ANALYTICAL THERMAL MODELLING OF DOUBLE SLOPE SOLAR STILL BY USING INNER GLASS COVER TEMPERATURE

by

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In this paper, expressions for water and glass temperatures, hourly yield and instantaneous efficiency for double slope solar distillation systems have been derived analytically. The analysis is based on the basic energy balance for the systems. A thermal model has been developed to predict the performance of the still based on both, the inner and the outer glass temperatures of the solar still. In the present work two sets of values of C and n of internal heat and mass transfer coefficients, obtained from the experimental data under Indian climatic conditions, have been used. It is concluded that (1) there is a significant effect of operating temperature range on the internal heat transfer coefficients and (2) by considering the inner glass cover temperature there is reasonable agreement between the experimental and predicted theoretical results.

Key words: *solar distillation, solar energy, purification of brackish/saline water*

Introduction

Water and energy are two inseparable items that govern our lives and promote civilization. Looking to the history of mankind one finds that water and civilization were also two inseparable entities. It is not a coincidence that all great civilizations were developed and flourished near large bodies of water. Rivers, seas, oases, and oceans have attracted mankind to their coasts because water is the source of life. The transportation of drinking water from far-off regions is usually not economically feasible/desirable, desalination of available brackish water has been considered as an alternative approach. Conventional desalination processes based on distillation involve phase change. These are multistage flash distillation (MSF), multieffect distillation (MED), and vapor compression (VC), which could be thermal (TVC) or mechanical (MVC). MSF and MED processes consist of a set of stages at successfully decreasing temperature and pressure. MSF process is based on the generation of vapors from seawater or brine due to a sudden pressure reduction when seawater enters to an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure. This process requires an external steam supply, normally at temperature around 100 C. The maximum temperature is limited by the salt concentration to avoid scaling and this maximum limits the performance of the process. On MED, vapors are generated due to the absorption of thermal energy by the seawater. The steam generated in one stage or effect is able to heat the salt solution in the next stage because next stage is at lower temperature and pressure. The performance of the process is proportional to stages or effects. MED plants normally use an external steam supply at temperature about 70 C. On TVC and MVC, after initial vapor is generated from the saline solution, this vapor is thermally or mechanically compressed to generate additional production. On the other hand the membrane processes such as reverse osmosis (RO) and electro-dialysis (ED) do not involve phase change. The first one require electricity or shaft power to drive the pump that increase the pressure of saline solution to that required. This required pressure depends on the salt concentration of the resource of saline solution, which is normally around 70 bar for sea water desalination. Both of them RO and ED (membrane processes) are used for brackish water desalination whereas distillation is applicable to the entire range of salinities up to seawater. In fact it is the only process, which removes with certainty any organisms (bacteria and viruses) contained in feed water. Theoretically distillation is capable of removing all non-volatile matter. In practice, however, some carryover of dissolved and colloidal matter into the distillate may take place. End product purity expressed in specific conductivity is between 4.0 and 0.066 µg/cm at 25 °C, depending upon the technique used.

Since the cost of heat plays a decisive role in various distillation processes, *viz.*, single stage, multistage distillation, flash distillation, and vapor compression distillation; it seems advantageous to harness the heat of the sun for this purpose. Over a period of hundred years several types of solar stills have been designed and tested. There has been a significant progress in the field of solar distillation during the past four decades, perhaps, due to the general increase of interest in solar energy utilization. Because of cost free energy and low operating cost, as there are no moving parts involved in these systems, the solar distillation shows a comfortable economic advantage over other seawater distillation processes. Further, solar distillation requires simple technology and less maintenance so that it can be used at any rural place. Thus, in order to capture this very advantage of distillation process, cost effective solar stills have been designed and developed. And they have proved their performance and cost effectiveness.

Heat and mass transfer relationships for a conventional basin type solar still have been analysed and discussed by Dunkle [1]. For a given ambient temperature and water temperature of still, the heat balance equations are solved by using trial and error method to calculate the glass cover temperature. Thus the rate of heat transfer by convection, evaporation, and radiation is obtained. It has been concluded that the productivity of the still can be improved considerably by increasing the water temperature (*e. g.*, by increasing irradiation from a reflector). Löf *et al.* [2] have analysed heat and mass transfer in a solar still in detail and studied the effects of various design parameters and climatic variables on the performance. Numerical solutions of the heat balance equations were obtained with the aid of a digital computer. Morse *et al*. [3] included the thermal capacity of the system and accordingly carried out a transient analysis. They have expressed the various heat fluxes as the functions of the glass cover temperature. Thus the glass temperature has been obtained by a graphical solution. Kumar *et al*. [4] has done thermal and computer modelling for determining heat and mass transfer coefficients namely C and n for different type of solar still. Sharma *et al*. [5] developed a method for estimation of heat transfer coefficients, upward heat flow and evaporation in still. Calculation of hourly output was done with a new approach. It was observed that the performance of solar still has an agreement with the result of an analysis based on Dunkle's relation with a factor of 0.65 to account for unsaturation. Nawayseh [6] obtained the heat and mass transfer coefficients in solar desalination on the basis of humidification process. Shruti *et al*. [7] developed the convective mass transfer relation for new type solar still namely double condensing chamber. In relation $\mathrm{Nu} = C(\mathrm{GrPr})^n$, the values of C and n were determined using regression analysis for different temperature ranges. It was found that the values of C and n proposed by Dunkle are valid only for lower temperature ranges, however for higher temperature ranges the values of C and n change. Shruti *et al.* [8] found that a wide variation of about 47% is observed between experimental and theoretical values of distillate output based on the values of internal heat and mass transfer relations obtained by using outer glass cover temperatures as determined by Dunkle and other scientists. Shukla *et al.* [9] have recently developed a model, based on regression analysis, to determine the values of

C and n using the experimental data obtained from the stills. This method uses both inner and outer glass cover temperatures to determine the expressions for internal heat transfer coefficients and does not impose any limitations.

In this paper, analytical expressions for various parameters have been derived for double slope solar stills. Experimental validation has also been carried out by using following measured climatic parameters:
– solar intensity on the glass cover,
– solar intensity on collector panel, and
– ambient air temperature.

Modified values of C and n, obtained from using the experimental data on the solar stills located at Allahabad Agricultural Institute-Deemed University, Allahabad, India, have been used in this model. The proposed model predicts the theoretical values of water temperature, glass temperature, and the yield at hourly intervals with respect to inner and outer glass temperatures, respectively. The calculated results are compared with the experimental data. Very close agreements between the theoretical predictions and experimental results have been observed on using the values of C and n based on the inner glass temperature.

Experimental setup

Figure 1 show the photograph of a double slope solar still. To intercept the maximum insolation, the still was oriented in the east-west direction. A frame was fixed at the middle of the still using which the glass covers on either side were kept at an inclination of 15°. Basin has an effective area of 2 m^2 and glass of area 1150×1040 mm is used as glazing. A distillate channel was provided at each end of the basin. For the collection of distillate output, a hole was drilled in each of the channels and plastic pipes were fixed through them with adhesive (araldite) to make an outlet for the distilled water. To feed the saline water in the basin and to drain the water from still for cleaning purpose an inlet pipe and outlet pipe was provided at the top of the side wall of the still and at the bottom of the basin tray, respectively. Rubber gaskets were fixed all along the edges of the still. The glass panes of 3 mm thickness were used as covers for the still.

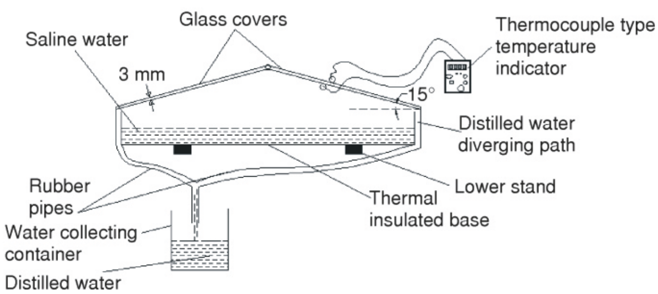

Figure 1. Photograph and schematic diagram of a double slope solar still

Experiments were performed on solar still during the months of January 2007 and May 2007 for several days, but the observations presented in tabs. 1, 2, 3, and 4 represent a typical winter day and a typical summer day, namely, January 19, 2007 and May 10, 2007, respectively. The sunshine hour is one hour more in summer climatic conditions than in winter. The experimental data are used to obtain the internal heat and mass transfer coefficients for double slope solar still as given in tab. 3.

Table 1. Experimental observations for double slope solar still (East and West) on January 19th, 2007

Slope No.	Time [h]	Intensity of solar radiation [W/m^2] (East)	Intensity of solar radiation [W/m^2] (West)	Water temperature [°C] (East)	Water temperature [°C] (West)	Inner glass temperature [°C] (East)	Inner glass temperature [°C] (West)	Outer glas temperature [°C] (East)	Outer glas temperature [°C] (West)	Distillate output [kg/m^2] (East)	Distillate outpu [kg/m^2] (West)	Ambient temperature [°C]
1	10:00	370	300	32.1	30.1	29.1	27.7	26.9	27.3	0.035	0.057	11.0
2	11:00	400	350	41.8	35.8	35.2	30.1	34.1	29.7	0.040	0.068	11.5
3	12:00	450	450	44.5	36.5	39.8	30.7	36.7	29.9	0.118	0.118	14.0
4	13:00	500	550	49.7	49.7	40.6	39.5	39.5	35.5	0.167	0.187	16.5
5	14:00	550	590	59.2	46.9	55.2	38.7	47.9	35.0	0.200	0.210	17.0
6	15:00	450	500	44.3	44.3	36.1	36.5	35.2	34.2	0.200	0.200	18.0
7	16:00	350	400	40.0	40.2	34.2	34.4	33.4	31.4	0.190	0.160	18.0
8	17:00	100	250	39.8	38.8	32.1	31.1	30.6	29.6	0.180	0.150	17.0

Table 2. Experimental observations for double slope solar still (East and West) on May 10th, 2007

Slope No.	Time [h]	Intensity of solar radiation [W/m^2] (East)	Intensity of solar radiation [W/m^2] (West)	Water temperature [°C] (East)	Water temperature [°C] (West)	Inner glass temperature [°C] (East)	Inner glass temperature [°C] (West)	Outer glas temperature [°C] (East)	Outer glas temperature [°C] (West)	Distillate output [kg/m^2] (East)	Distillate outpu [kg/m^2] (West)	Ambient temperature [°C]
1	10:00	440	430	45.2	42.2	40.2	33.7	38.3	30.3	0.100	0.100	32.0
2	11:00	740	630	64.3	65.1	53.9	53.9	47.2	44.2	0.150	0.150	34.0
3	12:00	760	780	69.3	70.3	56.3	56.3	50.3	50.3	0.210	0.210	37.6
4	13:00	620	730	77.2	78.2	60.2	67.2	56.2	57.2	0.280	0.240	38.8
5	14:00	600	670	82.5	82.1	66.3	71.3	62.3	61.3	0.280	0.270	37.9
6	15:00	550	600	76.7	76.2	62.9	64.9	55.4	53.4	0.260	0.260	39.0
7	16:00	400	460	72.9	71.5	59.2	61.2	52.3	50.3	0.180	0.180	40.2
8	17:00	300	300	66.2	65.2	49.3	56.3	48.2	47.2	0.170	0.170	40.0
9	18:00	180	220	58.3	57.3	47.2	50.2	44.1	43.1	0.160	0.160	39.0

Table 3. *C* and *n* values of internal heat transfer coefficients for double slope solar still

Date	Double slope solar still (East)				Double slope solar still (West)			
	With inner glass temperature		With outer glass temperature		With inner glass temperature		With outer glass temperature	
	C	*n*	*C*	*n*	*C*	*n*	*C*	*n*
January 19, 2007	0.066	0.34	0.069	0.54	0.077	0.33	0.068	0.44
May 10, 2007	0.074	0.33	0.088	0.57	0.078	0.38	0.097	0.58

Experimental uncertainty

The experimental method used is an indirect approach for estimating the convective heat transfer coefficient based on the mass of distillate collected from still. It will therefore have a considerable degree of experimental uncertainty. An estimation of uncertainty [10] has been carried out separately for passive and active solar stills. Data of a particular measurement for a number of days have been taken and an estimate of individual uncertainties of the sample values has been calculated. An estimate of internal uncertainty (U_{i}) has then been found by:

$$U_{\mathrm{i}} \quad \sqrt{\frac{\Sigma\sigma_i^2}{N^2}}$$

where σ_i are the standard deviations of each sample and N is the total number of samples.

Table 4. Sample calculations of experimental uncertainties in May 2007 for double slope solar still

Serial No.	Time [h]	May 10, Output [kg/m^{2}h]	May 11, Output [kg/m^{2}h]	May 12, Output [kg/m^{2}h]	May 13, Output [kg/m^{2}h]	May 14, Output [kg/m^{2}h]
1	10:00	0.2	0.2	0.2	0.22	0.20
2	11:00	0.25	0.25	0.26	0.28	0.26
3	12:00	0.30	0.31	0.32	0.34	0.35
4	13:00	0.30	0.40	0.42	0.40	0.46
5	14:00	0.52	0.53	0.54	0.55	0.56
6	15:00	0.34	0.34	0.35	0.35	0.36
7	16:00	0.30	0.30	0.30	0.32	0.32
8	17:00	0.22	0.22	0.25	0.25	0.26
Total	18:00	0.20	0.20	0.20	0.20	0.22
Average	–	0.292	0.305	0.315	0.323	0.332
Standard deviation	(σ)	0.093	0.101	0.103	0.100	0.110

$$U_{\mathrm{i}} \quad \sqrt{\frac{\Sigma\sigma_{1\ 5}^{2}}{N^{2}}} \quad \frac{\sqrt{0.052}}{5} \quad \frac{0.225}{5} \quad 0.046$$

% Uncertainty = 0.046 ×100/0.313 = 14.7%.

External uncertainties have been measured out by taking the least count of the measuring instruments. The total uncertainty for double slope solar stills has been calculated as 15-20%. The results will be also influenced by the thermal storage effect. The percentage error caused by thermal storage can be calculated as:

$$\%\ \text{Error} \quad \frac{\text{distillate output during non} - \text{sunshine hours}}{\text{distillate output during daylight hours}} 100$$

The errors due to thermal storage effect for still has been estimated to be 1-2%.

Mathematical models

In order to write the energy balance equations, the following assumptions were made:
- the heat capacity of insulating material and tray has been neglected,
- there is no temperature gradient along water depth and glass cover thickness,
- the system is in a quasi-steady-state condition,
- the side losses from tray have been neglected due to small water depth,
- inclination of glass cover is small, and
- the solar distiller unit is vapor leakage proof.

East glass cover

$$\alpha_{\mathrm{g}} A_{\mathrm{g}} I_{\mathrm{E}} \quad h_{1\,\mathrm{wE}} (T_{\mathrm{w}} \quad T_{\mathrm{gE}}) \quad h_{2\mathrm{g}} (T_{\mathrm{gE}} \quad T_{\mathrm{a}}) A_{\mathrm{g}} \tag{1}$$

where $h_{1\mathrm{wE}} = h_{\mathrm{cwE}} + h_{\mathrm{ewE}} + h_{\mathrm{rwE}}$

West glass cover

$$\alpha_{\mathrm{g}} A_{\mathrm{g}} I_{\mathrm{w}} \quad h_{1\,\mathrm{wW}} (T_{w} \quad T_{\mathrm{gW}}) A_{\mathrm{g}} \quad h_{2\mathrm{g}} (T_{\mathrm{gw}} \quad T_{\mathrm{a}}) A_{\mathrm{g}} \tag{2}$$

$$h_{1\,\mathrm{wW}} \quad h_{\mathrm{cwW}} \quad h_{\mathrm{ewW}} \quad h_{\mathrm{rwW}}$$

Water mass

$$\begin{aligned} &\alpha_{\mathrm{w}} A_{\mathrm{b}} (I_{\mathrm{E}} \quad I_{\mathrm{W}}) \quad h_3 (T_{\mathrm{b}} \quad T_{\mathrm{W}}) A_{\mathrm{b}} \\ (MC)_{\mathrm{W}} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} A_{\mathrm{b}} \quad &h_{1\,\mathrm{wE}} (T_{\mathrm{w}} \quad T_{\mathrm{gE}}) A_{\mathrm{g}} \quad h_{1\,\mathrm{wW}} (T_{\mathrm{w}} \quad T_{\mathrm{gW}}) A_{\mathrm{g}} \end{aligned} \tag{3}$$

Basin liner

$$\alpha_{\mathrm{b}} A_{\mathrm{b}} (I_{\mathrm{E}} \quad I_{\mathrm{W}}) \quad h_3 (T_{\mathrm{b}} \quad T_{\mathrm{w}}) A_{\mathrm{b}} \quad h_{\mathrm{b}} (T_{\mathrm{b}} \quad T_{\mathrm{a}}) A_{\mathrm{b}} \tag{4}$$

The values of T_{gE}, T_{gW}, and T_{b} were substituted form eqs. (1), (2), and (4) into water mass equation, eq. (3). The expression for T_{gE} and T_{gW} from eqs. (1) and (2) are obtained as follows:

$$T_{\mathrm{gE}} \quad \frac{\alpha_{\mathrm{g}} I_{\mathrm{E}} \quad h_{1\,\mathrm{wE}} T_{\mathrm{W}} \quad h_{2\mathrm{g}} T_{\mathrm{a}}}{h_{2\mathrm{g}} \quad h_{1\,\mathrm{wE}}} \tag{5}$$

$$T_{\mathrm{gW}} \quad \frac{\alpha_{\mathrm{g}} I_{\mathrm{w}} \quad h_{1\,\mathrm{wW}} T_{\mathrm{W}} \quad h_{2\mathrm{g}} T_{\mathrm{a}}}{h_{2\mathrm{g}} \quad h_{1\,\mathrm{wW}}} \tag{6}$$

On substituting values of east and west glass temperature in eq. (3) along with the T_{b} from eq. (4), water mass equation reduces into following form:

$$\frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} \quad aT_{\mathrm{w}} \quad \mathrm{f}(t) \tag{7}$$

where, a and f(t) have expressions as:

$$a \quad \frac{U_{\mathrm{L}}}{(MC)_{\mathrm{w}}}$$

$$\mathrm{f}(t) \quad \frac{(\alpha\tau)_{\mathrm{eff}} A_{\mathrm{g}} (I_{\mathrm{E}} \quad I_{\mathrm{W}}) \quad U_{\mathrm{L}} T_{\mathrm{a}}}{(MC)_{\mathrm{w}}}$$

The other expressions are given by:

$$(\alpha\tau)_{\mathrm{eff}} \quad \alpha_{\mathrm{b}} \frac{h_3}{h_3 \quad h_{\mathrm{b}}} \quad \alpha_{\mathrm{w}} \quad \alpha_{\mathrm{g}} \frac{h_{1\,\mathrm{wE}}}{h_{1\,\mathrm{wE}} \quad h_{2\mathrm{g}}}$$

$$U_{\mathrm{L}} = U_{\mathrm{b}} + U_{\mathrm{t}}$$

$$U_{\mathrm{b}} \quad \frac{hh_{\mathrm{b}}}{h_3 \quad h_{\mathrm{b}}}$$

$$U_{\mathrm{t}} \quad \frac{h_{1\mathrm{wE}} h_{2\mathrm{g}}}{h_{1\,\mathrm{wE}} \quad h_{2\mathrm{g}}}$$

In order to solve eq. (7), the following assumptions have been made:

– f(t) has been considered as constant, $\overline{\mathrm{f}(t)}$ over the time interval 0 – t, and
– a has also been considered constant over the same time interval 0 – t.

The solution of eq. (7) for the initial condition that at time $t = 0$, $T_{\mathrm{w}} = T_{\mathrm{w0}}$, and T_{gE} ($t = 0$) = = T_{gE0} is given by:

$$T_{\mathrm{w}} \quad \frac{\overline{\mathrm{f}(t)}}{a}[1 \quad \mathrm{e}^{\quad at}] \quad T_{\mathrm{w0}}\mathrm{e}^{\quad at} \tag{8}$$

Values of T_{w} and T_{g} calculated at the end of a time interval become the initial condition for the next set of numerical computations, and so on.

To evaluate rate theoretically, following expression for east and west condensing covers have been used:

$$\dot{M}_{\mathrm{E}} \quad 0.0163(P_{\mathrm{w}} \quad P_{\mathrm{gE}})\frac{K}{d}\frac{3600}{l} C_{\mathrm{E}} (\mathrm{Gr\,Pr})^{n_{\mathrm{E}}} \tag{9}$$

$$\dot{M}_{\mathrm{w}} \quad 0.0163(P_{\mathrm{w}} \quad P_{\mathrm{gW}})\frac{k}{d}\frac{3600}{l} C_{\mathrm{W}} (\mathrm{GrPr})^{n_{\mathrm{W}}} \tag{10}$$

Internal heat transfer coefficients

Computer programs have been developed in *C* language to predict the hourly variations of water temperature, glass temperature, distillate output, and the various heat transfer coefficients of solar still. This model takes the modified values of convective heat transfer coefficients for both inner and outer glass temperatures and carries out the computation of all performance parameters. It then compares them with the experimental data and finally brings out the percentage deviation between the experimental and theoretical results.

Methodology for evaluating C and n

The rate of heat transfer from the water surface to glass cover by convection (q_{cw}) in the upward direction through a humid fluid is given by the equation:

$$q_{cw} = h_{cw}(T_w - T_g) \tag{11}$$

The coefficient h_{cw} can be determined from the relation:

$$\mathrm{Nu} = \frac{h_{cw} d_f}{K_f} = C(\mathrm{Gr\,Pr})^n \tag{12}$$

Malik *et. al*. [2] have assumed that water vapour obeys the perfect gas equation and have given the expression for evaporative heat transfer rate (q_{ew}) as:

$$q_{ew} = 0.0163 h_{ew}(P_W - P_g) \tag{13}$$

Equation (13) combined with eq. (11) can be written as:

$$q_{ew} = 0.0163(P_W - P_g) \frac{K_f}{d_f} C(\mathrm{Ra})^n \tag{14}$$

where Ra = GrPr is Rayleigh number.

Further, the rate of distillate output is evaluated by:

$$\dot{m}_{ew} = \frac{q_{ew}}{l} 3600 \tag{15}$$

Equation (15) after substituting q_{ew} from eq. (14) becomes:

$$\dot{m}_{ew} = 0.0163(P_W - P_g) \frac{K_f}{d_f} \frac{3600}{l} C(\mathrm{Ra})^n \tag{16}$$

The above equation can be rewritten as

$$\dot{m}_{ew} = RC(\mathrm{Ra})^n \tag{17}$$

or

$$\frac{\dot{m}_{ew}}{R} = C(\mathrm{Ra})^n \tag{18}$$

where

$$R = 0.0163(P_W - P_g) \frac{K_f}{d_f} \frac{3600}{l} \tag{19}$$

Equation (18) can be rewritten in the following form:

$$Y = aX^b \tag{20}$$

where

$$Y \quad \frac{\dot{m}_{ew}}{R}; \quad X \quad \mathrm{Ra}; \quad a \quad C; \quad b \quad n$$

Equation (20) can be reduced to a linear equation by taking log on both the side:

$$\ln(Y) = \ln(a) + b\ln(X) \tag{21}$$

or

$$Y' = a' + b'X' \tag{22}$$

where

$$Y' = \ln(Y); \quad a' = \ln(a); \quad b' = b; \quad X' = \ln(X) \tag{23}$$

From eq. (23), the values of coefficients a' and b' are calculated using regression analysis. The expressions for a' and b' are given by:

$$b \quad \frac{N(\Sigma X\ Y\ ) \quad (\Sigma X\ )(\Sigma Y\ )}{N(\Sigma X\ ^2) \quad (\Sigma X\ )^2} \tag{23a}$$

$$a \quad \frac{\Sigma Y}{N} \quad b\ \frac{\Sigma X}{N} \tag{23b}$$

where N is the number of experimental observations.

Knowing a' and b' from eq. (23), the value of C and n can be obtained by the following expressions:

$$C = \mathrm{e}^{a'} \text{ and } n = b'$$

The experimental values of C and n for double slope solar still for January 19, 2007 and June 10, 2007 are shown in tab. 3.

Once the value of C and n are known, eq. (12) can be used to obtain the convective heat transfer coefficient h_{cw}. Dunkle [1], by using the values of $C = 0.075$ and $n = 1/3$, gave following expression for h_{cw}, valid for a mean operating temperature range of approximately 50 °C:

$$h_{cw} \quad 0.884\sqrt[3]{(T_W \quad T_g) \quad \frac{(P_w \quad P_g)(T_w \quad 273)}{268.9 \quad 10^3 \quad P_w}}$$

The variations of h_{cw} for double slope solar still for a typical day of winter and summer have been shown in fig. 2. It is clear that the values of h_{cw} based on the inner glass cover temperature are greater than the values of h_{cw} based on the outer glass cover temperature. It is due to fact that $T_w - T_{gi}$ is small but has higher operating temperature. The value of h_{cw} by present model is higher than value of h_{cw} obtained by Dunkle [1]. The hourly variations of convective h_{cw} obtained for calculated values of C and n corresponding to tab. 3 have been shown in the same figure. It is clear that the values of evaporative heat transfer coefficients for east condensing surface, obtained by using inner glass temperatures are greater than those obtained by using outer glass temperatures during the same time period. The value of h_{cw} is significantly higher under summer climatic conditions than winter climatic conditions. This is due to fact that the variation in solar intensity is greater in summer than in winter. Similar results have been obtained for west condensing cover as shown in fig. 3.

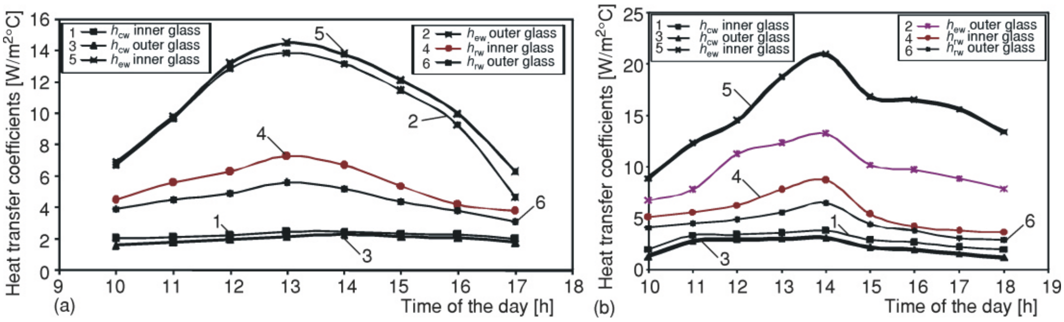

Figure 2. Hourly variation of convective, evaporative, and radiative heat transfer coefficients for double slope solar still (East) (a) on January 19, 2007, and (b) on May 10, 2007

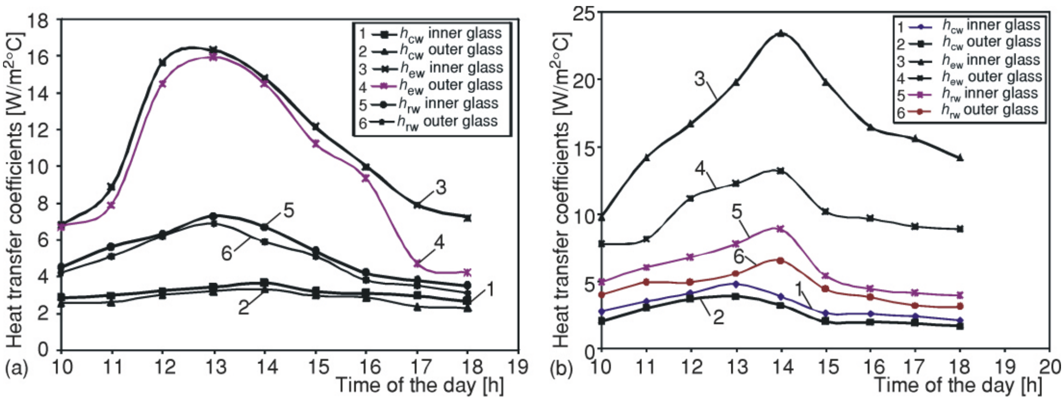

Figure 3. Hourly variation of convective, evaporative, and radiative heat transfer coefficients for double slope solar still (West) (a) on January 19, 2007, and (b) on May 10, 2007

Numerical results and discussions

Performance studies

Following parameters have been used to compute the hourly water temperature, glass temperature and distillate output for the solar stills using the new calculated values of C and n.

(a) *Design parameters*

For double slope conventional solar still:
$L_i = 0.005$m, $K_i = 0.04$ W/m°C, $d = 0.155$ m, $A_b = 2.23$ m^2, $A_g = 1.1$ m^2, $h_3 = 100$ W/m^2°C, $V = 1.0$ m/s, $\alpha_g = 0.1$, $\alpha_w = 0.6$, $\alpha_b = 0.8$, $T_{wi} = 33.0$, $T_{go} = 30.5$, $(MC)_w = 40 \cdot 4190$ J/°C

(b) *Climatic parameters*

The hourly variation of ambient temperature and solar intensities falling on the stills in conventional double slope solar still has been given in tabs. 1 and 2. From data of these tables we can see that solar intensities falling on east and west condensing surfaces are different during

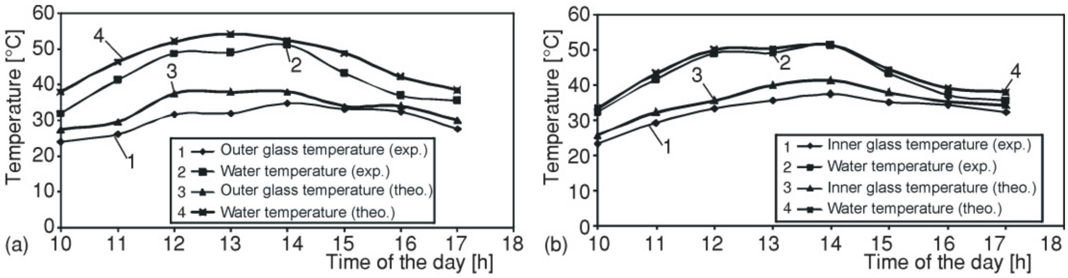

Figure 4. Hourly variations of theoretical and experimental outer glass and water temperature of double slope solar still (East) (a) on January 19, 2007, and (b) on January19, 2007

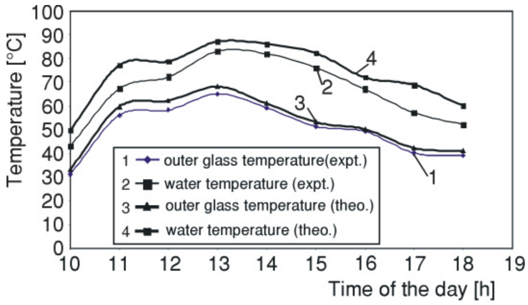

Figure 5. Hourly variations of theoretical and experimental outer glass and water temperature for double slope solar still (East) on May 10, 2007

same time period. This is the reason, for a given value of water temperature, the values of glass temperatures for east and west condensing surfaces are different. The inner glass cover temperature for both the conventional double slope solar stills is higher than outer glass cover temperature, as expected. It is due to fact that the rate of heat transfer takes place between water and inner surface of glass cover. Further, it is important to mention that the difference between inner and outer glass cover is more prominent in summer in comparison to winter. The water temperature, calculated by using inner glass temperature gives a closer value to experimental water temperature figs. 4 and 5.

Conclusion

On the basis of the present study, it is inferred that the internal heat transfer coefficients should be determined by using inner glass cover temperature for thermal modeling of passive and active solar stills. It is due to the fact that the heat transfer coefficients depend on the temperature difference between water and the inner glass cover, and the shape and material of the condensing cover of a solar still.

Nomenclature

A_g – area of glass cover, [m^2]
C_E – constant (East glass cover), [–]
C_W – constant (West glass cover), [–]
C_f – specific heat of working fluid, [Jkg^{-1}°C^{-1}]
d – cover spacing, [m]
d_f – average spacing between water and glass cover, [m]
F' – collector efficiency factor, [–]
Gr – Grashof number ($= d_d^3 \rho_f^2 g \beta\ \Delta T / \mu_f^2$)
g – acceleration due to gravity, [ms^{-2}]
h_b – bottom loss coefficient from basin to ambient, [Wm^{-2}°C^{-1}]
h_{cwE} – convective heat transfer coefficient from water surface to the East glass cover, [Wm^{-2}°C^{-1}]
h_{cwW} – convective heat transfer coefficient from water surface to the West glass cover, [Wm^{-2}°C^{-1}]
h_{ewE} – evaporative heat transfer coefficient from water surface to the East glass cover, [Wm^{-2}°C^{-1}]

h_{ewW} – evaporative heat transfer coefficient from water surface to the West glass cover, [Wm^{-2}°C^{-1}]
h_{rwE} – radiative heat transfer coefficient from water surface to the East glass cover, [Wm^{-2}°C^{-1}]
h_{rwW} – radiative heat transfer coefficient from water surface to the West glass cover, – [Wm^{-2}°C^{-1}]
h_w – convective heat transfer coefficient from basin liner to water, [Wm^{-2}°C^{-1}]
h_{1wE} – total heat loss coefficient from water surface to the East glass cover, [Wm^{-2}°C^{-1}]
h_{1wW} – total heat loss coefficient from water surface to the West glass cover, [Wm^{-2}°C^{-1}]
h_{2g} – total heat loss coefficient from the glass cover to the ambient, [Wm^{-2}°C^{-1}]
h_3 – convective heat transfer coefficient from basin liner to water, [Wm^{-2}°C^{-1}]
I_E – solar radiation on the East glass cover of the solar still, [Wm^{-2}]
I_W – solar radiation on the West glass cover of the solar still, [Wm^{-2}]
K_f – thermal conductivity of the humid air, [Wm^{-1}°C^{-1}]
K_i – thermal conductivity of the insulation [Wm^{-1}°C^{-1}]
L_i – thickness of the insulation, [m]
l – latent heat of vaporization, [Jkg^{-1}]
$\dot{M}_E$ – mass of distillate output from East surface of solar still, [kg]
$\dot{M}_W$ – mass of distillate output from west surface of solar still, [kg]
M_w – mass of distillate output, [kg]
$\dot{m}_{ew}$ – hourly distillate output, [kgm^{-2}h^{-1}]
$(MC)_w$ – heat capacity of water mass per m^2 in basin, [kg^{-1}°C^{-1}]
n_E – constant (East glass cover), [–]
n_W – constant (West glass cover), [–]
P_g – partial vapour pressure at glass temperature, [Pa]
P_w – partial vapour pressure of water temperature, [Pa]
Pr – Prandtl number (= $\mu_f C_f/K_f$)
Ra – Rayleigh number (= GrPr)
q_{cw} – convective heat transfer rate from water to glass cover, [Wm^{-2}]
q_{ew} – evaporative heat transfer rate from water to the glass surface, [Wm^{-2}]
T_a – ambient temperature, [°C]
T_{gE} – East glass cover temperature, [°C]
T_{gW} – West glass cover temperature, [°C]
$\Delta T'$ – effective temperature difference, [°C]
t – time, [s]
U_b – overall bottom heat loss coefficient, [Wm^{-2}°C^{-1}]
U_L – overall heat transfer coefficient, [Wm^{-2}°C^{-1}]
U_L' – overall top loss coefficient from water surface to ambient, [Wm^{-2}°C^{-1}]
U_t – top loss coefficient for passive solar still, [Wm^{-2}°C^{-1}]
V – wind velocity, [ms^{-1}]

Greek letters

α'_g – fraction of solar energy absorbed by glass cover
α'_w – fraction of solar energy absorbed by water mass
$(\alpha\tau)$ – product of absorptivity and transmittivity of collector
β' – coefficient of volumetric thermal expansion, [K^{-1}]
ε_g – emissivity of glass, [–]
ε_w – emissivity of water, [–]
μ_f – viscosity of fluid, [Nsm^{-2}]
σ – Stefan-Boltzman's constant (= 5.6697·10^{-8}), [Wm^{-2}K^{-4})
ρ_r – density of humid air, [kgm^{-3}]

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Appendix

The various heat transfer coefficients (h) are defined as follows:

$$h_{1\mathrm{w}} \quad h_{\mathrm{rw}} \quad h_{\mathrm{cw}} \quad h_{\mathrm{ew}}$$

$$h_{\mathrm{rw}} \quad \varepsilon_{\mathrm{eff}}\sigma[(T_{\mathrm{w}} \quad 273)^2 \quad (T_{\mathrm{g}} \quad 272)^2](T_{\mathrm{w}} \quad Tg \quad 546)$$

$$\varepsilon_{\mathrm{eff}} \quad \frac{1}{\varepsilon_{\mathrm{g}}} \quad \frac{1}{\varepsilon_{\mathrm{w}}} \quad 1 \;{}^{1}$$

$$h_{\mathrm{cw}} \quad \frac{K_{\mathrm{f}} C (\mathrm{Gr\ Pr})^n}{d_{\mathrm{f}}}$$

$$\Delta T = T_{\mathrm{w}} \quad T_{\mathrm{g}} \quad \frac{(P_{\mathrm{w}} \quad P_{\mathrm{g}})(T_{\mathrm{w}} \quad 273)}{268.9 \quad 10^3 P_{\mathrm{w}}}$$

$$h_{\mathrm{ew}} \quad 16.273 \quad 10 \;{}^{3} h_{\mathrm{cw}} \frac{P_{\mathrm{w}} \quad P_{\mathrm{g}}}{T_{\mathrm{w}} \quad T_{\mathrm{g}}}$$

$$h_{\mathrm{b}} \quad \frac{1}{\frac{K_{\mathrm{i}}}{L_{\mathrm{i}}}} \quad \frac{1}{h_{\mathrm{cb}} \quad h_{\mathrm{rb}}} \;{}^{1}$$

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