass exposed to atmosphere, h_{rg} — radiation heat transfer coefficient between glass and atmosphere, T_a — atmosphere temperature and T_s — sky temperature, it is less than (such as 6°C) ambient temperature.

The convection heat transfer from glass to ambient is

$$Q_{cg} = h_{cg} A_g \left(T_g - T_a\right) \quad (24)$$

where h_{cg} — convection heat transfer coefficient between glass and ambient. It is mainly depends on wind velocity (V), the expression is [10] $h_{cg} = 5.7 + 3.8\ V$.

5.3. Energy balance for the basin liner

The heat balance equation on basin liner

$$I_2 = Q_b + Q_{bot} \quad (25)$$

where Q_{bot} is the heat transfer rate from basin liner to atmosphere through bottom side, and it is expressed as

$$Q_{\text{bot}} = U_{\text{bot}} A_b \left(T_b - T_a\right) \quad (26)$$

where U_{bot} — overall heat transfer coefficient between basin liner to atmosphere.

The convection heat transfer from basin liner to water expression is

$$Q_b = h_b A_b \left(T_b - T_w\right) \quad (27)$$

Rearranging Eq. (15) by substituting Eqs. (16), (17), (18), (20) and (21)

$$\frac{dT_w}{dt} + T_w\left(\frac{h_{tw} + h_b}{C_w}\right) = \frac{1}{C_w}\left(\alpha_w I\left(1 - \alpha_g\right) + h_{tw} T_g + h_b T_b\right) \quad (28)$$

It is similar to the differential equation format of $dT_w/d_t + a_1\ T_w = f_1$; then the solution of Eq. (28) is

$$T_w = \frac{f_1}{a_1}\left(1 - e^{-a_1 t}\right) + T_{wi} e^{-a_1 t} \quad (29)$$

where

$$a_1 = \left(\frac{h_{tw} + h_b}{C_w}\right) \quad (30)$$

$$f_1 = \frac{1}{C_w}\left[\alpha_w I\left(1 - \alpha_g\right) + h_{tw} T_g + h_b T_b\right] \quad (31)$$

where $h_{tw} = h_{rw} + h_{cs} + h_{rw}$.

The following assumptions have been made for the solution of Eq. (29):

1. Initial condition for water T_w at $t = 0 = T_{wi}$;
2. f_1 is considered as average values of f_1 for shorter time intervals.
3. The heat transfer coefficient is constant for the time intervals, i.e. a_1 is constant.

Rearranging Eq. (22) by substituting Eqs. (23), (24), (18), (20) and (21)

$$\overline{T}_g = \frac{\alpha_g I_1 + h_{tw} T_w + h_{tg} \overline{T}_a}{h_{tw} + h_{tg}} \quad (32)$$

where $h_{tg} = h_{cg} + h_{rg}$.

Rearranging Eq. (25) by substituting Eqs. (26) and (27)

$$\overline{T}_b = \frac{\alpha_b I_2 + h_b T_w + U_{bot} \overline{T}_a}{h_{tw} + U_{bot}} \quad (33)$$

5.4. Numerical calculations

A computer program has been developed in 'C' language for the solution of the above mentioned nonlinear Eqs. (29), (32) and (33) to predict water temperature, glass temperature and basin liner temperature. The input parameters to the program include climatic, design, operational parameters and relevant thermo-physical parameters were taken from Table 3. Also this model takes the modified values of convection heat transfer coefficients which are obtained in the thermal model and carryout the computation of the performance of solar still.

Numerical calculations are initiated assuming the temperatures of different elements of the still to be equal

Table 3
Design parameters of solar still for theoretical simulation [11,12]

Notations	Dimensions
α_g	0.0475
α_b	0.96
h_{cg}, W/m^{2}K	8.8
h_{rg}, W/m^2 K	6.3
C_{pw}, J/kg K	4186
α_w	0.05
h_b, W/m^{2}K	100
h_{cw}, W/m^{2}K	1.79
h_{rw}, W/m^{2}K	6.6
U_{bot}, W/m^{2}K	7.0

to the ambient temperature at $t = 0$. Using known initial values for different temperatures, different internal and external heat transfer coefficients are calculated. Using these values along with climatic parameters, T_g, T_w and T_b are calculated from Eqs. (29), (32) and (33), respectively, for 60 s is used in the simulation. After knowing the hourly variation of T_g, T_w and T_b, the procedure is repeated with the new values of T_g, T_w and T_b for a additional time intervals. After knowing T_w and T_g the theoretical hourly yield can be evaluated from Eq. (7) and the calculated theoretical output is compared with the experimental values. The overall efficiency of the solar still is obtained from the following equation

$$\eta_o = \frac{Q_d}{I} \tag{34}$$

where Q_d — the amount of heat utilized for distilled output and I — solar intensity falling on the experimental field.

6. Results and discussion

The effect of sponge liner on the inner wall surfaces made large difference in the temperature of the components. In Fig. 6, it is seen that, the water temperature of lower thick sponge liner still is slightly lower than the conventional still, whereas water temperature of higher thick sponge liner still is higher than the conventional still. This may be due to the following reason (i) higher thick sponge liners (7 mm, 10 mm, 12 mm) extracts more amount of water by capillarity force from the basin, hence water depth as well as water capacity reduces in the basin, resulting in increase of basin water temperature, (ii) the lower sponge liners extract considerably low water, and will lead to lower the water temperature.

Fig. 7 shows the hourly variations of vapor temperature for different sponge liner thicknesses. It is seen that, the vapor temperature of sponge liner stills are much lower than the conventional still. This may be since the water present in the sponge liners extract heat from the vapor region due to the temperature difference between them, and hence vapor temperature becomes low. Fig. 8 shows the hourly variation of glass temperature. It is clearly seen that, the glass temperature of sponge liner stills are lower than the conventional still, which may due to the decrease of vapor temperature inside the cavity of the still. It is well known that the glass temperature is highly dependent on vapor temperature in the simple solar still. As mentioned earlier, the temperature of water is high for the higher thick sponge liner stills and will lead to increase in the radiation effect from water to glass, and this may be the reason for higher glass temperature for higher thick sponge liners. Also it is noticed that 5 mm thick sponge liner glass temperature is lower than other stills, it is due to lower radiation effect from the water surface to the glass surface.

Fig. 9 shows the effect of sponge liner on the inner wall surface temperatures for different thickness of sponge liners. It clearly shows that, the inner wall surface temperature of sponge liner stills are much lower than the conventional still. It may be because the water available

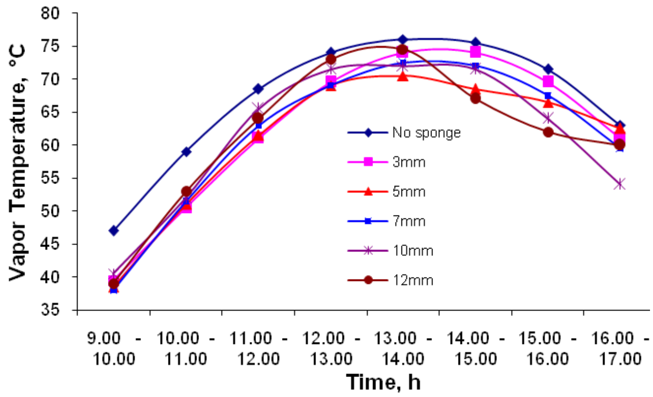

Fig. 7. Hourly variations of vapor temperature for different thickness sponge liners.

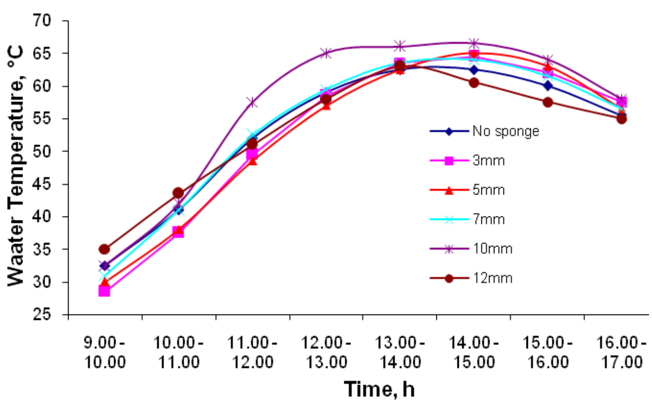

Fig. 6. Hourly variations of water temperature for different thickness sponge liners.

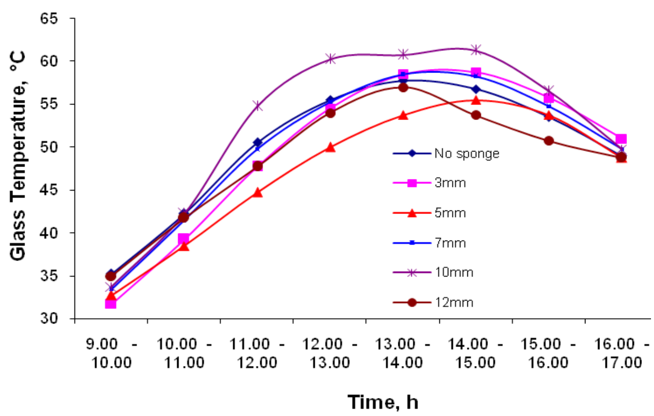

Fig. 8. Hourly variations of glass temperature for different sponge liner thicknesses.

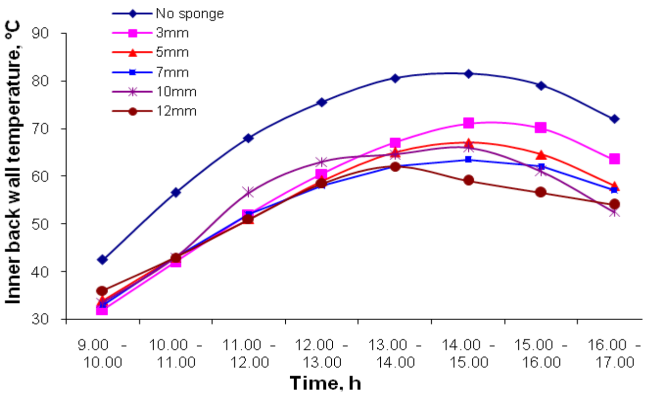

Fig. 9. Hourly variations of inner wall surface temperature for different sponge liner thicknesses.

in the sponge liner extracts heat from inner wall surfaces; hence its temperature gets lowered. Also, it is noticed that the inner wall surface temperature decreases with the increase in sponge liner thickness.

It is a well known fact in the field of distillation that the amount of distilled output received will be higher for the higher temperature of evaporation surface and also for lower temperature of condensing surface. In other words, the higher value of evaporation surface temperatures, both leads to the rise in distilled output. A little consideration reveals that both of these increases the temperature difference ΔT between evaporation and condensing surface. It plays an important role in optimizing the yield and so ultimately convection heat transfer coefficient as well. The effect of the thickness of sponge liner on the ΔT is given in Fig. 10. It is clearly shown that, in the sponge liner stills ΔT values are higher than the conventional still throughout the day and the lowest ΔT is observed in conventional still. It may be since the temperature of glass is much lower than conventional still (Fig. 8), whereas the water temperature of the sponge liner stills are closest value with conventional still (Fig. 6). It is also noticed from Fig. 10, that the lower and higher thick sponge liners reduce the ΔT values. In lower thick sponge liner water attains lower temperature due to higher capacity of water available in the basin whereas in higher thickness sponge liner water attains higher temperature due to lower water capacity in the basin, both these cases leads to reduce the ΔT value. It is also notice that, the ΔT value of 5 mm thick sponge liner still is higher than the other stills, it may due to lower glass temperature (Fig. 8). The process of higher ΔT values in sponge liner stills are explained clearly from Figs. 11–14 with 5 mm thick sponge liner still values. In Fig. 11, it is seen that, the difference between sponge liner and conventional still water temperature is comparatively low. The water temperature is almost same for both the stills, but in Fig. 12, the glass temperature of sponge liner still is lower than the conventional one. Figs. 13 and 14 show the hourly variations of glass and water temperature difference for conventional (no sponge) and 5 mm sponge liner stills. It is seen that, the 5 mm sponge liner still difference

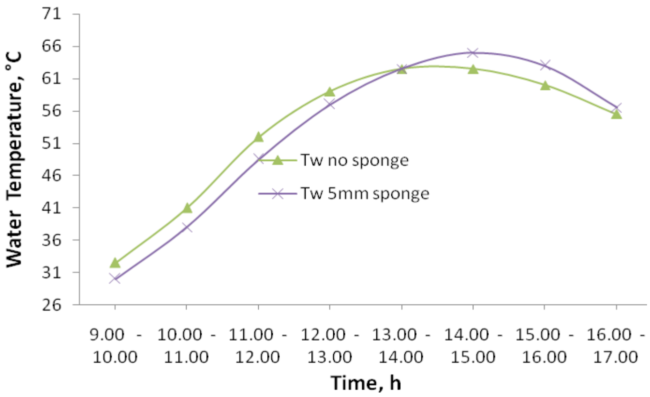

Fig. 11. Comparison of water temperature for 5 mm sponge liner still and conventional still.

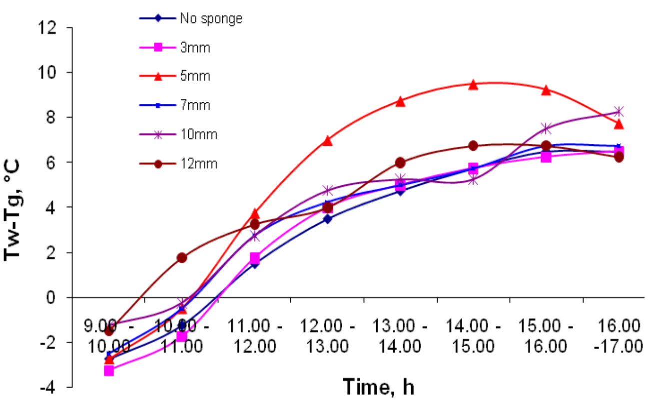

Fig. 10. Hourly variation of temperature difference between water and glass for different sponge liner thicknesses.

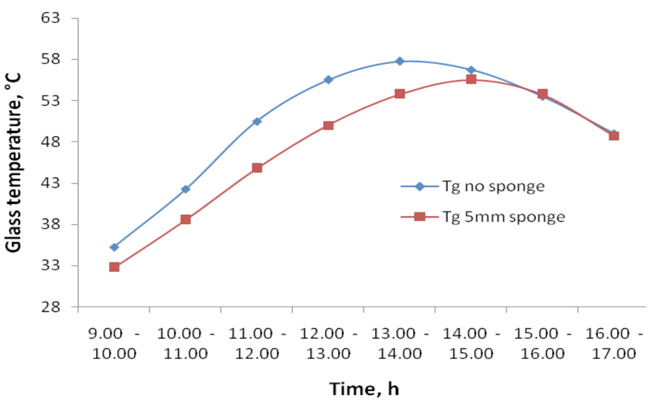

Fig. 12. Comparison of glass temperature for 5 mm sponge liner still and conventional still.

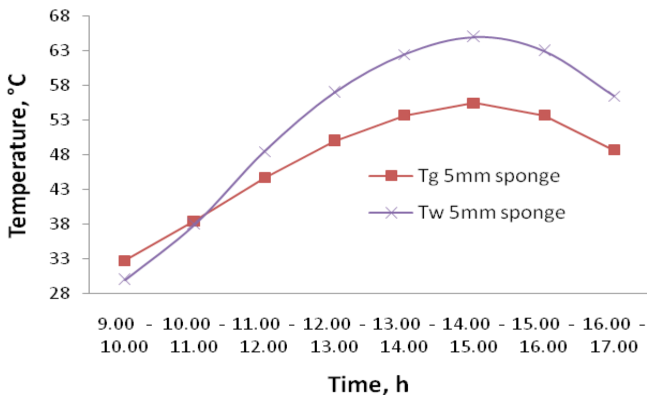

Fig. 13. Hourly variation of glass and water temperature for 5 mm sponge liner.

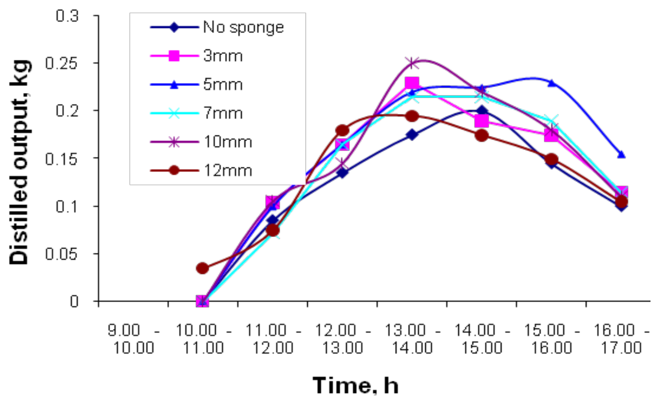

Fig. 15. Hourly variation of distilled yield for different sponge liner thicknesses.

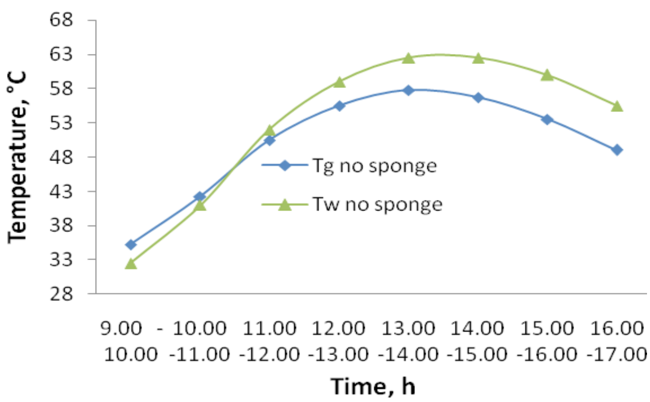

Fig. 14. Hourly variation of glass and water temperature for a conventional still.

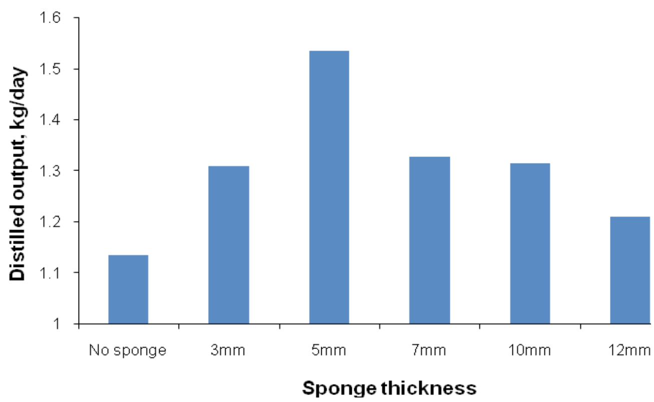

Fig. 16. Variation of daily yield with respect to all sponge liner thicknesses.

between water and glass temperature (ΔT) is high than the conventional still.

Fig. 15 shows the hourly variation of output yield for various thick sponge liner stills. It is seen that the output of the sponge liner stills are higher than conventional still since morning. It may be because the water available in the sponge liner extracts heat from inner wall surfaces and vapor surfaces, and gets evaporated; this results in getting additional yield. The yield of the solar still with 12 mm and 10 mm sponge liner is lesser than that of 3 mm, 5 mm and 7 mm sponge liner stills. It may be due to the following reason (i) due to higher components temperatures (Figs. 6–9), the convection and radiation losses from water to glass and glass to ambient are more which makes the output as low as in higher thick sponge liner stills (ii) the heat energy available at the inner wall surfaces are not sufficient for complete evaporation of water present in the sponge liner.

Fig. 16 shows the variations of daily yield of sponge liner with various thicknesses. It is observed that the 5 mm thick sponge still gives more yield than others and is equal to 1.535 kg, which is 35.2% higher than the conventional still. The lowest output is obtained from the sponge liner still with 12 mm sponge liner and is equal to 1.21 kg/d. The result also shows that the night time (17.00 o'clock – 9.00 o'clock) productivity of 3 mm (0.295 kg) and 5 mm thick sponge liner stills (0.275 kg) are higher than that of the 10 mm (0.245 kg) and 12 mm (0.235 kg) thick sponge liner stills (0.245 kg). It is easily understood that the productivity of the sponge liner still decreases with increase in thickness of sponge liner. This is due to the low heat capacity of the higher thick sponge liner still basins in the night hours.

The solar still efficiency is considered as the most important parameter to evaluate the system and to ensure the best still design. Fig. 17 shows clearly that the efficiency of the sponge liner stills is higher than that of conventional still. This may because to the sponge liner stills yield more by the combined evaporation of water from basin liner and inner wall surfaces. It is also noticed that, the efficiency of the sponge liner still increases with addition of sponge liner thickness up to 5 mm, after which

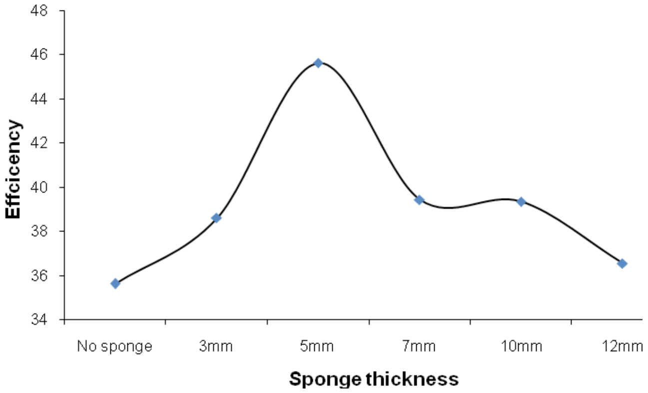

Fig. 17. Variations of overall efficiency for different sponge liner thicknesses.

decreases with addition of sponge liner thickness. The heat energy available in the inner wall surfaces is same for all the cases, but the quantity of water available in the sponge liner depends on the thickness of sponge liner. It is understood from the vertical wicking test that the high thickness sponge liner extracts more amount of water from the basin than the lower thickness sponge liner. The available heat energy at the inner wall surfaces is not fully utilized in the lower thickness sponge liner and is not sufficient for higher thickness sponge liner. This may be the reason for lower efficiency in both the low and higher thick sponge liner stills. The overall efficiency of the sponge liner still with 5 mm thickness is much higher than the others; which is equal to 45.61%, and which is 9% higher than conventional still. This may be due to the maximum utilization of heat energy available at the inner wall surfaces for the additional evaporation of water available in the sponge liner. Therefore from Figs. 16 and 17, it is understood that the optimum thickness for the typical simple solar still is 5 mm.

Tiwari and Tiwari [8] suggested from their detailed heat and mass transfer analysis on passive solar still and it is concluded that, to get more realistic values calculate the C and n value when ΔT is positive. Thus, in this proposed thermal model, the analyses are carried over the hours when the water temperature becomes higher than the inner glass temperature to obtain better realistic value of C and n. The proposed thermal model developed in the present work to evaluate values of C and n takes into account the effect of various thickness sponge liners on the convection and evaporation heat transfer coefficients. The convection and evaporation heat transfer coefficients are calculated by using the obtained value of C and n, and the values of $C = 0.075$, $n = 0.333$ proposed by Dunkle's (1961) for the same known values of water and glass temperature. As mentioned earlier, the values of C and n are evaluated when ΔT is positive. Almost all the case of the experiments, the positive ΔT values are getting after 11:00 o'clock only. Due to this factor the figures which related to convection and evaporation heat transfer coefficients are started with 11:00 o'clock in the time axis.

The values of convection heat transfer coefficient, evaporation heat transfer coefficients for thermal and Dunkle's models are compared in the same figure for easy understanding. To avoid prolong the paper a typical comparison graph, the hourly variation of convection and evaporation heat transfer coefficients for 5 mm sponge liner is given in Fig. 18. However, the consolidated average convection and evaporation heat transfer coefficients for all the sponge liner thicknesses are given in Table 4. By referring to Fig. 18 and Table 4, a significant deviation is observed in the convection and evaporation heat transfer coefficients between Dunkle and thermal models for all the cases. It may be due to the Ducnkle model has certain limitations, which were discussed earlier in this paper, and the proposed thermal model is based on the experimental observations. It is considering the operating condition, modification of the still, storage effect of the water etc; this may be the reason for thermal model is deviating from the Dunkle model.

From Table 4, it is very interesting to note that though the value of evaporation heat transfer coefficient is higher but the yield is lower for some cases, like 3 mm, 7 mm sponge liner. It is because of the fact that yield is the product of evaporation heat transfer coefficient and ΔT and if either of these two is lower the yield will be lower. In the above said cases, the water and glass temperature both remain on the higher side and ultimately ΔT falls, which reduces the yield obtained. It is understood that, either too high or low evaporation heat transfer coefficient lead to lower output.

The detailed consolidated results between theoretical and experimental values for all the sponge liner thicknesses are given in Table 5. A typical comparative graph of theoretical and experimental results of the temperature and output for 5 mm thick sponge liner has been shown

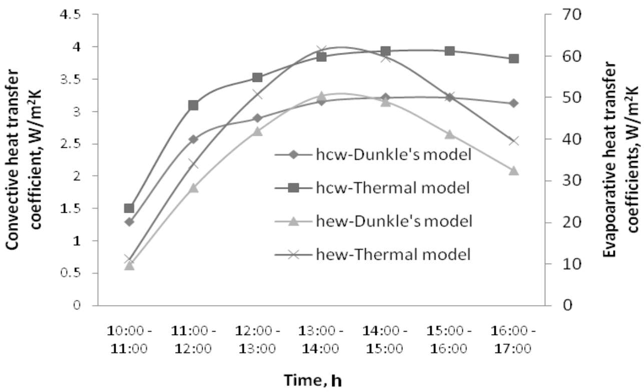

Fig. 18. Hourly variations of convection and evaporation heat transfer coefficients for 5 mm thick sponge liner.

Table 4
Average convection and evaporation heat transfer coefficient obtained from proposed thermal model for various experimental studies

No.	Parameters (C and n)	h_{cw} (W/m²K)	h_{ew} (W/m²K_	C	n
1	No sponge	2.95	31.21	0.085	0.34
2	3	3.24	36.27	0.092	0.35
3	5	2.92	33.29	0.097	0.33
4	7	2.77	33.71	0.092	0.35
5	10	2.78	33.34	0.098	0.33
6	12	2.49	31.22	0.099	0.34

Table 5
Comparison of consolidated experimental output with theoretical model and Dunkle model for various sponge liner thicknesses

No	Parameters	Distilled output (kg)			Deviation (%)	
		Exp	Dun	Theo	Dun	Theo
1	No sponge	1.14	0.98	1.18	14.0	3.5
2	3	1.31	1.07	1.43	18.3	9.2
3	5	1.54	1.77	1.52	14.9	1.4
4	7	1.33	1.22	1.38	8.3	3.7
5	10	1.32	1.47	1.36	11.4	3.0
6	12	1.21	1.07	1.30	11.6	7.4
Average deviation (%)					12.9	4.1

in Fig. 19 and Fig. 20, respectively. It is observed from Fig. 19 that the theoretical values of water and glass temperature reasonably match with the experimental values and found that the maximum percentage of discrepancy is 5.8% over the experimental value, thus minimizing the deviation. It is seen from Fig. 20, during the early hours, theoretical value of hourly yield is higher than the experimental value. This is due to the gap time between the maximum solar intensity and maximum water temperature. In the noon and afternoon hours both theoretical and experimental values of hourly yield are almost same. In the evening hours, the experimental values of hourly yield are higher than the theoretical values. This is due to the release of stored energy by the saline water.

The total theoretical yield per day is calculated for both theoretical and Dunkle model ($C = 0.075$, $n = 0.33$) and compared in Table 5. The average temperature of water and glass at 9:00 o'clock and 17:00 o'clock is considered

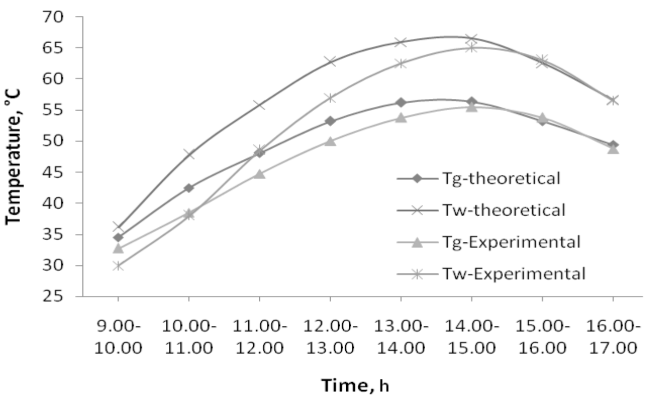

Fig. 19. Hourly variations of theoretical and experimental temperature of water and glass for 5 mm thick sponge liner.

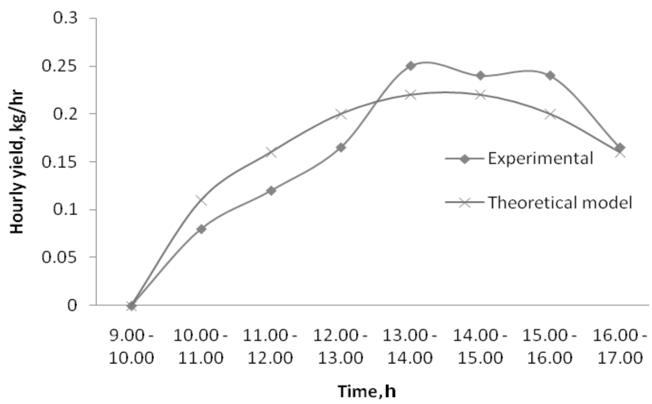

Fig. 20. Hourly variations of theoretical and experimental output for 5mm thick sponge liner.

for calculating night time productivity. It is seen that the theoretical model yield is very close to the experimental value and it is less than 5% discrepancy over the experimental yield for all the cases whereas the Dunkle model the discrepancy is very high. The following reasons can be attributed for the deviation observed between the theoretical and experimental results, (i) the glass cover absorption, reflection coefficients and water absorption coefficients are assumed to be constant throughout the day, (ii) the theory has not considered the condensate on the glass, which modifies the transmission coefficient, (iii) internal heat transfer coefficients especially evaporation heat transfer coefficient in solar stills are strongly temperature dependent.

It is understood from the present studies that there is a definite need for estimation of convection heat transfer coefficient for each type of solar still to predict their actual performances in field conditions. The values of convection and evaporation heat transfer coefficients differ for a particular condition and a particular model of solar still. Hence, use of any given standard value of *C* and *n* will result in erroneous results.

7. Conclusions

From the experimental studies, several conclusions obtained as follows:

- Sponge liner at the inner wall surfaces makes improvements in the solar still in many ways:
  - It reduces the operating temperature for the still components; it will increase the life of the components.
  - It works towards increasing the temperature difference between water and glass by reducing the temperature of glass.
  - It reduces the conduction heat losses from inner wall surfaces to outer wall surfaces by 50% and reduces its surface temperature by 24%.
  - The thicknesses of sponge liners influence the performance of the still.
  - The optimum thickness of the sponge liner on the inner wall surface is 5 mm, which has given 35.2% higher yield than the conventional still.
  - It has the advantage of using a low cost cheap material of sponge liner to enhance the still yield and its efficiency.

On the basis of analytical work carried out on the single slope passive solar still with sponge liner, the following conclusions can be drawn:

- The values of convection and evaporation heat transfer coefficients differ for a particular condition and a particular model of solar still.
- In order to predict the performance of solar still precisely, evaluation of *C* and *n* values are very essential.
- Evaporation heat transfer coefficients are too high; which will lead to reduce the output of the solar still by reducing the temperature difference between water and glass.
- The present studies prove that there is a definite need for estimation of convection heat transfer coefficient for each type of solar still to predict their actual performances in actual field conditions
- The internal heat transfer coefficients which are evaluated by thermal model have been found best suitable for theoretical model to get good agreement with experimental results.
- It is recommended that before predicting the performance parameters theoretically, an experiment must be carried out on a particular model of still for given climatic condition to evaluate the values of *C* and *n*.

The present studies that have been carried out can also be extended for the conventional solar still that includes:

- Studying the effect of sponge liner wickability on the solar still output.
- Studying the water depth in the sponge liner stills.

Symbols

A_b — Basin area, m^2
A_{bw} — Back wall area, m^2
A_g — Glass area, m^2
A_{sw} — Side wall area, m^2
A_w — Area of basin water, m^2
C — Convection correlation constant
C_p — Specific heat of the water vapor, kJ/kgK
C_w — Heat capacity of basin water, kJ/K
d_f — Average depth of air-vapour mixture, m
Gr — Grashof number
h_b — Convection heat transfer coefficient from basin liner to water, W/m^{2}K
h_{cg} — Convection heat transfer coefficient from glass to ambient W/m^{2}K
h_{cw} — Convection heat transfer coefficient from water to glass W/m^{2}K
h_{ew} — Evaporation heat transfer coefficient from water to glass W/m^{2}K
h_{fg} — Latent heat vapourization of water, kJ/kg
h_{rw} — Radiative heat transfer coefficient from water to –glass W/m^{2}K
h_{tw} — Total heat transfer coefficient from water to glass W/m^{2}K
I — Solar intensity, W
I_1 — Solar intensity falling on to the water surface after transmitting through glass, W
I_2 — Solar intensity falling on the basin liner after passing through the water mass, W
k_f — Thermal conductivity of the air vapour mixture at W/mK

K_{th} — Thermal conductivity of thermocol, W/mK
K_{wood} — Thermal conductivity of wood, W/mK
L_{th} — Thickness of thermocol, m
L_{wood} — Thickness of wood, m
m_w — Mass of distilled water collected, kg
n — Convection correlation constant
Nu — Nusselt number
P_g — Partial pressure of water vapour at the glass surface, N/m^2
Pr — Prantl number
P_w — Partial pressure of water vapour at the water surface, N/m^2
Q_{bot} — Conductive heat transfer from basin liner to ambient through bottom side, W
Q_b — Convection heat transfer from basin liner to water, W
Q_{cg} — Convection heat transfer from glass to ambient, W
Q_{cw} — Convection heat transfer from water to glass, W
Q_d — Amount of heat transfer utilized for converting fresh water, W
Q_{ew} — Evaporation heat transfer from water to glass, W
Q_{rg} — Radiation heat transfer from glass to ambient, W
Q_{rw} — Radiation heat transfer from water to glass, W
Ra — Rayleigh number
t — Time interval, sec
T_a — Ambient temperature, °C
T_b — Basin liner temperature, °C
T_{bwi} — Inside back wall temperature, °C
T_{bwo} — Outer back wall temperature, °C
T_f — Film temperature, °C
T_g — Glass temperature, °C
T_s — Sky temperature, °C
T_{swi} — Inside side wall temperature, °C
T_{swo} — Outer side wall temperature, °C
T_v — Vapour temperature, °C
T_w — Water temperature, °C
U_{bot} — Overall heat transfer coefficient between basin liner and ambient, W/m^2K

Greek

α_g — Radiation absorbtivity of glass
α_w — Radiation absorbtivity of water
β — Thermal expansion factor, K^{-1}
ΔT — Temperature difference between glass and water, °C
ε_g — Emissivity of glass
ε_w — Emissivity of water
ε_{eff} — Effective emissivity between water and glass
η_o — Overall efficiency
μ — Dynamic viscosity, $N\ s/m_2$
ρ — Density, kg/m^3
σ — Steffan Boltzmann constant, $W/m^2\ K^4$

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