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EVAPORATIVE MASS TRANSFER IN TUBULAR SOLAR STILL

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SYNOPSIS

This paper proposes an evaporative mass transfer model by natural convection in a Tubular Solar Still (TSS) using a dimensional analysis which takes account of the thermal properties of the humid air inside the TSS. From our previous laboratory-TSS experiment, the evaporative mass transfer coefficient, h_{ew}, was obtained empirically. The present laboratory-evaporation experiment was carried out to investigate the variation of the hourly evaporation from the whole water surface in a trough, W, by changing the trough width, B, and length, L. These two experimental results contributed to a better understanding of two unknown parameters in the equation of h_{ew} derived by dimensional analysis. As a result, the present evaporation model was successful in calculating W using four measurable parameters: the water temperature, humid air temperature, tubular cover temperature and the relative humidity of humid air in addition to the trough size (B and L). Furthermore, the validity of the present evaporation model was supported by establishing a close correlation between the calculated hourly evaporation flux and the observed one obtained from our previous field-TSS experiment.

INTRODUCTION

Tubular Solar Still and previous evaporation models

Solar distillation is the simplest desalination technique compared with other distillation methods; namely multi-effect distillation, multi-stage flash, reverse osmosis and vapor compression. Although solar distillation has low productivity, it could be one of the viable options in the future to provide drinking and cooking water for families or small societies in remote or coastal areas from the viewpoint of reduction of carbon dioxide (CO_2) emission and economy. A basin-type solar still is the most common among the conventional solar stills. The main drawbacks of this type of still are its rapid and easy removal of accumulated salt in the basin and rapid repairs of the still. A new type of solar distillation, Tubular Solar Still (TSS) was designed by authors (Islam et al. (1)) to meet these requirements and improved some limitations of basin-type still.

Many researchers (Chaibi (2), Clark (3), Cooper (4), Dunkle (5), Hongfei et al. (6), Malik et al. (7), Shawaqfeh and Farid (8)) have focused their research on conventional basin type stills rather than other types such as tubular still. Most of the heat and mass transfer models of the solar still have been described using temperature and vapor pressure on the water surface and still cover, without noting the presence of intermediate medium, i.e. humid air (Dunkle (5), Kumar and Anand (9), Tiwari and Kumar (10)). Nagai et al. (11) and Islam et al. (1), however, found that the relative humidity of the humid air is definitely not saturated in the daytime from the field experiments conducted in the United Arab Emirates (UAE) and Japan. Since then we have examined the effects of the solar radiation and the atmospheric temperature on the hourly production of the TSS and the humid air properties were incorporated in our theoretical model. Islam (12) formulated the evaporation in the TSS based on the humid air temperature and on the relative humidity in addition to the water temperature and obtained an empirical Eq. 1 of the evaporative mass transfer coefficient (m/s), h_{ew},

$$h_{ew} = 1.37\times10^{-3} + 5.15\times10^{-4}(T_w - T_c) \quad (1)$$

where, T_w = absolute temperature of the water surface; and T_c = absolute temperature of the tubular cover. Since Eq. 1 does not have a theoretical background, it is still not known whether Eq. 1 can be used, when the trough size (width or length) is changed.

Purposes and research flow of this study

The main purposes and procedures of this study are as follows:

(1) Making an evaporation model with theoretical expression of h_{ew}
(2) Verifying the validity of the evaporation model

In this study, three steps are taken in order to attain the two purposes described above and explained by the flow diagram of Table 1.

Table 1 Flow of this study using the present and previous experimental results

Purposes	Step	Flow diagram	Application of experiments
(1)	I	Evaporative mass transfer coefficient: $h_{ew}=f(\alpha,m)$ (Derived by dimensional analysis) → (Using) → Determination of m	Present laboratory-evaporation experiment
(1)	II	(Using) → Determination of α → Formulization of h_{ew}	Previous laboratory-TSS experiment
(2)	III	(Using) → Comparison of the present evaporation model with our field experimental results → Comparison of the present evaporation model with previous models	Previous field-TSS experiment

The purpose of the first step is to determine the value of m that is one of two unknown parameters in a new theoretical expression of h_{ew} derived by dimensional analysis. To achieve this, the evaporation experiment in this study (present laboratory-evaporation experiment) was designed and thus the correlation between the trough width, B, and hourly evaporation from the whole water surface in a trough, W, identifies the value of m.

The purpose of the second step is to determine the value of α that is another unknown parameter in the theoretical expression of h_{ew} using our previous laboratory-TSS experimental results. Consequently, the formulization of h_{ew} is given in the second step and the first purpose is completed.

Finally, the purpose of the third step is to verify the validity of the evaporation model with the new h_{ew} formulized in the second step. Therefore, the calculated evaporation mass flux was compared with the observed data obtained from our previous field-TSS experiment. Furthermore, the calculation accuracy of our previous evaporation model and another model proposed by Ueda (13) is examined using the same field-TSS experimental data. Thus, the second purpose is achieved in this study.

This paper aims to formulate a model for the evaporation in a TSS using the dimensional analysis and the evaporation data obtained from our laboratory and field experiments.

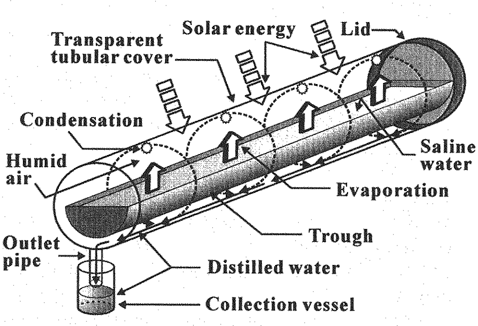


Fig. 1 Mechanism of pure water production in TSS

THEORY OF MASS TRANSFER

The TSS consists of a transparent tubular cover and a blackened semicircular trough to enable as much absorption of solar energy as possible. Saline water is poured into the trough in a TSS. The tubular cover permits the transmission of solar radiation into the still so that the saline water is heated up and the evaporation from saline water surface is enhanced. Thus, the vapor density of the humid air increases and then is condensed on the inner surface of the tubular cover. Finally, the condensed water trickles down into a collector. The production process of a TSS described above is illustrated in Fig. 1.

Humid air

The density of the humid air (After Brutsaert (14)) inside a TSS can be expressed as

$$\rho = \frac{P_o}{R_d T_{ha}}\left(1 - \frac{0.378 e_{vha}}{P_o}\right) \quad (2)$$

where, P_o = total pressure of the humid air; e_{vha} = partial pressure of water vapor in the humid air; T_{ha} = absolute temperature of the humid air; and R_d = specific gas constant of dry air. Note that $\rho=\rho_d+\rho_{vha}$, where, ρ_d = density of dry air; and ρ_{vha} = density of water vapor in the humid air. The density of the humid air on the water surface, ρ_s, can be written as

$$\rho_s = \frac{P_o}{R_d T_w}\left(1 - \frac{0.378 e_{vw}}{P_o}\right) \quad (3)$$

where, e_{vw} = saturated water vapor pressure. Similarly, $\rho_s=\rho_d+\rho_{vw}$, where, ρ_{vw} = density of saturated water vapor on the water surface. From Eqs. 2 and 3, the ratio of ρ to ρ_s is given by

$$\frac{\rho}{\rho_s} = \frac{P_o - 0.378 e_{vha}}{P_o - 0.378 e_{vw}} \cdot \frac{T_w}{T_{ha}} \quad (4)$$

Since the following conditions, $e_{vw}>e_{vha}$ and $T_{ha}\approx T_w$ are usually observed in a TSS (see Table 5), ρ is greater than ρ_s. This implies that the buoyancy of air occurs on the water surface and might increase the evaporation from the water surface.

Evaporation by natural convection

We modified a diffusion equation proposed by Ueda (13) that is applied for the evaporation from the water surface in the stagnant air with a uniform temperature. The modification of Ueda's model (present model) is attributed to the difference in the applicable condition of the diffusion equation as shown in Table 2 and is outlined below.

Table 2 Differences between present and Ueda's model

	Present model	Ueda's model[13)]
Evaporation equation (diffusion type)	$w_x = K_m \frac{e_{vw} - e_{vha}}{\delta}$	$w_x = K_o \frac{e_{vw} - e_{vha}}{\delta}$
Physical meaning of the coefficient	K_m = Dispersion due to instability of humid air	K_o = Diffusion due to molecular motion
	Air conditions on the water surface	
Temperature (°C)	Non-uniform (Upper part: low temperature, Lower part: high temperature)	Uniform
Stability of air	Unstable	Neutral

A modified diffusion equation to calculate the local evaporation mass flux, w_x, from the water surface in a trough inside a TSS is expressed as

$$w_x = K_m \frac{e_{vw} - e_{vha}}{\delta} \quad (5)$$

where, K_m = dispersion coefficient of the water vapor; x = transverse distance from the edge of the trough; and δ = effective boundary layer thickness of vapor pressure, e_v and depends on the convection due to the movement of the humid air in a TSS. K_m is expressed as the product of a new parameter, α_v, and the diffusion coefficient of water vapor in air, K_o (kg/m·s·Pa), i.e.

$$K_m = \alpha_v K_o \quad (6)$$

α_v is referred to as "evaporativity" in this paper and is influenced by not only the strength of buoyancy mentioned above (subsection "*Humid air*") but also the instability of the humid air on the water surface, because the bottom boundary temperature of the humid air, T_w, is higher than the upper boundary temperature, T_c. This is the main reason why we used K_m instead of K_o, which is expressed by the following equation,

$$K_o = \frac{D M_v}{R T_{ha}} \quad (7)$$

where, M_v = molecular weight of the water vapor; R = universal gas constant; and D = molecular diffusion coefficient of water vapor (m^2/s) at a normal atmospheric pressure and is calculated by means of the following empirical equation (After Ueda (13)),

$$D = 0.241\times10^{-4}\left(\frac{T_{ha}}{288}\right)^{1.75} \tag{8}$$

Although K_o is a function of T_{ha}, the change of K_o in the range of ordinary T_{ha} is small. For example, K_o=1.93×10^{-10} kg/m·s·Pa for T_{ha}=40°C and 2.07×10^{-10} kg/m·s·Pa for T_{ha}=70°C.

Dimensional analysis

Evaporative mass transfer is generalized by empirical equations using a dimensional analysis and correlating experimental results. Assuming that the evaporation in a TSS is induced by natural convection, the relation between δ and x is characterized using a local Grashof number, Gr, and the Schmidt number, Sc (After Ueda (13)).

$$\frac{x}{\delta} = \frac{w_x x}{\alpha_v K_o (e_{vw} - e_{vha})} = f(Gr \cdot Sc) = a(Gr \cdot Sc)^n \tag{9}$$

The coefficient a and the power n are different for convection regimes of the humid air (details in Appendix). The local Grashof number is formed as a function of x:

$$Gr = \frac{gx^3}{\nu^2}\cdot\left|\frac{\rho - \rho_s}{\rho_s}\right| \tag{10}$$

where, g = gravitational acceleration; and ν = kinematic viscosity. The Schmidt number is denoted as

$$Sc = \frac{\nu}{D} \tag{11}$$

The product of the Grashof number and the Schmidt number is expressed in the form

$$Gr \cdot Sc = A \cdot \frac{gx^3}{\nu D} \tag{12}$$

where, $A = \left|\frac{\rho}{\rho_s} - 1\right|$. Substituting Eq. 12 into Eq. 9, w_x is given by

$$w_x = a\alpha_v K_o (e_{vw} - e_{vha})\left[\frac{Ag}{\nu D}\right]^n x^{3n-1} \tag{13}$$

The total evaporation mass per hour (kg/hr), i.e. hourly evaporation, W, can be obtained by integrating the local evaporation flux over the entire water surface, that is,

$$W = 3600 \times L \times 2\int_0^{B/2} w_x dx \tag{14}$$

where, B = width; and L = length of the trough. Integrating Eq. 14 yields the following form:

$$W = C\alpha K_o L\left[\frac{Ag}{\nu D}\right]^n B^m (e_{vw} - e_{vha}) \tag{15}$$

where, α (=$a\alpha_v$) = evaporation coefficient; m=3n; and $C = \frac{3600\times 2^{1-m}}{m}$.

When the water temperature, T_w, is different from the cover temperature, T_c, the coefficient A in Eq. 12 can be approximated by the following form:

$$A = \frac{\rho - \rho_s}{\rho_s} \approx \beta(T_w - T_c) = \beta\Delta T \tag{16}$$

where, β = volumetric thermal expansion coefficient. Substituting Eq. 16 into Eq. 15, W is given by

$$W = C\alpha K_o L\left[\frac{g\beta\Delta T}{\nu D}\right]^n B^m (e_{vw} - e_{vha}) \tag{17}$$

Eq. 17 can be expressed in terms of the vapor density difference using the equation of state,

$$W = C\alpha K_o L\left[\frac{g\beta\Delta T}{\nu D}\right]^n B^m R_v (T_w \rho_{vw} - T_{ha}\rho_{vha}) \tag{18}$$

where, R_v = specific gas constant of the water vapor. Taking into account of the fact, $T_{ha} \approx T_w$, Eq. 18 is approximated as follows:

$$W = C\alpha K_o L\left[\frac{g\beta\Delta T}{\nu D}\right]^n B^m R_v \bar{T}(\rho_{vw} - \rho_{vha}) \tag{19}$$

where, $\bar{T} = \frac{T_w + T_{ha}}{2}$. Eq. 19 is transformed as

$$W = C\alpha K_o L \left[\frac{g\beta}{\nu D}\right]^n B^m R_v T^* (\rho_{vw} - \rho_{vha}) \tag{20}$$

where, $T^* = \bar{T}\Delta T^n$.

Finally, the evaporation mass flux (kg/m²/s), $w(=W/3600BL)$, is calculated by the following equation,

$$w = h_{ew}(\rho_{vw} - \rho_{vha}) \tag{21}$$

where, h_{ew} is given by

$$h_{ew} = \frac{2^{1-m}\alpha K_o}{m}\left[\frac{g\beta}{\nu D}\right]^n B^{m-1} R_v T^* \tag{22}$$

Application of the present model to the present laboratory-evaporation experiment

When the vapor pressure difference, e_{vw}-e_{vha}, α and L are constant as shown in the section "RESULTS AND DISCUSSIONS", Eq. 15 can be rewritten in terms of B,

$$W = \eta B^m \tag{23}$$

where, η (kg/m/hr) is expressed as

$$\eta = C\alpha K_o L \left[\frac{Ag}{\nu D}\right]^n (e_{vw} - e_{vha}) \tag{24}$$

Note that e_{vha} in Eq. 24 is the vapor pressure of the stagnant ambient air surrounding the trough for the present evaporation experiment (see the section "EXPERIMENTAL PROGRAM").

EXPERIMENTAL PROGRAM

Laboratory experiments

Present evaporation experiment:

The present evaporation experiment was carried out in a temperature and relative humidity controlled room to keep e_{vw} and e_{vha} constant and the same. Table 3 shows the representative factors of the experiment such as L, B, radiant heat flux, R_s, ambient temperature, T_a, and ambient relative humidity, RH_a. The purpose is to investigate the relationship between W and B and to identify the value of m in Eq. 23. For this reason, we prepared eight troughs with four different widths (0.05m, 0.1m, 0.2m and 0.3m) and two different lengths (0.49m and 1.5m). The trough was made of a corrugated carton paper of 3.0mm in thickness and covered by a black polythene film of 0.05mm in thickness. To measure the value of W, we prepared four electric balances with a minimum reading of 0.01g and each trough was placed on each electric balance. All of the electric balances were connected to computers. In this way, W was automatically and simultaneously recorded in computers at five-minute intervals. T_w was measured with a thermocouple and was recorded in a data logger. T_a and RH_a were monitored by a thermo-hygrometer.

Table 3 Present laboratory-evaporation experimental conditions and observed steady state values

Case No.	Trough length L (m)	Trough width B (m)	Radiant heat flux R_s (W/m²)	Room air conditions		Observed steady state values		
				T_a (°C)	RH_a (%)	T_w (°C)	Hourly evaporation W (kg/hr)	$Gr_B{\cdot}Sc$
1	0.49	0.05	Nil	29	21	24.1	0.0016	4.03×10^4
2		0.10				24.4	0.0031	2.70×10^5
3		0.20				24.3	0.0059	2.28×10^6
4		0.30				24.3	0.0090	7.70×10^6
5	1.5	0.05	Nil	29	21	24.0	0.0051	4.12×10^4
6		0.10				23.9	0.0090	3.47×10^5
7		0.20				24.1	0.0184	2.53×10^6
8		0.30				24.3	0.0280	7.61×10^6

Previous TSS experiment[12]*:*

The results of our previous laboratory experiment using a TSS are cited to find the properties of α in Eq. 20. The TSS was comprised of a tubular cover and a black trough in it. The length and outer diameter of the tubular cover were 0.52m and 0.13m, respectively. Evaporation was enhanced with 12 infrared lamps (125W) and was controlled by changing the radiant heat (i.e. changing the height of lamp from the TSS) and the ambient air temperature.

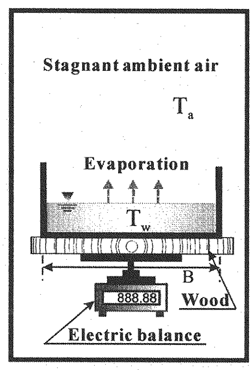
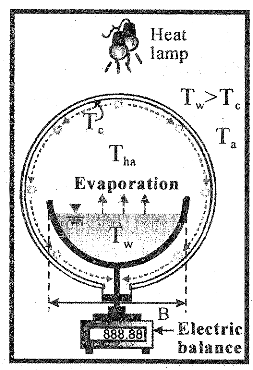
Differences between our present and previous experiments:

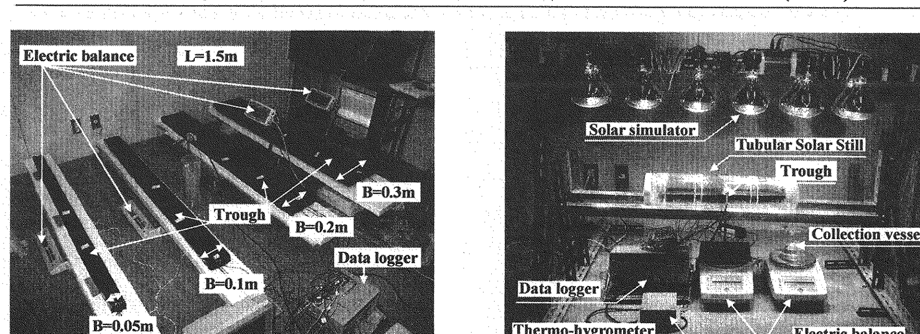
Table 4 summarizes the main differences between our present and previous experiments. The schematic views of both experiments are also drawn in Table 4. Fig. 2 shows the photographs of our present and previous experiments. The size of the trough was changed in the present evaporation experiment, but the external environment surrounding the trough maintained the same conditions. On the other hand, the external conditions (R_s and T_a) were changed in our previous experiment, but the same tough size (L=0.49m and B=0.1m) was used then.

Previous field-TSS experiment[1),15)]

In order to support the validity of the present model, our previous field experimental results are cited in this paper. The same specification of TSS was produced for both laboratory and filed experiments.

Table 4 Laboratory experimental conditions of present and previous experiments

Experiment	Present evaporation experiment	Previous TSS experiment[12)]
Schematic view		
State of evaporation	From trough in stagnant air	From trough in TSS
Main differences in experimental conditions		
Ambient temperature, T_a	Constant (29°C)	Variable (20~35°C)
Ambient relative humidity, RH_a	Constant (21%)	Constant (35%)
Radiant heat flux, R_s	Nil	Variable (500~1200W/m^2)
Width of trough, B	Variable (0.05~0.3m)	Constant (0.1m)
Length of trough, L	Variable (0.49~1.5m)	Constant (0.49m)



a) Present evaporation experiment b) Previous TSS experiment[12)]

Fig. 2 Photographs of laboratory experiments

RESULTS AND DISCUSSIONS

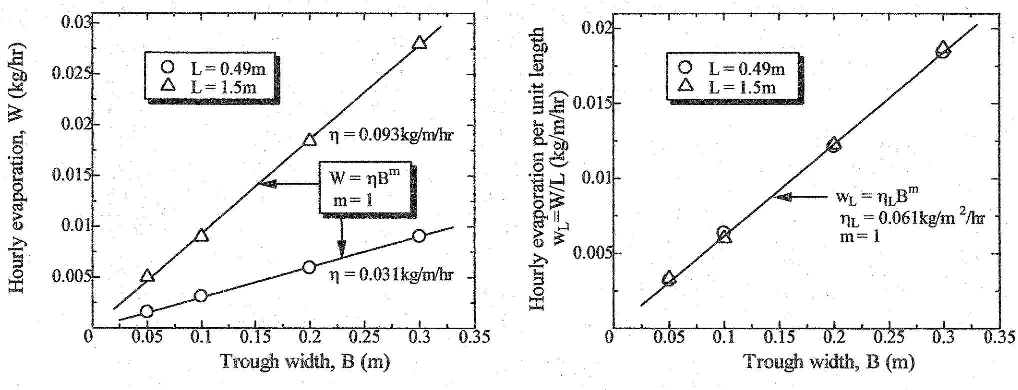
In this section, results and discussions are presented according to the research steps of the flow diagram shown in Table 1.

Results and discussions of laboratory experiments

Present evaporation experiment:

The brief results of the present evaporation experiment are also shown in Table 3. T_w for the eight different troughs were nearly the same (maximum difference 0.5°C) and T_a and RH_a were also the same (29°C and 21%, respectively). Therefore, it was established that e_{vw}-e_{vha} was the same for every experimental case. Furthermore, it is assumed that the instability of air and the strength of buoyancy on the water surface might be the same for every experimental case. Therefore, we expected that α would have the same value for every experimental case and that η is treated as a constant.

The values of $Gr_B{\cdot}Sc\left(=A\cdot\dfrac{gB^3}{\nu D}\right)$ ranged from 4.03×10^4 to 7.70×10^6. The state of air flow over the trough would be, therefore, in turbulent natural convection (see Appendix).



a) Relation between W and B b) Relation between w_L and B

Fig. 3 Variation of the hourly evaporation by changing the trough width and length

Fig. 3(a) shows the effect of the trough size (B and L) on W. W is linearly proportional to B. We found that the value of m in Eq. 23 is 1, i.e. n=1/3, regardless of L. W for L=1.5m is nearly three times larger than that for L=0.49m for the same B. Consequently, the hourly evaporation per unit length, $w_L(=W/L)$, is expressed as a function of B as shown in Fig. 3(b) and all data is on a regression straight line; $w_L=\eta_L B^m$ where $\eta_L(=\eta/L)$ is 0.061kg/m²/hr and might be independent of L for $0.49\le L\le1.5$m. The value of m is 1 and is in agreement with the results of Ueda (13).

Using η_L=0.061kg/m²/hr and m=1, α can be calculated by Eq. 24. It can be observed that the value of α is a constant (=0.06) for every experimental case, regardless of B.

Previous TSS experiment:

Table 5 shows the results of our previous laboratory-TSS experiment under twelve sets of external conditions[12]. Since the vapor density difference, ρ_{vw}-ρ_{vha}, is different for every experimental case unlike the present evaporation experiment, α should be calculated by Eq. 25 after substituting m=1 into Eq. 20,

$$\alpha=\frac{W}{3600K_oL\left[\dfrac{g\beta}{\nu D}\right]^{\frac{1}{3}}BR_vT^*(\rho_{vw}-\rho_{vha})} \qquad (25)$$

As $Gr_B{\cdot}Sc$ exceeds 4×10^4 for every case, it is inferred that the humid air flow on the trough in the TSS would be in turbulent natural convection state.

The temperature difference, T_w-T_c, might be one of the parameters that represent the instability of the humid air. Since T_w is higher than T_c (see Table 5), it is inferred that the humid air would become unstable as the temperature difference T_w-T_c (>0) increases. Based on this concept, Fig. 4 shows the relation between T_w-T_c and α. The value of α is proportional to T_w-T_c and the regression can be expressed as

$$\alpha=0.123+0.012(T_w-T_c) \qquad (26)$$

Eq. 26 is also drawn in Fig. 4. Substituting Eq. 26 and m=1 into Eq. 22, h_{ew} is given by

$$h_{ew} = [0.123 + 0.012(T_w - T_c)]\cdot\left[\frac{g\beta}{\nu D}\right]^{\frac{1}{3}} K_o R_v T^* \qquad (27)$$

The hourly evaporation mass flux, $w_h(=W/BL)$, is expressed as

$$w_h = 3600 h_{ew}(\rho_{vw} - \rho_{vha}) \qquad (28)$$

Once the four parameters (T_w, T_{ha}, T_c and RH_{ha}) are measured, w_h can be calculated by combining Eqs. 27 and 28.

Table 5 Previous laboratory-TSS experimental conditions and observed steady state values[12)]

Case No.	Radiant heat flux R_s (W/m^2)	Room air conditions		Observed steady state values					
				Temperature (°C)			Relative humidity	Hourly evaporation mass flux, w_h (kg/m^2/hr)	$Gr_B \cdot Sc$
		T_a (°C)	RH_a (%)	T_w	T_{ha}	T_c	RH_{ha} (%)		
1	1200	35	35	66.2	66.1	55.8	78	1.02	2.59×10^5
2		30		64.0	63.4	52.9	78	0.98	2.77×10^5
3		25		61.0	59.4	49.4	77	0.97	3.36×10^5
4		20		58.6	59.8	44.5	73	0.88	1.55×10^5
5	800	35	35	59.6	58.2	50.0	81	0.64	2.75×10^5
6		30		56.7	55.6	48.0	81	0.60	2.36×10^5
7		25		53.3	51.6	43.3	81	0.58	2.61×10^5
8		20		51.1	51.0	38.6	76	0.57	1.70×10^5
9	500	35	35	52.1	50.7	45.1	85	0.33	2.07×10^5
10		30		49.5	47.6	42.1	86	0.31	2.29×10^5
11		25		45.1	42.8	36.7	86	0.29	2.48×10^5
12		20		36.6	33.9	26.2	90	0.23	2.56×10^5

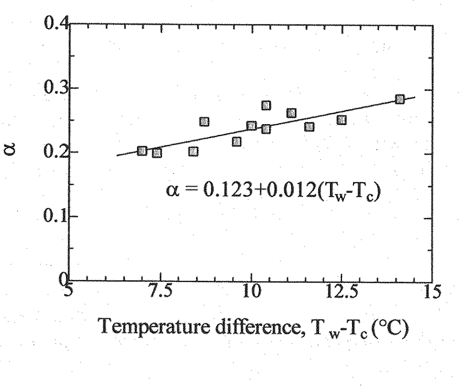


Fig. 4 Relation between the evaporation coefficient, α, and the temperature difference, T_w−T_c, obtained from the previous laboratory-TSS experiment

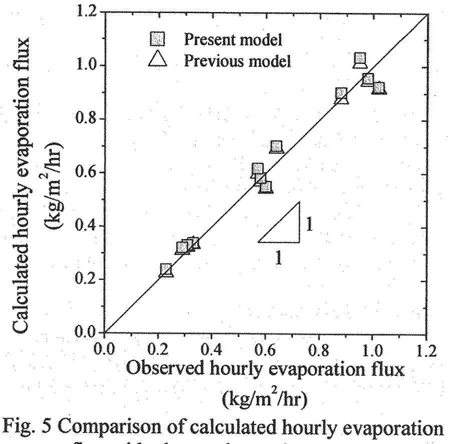


Fig. 5 Comparison of calculated hourly evaporation mass flux with observed one obtained from the previous laboratory-TSS experiment

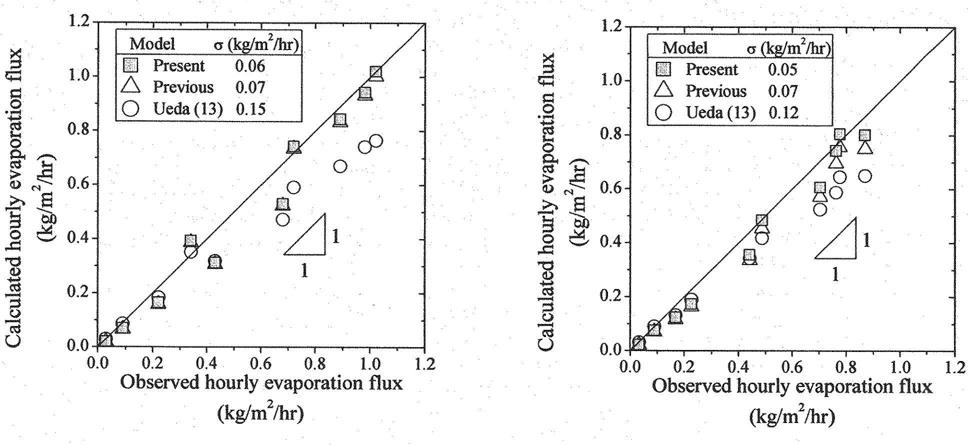
Fig. 5 shows the calculation accuracy of w_h calculated by the present evaporation model (using Eqs. 27 and 28) and our previous model (using Eqs. 1 and 28), respectively. The calculated and observed w_h are chosen as the vertical and horizontal axis, respectively. It is seen that there is no significant difference in calculation accuracy between these two models.

Results and discussions of previous field-TSS experiment

The applicability of the present and previous evaporation models were examined by comparing them with our previous field-TSS experimental results[1)] obtained in Fukui, Japan (September 29 and October 6, 2005).

Fig. 6(a) and (b) show the calculation accuracy of w_h calculated by our two models (present and previous) and Ueda's model (see Appendix). The accuracy of the present model is satisfactory and is applicable to both laboratory and field experiments. However, w_h calculated by our previous model using the empirical Eq. 1 slightly underestimates the observed w_h.

Ueda's model also underestimates the calculated value and the deviation from the observed value is largest among the three models. Using the coefficient K_o related to the molecular diffusion in Table 2 might be the reason for such underestimation. A better estimation of w_h could be found using Ueda's model when α_v (=K_m/K_o) is 1.14 (in average), assuming that the coefficient a in Eq. 9 is 0.21 for turbulent natural convection according to Ueda (13).



a) September 29, 2005 in Fukui, Japan b) October 6, 2005 in Fukui, Japan

Fig. 6 Comparison of calculated hourly evaporation mass flux with the observed value of the previous field-TSS experiment

The calculation accuracy of these three models was quantitatively evaluated by the root mean squared deviation, σ. That is,

$$\sigma = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}(w_{hoi} - w_{hci})^2\right]} \tag{29}$$

where, w_{hoi} = observed hourly evaporation mass flux; w_{hci} = calculated hourly evaporation mass flux; and N is the data number. The value of σ is given for each model in Fig. 6. The present model has the smallest σ among the three models and the difference in σ between our models (present and previous) is small. σ of Ueda's model is more than twice than that of our present model.

CONCLUSIONS

This study proposes an evaporative mass transfer model with the semi-theoretical expression of the evaporative mass transfer coefficient for a Tubular Solar Still using the dimensional analysis taking account of the humid air properties inside the still. Findings revealed from the present laboratory-evaporation experimental results that the hourly evaporation is linearly proportional to the trough width, B, regardless of the trough length, L, for $0.49 \leq L \leq 1.5$m. The movement of the humid air in the TSS belongs to turbulent natural convection state. The evaporation coefficient is proportional to the temperature difference between the water in a trough and the tubular still cover. The present model was able to reproduce the hourly evaporation mass flux obtained from our previous field-TSS experiment. We concluded that once the four parameters; that is, the water temperature, humid air temperature, tubular cover temperature and the relative humidity of humid air are measured, the present model is capable of evaluating the diurnal variation of evaporation mass flux from the water surface in a trough with an arbitrary size (B and L).

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APPENDIX-NOTATION

When a theoretical relation proposed by Ueda (13) for calculating evaporation from water surface in a plate is applied to the evaporation from the water surface in a trough inside a TSS, the hourly evaporation mass flux, w_h, is expressed as follows:

$$w_h = 3600 a K_o \left[\frac{Ag}{\nu D} \right]^n (e_{vw} - e_{vha}) \tag{A1}$$

The values of a and n are varied as follows:
a = 0.46 and n = 1/4 for the laminar natural convection ($1 < Gr_B \cdot Sc < 4 \times 10^4$); and
a = 0.21 and n = 1/3 for the turbulent natural convection ($4 \times 10^4 < Gr_B \cdot Sc$).

The following symbols are used in this paper:

B	= width of the trough (m);
D	= molecular diffusion coefficient of water vapor (m^2/s);
e_v	= vapor pressure (Pa);
e_{vha}	= partial pressure of water vapor in the humid air (Pa);
e_{vw}	= saturated water vapor pressure (Pa);
g	= gravitational acceleration (9.807 m/s^2);
Gr	= Grashof number (-);
h_{ew}	= evaporative mass transfer coefficient from water surface to humid air (m/s);
K_m	= dispersion coefficient of the water vapor (kg/m·s·Pa);
K_o	= diffusion coefficient of the water vapor (kg/m·s·Pa);
L	= length of the trough (m);
M_v	= molecular weight of the water vapor (18.016 kg/kmol);
P_o	= total pressure in the humid air (101325 Pa);
R	= universal gas constant (8315 J/kmol·K);
R_d	= specific gas constant of dry air (287.04 J/kg·K);
R_s	= radiant heat flux (W/m^2);
R_v	= specific gas constant of the water vapor (461.5 J/kg·K);
RH_a	= relative humidity of ambient air (%);
RH_{ha}	= relative humidity of humid air (%);
Sc	= Schmidt number (-);
T_a	= ambient air temperature (K);
T_c	= tubular cover temperature (K);
T_{ha}	= humid air temperature (K);
T_w	= water surface temperature (K);
$\overline{T}$	= mean temperature of water and humid air (K);
w	= evaporation mass flux ($kg/m^2 \cdot s$);
w_h	= hourly evaporation mass flux ($kg/m^2 \cdot hr$);
w_{hci}	= calculated hourly evaporation mass flux ($kg/m^2 \cdot hr$);

w_{hoi} = observed hourly evaporation mass flux ($kg/m^2 \cdot hr$);
w_L = hourly evaporation per unit length ($kg/m \cdot hr$);
w_x = local evaporation mass flux ($kg/m^2 \cdot s$);
W = hourly evaporation (kg/hr);
x = transverse distance from the edge of trough (m);
α = evaporation coefficient (-);
α_v = evaporativity (-);
β = volumetric thermal expansion coefficient (1/K);
δ = effective boundary layer thickness of vapor pressure (m);
ΔT = temperature difference between water surface and cover (K);
ν = kinematic viscosity (m^2/s);
ρ = density of humid air (kg/m^3);
ρ_d = density of dry air (kg/m^3);
ρ_s = density of humid air on the water surface (kg/m^3);
ρ_{vha} = density of water vapor in the humid air at T_{ha} (kg/m^3);
ρ_{vw} = density of saturated water vapor on the water surface at T_w (kg/m^3); and
σ = root mean squared deviation ($kg/m^2 \cdot hr$).

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