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Modelling radiative heat transfer inside a basin type solar still

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HIGHLIGHTS

- Radiative heat transfer in a basin type solar still has been investigated.
- Two models with and without view factors were used.
- The model with view factors exhibits a lower magnitude of root mean square error.
- View factors affect the accuracy of modelling the performance of the solar still.

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ABSTRACT

Radiative heat transfer inside a basin type solar still has been investigated using two models with (model 1) and without (model 2) taking into account optical view factors. The coefficient of radiative heat exchange ($h_{r,w\text{-}gc}$) between the water and cover surfaces of a practical solar still was computed using the two models. Simulation results show that model 1 yields lower values of $h_{r,w\text{-}gc}$ and the root mean square error than model 2. It is therefore concluded that the accuracy of modelling the performance of a basin-type solar still can be improved by incorporating view factors.

1. Introduction

Solar distillation involves thermal processes with internal and external heat and mass transfer. Internal heat transfer occurs through convection, evaporation and radiation while convection and radiation are responsible for heat loss from the solar still envelope to the external environment (Fig. 1). All these processes influence the distillate yield of the solar still, and they have therefore attracted significant attention from different investigators.

The foundational correlation on internal heat and mass transfer was proposed by Dunkle [1]. This correlation has been widely applied but it has some limitations. Cooper [2] 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 [3] developed an alternative model for estimating heat and mass transfer in a basin type solar still. There was good agreement between theoretical and experimental data. Clark [4] and Shawaqfeh and Farid [5] 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 [6]. So, Kumar and Tiwari [6] included the mean height of the air space between the saline water and the cover in their model.

Tiwari and Tiwari [7] investigated the influence of water depth on heat and mass transfer in a passive solar still. They found that the coefficients of heat transfer were significantly affected by the depth of brine. Porta-Gándra et al. [8] examined the overall heat transfer from the hot water surface to the transparent cover in a shallow solar still. They found that heat flow from the water to the cover varied in the range 0–650 W m^{-2}, depending on the temperature gradient between the two surfaces. Rubio et al. [9] studied the effect of cavity geometry on the internal mass transfer inside solar stills with single and double slopes. Their results showed no difference between the two varieties of stills operated under the same water and cover temperatures. Tsilingiris [10] 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 the Prandtl and Schmidt numbers with a high degree of accuracy. Chen et al. [11] used a tubular solar still to analyse the characteristics of internal heat and mass transfer. They found a direct linear relationship between temperature and water production at normal pressure. Alvarado-Juárez et al. [12] studied the natural convection and surface thermal

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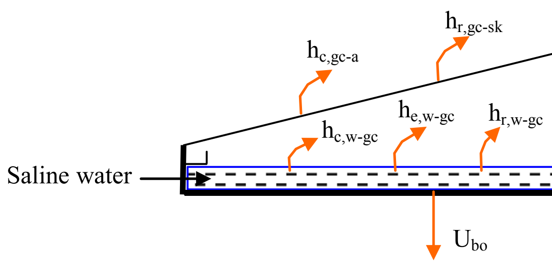

Fig. 1. Heat transfer in a basin type solar still.

radiation of heat inside an inclined cavity. They observed that thermal radiation modified the pattern of fluid flow. Setoodeh et al. [13] used computational fluid dynamics to study heat transfer in a basin type solar still. They found a good agreement between theoretical and experimental data. Kumar et al. [14] developed a correlation for estimation of the coefficients of heat transfer in a solar still. Nevertheless, in all these and other previous studies, limited attention has been paid to the accuracy of models for computation of internal radiative heat transfer in a basin type solar still.

2. Modelling internal radiative heat transfer

Heat radiation is the transfer of thermal energy through electromagnetic waves [15]. This mode of heat transfer takes place even in a vacuum. To incorporate the effect of the cavity geometry of the still, the net radiative heat transfer between the water surface and cover surfaces can be expressed in a linear form by defining a coefficient of radiative heat transfer [16]:

$$Q = A_w h_{r,w-gc}(T_w - T_{gc}) \tag{1a}$$

$$h_{r,w-gc} = \frac{\sigma\left(T_w^2 + T_{gc}^2\right)(T_w + T_{gc})}{\frac{1-\varepsilon_w}{\varepsilon_w} + \frac{A_w(1-\varepsilon_{gc})}{A_{gc}\varepsilon_{gc}} + \frac{1}{W_{w-gc}}} \tag{1b}$$

In this investigation, Eq. (1b) is model 1. It should be noted that $W_{w\text{-}gc}$ is a function of the geometric parameters of the still cavity, and it can be computed from [16]:

$$W_{w-gc} = 1 - \left(W_{w-bw} + W_{w-ew} + W_{w-fw} + W_{w-ww}\right) \tag{2}$$

The geometry of the still influences the values of the view factors [17]. For instance, the view factor of the water relative to the back wall ($W_{w\text{-}bw}$) can be calculated analytically. In this case, the water surface is rectangular and perpendicular to the back wall with a common edge along the length (L_w) of the brine surface. $W_{w\text{-}bw}$ can be calculated by using the geometry of these two mutually-perpendicular surfaces [16]. In this study, the two trapezoidal walls on the eastern and western sides of the solar still are assumed to be rectangular in shape with breadth B_w and height $0.5(Z_{bw} + Z_{fw})$. In addition, $W_{bw\text{-}ew} = W_{bw\text{-}ww}$ due to symmetry, and the surface of saline water is horizontal ($\beta_w = 0$).

It should also be noted that view factors influence radiation exchange amongst surfaces [18,19]. In a basin type solar still, there is a space between the brine and transparent cover surfaces. These characteristics of radiation transfer are therefore important in studying thermal processes in a practical solar still.

In previous work, the coefficient of internal radiative heat transfer ($h_{r,w\text{-}gc}$) is commonly given by [13,14]:

$$h_{r,w-gc} = \sigma\varepsilon_{w,gc}\left(T_w^2 + T_{gc}^2\right)(T_w + T_{gc}) \tag{3a}$$

$$\varepsilon_{w,gc} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{gc}} - 1\right)^{-1} \tag{3b}$$

In this study, Eq. (3a) is model 2, which does not include an optical view factor between the surface of water and the glass cover. The computed coefficients of radiative heat transfer, from models 1 and 2, can be used in the energy balance equations for a basin type solar still.

3. Model verification

3.1. Description of solar still

The test solar still had a galvanized steel basin liner (0.90 m × 0.80 m) which was painted black on the inner surface to optimize absorption of solar radiation (thickness of steel sheet = 0.0008 m). The basin was placed horizontally on polystyrene insulation inside a wooden box which was made of plywood. A float glass cover (0.004 m thick) was fitted on the top part of the basin.

It should be mentioned that the choice of the inclination angle (β) depends on the latitude (ϕ) of the location where the collector is mounted [20]. For Malawi Polytechnic, $\phi = 15° 48'$, and so, the glass cover of the solar still was tilted at 16° to the horizontal plane to optimize solar collection throughout the year. Details of the system design and operating parameters are presented in Table 1.

3.2. Energy balance equations

Some assumptions were made to apply the radiative heat models 1 and 2 to a conventional solar still: a) the solar still was air-tight, b) ground-reflected solar radiation did not reach saline water in the basin, c) solar radiation intercepted by the exterior surfaces of the walls was neglected, and d) there was no leakage of vapour and distillate from the distillation system. With these assumptions, the energy balance equations for the solar still components were formulated as follows:

Glass cover (gc)

$$m_{gc}C_{p,gc}\frac{dT_{gc}}{dt} = A_{gc}F_{gc}G_{g,ef} + A_w h_{w-gc}(T_w - T_{gc}) - A_{gc}h_{c,gc-a}(T_{gc} - T_a) - A_{gc}h_{r,gc-sk}(T_{gc} - T_{sk}) \tag{4a}$$

Table 1
Design and operational parameters for a basin type solar still.

Parameter	Unit	Value
Design parameters		
A_w	m^2	0.720
A_{gc}	m^2	0.750
B_w	m	0.800
L_w	m	0.900
m_{b1}	kg	5.0
m_{gc}	kg	10.0
U_{bo}	$W\ m^{-2}\ K^{-1}$	1.203
U_{sw}	$W\ m^{-2}\ K^{-1}$	0.500
$W_{w\text{-}gc}$	Dimensionless	0.53
x_{ps}	m	0.023
x_{pw}	m	0.020
Z_{bw}	m	0.425
Z_{fw}	m	0.195
β_{gc}	Degree	16
Operational parameters		
m_w	kg	20