MASS TRANSFER IN TUBULAR SOLAR STILL

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1. INTRODUCTION

Numerous empirical relations for heat and mass transfer coefficients to predict the hourly or daily distilled water (production) for different type of solar stills have been developed[1)~3)]. Their mass transfer models in the still are described using the temperature and vapor pressure of the saline water surface and glass cover, neglecting the presence of intermediate medium, i.e., humid air and have used the following equation[1)] to calculate the evaporative heat flux density.

$$q_{ew} = 16.273 \times 10^{-3} \quad h_{cw}(P_w - P_{ci}) \tag{1}$$

To enhance distilled water productivity, a new type of solar distillation, i.e., Tubular Solar Still (TSS) was designed by the authors and has been tested (since 2001) in the United Arab Emirates (UAE).
In this paper, an attempt was made to formulate the mass transfer in the TSS using the humid air properties.

2. CONVECTIVE HEAT TRANSFER COEFFICIENT

The mass of air transferred from the saline water surface per unit area per unit time by free convection is

$$m_a = \frac{q_{cw}}{C_{pa}(T_w - T_{ha})} = \frac{h_{cw}}{C_{pa}} \tag{2}$$

The water vapor content of the air, i.e., the mixing ratio (mass of water vapor per unit mass of dry air) is written as

$$m = \frac{M_v}{M_a} \cdot \frac{P_w}{(P_T - P_w)} \tag{3}$$

Thus, the mass flux density of water vapor transferred from the saline water surface to the humid air is

$$m_{eww} = \frac{M_v}{M_a} \cdot \frac{P_w}{(P_T - P_w)} \cdot \frac{h_{cw}}{C_{pa}} \tag{4}$$

Similarly, the mass flux density of water vapor transferred from the tubular cover inner surface to the humid air is

$$m_{ewci} = \frac{M_v}{M_a} \cdot \frac{P_{ha}}{(P_T - P_{ha})} \cdot \frac{h_{cw}}{C_{pa}} \tag{5}$$

The net mass flux density of water vapor transferred is given by the difference of Equations (4) and (5), i.e.,

$$m_{ew} = \frac{M_v}{M_a} \cdot \frac{h_{cw}}{C_{pa}} \left[\frac{P_w}{(P_T - P_w)} - \frac{P_{ha}}{(P_T - P_{ha})} \right] = \frac{M_v}{M_a} \cdot \frac{P_T(P_w - P_{ha})}{(P_T - P_w)(P_T - P_{ha})} \cdot \frac{h_{cw}}{C_{pa}} \tag{6}$$

The heat flux density transferred from the water surface to the humid air associated with the mass transfer of the water vapor is

$$q_{ew} = \frac{M_v}{M_a} \cdot \frac{P_T(P_w - P_{ha})}{(P_T - P_w)(P_T - P_{ha})} \cdot \frac{h_{cw}}{C_{pa}} \cdot L = C \cdot h_{cw}(P_w - P_{ha}) = h_{ew}(P_w - P_{ha}) \tag{7}$$

where, $$C = \frac{M_v}{M_a} \cdot \frac{P_T}{(P_T - P_w)(P_T - P_{ha})} \cdot \frac{L}{C_{pa}} = \frac{h_{ew}}{h_{cw}} \tag{8}$$

For an air-water vapor system at normal atmospheric pressure: P_T = 101325 pa, M_v = 18, M_a = 28.96 are approved.
The production flux density is evaluated by

$$m_{ew} = \frac{q_{ew}}{L} \cdot 3600 = \frac{C \cdot h_{cw} \cdot (P_w - P_{ha})}{L} \cdot 3600 \tag{9}$$

or, $$h_{cw} = \frac{m_{ew} \cdot L}{C \cdot (P_w - P_{ha}) \cdot 3600} \tag{10}$$

3. FIELD EXPERIMENTS

Field experiments on the TSS have been carried out since September 2001, at the Hamuraniyah farm in Ras Al Khaimah Emirate in the UAE. The schematic diagram of the TSS is shown in Figure 1. The TSS is comprised of a tubular cover and a semicircular trough. The tubular cover is made of a curled transparent vinyl chloride sheet of 0.5mm in thickness and a transparent polyvinyl chloride bottle. The tubular cover is 1.26m in length and has an outside diameter of 0.134m. The black trough for storing saline water in the TSS is 1.0mm in thickness, 0.1m in outside diameter and 1.2m in length. Daily measurements of production were made at 7:00 and then saline water was supplied to the trough to maintain the initial volume of 1.5kg. Occasionally, the production was also measured on the hour from 9:00 to 20:00.
In this experiment, T_w, T_{ha}, T_{ci} and RH_{ha}, were measured in the TSS using thermocouples and thermo-hygrometers. The

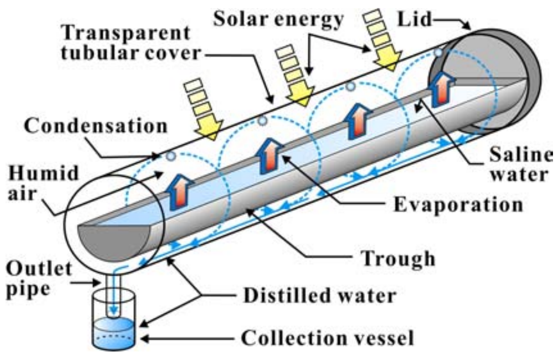

Fig. 1 Schematic diagram of TSS

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data was automatically recorded in a data logger at 30-minute intervals.

4. RESULTS AND DISCUSSIONS

In this paper, data of an arbitrary day (September 2, 2002) was used for the analysis shown in the above section.

Fig. 2 shows the variation of h_{ew}/h_{cw} with T_w. It is seen that the value of h_{ew}/h_{cw} is not a constant value of 16.273×10^{-3} used in Equation (1) as many investigators have pointed out. Table 1 shows the calculated value of h_{ew}/h_{cw} using a regression curve obtained from Fig. 2.

Fig. 3 shows the time variations of h_{ew} and h_{cw}. Both values behave a same pattern from 9:00 to 20:00.

Fig. 4 shows the relationship between D_{ph} and two kinds of vapor density differences, i.e., $(\rho_{vw}-\rho_{vha})$ and $(\rho_{vw}-\rho_{vci})$. The former relation is derived from the proposed idea and the latter is expressed based on the past theories that are represented with Equation (1). The scatter of plots for $(\rho_{vw}-\rho_{vha})$ is smaller than that for $(\rho_{vw}-\rho_{vci})$. It is seen that Equation (7) is better than Equation (1). Comparing D_{ph} to the same value of $(\rho_{vw}-\rho_{vha})$ and $(\rho_{vw}-\rho_{vci})$ in the morning and afternoon, the value of D_{ph} was slightly larger in the afternoon than the morning.

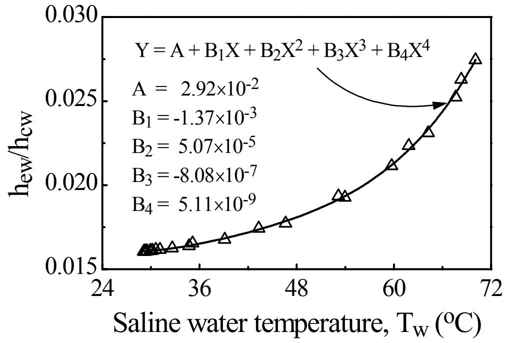

Fig. 2 Variation of h_{ew}/h_{cw} with T_w

Table 1 Value of h_{ew}/h_{cw} for TSS

Saline water temperature, T_w (°C)	Value of h_{ew}/h_{cw}
30	16.094×10^{-3}
40	16.944×10^{-3}
50	18.457×10^{-3}
60	21.299×10^{-3}
70	27.366×10^{-3}

5. CONCLUSIONS

Many researchers have still now used the semi-empirical relation formulated by Dunkle[1] for the internal heat and mass transfer in solar stills. In this paper it is observed that the value of h_{ew}/h_{cw} is not a constant value of 16.273×10^{-3} formulated by Dunkle, rather than it is a function of water temperature in the still. It is also found that the humid air plays an important role in the mass transfer in the TSS.

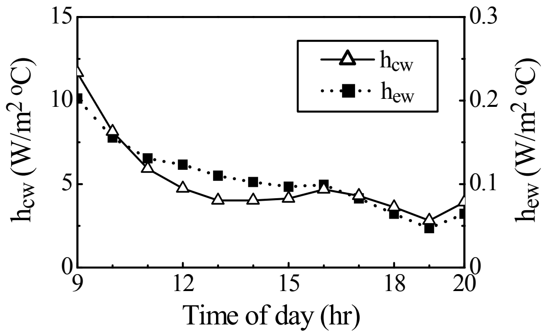

Fig. 3 Time variations of h_{cw} and h_{ew}

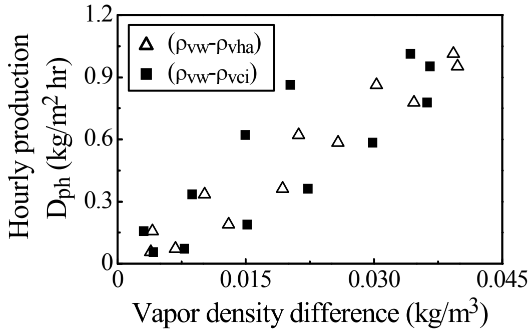

Fig. 4 Relationship between D_{ph} and vapor density difference

NOMENCLATURE

C_{pa} specific heat capacity of air, J/kg °C

h_{cw} convective heat transfer coefficient, W/m² °C

h_{ew} evaporative heat transfer coefficient, W/m² °C

L latent heat of vaporization of water, J/kg

M_a molecular weight of air

M_v molecular weight of water vapor

m_{ew} distilled water flux density (net mass flux density evaporated from saline water surface), kg/m² hr

P_{ci} saturation vapor pressure at T_{ci}, pa

P_{ha} humid air vapor pressure at T_{ha}, pa

P_T total pressure of air-water vapor, pa

P_w saturation vapor pressure at T_w, pa

q_{cw} convective heat transfer rate, W/m²

q_{ew} evaporative heat transfer rate, W/m²

RH_{ha} humid air relative humidity, %

T_{ci} tubular cover inner surface temperature, °C

T_{ha} humid air temperature, °C

T_w saline water temperature, °C

ρ_{vci} saturation vapor density at T_{ci}, kg/m³

ρ_{vha} humid air vapor density at T_{ha}, kg/m³

ρ_{vw} saturation vapor density at T_w, kg/m³

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