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MODELLING AND SIMULATION OF A LOCAL SOLAR STILL

Byung Jun YOON, Hyun-Ku RHEE and Won-Hoon PARK*

Department of Chemical Engineering, Seoul National University
*Korea Advanced Institute of Science and Technology, Seoul, Korea

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Abstract— Presented here is a mathematical model study of a prototype solar still built at Jug Island near Gunsan City. A pair of ODE was solved numerically with auxiliary equations to demonstrate that the predicted water productivity was in good agreement with experimental values. Monthly average water absorptance was the major factor that influenced the solar still performance. It was also found that the initial water depth, the degree of insulation and the ambient temperature had significant influence upon the water productivity, whereas the wind velocity, the cover slope and the still orientation exhibited negligible effects.

INTRODUCTION

The solar still is basically a simple unit in which saline or brine water is distilled to fresh water by utilizing the solar energy passing through a transparent cover. The attractiveness of this technique lies in the availability of a free energy supply. Some of its disadvantages are the requirement of large surface area and the high capital cost.

The performance of a solar still is directly affected by various factors such as design parameters, the solar radiation, and the weather conditions. These factors are interrelated to one another in such a complicated fashion that it is very difficult to obtain or to correlate all the data required for the design and operation of a solar still from time-consuming experiments. Such difficulties may be overcome by developing a mathematical model based on the material and energy conservation laws applied to a solar still and by analyzing the influences of various parameters on the still performance.

A considerable amount of development work has been carried out on solar stills since 1872 [1,2]. Since Löf et al. [3] developed the mass and energy balance equations for a solar still, many simulation and experimental works have been published [4-14]. The thermal characteristics of a solar still such as overall efficiency, internal efficiency, absorptivity and heat transfer have been discussed by Cooper [4,5] and Löf et al. [3]. The effects on the still performance of various parameters such as water depth, wind velocity, still insulation, number of glazing, cover slope, and daily variability have been studied extensively by many investigators [6,7,9,13,14].

In the present study, we developed a mathematical model for a local solar still constructed by KIST [15] for water supply in Jug Island off Gunsan City in 1980, and computer simulations are performed on this model. It is believed that this work will render a valuable contribution to the design and operation of a solar still under mild weather conditions of solarwise northern countries like Korea.

EXPERIMENT

Site description

Many of remote small islands in Korea suffer from the shortage of drinking water from June to November, and this problem can be solved by using the solar still method which converts saline water to fresh water. As the first step toward the feasibility study of this method, a pilot basin-type solar still was constructed at Jug Island in May, 1980, which is located about 10 km west from Gunsan City, Jeonlabuk-do. In Table 1, brief description of Jug Island is given.

Design and construction

Most of solar stills are designed in basin type [2] because it is easy to construct and operate. Four units were constructed with materials specified in Table 2. These units have a similar shape of double sloped symmetrical covers as shown in Fig. 1. Units 1, 2, and 3 have glass covers with 10, 15 and 20 degrees slopes, respectively, while Unit 4 is covered with Tedlar with the cover slope of 20 degrees as shown in Fig. 2. A schematic diagram of the pilot solar still is shown in Fig. 3.

*To whom all correspondence should be addressed.

Table 1. Site Description of Jug Island.

No. of villages	1
Inhabitants	28
Mobile population (Total)	10-15 (38-43)
No. of wells	2
Available drinking water amount	60-80 l/day
Dry season	Mar.-May, Sep.-Nov.
Water supply from inland supplier	Mi-Myeon branch office
Available idle lot for solar still	660 m^2

Location: Jugdo-ri, Mi-myeon, Ogku-gun, Jeonlabuk-do

Table 2. Construction material.

Foundation	Concrete
Still body	Cement + Sand
Basin lining	Butyl rubber (0.8 mm)
Cover	Glass (Unit 1, 2, 3) (3 mm) Tedlar film (PVF) (0.1 mm)
Cover frame	Stainless steel (1 mm)
Distillate trough	Cement
Sealant	Silicone rubber sealant
Piping	PVC
Valves	PVC
Storage tanks	Concrete PE tank

Experimental results

The test experiment of the solar still began in July, 1980 and the results are summarized in Table 3 and Fig. 4. It is evident that the overall efficiency of the Jug Island still was lower than those reported in the literature. It is probably due to the particular weather conditions of Jug Island. The performance of Unit 4 with Tedlar film cover was inferior to those with glass covered units, and the glass covered unit with 15 degrees slope (Unit 2) turned out to be the most efficient one.

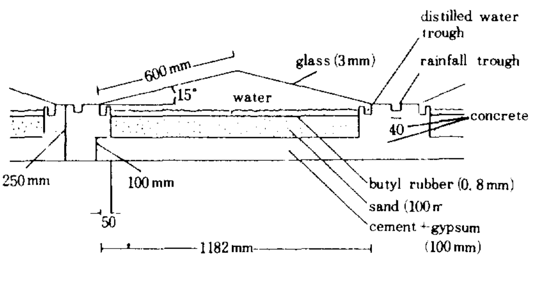

Fig. 1. Front view of the solar still (slope 15°).

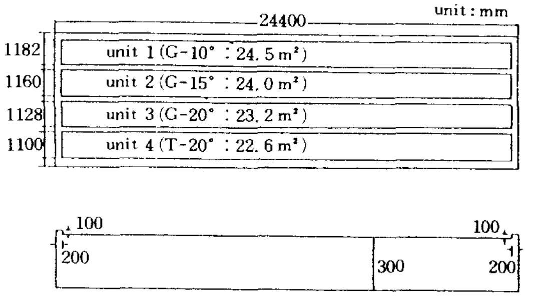

Fig. 2. Base and sidewall of the solar still.

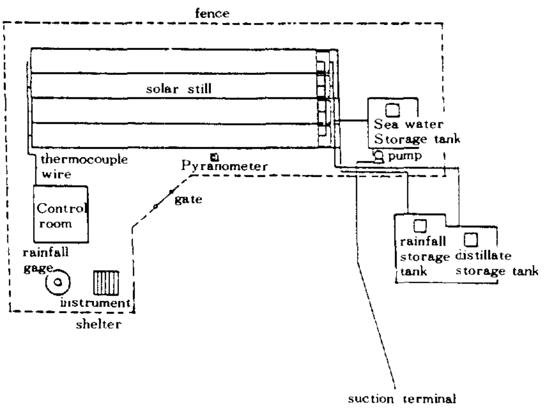

Fig. 3. A Schematic diagram of the pilot plant scale solar still.

MATHEMATICAL FORMULATIONS

Energy balances

The major heat fluxes which govern the performance

Table 3. Experimental results from the pilot solar still.

Month	No. of Experiment	Insolation (cal/cm²-day)	Productivity of each unit (l/m^2-day)				Total productivity
			1	2	3	4	
'80.7	19	314					0.97
8	11	359	1.7	0.02	1.84	1.20	1.69
9	20	409	1.14	1.57	1.68	1.26	1.41
10	19	391	1.07	1.35	1.38	1.00	1.20
'81.4	12	193	1.18	1.62	1.41	1.04	1.32
Avg.			1.23	1.59	1.56	1.12	1.38

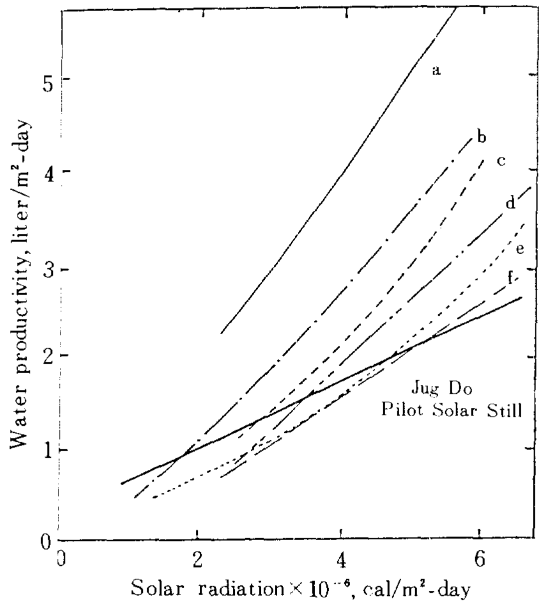

Fig. 4. Productivity comparison of Jug Do pilot solar still with others.

a. Church World Service; Daytona Beach, $50m^2$, inflated plastic, insulated basin.
b. Greece Patmos, $8600m^2$; Kimolos, $2500m^2$, Nisiros, $2000m^2$.
c. Battelle, Daytona Beach, $230m^2$, original and $250m^2$, second deep basin.
d. University of alifornia, $23m^2$, sawtoothtype cover.
e. CSIRO, Muresk, Australia, $370m^2$, Mark I & II designs.
f. Dupont, Daytona Beach, $220m^2$, inflated plastic.

of a solar still are shown schematically in Fig. 5. The solar radiation energy H_s is absorbed in part by the still cover and saline water with fractions of α_g and α_w, respectively. The energy balances are based on the assumptions as follows [6]:

1. The still is completely sealed so that no vapor leakage is present.
2. No temperature gradients exist within the cover and the saline water.

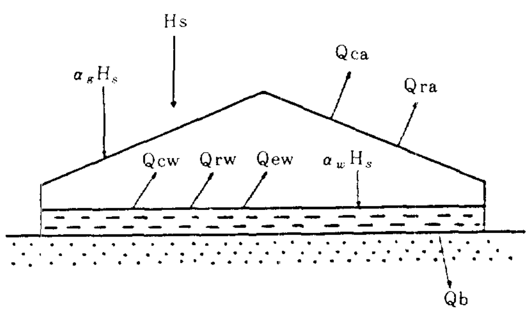

Fig. 5. Heat fluxes in a solar still.

3. Heat capacities of the cover and water remain constant.
4. The concentration of the saline water and its density remain constant.
5. The water vapor inside the still does not absorb the radiation energy.

(Saline water)

$$C_w A_w \frac{d}{dt}(mT_w) = \alpha_w H_s A_w - (Q_{cw} + Q_{rw} + Q_{ew} + Q_b) A_w \quad (1)$$

(Cover)

$$C_g A_g \frac{d}{dt}(T_g) = \alpha_g H_s A_g + (Q_{cw} + Q_{rw} + Q_{ew}) A_w - (Q_{ca} + Q_{ra}) A_g \quad (2)$$

The interpretations of the absorptance of the saline water α_w and the cover absorptance α_g will be made later. The expressions for the convective, radiative and evaporative heat fluxes are given below:

$$Q_{cw} = 159\,[T_w - T_g + A(T_w + 273)]^{1/3}(T_w - T_g) \quad (3)$$

$$Q_{rw} = F_s\,\sigma\,[(T_w + 273)^4 - (T_g + 273)^4] \quad (4)$$

$$Q_{ew} = Q_{em} h_w$$
$$= 2220.\,[T_w - T_g + A(T_w + 273)]^{1/3}(P_w - P_g) h_w$$
$$A = (P_w - P_g)/(2.655 - P_w) \quad (5)$$

where F_s is assumed to be a constant, 0.9. The partial pressure P_w is given by the following relationship:

$$P_w = 218.26 \times 10^{(X/T)(a + bX + cX^2)/(1 + dX)} \quad (6)$$

with $X = 647.27 - T$, $a = 3.24378$, $b = 0.00586826$, $c = 1.17024 \times 10^{-8}$, $d = 0.00218785$,

where T is in K. The water production rate, Q_{em}, is determined by using eqn. (5) and the latent heat of vaporization h_w given by the following equation:

$$h_w = 755.1 - 0.575(T_w + 273) \quad (7)$$

For heat losses through the ground and side walls, and the convective heat losses to the air, we use the following formulae:

$$Q_b = h_b (T_w - T_a) \quad (8)$$

$$Q_{ca} = h_{ga}(T_g - T_a) \quad (9)$$

$$Q_{ra} = \varepsilon_g \sigma [(T_g + 273)^4 - (T_a + 273)^4] \quad (10)$$

where h_{ga} can be determined from the correlation given in [6]:

$$h_{ga} = 4830 + 3360W;\quad W < 4.92\ \text{m/sec}$$
$$h_{ga} = 6170 \times W^{0.78};\quad 4.92 < W < 30.8\ \text{m/sec} \quad (11)$$

The temperature of the sky is assumed to be 11.1°C below the ambient temperature.

Absorption of radiation

The absorptances of the solar still are the major parameters in determining the still performance. Many factors influence the absorptances; i.e., angle of incidence θ, cover thickness s, extinction coefficient K, and the refractive index R of the cover. The relation of θ with other angular parameters is given in detail elsewhere [16]. The water absorptance through the cover material for arbitrary angle of incidence can be obtained from the following correlation given by Duffie and Beckman [16];

$$\alpha_w = \tau\alpha/[1-(1-\alpha)\rho_d]$$
$$\tau = 0.5[(1-\rho_1)/(1+\rho_1)+(1-\rho_2)/(1+\rho_2)]\exp(-Ks/\cos\theta_2)$$
$$\rho_1 = \sin^2(\theta_2-\theta_1)/\sin^2(\theta_2+\theta_1), \qquad (12)$$
$$\rho_2 = \tan^2(\theta_2-\theta_1)/\tan^2(\theta_2+\theta_1),$$
$$\theta_2 = \sin^{-1}(\sin\theta_1/R)$$

where α_u is the ultimate energy absorption through the multiple reflection of diffuse radiation and τ is the transmittance considering both absorption and reflection. The last equation represents the Snell's law. For the present work the following values taken from the reference [16] were used for the computation of monthly average water absorptance shown Figs. 6 and 7;

$\alpha = 0.94$, $\rho_d = 0.16$, $s = 0.3$ cm,

$K = 0.16$/cm, $R = 1.526$

The number on each curve in Figs. 6 and 7 denotes the month of a year. The effects of cover slope and still orientation are shown in Figs. 8 and 9, respectively.

Since it can be shown that the variation of the cover absorptance is not significant, we assume that the cover absorptance α_g remains constant. For the glass cover system, we use 0.06 for α_g.

NUMERICAL ANALYSIS AND RESULTS

For the prediction of the performance of a solar still first order ordinary differential equations (1) and (2) with

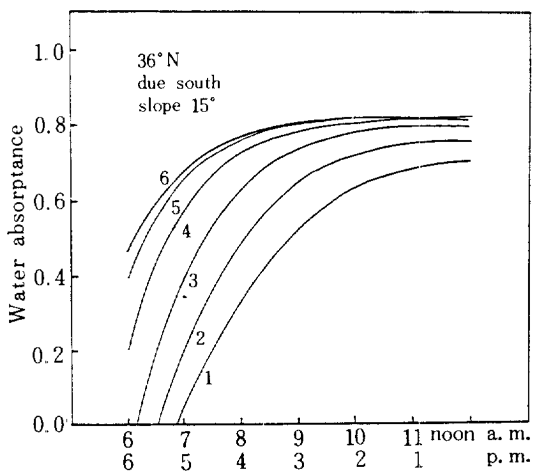

Fig. 6. Monthly average water absorptance.

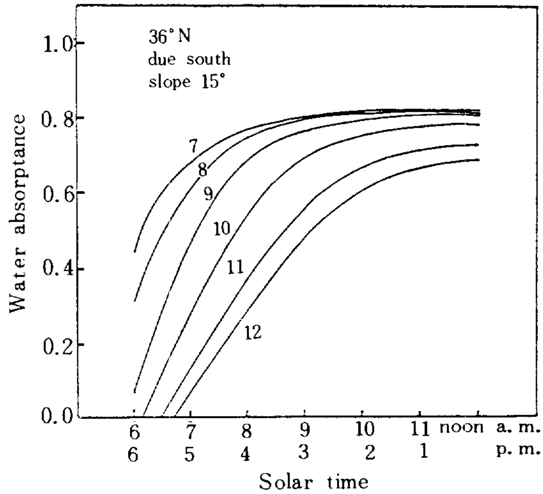

Fig. 7. Monthly average water absorptance.

auxiliary equations (3) to (6) were solved using the Runge-Kutta method. Input data are the solar radiation, the ambient temperature and the water absorptance as functions of the time. Hourly solar radiation data were not easy to obtain, so we used the following formula;

$$H_S = H_t/2t_S \sin[t/t_S(1+\cos V\pi t/t_S)] \qquad (13)$$

where the intermittency factor, V, represents the departure from the clear day profile.

In the numerical calculation values of ambient temperature and water absorptance at each hour of a day are given and the linear interpolation procedure is employed to determine intermediate values. Initial temperatures of the cover and the saline water were assumed to be the same as that of the ambient air.

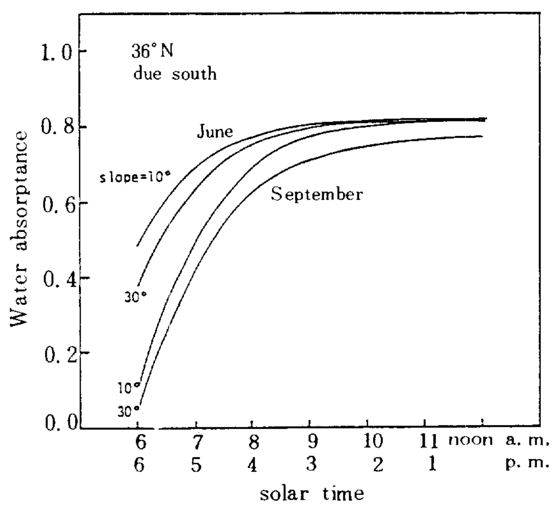

Fig. 8. Water absorptance for different cover slopes.

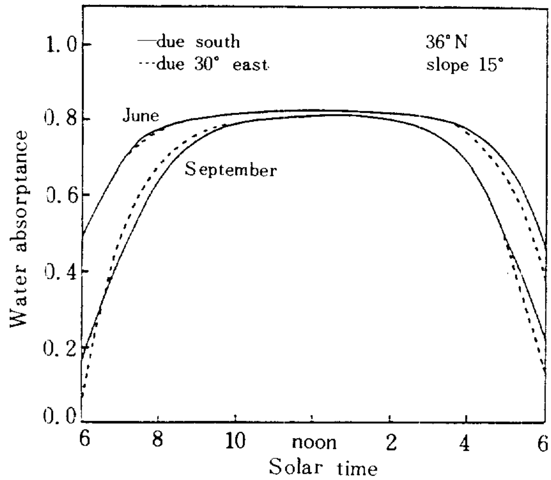

Fig. 9. Water absorptance for different still orientations.

Comparison with experiments.

The numerical results are compared in Fig. 10 with experimental data taken from the pilot solar still of cover slope 15° with orientation due south. Although the experimental data are widely scattered, we observe that both are in fair agreement.

To give a guideline for the design and operation of a solar still, the monthly average water productivity is calculated and presented in Fig. 11. For this computation the monthly average values of daily insolation and the ambient temperature around Gunsan area were used (see Table 4). It is estimated that the pilot solar still can produce about 1.4 liter of water per square meter in summer.

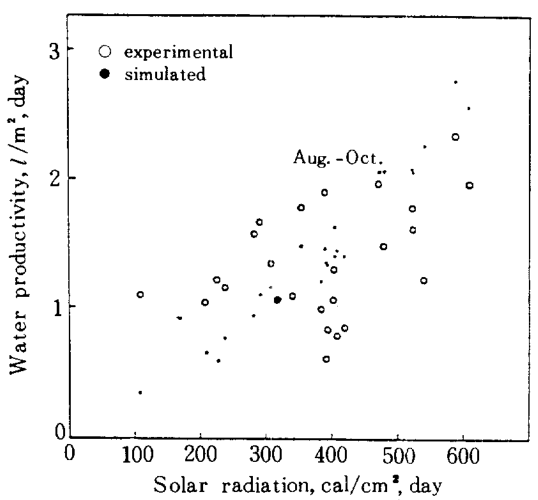

Fig. 10. Water productivity comparison of Unit 2(cover slope 15°) between the experimental values and the simulation results.

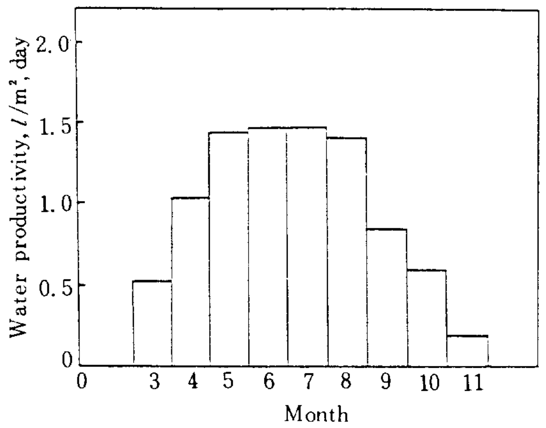

Fig. 11. Monthly average water productivity of a solar still in Gunsan area.

Table 4. Monthly average weather condition around Gunsan area.

Month	Daily insolation cal/cm²-day	Average ambient temperature, ℃
March	283.7	4.8
April	370.1	11.3
May	420.0	16.6
June	401.6	21.4
July	380.7	26.8
August	375.7	25.7
September	288.4	21.7
October	266.6	16.1
November	162.2	9.0

Effects of parameters

To study the effects of various parameters such as structural and weather conditions, we choose the reference conditions as shown in Table 5.

1. Solar radiation

The effect of solar radiation on the water productivity is shown in Fig. 12. It is found that both the water productivity and the temperature difference between the saline water and the cover increase as the solar radiation increases.

2. Initial saline water depth

The effect of the initial water depth on the water productivity is shown in Fig. 13. The greater the initial depth is, the lower the water productivity becomes. The average temperature difference between the saline water and the cover decreases as the initial depth increases.

Table 5. Standard parameters for the parametric study.

latitude	36° N
cover slope	15°
still orientation	due south
water absorptance	data of June
daily solar radiation	400 cal/cm²-day
initial saline water depth	4 cm
heat loss	none
wind velocity	5 cm/sec
average ambient temperature	20℃

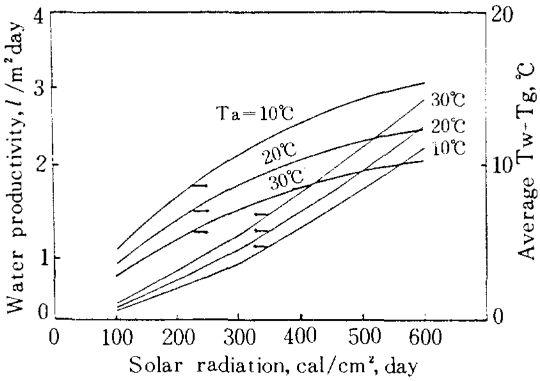

Fig. 12. Water productivity and water-cover temperature difference for various values of the solar radiation.

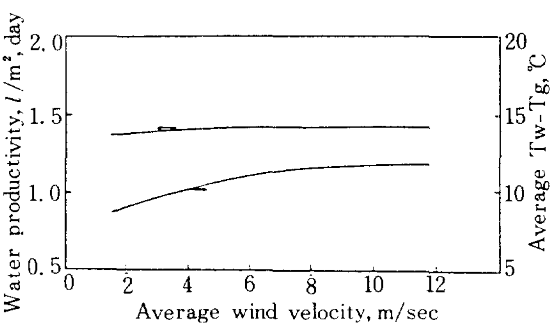

Fig. 14. Water productivity and water-cover temperature difference for various wind velocities.

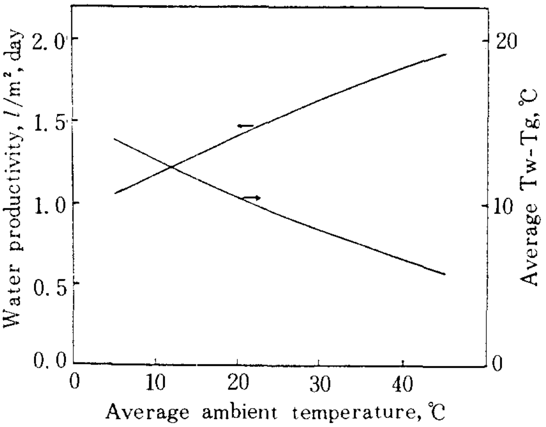

Fig. 15. Water productivity and water-cover temperature difference for various average ambient temperatures.

3. Wind velocity

Fig. 14 shows that the water productivity increases with the wind velocity but the effect is not significant.

4. Average ambient temperature

The higher the ambient temperature, the greater the water productivity becomes as shown in Fig. 15. The average temperature difference between the saline water and the cover decreases as the ambient temperature increases.

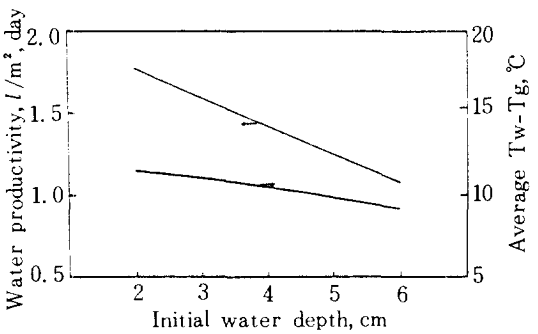

Fig. 13. Water productivity and water-cover temperature difference for various initial water depths.

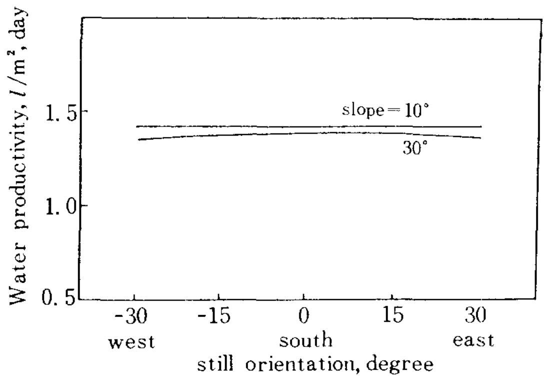

Fig. 16. Water productivity for various still orientations.

5. Cover slope and orientation

Fig. 16 shows that the effects of the cover slope and the still orientation are not significant.

CONCLUSION

From the present simulation work of a local solar still the following conclusions are derived.

1. The water productivity estimated by the mathematical model is in good agreement with experimental results, so the model may be used to provide a guideline for the design and operation of solar stills.
2. The water aborptance is the major factor that influences the water productivity.
3. A lower inital depth of saline water and a higher ambient temperature are favored for higher water productivity.
4. The effects of cover slope, orientation of the solar still and wind velocity are less significant under the mild weather conditions in Korea.

NOMENCLATURE

A_g : surface area of cover, m^2
A_w : surface area of saline water, m^2
C_g : area specific heat of cover, cal/m^2 °C
C_w : specific heat of saline water, cal/m^2 °C
F_s : shape facter of a still
h_b : local heat transfer coefficient to ground and side wall cal/m^2hr °C
h_{ga} : convective heat transfer coefficient to the air, cal/m^2hr °C
H_s : solar radiation, cal/m^2hr
H_t : daily solar radiation, cal/m^2day
h_w : latent heat of vaporization, cal/g
K : extinction coefficient of the cover material, cm^{-1}
m : mass of the saline water in unit area, g/m^2
P_g : partial pressure of water vapor at cover temp., atm
P_w : partial pressure of water vapor at saline water temp., atm
Q_b : ground and side wall heat losses, cal/m^2hr
Q_{ca} : convective heat flux from the cover, cal/m^2hr
Q_{cw} : convective heat flux from saline water, cal/m^2hr
Q_{em} : water production rate, liter/m^2hr
Q_{ew} : evaporative heat flux from saline water, cal/m^2hr
Q_{ra} : radiative heat flux from the cover, cal/m^2hr
Q_{rw} : radiative heat flux from saline water, cal/m^2hr
R : refractive index of the cover material
s : cover thickness, cm
t : time, hr
t_s : time from sunrise to sunset, hr
T : temperature, K
T_a : ambient temperature, °C
T_g : cover temperature, °C
T_w : saline water temperature, °C
V : intermittency factor
W : wind velocity, m/sec

Greek Letters

α : angular absorptance of saline water
α_g : cover absorptance
α_w : water absorptance
ε_g : emissivity of the cover
θ : angle of incidence, degree
ρ_d : reflectance
ρ : diffuse reflectance
σ : Stefan-Boltzmann constant

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