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Experimental study of the distillation process in a tilted cavity

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Abstract. Heat and mass transfer correlations in a basin solar still are not applicable for brine-flowing type solar still. Thermal efficiency is hard to determine explicitly due to the varying temperature of brine along the flow direction. A simple method is proposed in the present work to evaluate the performance of the brine-flowing type still through the energy balance equation of brine. Experiments in a tilted cavity which is used to simulate a brine-flowing type solar still are conducted, and it is found that thermal efficiency of the simulated still is always less than 76.3%. An empirical equation is obtained, which may provide a clue for the development of an explicit theoretical model to predict fresh water production of the brine-flowing solar still.

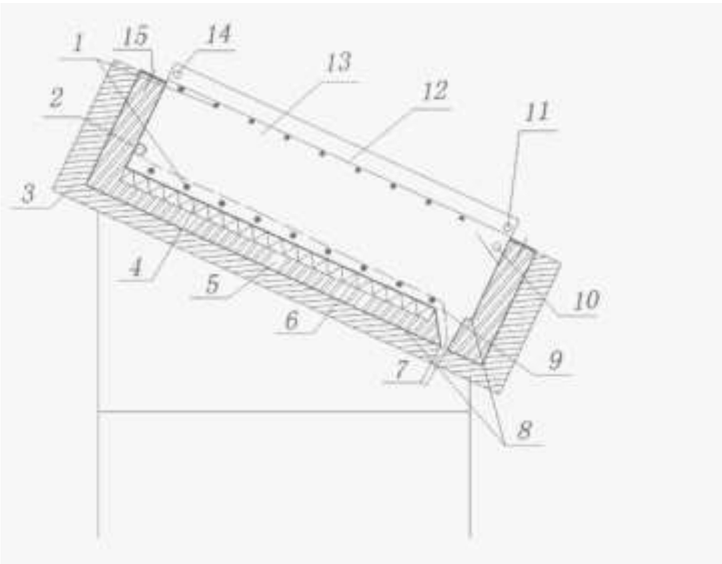
1. Introduction

Solar stills are widely used in remote areas to produce fresh water by brine, e.g. sea water, brackish water, alkaline water, because of simple structures and easy operating skills. Main factors on fresh water production in basin solar still were studied, including input amount of solar radiation, depth of brine layer, thickness of insulation, temperature difference between brine and condensation surface, wind speed and etc. [1-5]. Besides fresh water production, thermal efficiency is another important index to evaluate a solar still. Dunkle [6], Adhikari and Kumar [7] and Zheng et al. [8] proposed theoretical models to describe heat and mass transfer process in basin type solar stills, respectively. Kumar et al. [9] proposed an empirical correlation to predict fresh water production by hot brine temperature. However, all the correlations mentioned above are applicable under conditions that the temperatures of brine in the still are uniform.

Another kind of solar still, called brine-flowing solar still in the present work, allows a thin brine layer flowing on a heating basin, including weir-type inclined solar still [10], weir-type cascade solar still [11], floating cum tilted-wick type solar still [12], inclined solar water distillation system [13] and etc. Brine flows over a basin and its temperature increases along the flow direction. Heat and mass transfer models of a basin type solar still are not applicable to the brine-flowing solar still due to the varying temperature. This paper attempts to propose a simple method to evaluate the performance of brine-flowing solar still through energy balance equations and find out quantitative relationship between fresh water production and influencing factors. An empirical relation is obtained to provide a clue for the development of explicit theoretical model to predict fresh water. To ensure the repeatability of experiments, electrical heating plate is used to simulate solar radiation.

2. Experimental setup and methods

Figure 1 shows a schematic of experimental equipment. It mainly consists of a two-layer box without a cover, the up-layer surface of which acts as an evaporation basin, a condenser in which cooling water passes through and an electrically heating plate. The condenser is connected to the box by screws with a distance of 0.08 m to the evaporation basin which has a length of 0.5 m and width of 0.3 m. Wicks are uniformly paved on the evaporation basin. A water-feeding tube of 8mm diameter with 15 holes of 0.2 mm diameter upside is at the upstream and 10 mm over the evaporation basin. 18 K-type thermocouples are arranged along the centric line of the evaporation basin and the centric line of the condensation surface. The heating plate with the same size of the evaporation basin is closely fixed beneath the up-layer of the box and is controlled by a transformer. The input voltage and electric current of the heating plate are measured by a voltmeter with accuracy of 0.1 V and an ammeter with accuracy of 0.01 A, respectively. The space between the heating plate and the box is tightly filled with insulation 1 which has a thermal conductivity of 0.036 W/m·K and thickness of 0.3 m. To reduce heat loss, an insulation 2 which has a thermal conductivity of 0.046 W/m·K and thickness of 0.5 m is wrapped outside the box. Tap water with salt is used to simulate brine in this study. Brine from the feeding tube flows along the evaporation basin as a uniform thin film due to the capillary force of the paved wicks and is heated by the heating plate. Vapor goes up to the condensing surface and condenses into water drops that are collected in the fresh water tank. The remained hot brine is drained out. Fresh water production is measured with a weighing machine with sensitivity of 10^{-4} kg and a stopwatch. All the thermocouples are connected to an Agilent 34970A data acquisition and then to a computer.



1-thermocouples 2-feeding water tube 3-insulation 2 4-wicks 5- insulation 1 6-heating plate 7-feeding water outlet 8-two-layer stainless box 9-water film 10- fresh water outlet 11-cooling water inlet 12-condenser 13-space between evaporation basin and condenser 14- cooling water outlet 15-sealing pad

Fig.1 Schematic of experimental device

As shown in Figure 2, flowing brine is heated by the heating plate, and at the same time heat is transferred through evaporation, convection and radiation from hot brine to the condensation surface. It is assumed: evaporation, convection and radiation heat fluxes are uniform and temperature of brine is equivalent along the *x* direction; vapor leakage and heat loss is neglected. A steady-state energy balance equation is given by,

$$q_f dy = \frac{1}{3.6} M_{in} c_p dT + (q_e + q_c + q_r) dy \tag{1}$$

$$\overline{q_e + q_c + q_r} = \frac{\int_0^l (q_e + q_c + q_r) dy}{l} \tag{2}$$

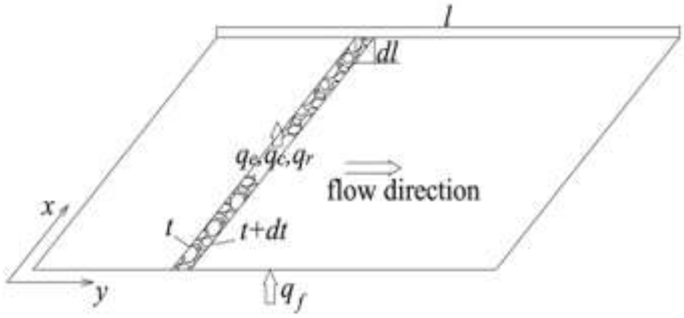


Fig. 2 Schematic illustration for energy balance analysis

α_1 is defined as a ratio of the mean total heat flux including evaporation, convection and radiation to the input heat flux, thus

$$\alpha_1 = \frac{\overline{q_e + q_c + q_r}}{q_f} \quad q_f > 0 \tag{3}$$

α_2 is defined as a temperature increase by unit length along *y* axis, thus

$$\alpha_2 = \frac{3.6 q_f}{M_{in} c_p} (M_{in} > 0) \tag{4}$$

δ is defined as:

$$\delta = \frac{\overline{q_c + q_r}}{q_f} \tag{5}$$

In which:

$$\overline{q_c + q_r} = q_f - m_d \cdot \bar{\gamma} / 3.6 \tag{6}$$

Combining equations (1), (3) and (4), the following equation is obtained:

$$\alpha_2 l-(T_o-T_{in})=\alpha_1\cdot\alpha_2 l \tag{7}$$

Values of T_{in} and T_o are measured by thermocouples.

3. Results and Discussion

3.1. Analysis of thermal efficiency

Assuming $\alpha_2 l$ is an abscissa and $\alpha_2 l-(T_o-T_{in})$ is an ordinate, experimental data are shown in Figure 3 and a linear equation is fitted,

$$\alpha_1\cdot\alpha_2 l = 0.763\alpha_2 l - 10.155 \tag{8}$$

Based on equations (3) and (4), equation (8) is rewritten by,

$$\frac{\overline{q_e+q_c+q_r}}{q_f} = 0.763 - \frac{2.82M_{in}c_p}{q_f l} \tag{9}$$

Thermal efficiency is defined as:

$$\eta = \frac{q_e}{q_f} \tag{10}$$

which is apparently less than the left side of equation (9). This indicates that the thermal efficiency of a brine-flowing type solar still could hardly exceed 76.3%.

Figure 4 shows temperatures of feeding brine along *y* axis. The maximum temperature difference between the inlet and the outlet in the figure is ~40 °C and the minimum difference is ~15°C. Since vapour latent heat changes less than 5.3% when the temperature of brine ranges from 30 °C to 80 °C, which is the interesting range for solar still desalination. As a result, it is acceptable to choose a mean vapour latent value (e. g. 2346.25 kJ/kg which is a value of saturation vapour latent heat corresponding to a temperature of 55 °C) to represent the evaporation heat flux.

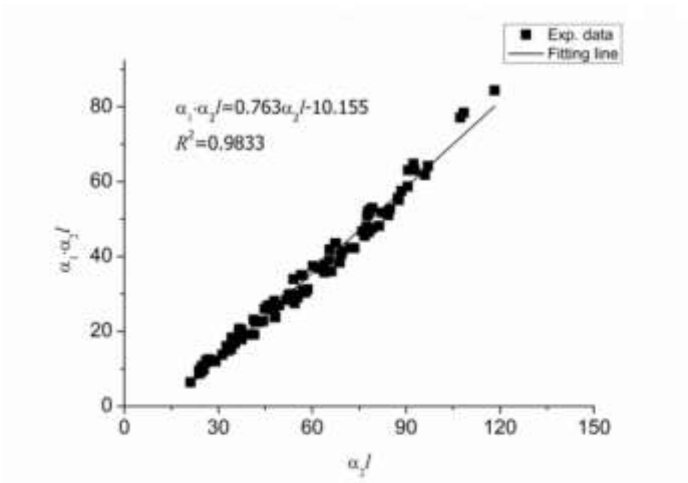


Fig. 3 Function of $\alpha_2 l-(T_o-T_{in})$ vs. $\alpha_2 l$. Experimental condition: feed brine flow rate 5.47, 6.67, 7.67, 8.80 kg/h ·m respectively; inlet temperature of feed brine: 13-18 °C; heating flux: 400-1500 W/m^2

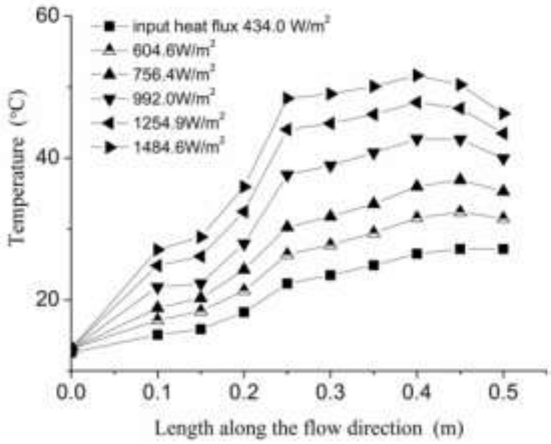


Fig. 4 Temperatures along *y* axis when feed brine flow rate is 7.67 kg/h m

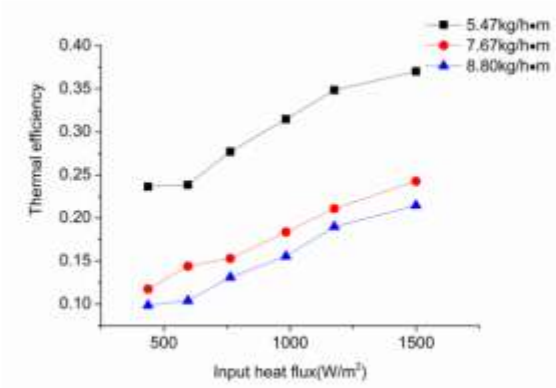


Fig. 5 η vs. input heat flux and feeding brine flow rate.

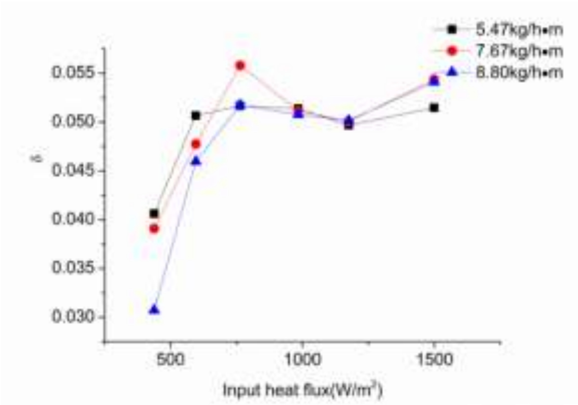
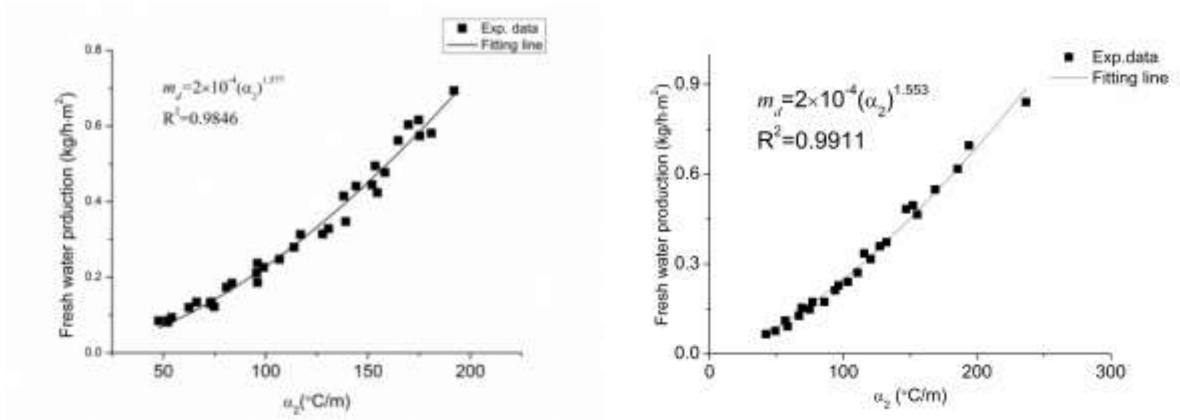


Fig. 6 δ vs. input heat flux and feeding brine flow rate.

Figure 5 shows that η increases with the increase of input heat flux and the decrease of feed brine flow rate. This indicates that a solar concentrator is practical for brine-flowing solar still. Figure 6 shows that δ increases with the increase of input heat flux when the input heat flux is less than 750 W/m^2. When the input heat flux is greater than 750 W/m^2, δ maintains unchanged at a value of ~5%. It is also seen that feed brine flow rate has little influence on the value of δ . This indicates that heat transferred from hot brine to condensation surface by convection and radiation is no more than 6% of the input heat flux for a brine-flowing type solar still. The sum of δ and η is no more than 45%. It suggests that most of input heat wastes with hot brine drained out, which should be avoided in practical application. An external pump which re-imports hot brine at the outlet of the device into still will increase the thermal efficiency.

3.2. *Empirical relations of fresh water production*

$Nu=C\ (GrPr)^n$ is not applicable due to the varying temperature (as shown in figure 4). In order to find out the relationship between the fresh water production and factors include input heating flux, feed brine flow rate, condensation condition and the inlet temperature of feeding brine, lots of experiments at conditions that feed brine flow rate are 5.47, 6.67, 7.67, 8.80 kg/h m respectively, flow rates of cooling water changes from 10 to140 kg/h ·m inlet brine temperature changes from 13 to 18 °C and heating flux changes from 400 to 1500 W/m^2 are conducted. The results show that varying cooling water flow rate brings little effect on fresh water production. This may because that the condensation surface is capable enough of condensing the vapour produced in the still. In these cases, input heat flux, inlet temperature and feed brine flow rate are the three most important factors to fresh water production. Assuming α_2 and m_d are *x* and *y* axis, respectively, experimental data and fitting lines are plotted in Figure 7 (a) and (b). The fresh water production can be expressed as: $m_d = 2\times10^{-4}\alpha_2{}^{1.553}$ for inlet temperature of 13-15 °C, and for inlet temperature of 15-18 °C : $m_d = 2\times10^{-4}\alpha_2{}^{1.577}$. According to the fitted expression and equation (4), the fresh water production is expressed as: $m_d=2\times10^{-4}\times(3.6q_f/M_{in}c_p)^b$. The value of *b* is related to the inlet temperature of the brine. Much more experiments are under going to find out the quantitative relationship between the inlet brine temperature and value of *b*.



(a) inlet brine temperature: 15-18 °C (b) inlet brine temperature: 13-15 °C

Fig. 7 Fresh water production vs. α_2.

4. Conclusion

Based on the experimental data in a simulated still, it is found that the thermal efficiency of a bring-flowing type solar still, being less than 76.3%, increases with the increase of input heat flux and decrease of feed brine flow rate. An external assisting system which re-imports hot brine into still will increase the thermal efficiency. Empirical relations are fitted to predict fresh water production by input heat flux, inlet temperature and feed brine flow rate, which are regardless of comprehensive heat and mass transfer analysis.

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