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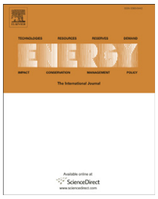

Theoretical and empirical study of heat and mass transfer inside a basin type solar still

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ABSTRACT

Heat and mass transfer between the surfaces of the cover and saline water in a solar still occurs through convection ($h_{c,w-gc}$), evaporation ($h_{e,w-gc}$) and radiation ($h_{r,w-gc}$). All these three coefficients of heat transfer influence the performance of the solar still, and so they need to be computed accurately. In this study, two recent models for calculating the coefficient of evaporative heat transfer ($h_{e,w-gc}$) have been investigated by taking into account view factors of radiative heat exchange. In the first model (Model 1), the vapour concentration ratio ($C_r = h_{e,w-gc}/h_{c,w-gc}$) depends on different thermodynamic variables inside the solar still. The other model of C_r (Model 2) is a third-order polynomial function of the operating temperature of the solar still (T_i). Results show that C_r has a critical value for Model 1 with no turning point for Model 2 in the considered temperature range. There exists an operating temperature $T_i = T_{is}$ at which the two models yield the same value of C_r. Estimates of the coefficient of $h_{e,w-gc}$ obtained by using Model 1 are higher than those of Model 2 when $T_i < T_{is}$, with a reversed trend when $T_i > T_{is}$. Model 1 exhibits lower values of the root mean square error.

1. Introduction

Water plays an important role in the socio-economic development of any country. However, there is limited access to clean water on a global scale. Most of the available water on the earth's surface needs treatment to meet stipulated standards before it can be used in different sectors of the economy. In this regard, solar desalination is a promising technique for improving the quality of water. Delyannis [1] investigated a historical background of desalination which included landmarks achieved in the development of the solar desalination technology. Tiwari et al. [2] comprehensively reviewed the status of solar distillation. They observed that solar distillation is the commonest non-conventional method of water desalination.

A basin type solar still is exploited most widely [3]. This desalination system has a thin layer of saline water in a shallow basin, with a single- or double-sloped transparent cover over the water and a channel for collecting the distillate. The water in the basin is heated by solar radiation which is transmitted through an inclined transparent cover and absorbed by the water and the bottom part of the still basin (Fig. 1). Vapour rises from the hot water and condenses on the inner surface of the transparent cover. The condensate is collected in a channel fitted along the lower edge of the transparent cover. This variety of solar desalination technologies has attracted a lot of attention from researchers.

Kumar and Tiwari [4] studied single and double-effect active solar stills. They found that a single-effect active solar still with water flow over the transparent cover produced the highest amount of distilled water. Rahbar and Esfahani [5] used computational fluid dynamics (CFD) to estimate the distillate output of a single-slope solar still. They observed that: a) the distillate yield was maximum at an optimum length of the system, b) the hourly amount of distilled water declined with increasing the specific height of the system, and c) the trend of convective heat transfer was like that of the distillate yield. Ibrahim et al. [6] developed a basin type solar still operating at a pressure lower than atmospheric level. They observed that the distillate productivity increased by 16.2% over a conventional solar still.

Thermal processes in a solar still involve internal and external heat transfer (Fig. 2). Internal heat transfer occurs through conduction, convection, evaporation and radiation while convection and radiation are responsible for heat loss from the solar still cavity to the environment. These processes affect the performance of the still and it is therefore important to have a good understanding of them.

The correlation on internal heat and mass transfer was first

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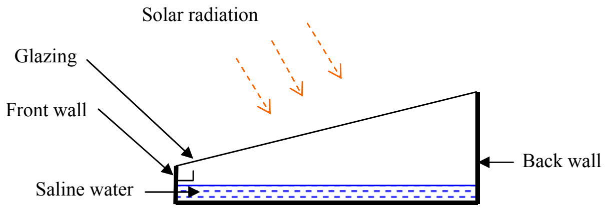

Fig. 1. A basin type solar still with single slope.

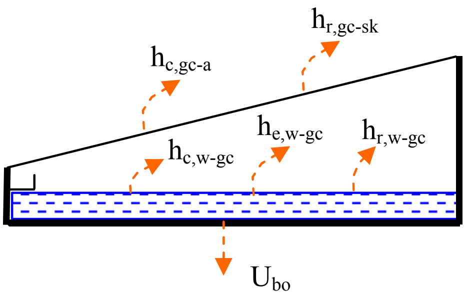

Fig. 2. Heat and mass transfer in a basin type solar still.

proposed by Dunkle [7]. This correlation has been widely applied but it has some limitations. Cooper [8] pointed out that the correlation was suitable for upward heat transfer across a horizontal air space. Due to the inclination of the transparent cover, the air space in a real solar still is trapezoidal. Consequently, Rheinlander [9] developed an alternative model for estimating heat and mass transfer in a basin type solar still. Clark [10] and Shawaqfeh and Farid [11] observed that the correlation proposed by Dunkle overestimated the evaporative coefficient of heat transfer. In addition, Dunkle's correlation excluded the volume of the air space between the hot water and the condensing cover [12]. So, Kumar and Tiwari [12] included the mean height of the air space between the saline water and the cover in their model.

Porta-Gándra et al. [13] examined the overall heat transfer from the hot water surface to the transparent cover in a shallow solar still. Rubio et al. [14] studied the effect of cavity geometry on the internal mass transfer inside solar stills with single and double slopes. Tsilingiris [15] developed a theoretical model for computation of heat and mass transfer in a basin-type solar still. The proposed model could be applied in a wide range of Prandtl and Schmidt numbers with a high degree of accuracy. Chen et al. [16] used a tubular solar still to analyze the characteristics of internal heat and mass transfer. Alvarado-Juárez et al. [17] studied the natural convection and surface thermal radiation of heat inside an inclined cavity. Setoodeh et al. [18] used CFD to study the heat transfer in a basin type solar still. Kumar et al. [19] developed a correlation for estimation of the coefficients of heat transfer in a solar still. Nevertheless, there have been some new developments in modelling the coefficients of heat transfer in a basin type solar still. The objective of this study is to compare recent models for calculating the coefficients of evaporative heat transfer.

2. Recent improvement in modelling internal heat transfer

Air inside a solar still contains a high proportion of moisture. In view of this, Tsilingiris [20] studied the influence of using the thermophysical properties of the mixture of moisture and dry air in the derivation of the coefficients of heat and mass transfer in solar stills. It was found that the accuracy of modelling the transfer of heat and mass in basin type solar stills improved when the thermophysical properties of a binary mixture were used instead of those of dry air. Later, Tsilingiris [21] reported the following general equations for calculating coefficients of heat transfer by natural convection and evaporation from the surface of hot water to a condensing cover:

$$h_{c,w-gc} = bk_a Z^{3d-1}\left(\frac{g\rho_a\beta_a}{\mu_a\alpha_a}\right)^d\left[(T_w - T_{gc})\frac{T_w(P_w - P_{gc})(M_a - M_v)}{M_a P_{to} - P_w(M_a - M_v)}\right]^d \tag{1}$$

$$h_{e,w-gc} = \frac{1000 H h_{c,w-gc} R_a P_{to}}{C_{p,a} R_v (P_{to} - P_w)(P_{to} - P_{gc})} \tag{2}$$

Thermophysical properties of a binary mixture were used in the study. It was found that $d = 1/3$ can be used in a wide range of operating temperatures for a practical solar still, and $b = 0.075$ when the rate of distillation is lower than 1×10^{-4} kg m^{-2} s^{-1} and $b = 0.05$ at higher distillate outputs. In addition, there was good agreement between theoretical and experimental rates of distillate production. Based on Eq. (2), the concentration ratio of evaporative to convective (C_r) heat transfer can be given by (Model 1):

$$C_r = \frac{h_{e,w-gc}}{h_{c,w-gc}} = \frac{1000 H R_a P_{to}}{C_{p,a} R_v (P_{to} - P_w)(P_{to} - P_{gc})} \tag{3}$$

The specific heat capacity of air ($C_{p,a}$), specific latent heat of vaporization (H), and partial vapour pressure are temperature-dependent and can respectively be computed according to Tsilingiris [20], Belessiotis et al. [22] and ASHRAE [23]:

$$C_{p,a} = 1088.022802 - 10.57758092 t_i + 0.4769110559 t_i^2 - 7.898561559{*}10^{-3} t_i^3 + 5.122303796{*}10^{-5} t_i^4 \tag{4}$$

where $t_i = T_i - 273.15$, and T_i is the operating temperature of the still.

$$H = 3044205.5 - 1679.1109 T_w - 1.14258 T_w^2 \tag{5}$$

$$P_{gc} = e^{\left\{\left(-\frac{5800.2206}{T_{gc}}\right) + 1.3914993 - 0.048640239 T_{gc} + 4.1764768{*}10^{-5} T_{gc}^2 - 1.4452093{*}10^{-8} T_{gc}^3 + 6.5459673 \ln(T_{gc})\right\}} \tag{6}$$

$$P_w = e^{\left\{\left(-\frac{5800.2206}{T_w}\right) + 1.3914993 - 0.048640239 T_w + 4.1764768{*}10^{-5} T_w^2 - 1.4452093{*}10^{-8} T_w^3 + 6.5459673 \ln(T_w)\right\}} \tag{7}$$

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