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Estimation of convective mass transfer in solar distillation systems

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Abstract
The main goal in this paper is to determine the convective mass transfer for different Grash of Number range in solar distillation process. The model is based on simple regression analysis. It is deserved there is a reasonable arrangement with in an accuracy of 12% between experimental observations and theoretical results calculated.

Keywords: Convective mass transfer, solar distillation systems, solar distillation process

Introduction

Clark developed a model for a higher-operating temperature range (> 55 °C) in simulated conditions for small inclination of the condensing surface. He found that values of coefficients for convective mass transfer reduce to half that of Dunkle. This is based on the fact that the rate of evaporation is equal to the rate of condensation in an ideal condition. This condition is achieved by using a fan across the condensing cover which is not a practicable solution for solar distillation systems, operating in the field conditions.

Later, Tiwari and Lawrence (1991) attempted to incorporate the effect of inclination of the condensing surface taking the same values of C and n as proposed by Dunkle. Further, Adhikari *et al*. (1990, 1991, 1995) tried to modify the values of these coefficients in simulated conditions. Here, the authors have presented the modified values of C and n obtained from the outdoor experimental data. This model has been developed by using simple regression analysis. These values of C and n have again been used to find the theoretical distillate output. It is observed that there is a reasonable agreement within an accuracy of 12% between experimental observations and theoretical results calculated by modified values of C and n for summer climatic conditions.

Formulation

The rate of heat transfer from the water surface to the glass cover (q_{cw}) by convection can be estimated by,

$$\dot{q}_{cw} = h_{cw}(T_w - T_g) \qquad \text{.......................... (1)}$$

Where h_{ew} is found from the relation

$$Nu = \frac{\mathrm{h_{cw}}.d_f}{k_f} = C(Gr.Pr)^{\mathrm{n}} \qquad \text{.......................... (2)}$$

Where

$$Gr = \frac{g\beta' \rho^2 (d_f)^3 (\Delta T')}{\mu^2} \qquad \text{.......................... (3)}$$

$$Pr = \frac{\mu.C_p}{k_f} \qquad \text{.......................... (4)}$$

And

$$\Delta T' = \left(T_w - T_g\right) + \left[\frac{(P_w - P_g)(T_w + 273)}{268.9\times10^3 - P_w}\right] \text{ .... (5)}$$

(Malik *et al*., 1982). It is seen from eqn. (2) that the value of h_{ew} depends upon the values of two constants, namely C and n. It is observed from the different values of C and n for a particular range of Grash of Number given by various authors that the percentage deviation between the theoretical and experimental distillate output remains within a reasonable percentage of accuracy for indoor simulated conditions only, whereas for outdoor conditions the deviation increases significantly. Hence, there is a need to modify the values of C and n in eqn (2). The modification for values of C and n has been carried out by regression analysis using experimental distillate output (M_w), basin water temperature (T_w) and glass temperature (T_g).

Evaporative heat transfer rate (q_{ew}) is given by

$$\dot{q}_{ew} = 0.016273\left(P_w - P_g\right).\,\mathrm{h}_{cw} \qquad \text{......................... (6)}$$

(Malik *et al.*, 1982) Using eqn (2), eqn (6) can be rewritten as

$$\dot{q}_{ew} = 0.016273\left(P_w - P_g\right).\left(k_f/d_f\right).C(Ra)^n \text{......................... (7)}$$

where Ra = Gr. Pr. Also,

$$\dot{M}w = \frac{\dot{q}_{ew}\times3600}{L} \qquad \text{......................... (8)}$$

eqn (8) can be rewritten using eqn (7)

$$\dot{M}_w = 0.016273\left(P_w - P_g\right).\left(k_f/d_f\right).(3600/L).C(Ra)^n \text{ .... (9)}$$

Therefore,

$$\dot{M}_w/R = C(Ra)^n \qquad \text{......................... (10)}$$

Where

$$R = 0.016273\left(P_w - P_g\right).\left(k_f/d_f\right).(3600/L) \text{ .... (11)}$$

For field conditions, the values of T_w and T_g vary significantly because of variations in climatic conditions and correspondingly M_w and Ra also vary. A cross-sectional view of a single slope passive solar still made of fibre-reinforced plastic (FRP) is shown in Fig. l(a).

The bottom surface of the still was painted black by mixing a special black dye with resin for better absorptivity. A window glass of 3 mm thickness was placed at an inclination (β) of 15° over the FRP still. Figure 1 (b) shows the schematic diagram of an active solar still coupled with a fiat plate collector (FPC). The area of the still and FPC was taken as 1 and 2 m^2 respectively. The collector was kept inclined at an angle of 45° to the horizontal. The hot water from the collector was pumped into the still basin to raise the evaporative surface temperature. The pump was kept in the "off" position during non-sunshine hours to avoid heat losses caused by reverse flow.

To perform the experiment with a minimum storage effect, the basin of the solar still was filled with 2 cm of water. The average spacing (df) between the water surface and the glass cover was kept as 0.155 m. The outputs from the passive and active stills were measured every hour during daylight for 30 days in the months of May and June, 1995. The outputs during non-sunshine hours were collected daily in the morning before the commencement of the experiment. It was observed that only 5-10% yields were obtained during non-sunshine hours for both the passive and the active distillation systems.

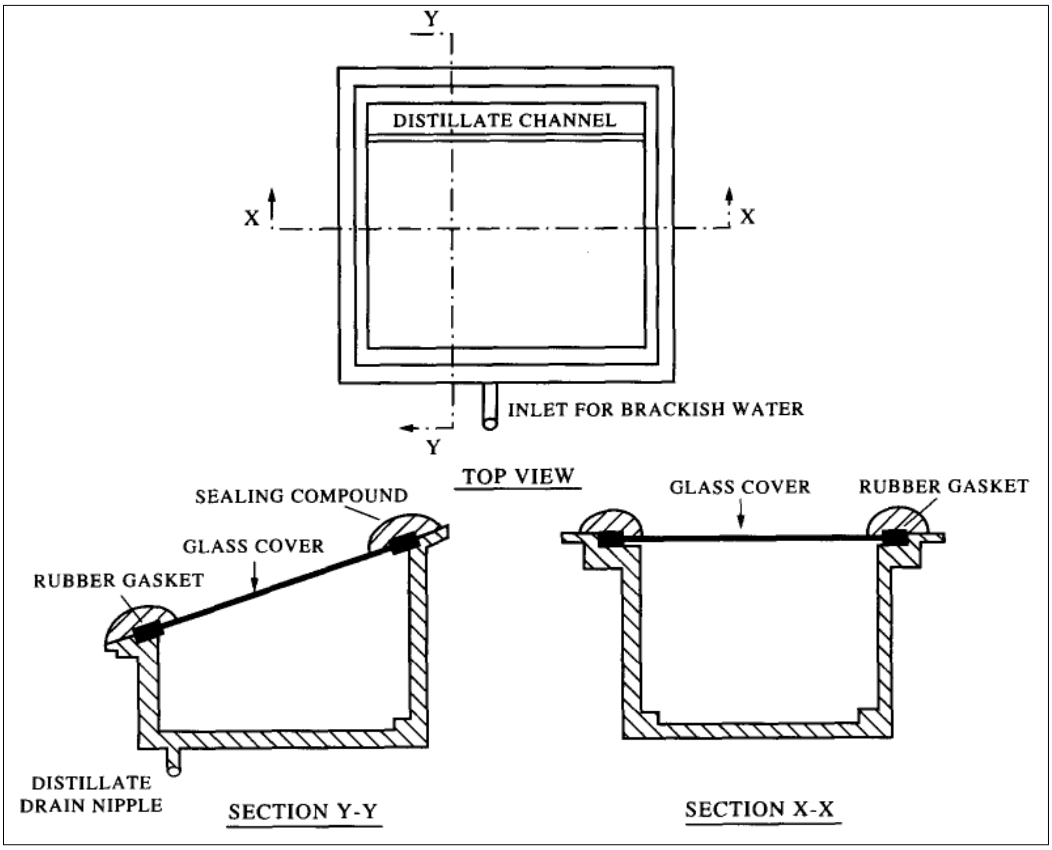

Fig 1a: Cross-sectional view of a single slope passive solar still

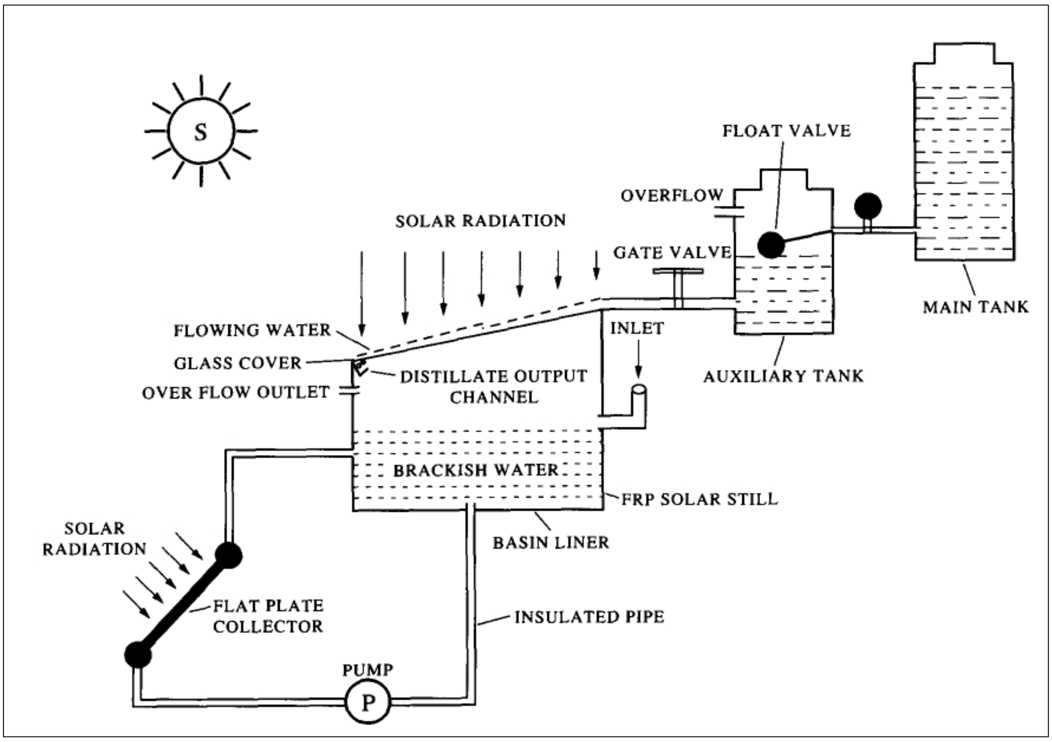

Fig 1 b: Single slope active solar still coupled with FPC

Table 1: Observations of a typical day for a single slope passive solar still

Serial no.	Time (h)	Water temp (^{0}C)	Glass temp (^{0}C)	Ambient temp (^{0}C)	Distillate output (ml)
1	1000	45.5	40.5	36	130
2	1100	50.6	43.5	40	230
3	1200	55.7	47.3	42	360
4	1300	54.9	47.3	42.5	320
5	1400	52.8	45.6	42	280
6	1500	49.7	44.5	41.5	200
7	1600	41.6	36.7	41	100

Table 2: Observations of a typical day for a single slope active solar still

Serial no.	Time (h)	Water temp (^{0}C)	Glass temp (^{0}C)	Ambient temp (^{0}C)	Distillate output (ml)
1	1000	46.5	37.5	43	310
2	1100	53.9	42.4	40	530
3	1200	59.2	46.3	43	810
4	1300	59.5	46.3	45	970
5	1400	58.4	44.4	47	940
6	1500	56.5	43.5	48	710
7	1600	53.1	38.9	44	650

Experimental observations for a typical hot day for both cases, i.e. passive and active stills, are shown in Tables 1 and 2, respectively This indirect method will certainly have a considerable degree of experimental uncertainty in the estimation of convective heat transfer coefficients. An estimate of internal and external uncertainty (Nakra and Choudhary, 1985) has been carried out separately for passive and active solar stills. For this, 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 by taking the square root of the sum of each sample standard deviation divided by the square root of the number of samples. Estimate of internal uncertainty (U_i):

$$U_i = \sqrt{\frac{\sigma_1^2+\sigma_2^2+.......\sigma_N^2}{N^2}} \quad .... (12)$$

The total uncertainty (internal and external) for passive and active stills has been calculated as 25 and 19%, respectively. Also, the results will be influenced by a thermal storage effect. The percentage error caused by thermal storage can be calculated as follows:

$$\%error = \frac{\text{distillate output during non} - \text{sushinehours}}{\text{distillate output during day light hours}} \times 100$$

The errors for passive and active stills have been estimated as 8 and 5%, respectively.

Results and Discussion

To calculate the values of C and n based on the experimental data, namely basin water temperature, glass temperature and distillate output.

It is observed that when the solar intensity is quite low, 7-9 a.m., the output is reduced and there are difficulties in accurately measuring outputs of the order of 10-15 ml. This low distillate output also causes inconsistency in the computation of C and *n*.

Therefore, certain observations in the morning and in the evening when distillate output was found to be extremely low have not been taken into account. It is interesting to note that we get very consistent values of C= 0.0322 and n=0.411 for each set of six or more numbers of observations for the Grashof range of 1.794 × l06 to 5.724 x 107 in the case of a passive solar still and C=0.0538 and n=0.383 for a Grashof range of 5.498 x 10 6 to 9.128 x l06 in the case of an active solar still. Tables 3 and 4 show the computed values of convective heat transfer coefficients (h_{ew}), evaporative heat transfer coefficients (h_{ew}), evaporative transfer validated experimentally.

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