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Validation of thermal models to predict the heat and mass transfer coefficients for indoor simulation

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ABSTRACT

The objective of this study is to predict the heat and mass transfer coefficients for indoor simulation of distillation unit with cooled condensing cover. The condensing cover was cooled externally in the range of 0.5–2.0°C during indoor experiment. A modified thermal model has been used along with other thermal models for wide range (35–85°C) of water temperature to predict the heat and mass transfer coefficients. The experimental yield has been found in better agreement with yield predicted using present thermal model in this study, with least percentage deviation of 10.7%. Further, the yield obtained in present design of distillation unit is about 165% higher than the yield obtained without cooled condensing cover. The evaporative fractional energy has also been increased.

Keywords: Indoor simulation; Heat and mass transfer coefficients; Fractional energy

1. Introduction

Many new designs of solar still have been studied by various researchers to increase the yield and efficiency. Numerous thermal models have been developed to evaluate the internal heat and mass transfer coefficients. These models have also been validated to predict the yield for different designs of solar stills, operating in different operating conditions. The relations are based on indoor experimental studies in steady state condition. The indoor operating condition can be:

1. Without cooled condensing cover [1–9].
2. With cooled condensing cover [5,8,10].

The most acceptable study has been carried out by Dunkle [1] in this regard within the horizontal enclosure of basin type solar still. He proposed the values for C and n as 0.075 and 0.33 respectively for $Gr > 3.2 \times 10^5$ (the C and n are the constants, used to calculate the value of convective heat transfer coefficient, expression is given in Eq.(2a)). However, the relation has its own limitations namely the thermo physical properties of moist air are taken at 50°C, the equivalent range of temperature difference between water and condensing surface is considered nearly 17°C, the evaporative and condensing surface are considered as parallel, which have been discussed by many researchers.

Chen et al. [2] proposed the simple correlation, which is based on free convective heat transfer in an enclosure and can be used in a wide range of Rayleigh number $\left(3.5 \times 10^3 < Ra < 10^6\right)$. Clark [3] made an attempt to find out heat and mass transfer rate for steady state condition in basin type solar still on for ideal condition and proposed the different values of C and n (C = 0.21, n = 1/4 for $10^4 < Gr$ 2.5×10^5 and C = 0.1255, n = 1/3 for $2.5 \times 10^5 < Gr$ 10^7). Based on previous studies, Adhikari et al. [10] developed correlation for estimating the mass transfer rate for double stacked tray solar still in air conditioned room after considering the

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influence of characteristic space but ignored the basic fact in the relation that the relationship between the evaporative and free convective heat transfer coefficients will change with temperature. The model can be used to predict the rate of distillate output. Tiwari and Lawrence [11] proposed effect of inclination of the condensing surface and spacing between the evaporating and condensing surfaces on an outdoor solar distillation unit. On the basis of indoor simulation, Shawaqfeh and Farid [4] developed modified model for predicting the heat and mass transfer coefficients and reported that Dunkle's model might over predict evaporation rates about 30% in outdoor simulation. Further, Tiwari et al. [5] developed a modified Nusselt number, precisely for a trapezoidal cavity, for evaluation of convective mass transfer in a solar distillation and validated the experimental results for water temperatures higher than 60°C. Later on Kumar and Tiwari [12] have developed a thermal model to determine convective mass transfer for different Grashof numbers for solar distillation on a passive and active distillation system for only summer climatic conditions. Tiwari and Tiwari [6] have carried out indoor simulation for different inclination (15°, 30° and 45°) of condensing cover in the temperature range of 40–80 °C to study heat and mass transfer.

In order to express accurately the evaporation rate in a basin type distillation unit, an attempt has been made to develop new thermal model (present model) to evaluate heat and mass transfer coefficients. The work is confined to a regression analysis, which is based on experimental observations obtained from indoor experimentation with ice cooled condensing cover. The indoor simulation in present work is carried out in the wide range of water temperature (35–85 °C) unlike other researcher's work [5,8] at 42°C, 48°C and 65.3 °C water temperatures. The temperature range of 35–85 °C is the working temperature range of passive and active solar still. To examine the validity of various thermal models, the predicted yields obtained using evaporative heat transfer coefficients evaluated from the present and other thermal model are validated with experimental yield. The best-fit model for present operating condition of distillation units has been discussed.

1.1. Significance of study

From the past research it is clear that more conclusive measurements are required for the accurate evaluation of the convective heat transfer correlation for higher operational temperatures, where the influence of thermophysical properties becomes noticeable. Here an attempt has been made to evaluate the predictive accuracy of the convective heat transfer coefficient. The first fundamental theoretical modeling of the complex phenomena of heat transfer in the solar still was developed by Dunkle almost four decades ago. Although it has been based on several simplified assumptions, and a accurate predictive tool for solar stills working under ordinary operating conditions but at higher temperature it fails. The aim of the present study is to relax the initially established simplified assumptions of the fundamental Dunkle's model and all others models to evaluate the comparative accuracy of heat transfer coefficients. The developed model has no limitation as all models like Dunkle, Chen and Adhikari models and also predict heat transfer coefficient more accurately at high operating temperature range, i.e., 35–85 °C.

The reason of keeping ice on the condensing surface is to study the heat and mass transfer in the solar still where the cold climatic condition exists like in Leh and Ladakh in India and also some places of Europe.

2. Experimental set-up

An indoor experiment was carried out to obtain the yield as a function of evaporation and condensing cover temperatures in steady state. The photograph of distillation unit is shown in Fig. 1. It consists of constant temperature bath of 40 L capacity with effective evaporative surface area of 320 × 250 mm. The condensing cover is inclined at 15°, which depends upon test requirements. The dimensions of double walled condensing chamber are given in Table 1.

The side walls of condensing chamber are made up of double wall of transparent acrylic sheet of 6 mm thickness. The condensing cover is single layered acrylic sheet. The condensing chamber placed at the top of constant temperature bath and has an opening to collect distillate. The four calibrated thermocouples are fixed at different surfaces to read the water temperature, inner and outer condensing cover temperature, and vapour temperature. These thermocouples

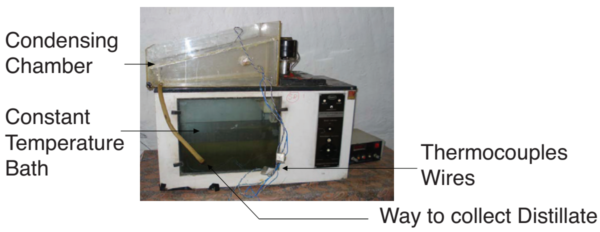

Fig. 1. Photograph of indoor distillation unit at 15° slope of the condensing cover.

Table 1
Linear dimensions of condensing chamber

SI. No.	Specification	Dimensions	
		Inner (m)	Outer (m)
1	Length	0.365	0.472
2	Lower Height	0.070	0.095
3	Higher height	0.185	0.237
4	Width	0.250	0.335

are attached to a digital temperature indicator having least count of 0.1 ºC. The water is heated by heating coils and the stirrer maintains the uniform temperature of water. The temperature control facilitates a desired temperature of water. The provision for putting the ice at the top of condensing cover and drainage for water, which comes out after melting of ice is also incorporated. The condensed water trickles down in the collecting trough fixed at lower side of condensing cover and taken outside through a pipe in the measuring jar of accuracy 0.1 g. The gasket is also used between the contact surface of condensing chamber and constant temperature water bath to prevent the leakage of water vapour outside.

3. Experimental procedure and observations

During experimentation, the constant temperature bath is filled with 40 L of water. Temperature of constant temperature bath is set at desired value. The water is heated by heating coils and a uniform temperature is maintained by stirrer. Ice blocks are kept above the outer surface of the condensing cover to maintain its temperature closer to freezing point of water. During the experimentation the average value of outer surface condensing cover temperature (T_{co}) and average value of temperature difference between the water and inner condensing cover (T_w–T_{ci}) are 1.7 ºC and 19.4 ºC respectively. The vapour temperature is measured at center position of sill cavity with assumption of constant vapour temperature throughout the still cavity.

The experiments have been performed at water temperature from 35 ºC to 85 ºC at intervals of 5 ºC in steady state conditions. The following parameters have been measured at a time interval of 10 min at uniform water temperature and 0.091 m^2 surface area:

- Water temperature.
- Temperature of vapour.
- Temperature of inner and outer condensing cover.
- Distillate yield.

The rigorous indoor experiments are carried out in the same operating condition and the observations are given in Table 2.

4. Thermal models

In the distillation unit the moist air above the water surface is freely convected (by natural convection) to the condensing cover by the action of a buoyancy force caused by density variation due to the difference in temperatures between the water surface and the condensing cover.

The general equation of convective heat transfer is given as

$$\dot{Q} = h_{cw}\, A(T_w - T_\infty) = h_{cw}\, A\Delta T \tag{1}$$

Table 2
Measured temperature and yield for 15° slope of cooled condensing cover for operating temperature range from 35–85 °C

Sl. No	Set temperature of bath, (°C)	Vapour temperature, T_v (°C)	Water temperature, T_w (°C)	Inner glass temperature, T_{ci} (°C)	Yield in 10 min, m_{ew} (kg)
1	35	27.3	36	20.2	0.0058
2	40	28.4	38.24	20.5	0.0068
3	345	31.5	42.5	23.6	0.0072
4	50	36.5	47.7	28.3	0.0100
5	55	40.4	53.4	34.2	0.0140
6	60	45.2	59.5	38.5	0.0180
7	65	53.2	66.7	43.2	0.0220
8	70	56.4	69.5	46.6	0.0270
9	75	62.7	75.5	55.3	0.0320
10	80	69.1	80.5	62.2	0.0380
11	85	75.1	86.5	69.6	0.0470

where h_{cw} is convective heat transfer coefficient, which dependents on the following parameters:

- Operating range of temperature.
- Geometry of condensing cover.
- Physical properties of the fluid with in operating temperature.

This convective heat transfer is calculated using the relation of non dimensional Nusselt number as

$$Nu = \frac{h_{cw} \cdot L_v}{K_v} = C\left(Gr\ Pr\right)^n \tag{2a}$$

or

$$h_{cw} = \frac{K_v}{L_v} \cdot C\left(Gr\ Pr\right)^n \tag{2b}$$

where $Gr = \frac{\beta g L_v{}^3 \rho^2 \Delta T}{\mu^2}$ and $Pr = \frac{\mu C_p}{K_v}$

where Gr and Pr are the Grashoff and Prandtl numbers, respectively, and C and n are unknown constants. The temperature dependent thermophysical properties of vapour used to evaluate Gr and Pr are given in Table 3.

The different values of C and n have been proposed by various researchers to establish the thermal models for their design and operating conditions of solar stills. Some of these models are listed in Section 4.1.

4.1. Dunkle's model (DM)

The most popular Dunkle's (1961) model to evaluate convective heat transfer coefficients (h_{cw}) is given as:

$$h_{cw} = 0.884\left(\Delta T\right)^{1/3} \tag{3a}$$

where $\Delta T = \left[T_w - T_{ci} + \frac{\left(P_w - P_{ci}\right)\left(T_w + 273\right)}{268.9 \times 10^3 - P_w}\right]$

Moreover, evaporative heat transfer coefficient (h_{ew}) [15] is determined as

$$h_{ew} = \frac{0.01623 \times h_{cw}\left(P_w - P_{ci}\right)}{T_w - T_{ci}} \tag{3b}$$

4.2. Chen et al. model (CM)

Chen et al. (1988) proposed a simple empirical correlation for convective heat transfer of the solar stills for wide range of Rayleigh number $\left(3.5 \times 10^3 < Ra < 10^6\right)$ and is given as

$$h_{cw} = 0.2\left(Ra\right)^{0.26} \frac{k_v}{L_v} \tag{4}$$

4.3. Adhikari et al. model (AM)

Adhikari et al. (1990) developed correlation for estimating the mass transfer rate for double stacked tray solar still after considering the influence of characteristic space in air conditioned room and is given as

Table 3
Temperature-dependent thermophysical properties of vapour [6]

Quantity	Symbol	Expression
Specific heat	C_p	$999.2 + 0.1434 \times T_v + 1.101 \times 10^{-4} \times T_v^2 - 6.7581 \times 10^{-8} \times T_v^3$
Density	ρ	$353.44/(T_v + 273.15)$
Thermal conductivity	K_v	$0.0244 + 0.7673 * 10^{-4} \times T_v$
Viscosity	μ	$1.718 \times 10^{-5} + 4.620 * 10^{-8} \times T_v$
Latent heat of vaporization of water	L	$3.1615 \times 10^6 \times [1-(7.616 \times 10^{-4} \times T_v)]$; for T_v<70 °C and $2.4935 \times 10^6 \times [1-9.4779 \times 10^{-4} T_v + 1.3132 \times 10^{-7} \times T_v^2 - 4.7974 \times 10^{-9} \times T_v^3]$; for T_v<70 °C
Partial saturated vapor pressure at condensing cover temperature	P_{ci}	$\mathrm{Exp}[25.317 - 5144/(T_{ci} + 273)]$
Partial saturated vapor pressure at water temperature	P_w	$\mathrm{Exp}[25.317 - 5144/(T_w + 273)]$
Expansion factor	β	$1/(T_v + 273.15)$
Derived by Tshilingiri's [13]		
Specific heat	C_p	$1.088022802-(0.010557758092) \times T_v+(4.7691105559 \times 10^{-4}) \times T_v^2-(7.898561559 \times 10^{-6}) \times T_v^3 + (5.122303796 \times 10^{-8}) \times T_v^4$
Density	ρ	$1.299995662-(6.043625845 \times 10^{-3}) \times T_v+(4.697926602 \times 10^{-5}) \times T_v^2-(5.760867827 \times 10^{-7}) \times T_v^3$
Thermal conductivity	K_v	$0.02416826077 + (5.526004579 \times 10^{-5}) \times T_v + (4.631207189 \times 10^{-7}) \times T_v^2-(9.489325324 \times 10^{-9}) \times T_v^3$
Viscosity	μ	$(1.685731754 \times 10 - 5) + (9.151853945 \times 10-8) \times T_v-2.1627622 \times 10^{-9}) \times T_v^2 + (3.4139222553 \times 10^{-11}) \times T_v^3-(2.644372665 \times 10^{-13}) \times T_v^4$

Table 4
Values of α for different operating temperature ranges [10]

Temperature (°C)	$\alpha \times 10^9$	
	$Gr < 2.51 \times 10^5$	$Gr > 2.51 \times 10^5$
40	8.1202	9.7798
60	8.1518	9.6707
80	8.1895	9.4936

$$\dot{m}_{ew} = \alpha (\Delta T)^n (P_w - P_{ci}) \tag{5}$$

The equation can be used to calculate evaporative and convective heat transfer coefficients by using Eq. (3). The values of n used in this correlation are suggested as follows:

$n = 1/3$ for $2.51 \times 10^5 < Gr < 10^7$
$n = 1/4$ for $10^4 < Gr < 2.51 \times 10^5$

The values of constant α for different basin water temperature and Grashof number are given in Table 4.

4.4. Kumar and Tiwari model (KTM)

Kumar and Tiwari [12] have given a model for calculating heat transfer coefficient more accurately for wider range of water temperature. The values of constant C and n are not fixed as in other models. The effects of solar still cavity, operating temperature range and orientation of condenser cover have been taken into account. The regression analysis based on experimental data are used to evaluate the C and n and explained in the section of present model.

In all the above models the following value of ΔT has been used during analysis.

$$\Delta T = \left[T_w - T_{ci} + \frac{(P_w - P_{ci})(T_w + 273)}{268.9 \times 10^3 - P_w} \right] \tag{6}$$

4.5. Present model (PM)

In this model, total pressure of binary mixture in the still cavity is considered as a function of temperature to evaluate Grashof number. The Grashof number (Gr') is given as:

$$Gr' = \frac{\beta g L_v^3 \rho^2 \Delta T'}{\mu^2} \tag{7a}$$

here

$$\Delta T' = \left[T_w - T_{ci} + \frac{(P_w - P_{ci})(T_w + 273)}{\dfrac{M_a \times P_t}{M_a - M_w} - P_w} \right] \tag{7b}$$

where in the present model the value of $\dfrac{M_a \times P_t}{M_a - M_w}$ in the expression of $\Delta T'$ is considered as temperature dependent rather than constant as considered by all other researchers.

The regression analysis used to evaluate the values of C and n using experimental data is as follows:

Using the Eq. (2b), (7a) and replacing the value of h_{cw} [12] in Eq. (3b) we get

$$h_{ew} = \frac{0.01623 \times \dfrac{K_v}{L_v} \cdot C (Gr' \,\mathrm{Pr})^n (P_w - P_{ci})}{T_w - T_{ci}} \tag{8}$$

The distillate yield from the distillation unit can be obtained as

$$m_{ew} = \frac{\dot{q}_{ew} A_w t}{L} \tag{9}$$

where

$$\dot{q}_{ew} = h_{ew} (T_w - T_{ci})$$

From the Eqs. (8) and (9) the yield obtained in time t [8,12] can be given as

$$m_{ew} = \frac{0.01623}{L} \times \frac{K_v}{L_v} \times (P_w - P_{ci}) \times A_w \times t \times C (Gr' \times Pr)^n \tag{10}$$

or

$$\frac{m_{ew}}{R} = C (Gr' \times Pr)^n \tag{11}$$

where

$$R = \frac{0.01623}{L} \times \frac{K_v}{L_v} \times (P_w - P_{ci}) \times A_w \times t$$

Taking the logarithm of Eq. (11) and comparing with equation of straight line ($y = mx + c$), one gets,

$$\ln\left(\frac{m_{ew}}{R}\right) = n \ln (Gr' \times Pr) + \ln (C) \tag{12}$$

$$y = \ln\left(\frac{m_{ew}}{R}\right), \; c = \ln(C), \; x = \ln(Gr' \times Pr) \text{ and } m = n$$

Using the linear regression analysis the coefficient C_o and m can be obtained as

$$m = \frac{N\left(\sum_{i=1}^{N} x_i y_i\right) - \left(\sum_{i=1}^{N} x_i\right)\left(\sum_{i=1}^{N} y_i\right)}{N\left(\sum_{i=1}^{N} x_i^2\right) - \left(\sum_{i=1}^{N} x_i\right)^2} \tag{13}$$

$$c = \frac{\left(\sum_{i=1}^{N} y_i\right)\left(\sum_{i=1}^{N} x_i^2\right) - \left(\sum_{i=1}^{N} x_i\right)\left(\sum_{i=1}^{N} x_i y_i\right)}{N\left(\sum_{i=1}^{N} x_i^2\right) - \left(\sum_{i=1}^{N} x_i\right)^2} \tag{14}$$

where N are the values of observations. After knowing the m and c the value of C and n can be calculated by the following expressions.

$$C = \exp(c) \qquad \text{and} \qquad n = m$$

4.6. PM-Ts model

In this model, the new correlations of thermophysical properties given by Tsilingiris [13] are used in the present model to calculate internal heat transfer coefficients.

5. Fractional heat transfer

The exchange of internal heat from the hot water surface to the condensing condensing cover cover is governed by evaporation, convection and radiation. The rate of heat transfer by radiation (q_{rw}), convection (q_{cw}) and evaporation (q_{cw}) within the distillation unit are expressed as

$$\dot{q}_{rw} = h_{rw}\left(T_w - T_{ci}\right) \tag{15a}$$

$$\dot{q}_{cw} = h_{cw}\left(T_w - T_{ci}\right) \tag{15b}$$

$$\dot{q}_{ew} = h_{ew}\left(T_w - T_{ci}\right) \tag{15c}$$

The total internal energy ($\dot{q}$) transfers from water surface to inner condensing cover can be expressed by adding the Eqs. (15a) to (15c);

$$\dot{q} = h_{1w}\left(T_w - T_{ci}\right) \tag{15d}$$

where h_{rw} is the radiative heat transfer coefficient between water and condensing cover is written as

$$h_{rw} = \varepsilon_{eff}\ \sigma\left(T_w^2 + T_{ci}^2\right) \times \left(T_w + T_{ci}\right) \tag{15e}$$

where $\varepsilon_{eff} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{ci}} - 1\right]^{-1} = 0.9$ between water and condensing cover.

The computed internal heat transfer coefficients, between water surface and condensing cover can be used to evaluate the total internal energy transfer. The relative influence of magnitudes in each one of three modes on total energy transferred inside the distillation unit can be expressed as fractional energy and given as

$$F_e = \frac{\dot{q}_{ew}}{\dot{q}}, \qquad F_c = \frac{\dot{q}_{cw}}{\dot{q}}, \qquad F_r = \frac{\dot{q}_{rw}}{\dot{q}} \tag{16}$$

6. Methodology

Various models, described above, have been used to calculate the internal heat and mass transfer coefficients using algorithm in MATLAB 7. The observed values of water temperature, vapour temperature, inner glass temperature and distillate yield are used as input. 100% relative humidity is assumed inside the distillation unit during computation. The following procedure is followed for computing the values of C, n, convective and evaporative heat transfer coefficients:

- Temperature dependent thermophysical properties is evaluated at water, inner glass cover and at vapour temperatures.
- With the help of evaluated values of physical properties of vapour, Grashof number (Gr) and Prandtl (Pr) are determined.
- Using regression analysis the values of m and C_o are evaluated.
- With the help of calculated values of m and C_o, values of n and C have been determined.
- With the help of calculated values of n and C, convective heat transfer and evaporative heat transfer coefficients are determined.
- Fractional heat transfers have been calculated by using Eqs. (15–16).
- The above steps have been repeated for a given water temperature for indoor simulation.

7. Results and discussion

The present thermal model has been developed to determine heat and mass transfer coefficients over the temperature range of 35–85°C using same analogy of regression as Kumar and Tiwari model. The values of constant C and n using Kumar and Tiwari model and present model have been summarized in Table 5. The ranges of the values of h_{cw}, h_{ew} and Gr, Pr are also given in same table. It is observed that a value of constant C almost remains about 1.0 for both the models for all temperature ranges. However, the values of constant n are

Table 5
Value of C, n, h_{cw} and h_{ew} obtained using Kumar and Tiwari model (KTM) and present model (PM) for the temperature range of 35–85 ºC

S. No.	Temperature range (ºC)	$Gr \times Pr$	Kumar and Tiwari model				Present model			
			C	n	h_{cw} (W/m² ºC)	h_{ew} (W/m² ºC)	C	n	h_{cw} (W/m² ºC)	h_{ew} (W/m² ºC)
1	35–45	$3817163 < Gr.Pr > 4568422$	1.00	0.20	$4.20 < h_{cw} > 4.41$	$14.68 < h_{ew} > 19.79$	1.00	0.17	$4.16 < h_{cw} > 4.45$	$14.52 < h_{ew} > 19.98$
2	35–55	$3817163 < Gr.Pr > 4831709$	1.00	0.20	$4.06 < h_{cw} > 4.42$	$14.20 < h_{ew} > 32.63$	1.00	0.17	$4.02 < h_{cw} > 4.47$	$14.04 < h_{ew} > 33.00$
3	35–65	$3817163 < Gr.Pr > 6354210$	1.01	0.19	$3.79 < h_{cw} > 4.49$	$13.23 < h_{ew} > 54.11$	1.00	0.16	$3.78 < h_{cw} > 4.35$	$13.21 < h_{ew} > 51.10$
4	35–75	$3817163 < Gr.Pr > 6328124$	1.02	0.19	$3.62 < h_{cw} > 4.39$	$12.66 < h_{ew} > 79.79$	1.00	0.16	$3.70 < h_{cw} > 4.26$	$12.93 < h_{ew} > 72.18$
5	35–85	$3817163 < Gr.Pr > 6790630$	1.02	0.19	$3.62 < h_{cw} > 4.60$	$12.65 < h_{ew} > 132.98$	1.02	0.16	$3.82 < h_{cw} > 4.39$	$13.34 < h_{ew} > 112.11$
6	45–85	$4568422 < Gr.Pr > 6790630$	1.00	0.19	$3.61 < h_{cw} > 4.37$	$16.21 < h_{ew} > 126.46$	1.02	0.16	$3.93 < h_{cw} > 4.22$	$17.2 < h_{ew} > 108.1$
7	55–85	$4831709 < Gr.Pr > 6790630$	1.00	0.18	$3.68 < h_{cw} > 4.29$	$27.16 < h_{ew} > 124.2$	1.02	0.16	$4.09 < h_{cw} > 4.24$	$30.23 < h_{ew} > 108.47$
8	65–85	$6354210 < Gr.Pr > 6790630$	1.00	0.18	$3.84 < h_{cw} > 4.11$	$46.28 < h_{ew} > 119.04$	1.02	0.16	$3.75 < h_{cw} > 4.13$	$49.8 < h_{ew} > 108.38$
9	75–85	$6328124 < Gr.Pr > 6790630$	1.00	0.19	$4.16 < h_{cw} > 4.35$	$75.61 < h_{ew} > 126.01$	1.01	0.17	$4.14 < h_{cw} > 4.39$	$79.67 < h_{ew} > 119.69$

lower using present model. The value of convective heat transfer increases about 14.9% from 3.82 to 4.39 W/m²ºC for an operating range of 35–85ºC, using present model, which is less than the values obtained using Kumar and Tiwari model (22.0% increase from 3.62–4.6 W/m²ºC). For the same temperature range the evaporative heat transfer coefficient increases by 739.6% from 13.34 to 112.11 W/m²ºC, which is less than obtained using Kumar and Tiwari model (951.1% increase from 12.65–132.98 W/m²ºC). It is also observed that if the span of temperature range is reduced, the increase in value of convective and evaporative heat transfer coefficients is also reduced.

Figs. 2a and 2b shows the variation of convective and evaporative heat transfer coefficients, respectively for the temperature range of 35–85ºC, obtained using various thermal models. The values of convective and evaporative heat transfer coefficients for Adhikari et al. model [AM] are highest than obtained by all other models throughout the temperature range. The lowest values are obtained from Chen et al. model [CM]. It is noticed that the values obtained using present model [PM] and present model with Tsilingiris vapour properties (PM-Ts), initially show increase in the value these coefficients with increase in water temperature from 35 to 65ºC and obtained between Adhikari et al. model [AM] and Kumar and Tiwari model [KTM]. Further, this trend reversed and these values of convective and evaporative heat transfer coefficients decrease with increase in water temperature from 65 to 85ºC and obtained between Kumar and Tiwari model [KTM] and Dunkle's model [DM]. It is due to decrease in value ofin Eq. (7b) because of comparative higher increase in the value of denominator term $\left(\dfrac{M_a \times P_t}{M_a - M_w} - P_w\right)$ in Eq. (7b).

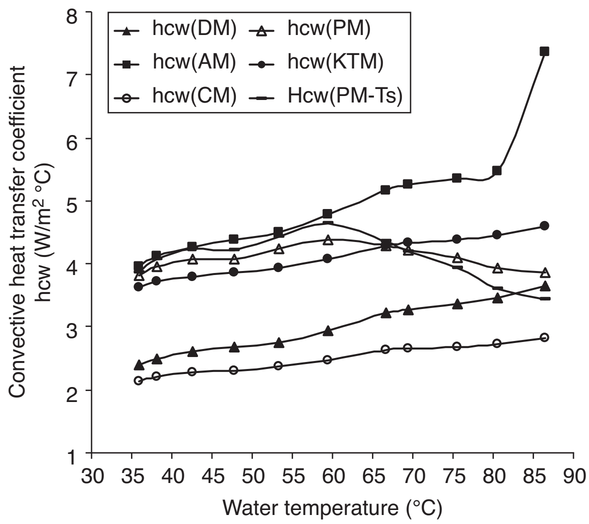

Fig. 2a. Variation of convective heat transfer coefficient (h_{cw}) within temperature range of 35–85ºC.

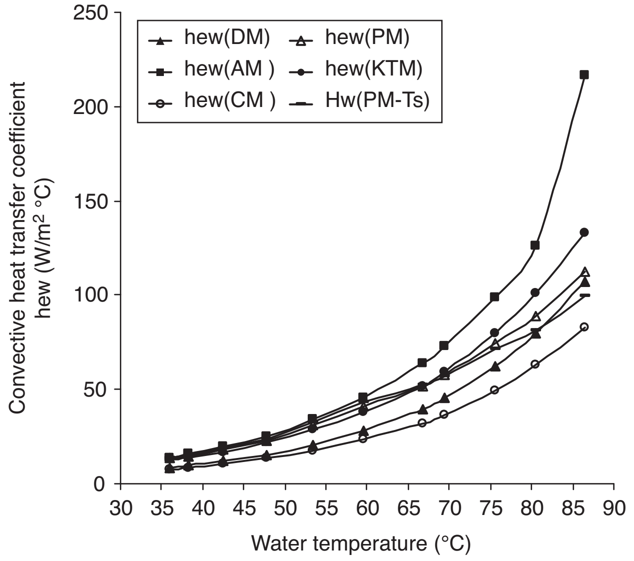

Fig. 2b. Variation of evaporative heat transfer coefficient (h_{ew}) within temperature range of 35–85°C.

At low temperature range of 35–55°C it is observed that AM, PM and KTM predict almost no deviation of evaporative heat transfer coefficient but deviation increases at higher temperatures. The convective and evaporative heat transfer coefficients obtained using present thermal model are between the values predicted by Adhikari et al. model and Kumar and Tiwari model up to 70°C but at higher temperature range the values of coefficients are between Kumar and Tiwari model and Dunkle's model.

The predicted yield is obtained using value of h_{ew} evaluated from respective thermal model and using Eq. (9) for known experimental values of water and inner glass cover temperatures. The predicted distillate yield using various thermal models show the same trends as obtained experimentally. The distillate yields predicted using Adhikari et al. model [AM] are much higher than the experimental yield at most of the temperature ranges. Moreover, Dunkle's (DM) and Chen et al. model (CM) under predict the yield. The accuracy of curve fitting of various models has been checked using correlation coefficient and root mean square percentage deviation as a statistical tool. It has been observed that value of correlation coefficient in the model is almost 0.99 for all span of temperature range. Lowest deviation of 11.0 % has been noticed in the yield predicted by Adhikari et al. model [AM] at low temperature range of 35–55°C. The Kumar and Tiwari model [KTM] predicts the yield with least deviation of 6.25% in the temperature range of 65–85°C, while Dunkle's model (DM) in the range of 75–85°C with deviation of 7.6%. Highest deviation in the predicted yield has been noticed using Chen et al. model [CM] for all temperature ranges. It has been found that the predicted yields are in close agreement with experimental yield with least percentage deviation of 10.7% in wide range of water temperature, 35–85°C using present model [PM] along with thermophysical properties [6] as depicted in Fig. 3.

Fig. 4 shows the relative influence of each one of three modes on total energy transferred within the distillation unit evaluated using the Eq. (16). The computed internal heat transfer coefficients using present model have been used for the two operating conditions (with and without cooled condensing cover) of distillation unit for respective temperature range. The values of convective, radiative, and evaporative energy fraction, lies in the range of 0.17–0.03, 0.21–0.07 and 0.5–0.9 respectively in the distillation unit with cooled condensing cover. It is also noticed that convective and evaporative fraction

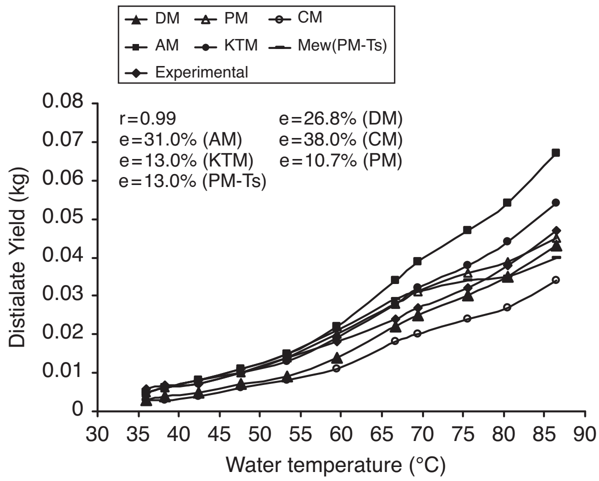

Fig. 3. Variation of distillate yield for different heat transfer models within temperature range of 35–85°C.

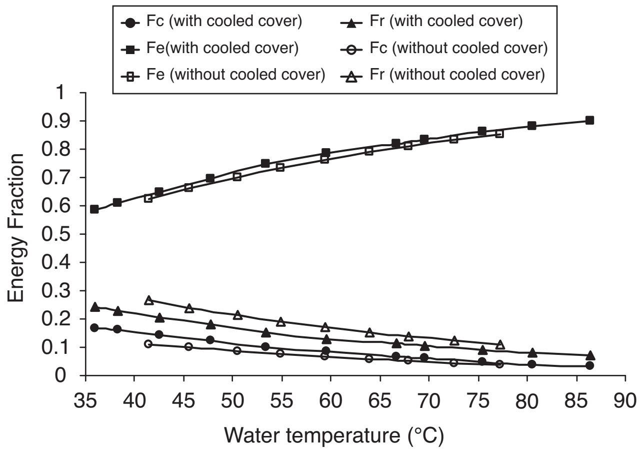

Fig. 4. Influence of energy fractions (*Fr*, *Fc* and *Fe*) within temperature range of 35–85°C for the cooled and without cooled condensing cover of solar still.

increases while radiative fraction decreases as compared with the distillation unit operating without cooled condensing cover and the results are in accordance with Cooper [14]. The higher the evaporative energy fraction higher will be distillate yield and hence energy efficiency of the distillation unit with cooled condensing cover will be increased.

8. Conclusions

On the basis of present studies the following conclusions are drawn:

- The convective and evaporative heat transfer coefficients obtained using present thermal model are between the values predicted by Adhikari et al. model and Kumar and Tiwari model up to 70°C and between Kumar and Tiwari model and Dunkle's model for higher temperature range.
- The present model better predict the distillate yield and is closer to the experimental yield with least percentage deviation of 10.7% over the wide temperature range of 35–85°C.
- The distillate yield increases almost by 165.0% when using cooled condensing cover rather than without cooled condensing cover.
- The convective and evaporative energy fractions of distillation unit with cooled condensing cover are higher than without cooled condensing cover.

Symbols

L — Length of condensing cover, (m)
A_w — Surface area, m^2
C — Unknown constant in the Nusselt number expression
F_{cw} — Convective fractional energy
F_{ew} — Evaporative fractional energy
F_{rw} — Radiative fractional energy
Gr — Grashof number
h_{cw} — Convective heat transfer coefficient from water to condensing cover, W/m^2°C
h_{ew} — Evaporative heat transfer coefficient from water to condensing cover, W/m^2°C
h_{rw} — Radiative heat transfer coefficient from water to condensing cover, W/m^2°C
K_v — Thermal conductivity of the humid air, W/m°C
h_{1w} — Total internal heat transfer coefficient, W/m^2°C
L — Latent heat of vaporization of water, J/kg
L_v — Characteristic dimension of condensing cover, m
n — Unknown constant in the Nusselt number expression
m_{ew} — Distillate Yield, kg
Nu — Nusselt number
P_{ci} — Partial saturated vapour pressure at condensing cover temperature, N/m^2
P_w — Partial saturated vapour pressure at water temperature, N/m^2
P_t — Total partial vapour pressure i.e. Partial saturated vapour pressure at condensing cover temperature and Partial saturated vapour pressure at water temperature, N/m^2
Pr — Prandtl number
$\dot{q}$ — Total heat transfer rate from water surface to condensing cover, W/m^2
$\dot{q}_{cw}$ — Rate of convective heat transfer, W/m^2
$\dot{q}_{ew}$ — Rate of evaporative heat transfer, W/m^2
$\dot{q}_{rw}$ — Rate of radiative heat transfer, W/m^2
$\dot{Q}$ — Rate of heat transfer by convection, W
Ra — Rayleigh number
t — Time interval, s
T_{ci} — Inner temperature of condensing cover, °C
T_{co} — Outer temperature of condensing cover, °C
T_w — Water temperature, °C

Greek

β — Coefficient of volumetric thermal expansion, K^{-1}

ρ — Density of humid air, kg/m^3

μ — Dynamic viscosity of humid air, N.s/m^2

$\dot{q}_{cw}$— Temperature difference, °C

σ — Stefan Boltzman constant (5.67 × 10^{-8} W/m^2 K^4)

ε — Emissivity (0.9)

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