

SIMULATION OF CONVECTIVE MASS TRANSFER IN A SOLAR DISTILLATION PROCESS

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Abstract—In this communication, an attempt has been made to develop a modified Nusselt number for a trapezoidal cavity, which can be used for evaluation of convective mass transfer in a solar distillation process. The modified expression has been obtained by regression analysis using experimental data and from simulations for different environment conditions. It is observed that there is a reasonable agreement between experimental observations and theoretical results calculated by the modified Nusselt number expression for a higher operating temperature range ($\geq 60^\circ\text{C}$).

Heat transfer Convection process Distillation

NOMENCLATURE

- C = Constant
 C_p = Specific heat capacity of humid air ($\text{J kg}^{-1} \text{K}^{-1}$)
 $\bar{x} = d_f$ = Average spacing between water surface and glass cover (m)
 g = Acceleration due to gravity (ms^{-2})
 Gr = Grashoff number
 h_{cw} = Convective heat transfer coefficient from water surface to glass cover ($\text{W/m}^2/\text{k}$)
 h_{ew} = Evaporation heat transfer coefficient from water surface to glass cover ($\text{W/m}^2/\text{k}$)
 h_{rw} = Radiative heat transfer coefficient from water surface to glass cover ($\text{W/m}^2/\text{k}$)
 K = Constant
 K_r = Thermal conductivity of humid air (W/m/k)
 L = Latent heat of humid air (J/kg)
 \dot{M}_w = Mass of distillate ($\text{kg/m}^2/\text{h}$)
 n = Constant
 P_s = Pressure of air in still (N/m^2)
 P_G = Saturated vapour pressure of water at T_G (N/m^2)
 P_w = Saturated vapour pressure of water at T_w (N/m^2)
 Pr = Prandtl number
 \dot{q}_{cw} = Convective heat transfer rate from water to glass surface (W/m^2)
 \dot{q}_{ew} = Evaporative heat transfer rate from water to glass surface (W/m^2)
 Ra = Rayleigh number
 T_a = Ambient temperature ($^\circ\text{C}$)
 T_s = Average outer glass cover temperature ($^\circ\text{C}$)
 T_G = Average inner glass temperature ($^\circ\text{C}$)
 T_v = Water vapour temperature ($^\circ\text{C}$)
 T_w = Temperature of water ($^\circ\text{C}$)
 $\Delta T'$ = Temperature difference $T_G - T_s$, ($^\circ\text{C}$)

Greek letters

- α_0 = Thermal diffusivity of humid air ($\text{m}^2 \text{s}^{-1}$)
 β = Inclination of glass cover with horizontal (degree)
 β' = Expansion factor
 μ = Dynamic viscosity of humid air (N.S/m^2)
 ν = Kinematic viscosity (m^2/s)
 ρ = Density of humid air (kg/m^3)

INTRODUCTION

The performance prediction of a solar distillation unit mainly depends on an accurate estimation of the basic internal heat and mass transfer relations. Dunkle [1] derived a semi-empirical relation for internal heat and mass transfer in solar distillation units, generally known as Dunkle's relation. Based on Dunkle's relation, a number of solar stills with different geometry have been analyzed by various workers [2]. The following are basic limitations of Dunkle's relation:

- (i) It is valid for cavities that have parallel condensing and evaporative surfaces.
- (ii) It is independent of the cavity volume, i.e. the distance between the condensing and evaporative surface.
- (iii) It is valid for a low operating temperature range (45–50°C).

Spalding [3] also proposed a theory for evaluating mass transfer based on Reynolds' flow model in a solar distillation unit, generally known as the Spalding mass transfer theory. Clark [4] developed a model for a higher operating temperature range ($\geq 55^\circ\text{C}$) in a simulated condition for small inclinations of the condensing surface ($\beta \leq 15^\circ$). Clark [4] has observed that the coefficient of convective mass transfer becomes half that given by Dunkle. This is also based on the fact that the rate of evaporation is equal to the rate of condensation in steady state conditions. This condition is achieved by using a fan across the condensing cover, which is not possible in the operation of a normal solar distillation system.

In this communication, the convective mass transfer has been evaluated by a modified Nusselt number by considering the effects of inclination and cavity volume. The modified Nusselt number has been obtained by regression analysis using experimental data. The experimental results have also been compared with theoretical results obtained by the proposed modified relation for evaluating the convective mass transfer for a higher operating temperature range ($\geq 60^\circ\text{C}$). The accuracy of the results is within 10%.

EXPERIMENTAL SETUP FOR SIMULATION

A constant temperature bath filled with water (having a capacity of 40 litres) was used as a basin for the distillation unit. The temperature range of the bath was from 5°C above room temperature to 120°C (least count temperature was 0.1°C). The steady state temperature and heating of water was controlled by an electronic control panel.

Three condensing chambers were made of PVC sheets with glass as the condensing surface. The chambers were double walled on three sides with air inside the 3 cm thick cavity between the two PVC surfaces, which acts as an air insulation. The hollow base of the condensing chamber is the same size as the constant temperature bath opening, and it can be placed over it to form an air tight enclosure. Channels have been made along the length and the breadth of the condensing chamber in order to collect the condensate. The inclination of the glass cover with the horizontal (β) and the average cavity volume height (\bar{x}) of the three condensing chambers were as follows:

- (a) Condensing chamber 1: = 7.3° , $\bar{x} = 15.5$ cm
- (b) Condensing chamber 2: = 14.3° , $\bar{x} = 16.5$ cm
- (c) Condensing chamber 3: = 14.3° , $\bar{x} = 24.0$ cm

Copper-constantan thermocouples are used, along with a digital temperature indicator, to record the glass temperature, water temperature and water vapour temperature in the experimental setup. These thermocouples, over a prolonged usage period, tend to deviate from the actual temperature. Therefore, they were calibrated with respect to a standard thermometer.

The glass cover (condensing surface for water vapour) is 3 mm thick. In order to conduct the heat released by the condensing water (latent heat) from the inner surface of the glass to the outer surface, a temperature gradient exists across the thickness of the glass. Therefore, the inner and outer temperatures of the glass cover are not equal, the inner temperature being higher. The average inner (T_G) and outer (T_g) glass cover temperatures have been obtained in steady state conditions. The temperature differences obtained experimentally, as well as theoretically, match with each other within an accuracy of 5%. In our experiment, it was possible to record the outer glass temperature

only. This was changed to the average inner glass temperature by using the previously obtained steady state values for the inner and outer glass temperatures. A view of the condensing chamber and a photograph of the experimental setup are shown in Figs 1 and 2, respectively [14].

EXPERIMENTAL OBSERVATIONS

Observations were taken for steady state water temperatures (maintained in the constant temperature bath) of 40°C, 60°C and 80°C. The temperature of the condensing surface (glass cover) was varied by changing the atmospheric conditions as described below:

- (i) The glass cover was exposed to an atmosphere of normal condition. The windows and door were kept open and the fans switched off.
- (ii) The glass cover was exposed to an atmosphere in which an air conditioner was used. In this case, the windows and door of the room were closed and the air conditioner switched on.
- (iii) The glass cover was entirely covered with ice to get a very low temperature of the condensing surface.

For each set of observations, the experiment was repeated 15 times, and the average values of temperature and distillate output were considered for computation and comparisons. Each set of experiments was repeated three to four times for confirming the consistency of distillate output.

The experimental observations for the different water temperatures for the different condensing chambers under different environmental conditions were taken. Three samples of the set of observations, out of the 13 sets of observations, are being given, along with the calculated experimental and theoretical distillate outputs, h_{tw} , h_{cw} , h_{ew} and the percentage deviation between experimental and theoretical distillate outputs.

- (i) Water temperature 46°C and ice on top of condensing surface for condensing chamber 1 (Tables 1 and 2).

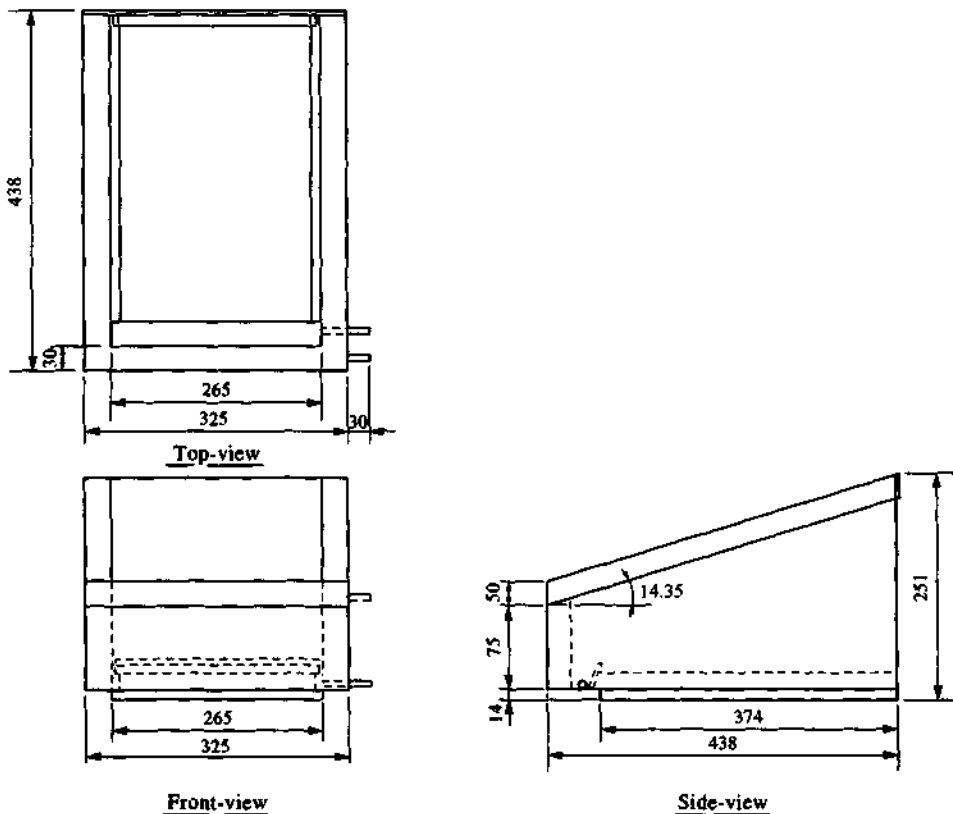


Fig. 1. Views of the condensing chamber.



Fig. 2. Photograph of the experimental setup.

- (ii) Water temperature 63°C and condensing surface exposed to normal atmosphere without treatment for condensing chamber 2 (Tables 3 and 4).
- (iii) Water temperature 83°C and condensing surface exposed to normal atmosphere without treatment for condensing chamber 1 (Tables 5 and 6).

EVALUATION OF CONVECTIVE AND EVAPORATIVE MASS TRANSFER

Convective heat transfer coefficient

Heat transfer occurs across humid air inside the enclosure of a solar distillation unit by free convection, which is caused by the action of the buoyancy force due to density variation in the humid air. Further, the density variation exists due to the temperature gradient in the fluid. Hence,

Table 1. Water temperature 46°C and ice on top of condensing surface for condensing chamber 1

Sl. No.	Time	Water temp. $T_w(^{\circ}\text{C})$	Outer glass temp. $T_g(^{\circ}\text{C})$	Vapour temp. $T_v(^{\circ}\text{C})$	Ambient temp. $T_a(^{\circ}\text{C})$	Distillate output $m_w(\text{ml})$	$\dot{M}_w \text{kg/m}^2\text{-hr}$
1.	9.30 a.m.-						
	10.00 a.m.	46	10.0	29.0	27	32	0.64
2.	10.30 a.m.	46	9.8	29.0	27	32	0.64
3.	11.00 a.m.	46	10.0	28.6	27	32	0.64
4.	11.30 a.m.	46	10.0	29.2	27	32	0.64
5.	12.00 noon	46	9.8	29.0	27	32	0.64
6.	12.30 p.m.	46	10.0	29.0	27	32	0.64
7.	1.00 p.m.	46	10.0	28.6	27	32	0.64
8.	1.30 p.m.	46	9.8	28.8	27	33	0.66
9.	2.00 p.m.	46	10.0	28.8	27	32	0.64
10.	2.30 p.m.	46	10.0	28.6	27	33	0.66
11.	3.00 p.m.	46	9.8	29.0	27	33	0.66
12.	3.30 p.m.	46	10.0	24.0	27	32	0.64
13.	4.00 p.m.	46	9.8	29.0	27	32	0.64
14.	4.30 p.m.	46	10.0	28.6	27	32	0.64
15.	5.00 p.m.	46	10.0	29.0	27	32	0.64

Table 2. Theoretical and experimental distillate output, h_{rw} , h_{cw} and h_{cw} under ice on condensing surface for $T_w = 48^\circ\text{C}$ and $T_G = 12^\circ\text{C}$ for condensing chamber 1 ($\beta = 7.8^\circ$, $\bar{x} = 0.155$ m)

Sl. No.	Reference	Experimental distillate output in $\text{kg/m}^2\cdot\text{h}$	Theoretical distillate output in $\text{kg/m}^2\cdot\text{h}$	h_{rw} $\text{W/m}^2\cdot^\circ\text{C}$	h_{cw} $\text{W/m}^2\cdot^\circ\text{C}$	h_{cw} $\text{W/m}^2\cdot^\circ\text{C}$	Percentage deviation between experimental and theoretical distillate output (%)
1.	Dunkle model	0.64	0.65	6.85	3.03	15.58	1.5
2.	Tiwari and Lawrence model	0.64	0.53	6.85	2.47	12.67	-17.2
3.	Proposed model	0.64	0.65	6.85	3.03	15.56	1.5
4.	Inaba model	0.64	0.64	6.85	2.99	15.38	0
5.	Lam <i>et al.</i> model	0.64	0.58	6.85	2.69	13.84	-9

Table 3. Water temperature 63°C and condensing surface exposed to normal atmosphere without treatment for condensing chamber 2

Sl. No.	Time	Water temp. T_w ($^\circ\text{C}$)	Outer glass temp. T_g ($^\circ\text{C}$)	Vapour temp. T_v ($^\circ\text{C}$)	Ambient temp. T_a ($^\circ\text{C}$)	Distillate output m_w (ml)	\dot{M}_w $\text{kg/m}^2\cdot\text{h}$
1.	9.30 a.m.-						
	10.00 a.m.	63	46.2	56.0	28	26	0.52
2.	10.30 a.m.	63	46.4	56.2	28	27	0.54
3.	11.00 a.m.	63	46.0	56.4	29	27	0.54
4.	11.30 a.m.	63	46.2	56.4	29	26	0.52
5.	12.00 noon	63	46.0	56.6	30	27	0.54
6.	12.30 p.m.	63	46.0	56.4	30	27	0.54
7.	1.00 p.m.	63	46.2	56.2	30	26	0.52
8.	1.30 p.m.	63	46.0	56.4	30	27	0.54
9.	2.00 p.m.	63	46.2	56.2	40	26	0.52
10.	2.30 p.m.	63	46.0	56.0	30	27	0.54
11.	3.00 p.m.	63	46.0	56.4	30	27	0.54
12.	3.30 p.m.	63	46.0	56.2	29	27	0.54
13.	4.00 p.m.	63	46.2	56.2	29	26	0.52
14.	4.30 p.m.	63	46.0	56.2	29	27	0.54
15.	5.00 p.m.	63	46.0	56.4	29	26	0.52

the rate of heat transfer from the water surface to the glass cover (\dot{q}_{cw}) by convection in the upward direction through humid fluid can be estimated by

$$\dot{q}_{cw} = h_{cw}(T_w - T_G), \quad (1)$$

where h_{cw} is found from the relation

$$N_u = \frac{h_{cw} \cdot d_f}{k_f} = C[\text{Gr.Pr.}]^n \quad (2)$$

Table 4. Theoretical and experimental distillate output, h_{rw} , h_{cw} and h_{cw} under normal conditions for $T_w = 63^\circ\text{C}$ and $T_G = 48^\circ\text{C}$ for condensing chamber 2 ($\beta = 14.35^\circ$, $\bar{x} = 0.165$ m)

Sl. No.	Reference	Experimental distillate output in $\text{kg/m}^2\cdot\text{h}$	Theoretical distillate output in $\text{kg/m}^2\cdot\text{h}$	h_{rw} $\text{W/m}^2\cdot^\circ\text{C}$	h_{cw} $\text{W/m}^2\cdot^\circ\text{C}$	h_{cw} $\text{W/m}^2\cdot^\circ\text{C}$	Percentage deviation between experimental and theoretical distillate output (%)
1.	Dunkle model	0.54	0.76	7.24	2.65	33.09	40.7
2.	Tiwari and Lawrence model	0.54	0.63	7.24	2.19	27.37	16.7
3.	Proposed model	0.54	0.75	7.24	2.64	32.92	38.9
4.	Inaba model	0.54	0.74	7.24	2.61	32.50	37.0
5.	Lam <i>et al.</i> model	0.54	0.69	7.24	2.43	30.33	27.8

Table 5. Water temperature 83°C and condensing surface exposed to normal atmosphere without treatment for condensing chamber I

Sl. No.	Time	Water temp. $T_w(^{\circ}\text{C})$	Outer glass temp. $T_g(^{\circ}\text{C})$	Vapour temp. $T_v(^{\circ}\text{C})$	Ambient temp. $T_a(^{\circ}\text{C})$	Distillate output $m_w(\text{ml})$	$\dot{M}_w \text{kg/m}^2 \cdot \text{h}$
1.	9.30 a.m. - 10.00 a.m.	83	62.0	76.3	29	69	1.38
2.	10.30 a.m.	83	62.4	75.9	29	68	1.36
3.	11.00 a.m.	83	62.8	76.5	30	66	1.32
4.	11.30 a.m.	83	63.0	76.3	30	66	1.32
5.	12.00 noon	83	64.0	75.5	30	65	1.30
6.	12.30 p.m.	83	63.6	75.6	30	66	1.32
7.	1.00 p.m.	83	63.5	75.7	31	66	1.32
8.	1.30 p.m.	83	64.0	75.7	31	66	1.32
9.	2.00 p.m.	83	63.4	77.0	31	66	1.32
10.	2.30 p.m.	83	63.4	76.7	31	66	1.32
11.	3.00 p.m.	85	64.1	75.3	31	68	1.36
12.	3.30 p.m.	85	64.4	75.3	31	65	1.30
13.	4.00 p.m.	83	63.5	75.8	30	66	1.32
14.	4.30 p.m.	83	63.9	75.7	30	66	1.32
15.	5.00 p.m.	83	63.4	75.8	30	65	1.30

where

$$\text{Pr} = \frac{\mu C_p}{k_f} \quad (3)$$

$$\text{Gr} = \frac{g \beta' \rho^2 (d_i)^3 (\Delta T')}{\mu^2} \quad (4)$$

The effective temperature difference

$$(\Delta T') = (T_w - T_G) + \left[\frac{(P_w - P_G)(T_w + 273)}{268.9 \times 10^3 - P_w} \right] \quad (5)$$

From equation (2) it is seen that the value of h_{cw} depends upon the value of the two constants C and n . Various researchers have given different values of C and n for different Grashoff number ranges [5, 8–10].

Dunkle [1] has taken the value of $C = 0.075$ and $n = 1/3$ for $\text{Gr} \geq 4.39 \times 10^5$ for average spacing $d_i \geq 0.25$ m, and the expression for h_{cw} is given as:

$$h_{cw} = 0.884 \left[(T_w - T_G) + \frac{(P_w - P_G)(T_w + 273)}{(268.9 \times 10^3 - P_w)} \right]^{1/3} \quad (6)$$

To calculate the Grashoff number, the physical properties of humid air are needed, which are based on standard equations. These properties, with the respective expressions and references, are given in Table 7.

Table 6. Theoretical and experimental distillate output, h_w , h_{cw} and h_{ew} under normal conditions for $T_w = 83^{\circ}\text{C}$ and $T_G = 67.5^{\circ}\text{C}$ for condensing chamber I ($\beta = 7.3^{\circ}$, $\bar{x} = 0.155$ m)

Sl. No.	Reference	Experimental distillate output in $\text{kg/m}^2 \cdot \text{h}$	Theoretical distillate output in $\text{kg/m}^2 \cdot \text{h}$	h_w $\text{W/m}^2 \cdot ^{\circ}\text{C}$	h_{cw} $\text{W/m}^2 \cdot ^{\circ}\text{C}$	h_{ew} $\text{W/m}^2 \cdot ^{\circ}\text{C}$	Percentage deviation between experimental and theoretical distillate output (%)
1.	Dunkle model	1.32	1.97	8.62	3.13	81.53	49
2.	Tiwari and Lawrence model	1.32	1.63	8.62	2.59	67.54	31
3.	Proposed model	1.32	1.97	8.62	3.12	81.42	49
4.	Inaba model	1.32	1.95	8.62	3.09	80.66	47
5.	Lam <i>et al.</i> model	1.32	1.81	8.62	2.87	74.72	37

Table 7. Physical properties of humid air as function of temperature

Physical constants	Units	Expressions $T_i(^{\circ}\text{C}) = (T_w + T_G)/2$	
		Toyama <i>et al.</i> [11]	Mahdi (1990)
Specific heat capacity (C_p)	J/Kg $^{\circ}$ K	$999.2 + 0.1434 T_i + 1.101 \times 10^{-4} T_i^2 - 6.758 \times 10^{-8} T_i^3$	$(1.00324 + 6.76 \times 10^{-5} T_i) \times 10^3$
Thermal conductivity (K_t)	W/ $^{\circ}$ K	$0.0244 + 0.7673 \times 10^{-4} T_i$	$(2.4172 + 7.580 \times 10^{-3} T_i) \times 10^{-2}$
Viscosity (μ)	N:S/m 2	$1.718 \times 10^{-5} + 4.62 \times 10^{-8} T_i$	$(1.7205 + 4.564 \times 10^{-3} T_i) \times 10^{-5}$
Diffusivity (α_0)	m 2 /S	$7.7255 \times 10^{-10} \times (T_i + 273)^{1.83}$	$7.6105 \times 10^{-4} - 1.0149 \times 10^{-5} T_i + 4.4015 \times 10^{-8} T_i^2 - (2998 \times 10^{-2}/T_i^2) + (9.8086 \times 10^{-3} T_i)$
Density (ρ)	Kg/m 3	$353.44/(T_i + 273.15)$	$1.2923 - 4.514 \times 10^{-3} T_i + 1.0583 \times 10^{-5} T_i^2$
Expansion factor (β')	0_K^{-1}	$1/(T_i + 273.15)$ (standard)	$1/(T_i + 273.15)$
Acceleration due to gravity (g)	m/s 2	9.81 (standard)	9.81

Evaporative heat-transfer coefficient

The rate of heat transfer per unit area from the water surface to the glass cover can be written as

$$\dot{q}_{ew} = 0.013h_{ew}(P_w - P_G). \quad (7)$$

The value of the constant in equation (7), used by Dunkle, is 0.016273.

Further, equation (7) can be re-arranged as

$$\dot{q}_{ew} = h_{ew}(T_w - T_G). \quad (8)$$

Here, h_{ew} is the evaporative heat transfer coefficient and is given by

$$h_{ew} = 0.016273h_{cw} \frac{(P_w - P_G)}{(T_w - T_G)}. \quad (9)$$

The value of the saturated vapour pressure of water in N/m 2 is given by the expression:

$$P = 6893.0 \times \exp\{54.63 - 12301.6 \times T_0^{-1} - 5.17 \log_e T_0\} \quad (10)$$

where $T_0 = 1.8T(^{\circ}\text{C}) + 491.69$.

This equation is valid for the temperature range of 10–90 $^{\circ}$ C and is given by Brooker *et al.* [15]. P can also be taken from the Steam Tables.

EVALUATION OF DISTILLATE

The hourly distillate output per m 2 from a solar distillation unit can be obtained as

$$\begin{aligned} \dot{M}_w &= \frac{\dot{q}_{ew} \times 3600}{L} \\ &= \frac{h_{ew} \times (T_w - T_G) \times 3600}{L}, \end{aligned} \quad (11)$$

where L = latent heat of humid air in J/kg and is given by the expression:

$$L = 3.1615 \times 10^6 [1 - 7.6166 \times 10^{-4} T_w] \text{ J/kg}, \quad (12)$$

where T_w is in K, and L can also be taken from the steam tables.

IMPROVED EXPRESSIONS FOR CONVECTIVE HEAT TRANSFER COEFFICIENT

Tiwari and Lawrence expression [6]

The convective heat transfer coefficient has been given for parallel water and glass surfaces, which are inclined to the horizontal surface to receive maximum solar radiation.

The Nusselt number is

$$Nu = \frac{h_{cw} \cdot d_f}{K_f} = 1 + 1.44 \left[1 - \frac{1708}{Ra \cos \beta} \right]^+ \times \left[1 - \frac{\sin(1.8\beta^{1.6} 1708)}{Ra \cos \beta} \right] + \left[\left(\frac{Ra \cos \beta}{5830} \right)^{1/3} - 1 \right]^+ \quad (13)$$

In writing equation (13), the following assumptions have been made:

- (i) The meaning of the “+” exponent is that only positive values of the term in the square brackets are to be used, otherwise it is zero for negative values.
- (ii) It is valid for all solar stills having inclinations between 0 and 75°.
- (iii) Water vapour behaves as an ideal gas.
- (iv) The cavity volume is saturated.

Hideo inaba expression [12]

This study deals with the thermal natural convection motion and heat transfer rate in an inclined narrow rectangular cavity filled with air, whose two opposing isothermal walls are separated by a width, and maintained at different temperatures in the wide range of inclination angles from the horizontal (heated from below).

Various aspect ratios (width to mean height of rectangular cavity) = 5 to 83.

$$Ra = 1.2 \times 10^3 \text{ to } 2 \times 10^6$$

$$\beta = 0-60^\circ$$

$$Nu = \frac{h_{cw} \cdot d_f}{K_f} = 0.0785(Ra \cos \beta)^{0.330} \quad (14)$$

Lam et al. expression [13]

Natural convection heat transfer has been studied experimentally and numerically for horizontal prismatic cavities of trapezoidal section having a hot horizontal base, a cool inclined top, and insulated vertical walls. Experimental results are presented for an aspect ratio ≥ 4 , Rayleigh number (based on the mean cavity height) from 10^3 to 10^7 and β from 0 to 25°. $\beta_{max} = 25^\circ$.

$$Nu = \frac{h_{cw} \cdot d_f}{K_f} = 0.168 \left[\frac{Ra(1 + \cos \beta)}{2} \right]^{0.278} \times \left[\frac{(1 - \cos \beta_{max})}{(\cos \beta - \cos \beta_{max})} \right]^{-0.199} \quad (15)$$

Proposed expression

The following model has been proposed for determination of h_{cw} in a trapezoidal air cavity of a solar distillation unit.

$$Nu = \frac{h_{cw} \cdot d_f}{K_f} = 0.075 \left[\frac{Ra(1 + \cos \beta)}{2} \right]^{1/3} \quad (16)$$

Aspect ratio: 2 to 10. For

$$Ra > 3.0 \times 10^5$$

$$0^\circ \leq \beta < 90^\circ.$$

In the proposed model, the effect of inclination of the condensing surface (glass cover) is considered by introducing a factor $(1 + \cos \beta)/2$.

Considering equation (16), for extreme values of the inclination of the glass cover:

- (i) When $\beta = 0^\circ$, $\cos \beta = 1$, then equation (16) reduces to Dunkle's expression.
- (ii) When $\beta = 90^\circ$, $\cos \beta = 0$, this implies that there are two parallel vertical surfaces of infinite length. Then, half of the vapours will condense on each of the vertical surfaces, and we will get half of the maximum possible distillate output.

CONCLUSIONS AND RECOMMENDATIONS

(a) The experimental observations (Tables 1–6) for the distillate output at various operating temperatures (steady state water temperature) do not match the theoretically obtained distillate outputs for the higher operating temperature range ($\geq 60^\circ\text{C}$), calculated using Dunkle's and the proposed model. The expressions for Nusselt number, as given by the two models, are as follows:

$$\text{Dunkle model: } Nu = C(Ra)^n$$

$$C = 0.075, \quad n = 1/3 \quad \text{For } Ra \geq 3.0 \times 10^5.$$

$$\text{Proposed model: } Nu = C \left[\frac{Ra(1 + \cos \beta)}{2} \right]^n$$

$$C = 0.075, \quad n = 1/3 \quad \text{for } Ra \geq 3.0 \times 10^5.$$

Hence, there is a need for modification of the models by using appropriate values of the two constants "C" and "n" to give closer results to experimental observations.

(b) The percentage deviation of the theoretical results computed by the various models from the experimental observations is minimum for a condensing surface with ice on top of it.

For the average inner glass temperature (T_G) varying from 12 to 22°C and the operating temperature of water varying from 40 to 80°C , the new modified expression for Nusselt number is

$$Nu = 0.0718 \left[\frac{Ra(1 + \cos \beta)}{2} \right]^{0.328} \quad \text{for } Ra \geq 3 \times 10^5 \text{ and aspect ratio 2 to 10.}$$

(c) The percentage deviation of the theoretical results computed by the various models increases with the increase of operating temperature range ($60\text{--}80^\circ\text{C}$) significantly in all environment conditions for any design of condensing chamber.

Therefore, for the environment temperature around the condensing chamber varying from 20 to 30°C and the steady state water temperature varying from 60 to 80°C , the new modified expression for Nusselt number is

$$Nu = 0.4178 \left[\frac{Ra(1 + \cos \beta)}{2} \right]^{0.2106} \quad \text{for } Ra \geq 3 \times 10^5 \text{ and aspect ratio 2 to 10.}$$

The new constants "C" and "n" have been obtained by regression analysis (given in the Appendix) using experimental data. The percentage deviation (using the obtained expression) between the experimental and theoretical distillate output is within 10%.

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APPENDIX

The percentage deviation between the theoretical and experimental distillate outputs is greater than 10%, and hence, there is a need to modify the value of constants "C" and "n" in the expression $Nu = C(Ra)^n$ from which h_{cw} is obtained. This modification, using experimental distillate output \dot{M}_w , is done as follows:

$$Nu = C(Ra)^n \quad (A1)$$

$$Nu = \frac{h_{cw} d_f}{K_f} = C(Ra)^n, \quad (A2)$$

$$\therefore h_{cw} = \frac{K_f}{d_f} C(Ra)^n, \text{ from equation (A2)}. \quad (A3)$$

Now

$$\dot{q}_{cw} = 0.016273(P_w - P_G) \cdot h_{cw}, \quad (A4)$$

$$\therefore \dot{q}_{cw} = 0.016273(P_w - P_G) \frac{K_f}{d_f} C(Ra)^n, \text{ from equation (A4)}. \quad (A5)$$

Also

$$\dot{M}_w = \frac{\dot{q}_{cw} \times 3600}{L}, \quad (A6)$$

$$\therefore \dot{M}_w = 0.016273(P_w - P_G) \times \frac{K_f}{d_f} \times \frac{3600}{L} \times C(Ra)^n, \text{ from equation (A6)}. \quad (A7)$$

Now,

$$K = 0.016273(P_w - P_G) \times \frac{K_f}{d_f} \times \frac{3600}{L}. \quad (A8)$$

K is a constant for a given steady state value of T_w and T_G .

$$\therefore \dot{M}_w = KC(Ra)^n \quad (A9)$$

or

$$\frac{\dot{M}_w}{K} = C(Ra)^n. \quad (A10)$$

Now, for different operating conditions, the steady state values of T_w and T_G vary and the corresponding \dot{M}_w and Ra for these conditions vary. Therefore, we get different values for \dot{M}_w and Ra from the experimental data. Equation (A10) can be written as

$$Y = aX^b \quad (A11)$$

where

$$Y = \frac{\dot{M}_w}{K}, X = Ra, a = C, \text{ and } b = n.$$

Taking the log on both sides of equation (A11)

$$\ln Y = \ln a + b \ln X \quad (A12)$$

which can be written as

$$Y_1 = a_1 + b_1 X_1, \quad (A13)$$

where $Y_1 = \ln Y$, $a_1 = \ln a$, $b_1 = b$ and $X_1 = \ln X$.

We obtain various values for Y_1 and X_1 for the different values of \dot{M}_w and Ra obtained from the experimental data.

To determine a_1 and b_1 , we use regression analysis, and their values are given by the following expressions:

$$b_1 = \frac{N(\sum X_1 Y_1) - (\sum X_1)(\sum Y_1)}{N\sum X_1^2 - (\sum X_1)^2}$$

$$a_1 = \frac{\sum Y_1}{N} - b_1 \frac{\sum X_1}{N},$$

where N is the number of experimental data sets used ($N \geq 6$).