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Optimum inclination of still and bottom reflector for tilted wick solar still with flat plate bottom reflector

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ABSTRACT

In this report we present a theoretical analysis of a tilted wick solar still with a flat plate bottom reflector extending from the lower edge of the still. We theoretically predicted the daily amount of distillate produced by the still, and determined the optimum inclination of both the still and the reflector throughout the year at 30˚N latitude, both of which vary considerably from month to month and is slightly affected by the ratio of reflector length to still length. An increase in the daily amount of distillate produced by the still in comparison to a conventional tilted wick solar still would average about 21, 28 and 33% throughout the year by using a flat plate bottom reflector, and adjusting the inclination of both the still and the reflector to a proper angle for each month when the ratio of the reflector length to still length is 0.5, 1.0 and 2.0, respectively.

Keywords: Solar desalination; Solar distillation; Solar still; Tilted wick; Bottom reflector; Mirror

1. Introduction

An external reflector has the potential to increase the distillate productivity of a tilted wick solar still which basically consists of an evaporating wick and a glass cover, as indicated by Mahdi and Smith [1] and Al-Karaghouli and Minasian [2]. However, a detailed and quantitative analysis on the effect of an external reflector on a tilted wick solar still had not been reported.

Therefore, we have performed a numerical analysis on a tilted wick solar still with a flat plate top reflector extending from the upper edge of the still [3–7]. We presented the geometrical models to calculate the solar radiation reflected from a top reflector (vertical [3], and slightly inclined forwards [5] and backwards [6]) and then absorbed on the evaporating wick. We also performed a numerical analysis of heat and mass transfer in the still to predict the distillate productivity of the still. As a result, we found that a tilted wick solar still with a flat plate top reflector can produce an average of about 21%, more than a conventional tilted wick solar still throughout the year, when the height of the reflector is half of the still length and both the top reflector and the still is set to the optimum inclination for each month [7].

In addition, we have recently performed a numerical analysis to determine the effect of a flat plate bottom reflector extending from the lower edge of the still as shown in Fig. 1, on the distillate productivity of a tilted wick solar still [8], since the bottom reflector would also serve to increase the solar radiation

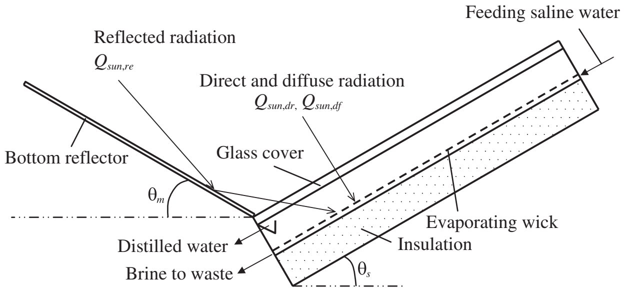

Fig. 1. Schematic diagram of a tilted wick solar still with a bottom reflector which can be inclined from horizontal.

absorbed on the evaporating wick as well as the distillate productivity of a tilted wick solar still. The amount of solar radiation reflected from the bottom reflector and absorbed on the evaporating wick cannot be calculated by the geometrical models of the top reflector [3,5,6]. Therefore, in our previous paper [8], we presented a new geometrical model to calculate the solar radiation reflected from the bottom reflector and then absorbed on the evaporating wick, and predicted the distillate productivity of the still using a heat and mass transfer model of the still. We determined the optimum inclination of the bottom reflector which maximizes the daily amount of distillate for four typical days (spring and autumn equinox and summer and winter solstices), and found that the bottom reflector can increase the daily amount of distillate produced by a tilted wick solar still to about 13% when the reflector length is the same as the still length and the still inclination is fixed at 30˚ throughout the year at 30˚N latitude.

One of the advantages of a tilted wick solar still is that the inclination angle of the still can be easily changed according to the seasons or months. So, the optimum inclination of the still as well as the optimum inclination of the bottom reflector of the tilted wick solar still should be adequately determined by considering the combination of the effects of these two inclinations to increase the distillate productivity of the still. Therefore, in this paper, we determine the optimum inclination angle of the still as well as the bottom reflector of the tilted wick solar still according to months, and the effect of the reflector length on the daily amount of distillate produced by the still at 30˚N latitude.

2. Theoretical analysis

The proposed still is shown in Fig. 1. The still consists of a glass cover, an evaporating wick, bottom insulation and a flat plate bottom reflector of highly reflective materials such as mirror-finished metal plate, which extends from the lower edge of the still. Saline water is fed to the wick constantly. The inclination angle of the still and of the bottom reflector from horizontal are defined as θ_s and θ_m, respectively. The still is assumed to be facing due south. The direct and diffuse solar radiation and also the reflected solar radiation from the bottom reflector are transmitted through the glass cover and absorbed onto the wick. The evaporation and condensation processes occur between the wick and the glass cover. The distilled water is gathered by a channel placed under the surface of the glass cover and the excess concentrated saline water flows out from the still.

The method used to calculate the amount of direct, diffuse and reflected solar radiation absorbed on the wick was described in detail in our previous paper [8], so an outline of the calculation is shown here. Fig. 2 shows a schematic diagram of the shadow of the still, and the shadow and reflected projection of the bottom reflector on a horizontal surface caused by a direct solar radiation. l_s or l_m is the length of the still (shown as ABCD) or the bottom reflector (shown as ABEF), and θ_s or θ_m is the inclination angle of the still or the reflector from horizontal, respectively. w is the width of both the still and the reflector. φ and ϕ are the azimuth and altitude angle of the sun, respectively. The shadow of the evaporating wick and the bottom reflector, and the reflected projection from the bottom reflector on a horizontal surface caused by direct solar radiation are shown as ABC´D´, ABE´F´ and ABE´´F´´, respectively. Here, the shadows of the evaporating wick and the glass cover would be approximately the same, since the height of the walls (10 mm) is negligible in relation to the still's length (1 m) and width (1 m).

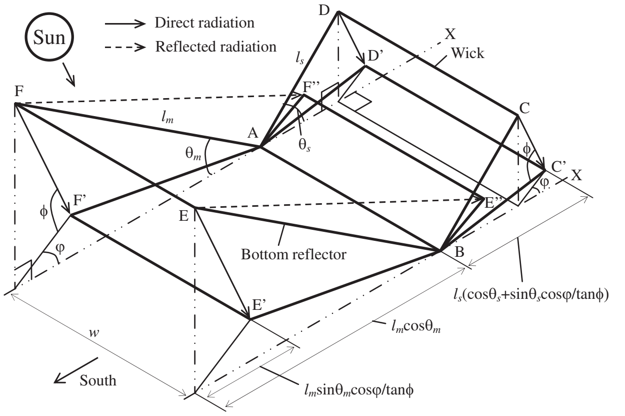

Fig. 2. Shadows of the still and bottom reflector and reflected projection of the reflector on a horizontal surface.

The direct and diffuse solar radiation absorbed on the wick, $Q_{\mathrm{sun,dr}}$ and $Q_{\mathrm{sun,df}}$, can be determined as follows:

$$Q_{\mathrm{sun,dr}} = G_{\mathrm{dr}}\tau_{\mathrm{g}}(\beta)\alpha_{\mathrm{w}} \times wl_{\mathrm{s}}(\cos\theta_{\mathrm{s}} + \sin\theta_{\mathrm{s}} \times \cos\varphi/\tan\phi) \quad (1)$$

$$Q_{\mathrm{sun,df}} = G_{\mathrm{df}}(\tau_{\mathrm{g}})_{\mathrm{df}}\alpha_{\mathrm{w}} \times wl_{\mathrm{s}} \quad (2)$$

where G_{dr} or G_{df} is the direct or diffuse solar irradiance on a horizontal surface, τ_{g} is transmittance of the glass cover, β is the incident angle of sunrays to the glass cover, α_{w} is absorptance of the wick and $(\tau_{\mathrm{g}})_{\mathrm{df}}$ is transmittance of glass cover for diffuse radiation which is a function of the still's inclination [8].

Not all of the reflected solar radiation from the bottom reflector can be absorbed by the wick, and part of or all of the reflected radiation would escape to the ground or the surroundings without hitting the wick. To calculate the solar radiation reflected by the bottom reflector and absorbed by the wick, a mirror-symmetric plane of the wick to the bottom reflector is introduced as shown in Fig. 3. The still (ABCD) and the reflector (ABEF) are exactly the same as those in Fig. 2. ABGH is a mirror-symmetric plane of the wick to the bottom reflector.

The incident point and incident angle of the reflected radiation, which is reflected by the bottom reflector and reaches the wick, and those of the direct radiation which goes through the bottom reflector and reaches the mirror-symmetric plane are exactly the same. So, the direct radiation reflected by the bottom reflector and absorbed by the wick can be calculated by determining the amount of direct radiation which goes through the bottom reflector and is absorbed on the mirror-symmetric plane. The shadow of the bottom reflector and the mirror-symmetric plane caused by direct radiation on a virtual horizontal surface, X''', on which the mirror-symmetric plane is placed, is shown as A‴B‴E‴F‴ and A‴B‴GH, respectively. The amount of reflected radiation from the reflector which can be absorbed by the wick can be determined as the overlapping area of these shadows (a trapezoid A‴B‴IH). Therefore, the solar radiation reflected from the bottom reflector and absorbed by the wick, $Q_{\mathrm{sun,re}}$, can be determined as

$$Q_{\mathrm{sun,re}} = G_{\mathrm{dr}}\tau_{\mathrm{g}}(\beta')\rho_{\mathrm{m}}\alpha_{\mathrm{w}} \times (l_3 + l_4)\{w - 0.5(l_2 + l_7)\} \quad (3)$$

where β' is the incident angle of reflected sunrays to the glass cover and ρ_{m} is the reflectance of the reflector. The lengths in Eq. (3) can be calculated with the lengths (l_1–l_8) and angles (ω_1–ω_3) as shown in Fig. 3. There are some exceptions when calculating Eqs. (1) and (3) as described in our previous paper [8].

When the altitude angle of the sun ϕ is too small in relation to the reflector inclination θ_{m}, the bottom reflector would shade a part of the wick. In these calculations, the effect of the shadow is taken into consideration. The way to calculate the effect of shadow of the bottom reflector on the wick was also described in our previous paper in detail [8].

Heat and mass transfer in the still was described in our previous paper in detail [8], which was basically the same in content as previous papers by Elsayed [9], Tanaka et al. [10] and Tanaka and Nakatake [3]. The equations of both the solar radiation ($Q_{\mathrm{sun,dr}}$, $Q_{\mathrm{sun,df}}$ and $Q_{\mathrm{sun,re}}$) and the energy balance for evaporating wick and glass cover, and the equations of properties were solved together to find the solar radiation absorbed on the wick, the temperature of the wick and glass cover and the distillate production rate throughout the day with 600 s time steps. Temperatures of the wick and the glass cover were set to be equal to the ambient air temperature at just before sunrise as the initial condition. The temperature and wind velocity of the ambient air were determined as the boundary conditions. The design and weather conditions are listed in Table 1.

3. Results

In this paper, the daily amount of distillate of the still is defined as that per unit effective glass cover area through which the solar radiation transmits. Fig. 4 shows the daily amount of distillate produced by a still without a bottom reflector (called NS) varying with still inclination θ_{s} throughout the year at 30˚N. Here, if the still inclination θ_{s} is too small, saline water fed to the wick cannot flow to the wick adequately, and the condensate on the glass cover cannot flow to the collecting channel placed at the bottom side of the glass cover and would fall back to the evaporating wick due to gravity. Therefore, we determined the minimum inclination of the still at 10° in this paper. The optimum still inclination to maximize the daily amount of distillate varies according to each month and would be smaller in summer and larger in winter, since the solar altitude angle is higher in summer and lower in winter.

To validate the heat and mass transfer model in the tilted wick solar still in this work, the numerical predictions of the daily amount of distillate of the still without reflector (NS) in Fig. 4 are re-plotted as varying with the daily solar radiation on a glass cover

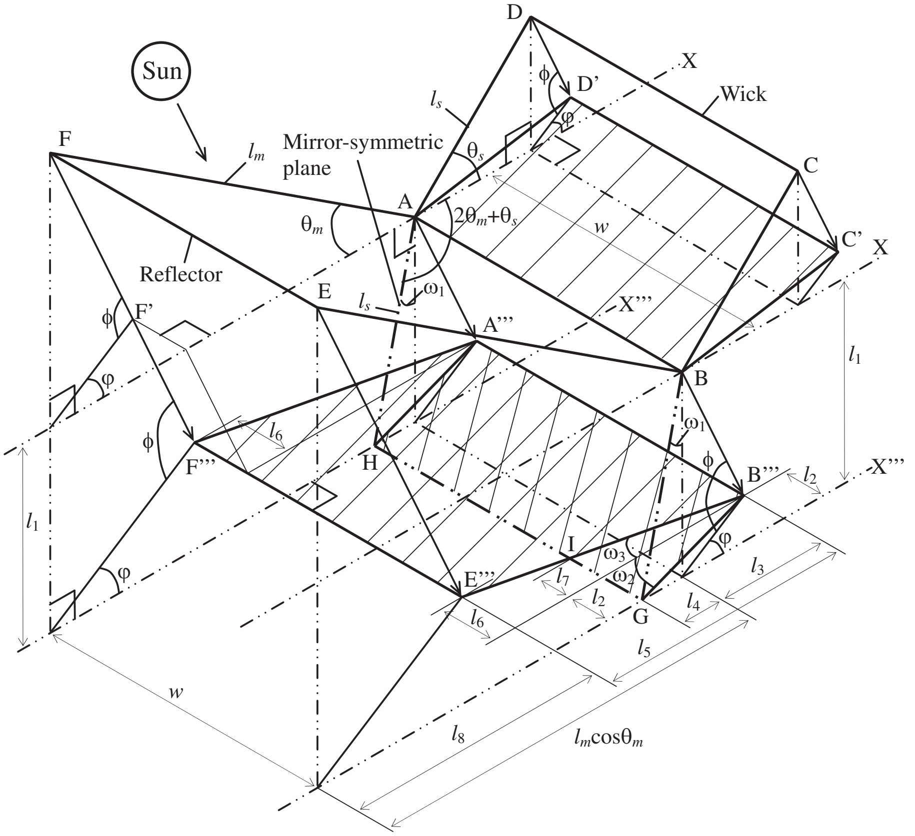

Fig. 3. Shadows of the reflector and the mirror-symmetric plane of the wick on a horizontal surface X´´´ to calculate the reflected radiation absorbed on the wick.

Notes: $l_1 = l_s\cos\omega_1$, $l_2 = l_1\sin|\varphi|/\tan\phi$, $l_3 = l_1\cos\varphi/\tan\phi$, $l_4 = l_s\sin\omega_1$, $l_5 = l_m(\cos\theta_m - \sin\theta_m\cos\varphi/\tan\phi)$, $l_6 = l_m\sin\theta_m\sin|\varphi|/\tan\phi$, $l_7 = (l_3 + l_4)\tan\omega_3$, $l_8 = (l_1 + l_m\sin\theta_m)\cos\varphi/\tan\phi$, $\omega_1 = 2\theta_m + \theta_s - \pi/2$, $\tan\omega_2 = l_2/(l_3 + l_4)$, $\tan\omega_3 = l_6/l_5$.

Table 1
Design and weather conditions

$w = 1$ m, $l_s = 1$ m, $\rho_m = 0.85$, $\alpha_w = 0.9$
Diffusion gap between wick and glass cover = 10 mm
Thickness and thermal conductivity of insulation = 50 mm and 0.04 W/mK
Temperature of feeding saline water = ambient air temperature
Flux feed rate of feeding saline water: Twice as large as the steady-state evaporation rate from the wick calculated on the assumption that solar radiation is kept constant at its peak value along the local day time
Wind velocity of ambient air = 1 m
Ambient air temperature = 25, 33, 30 and 20˚C in spring (February—April), summer (May—July), autumn (August—October) and winter (November—January)

in Fig. 5. The results of outdoor experiments of tilted wick solar still without reflector in literatures are also shown in Fig. 5. Sodha et al. [11], Tiwari et al. [12] and Shukla and Sorayan [13] used multiple wick still, which consists of a series of black cloth pieces of increasing length. Tanaka et al. [14] used a conventional tilted wick solar still and performed outdoor experiments during a year. The predictions of this work are in good agreement with the results of outdoor experiments in literatures. So, it can be said that the heat and mass transfer model in this paper is reasonable.

An isometric diagram of the daily amount of distillate (kg/m^{2}day) produced by a still with a bottom reflector (called RS) varying with the still inclination θ_s and the reflector inclination θ_m, when the ratio of

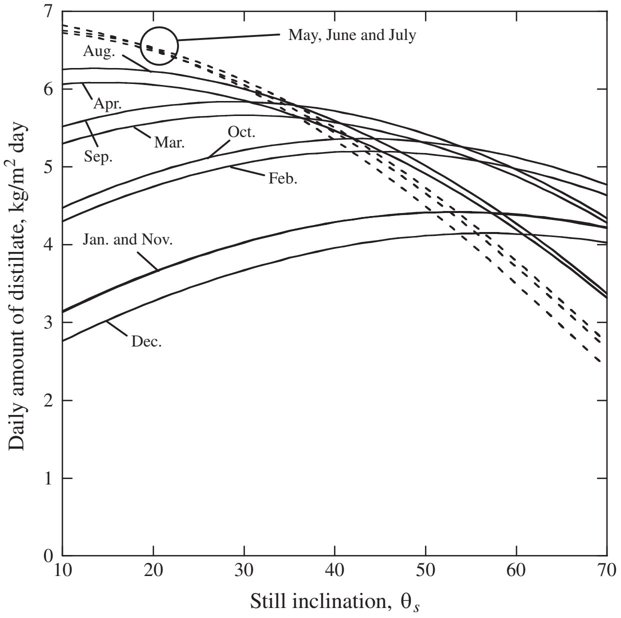

Fig. 4. The variation of the daily amount of distillate of NS with still inclination θ_s throughout the year.

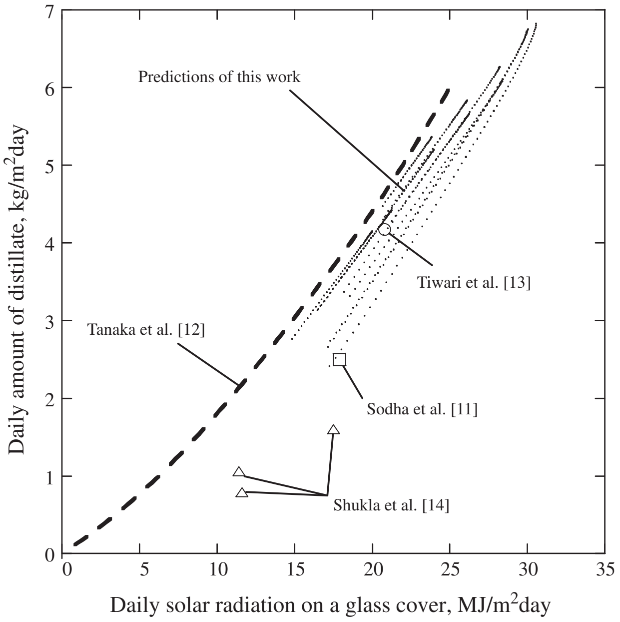

Fig. 5. Comparison of the prediction of this work and the results of outdoor experiments in literatures for the daily amount of distillate of tilted wick stills without reflector (NS).

the reflector length to still length l_m/l_s is 1.0 throughout the year at 30˚N is shown in Fig. 6. The daily amount of distillate on each month was calculated with 1˚ steps for both the inclinations θ_s and θ_m, that is, $60 \times 70 = 4{,}200$ calculations were performed to investigate the effect of both the inclinations on each month. The optimum combinations of the inclinations θ_s and θ_m would vary considerably from month to month. The optimum still inclination θ_s is lower in summer and higher in winter, and the optimum reflector inclination θ_m is higher in summer and lower in winter, since the solar altitude angle is higher in summer and lower in winter.

The optimum still inclination θ_s and reflector inclination θ_m, to produce the maximum daily amount of distillate at ratios $l_m/l_s = 0.5$, 1.0 and 2.0 throughout the year, is shown in Fig. 7. Here, both the optimum inclination of θ_s and θ_m at ratios $l_m/l_s = 0.5$ and 2.0 were determined by performing the same calculations as for Fig. 6 at each ratio, respectively, and $l_m/l_s = 0.0$ shows the results of a still without a reflector (NS). Both the optimum inclination θ_s and θ_m increase slightly with an increase in ratio l_m/l_s. The reason for this is as follows. The amount of solar radiation reflected from the bottom reflector and absorbed on the wick, $Q_{sun,re}$, basically increases with an increase in the still inclination θ_s, since the angle ω_1 ($=2\theta_m + \theta_s - \pi/2$) and length l_4 ($= l_s \sin\omega_1$) as well as the shadow area of the mirror-symmetric plane (A′′′B′′′GH) in Fig. 3 increase with an increase in the still inclination θ_s. On the other hand, as the reflector inclination θ_m increases, the angle ω_1 and length l_4 as well as the shadow area of the mirror-symmetric plane increase, while the length l_5 as well as the shadow area of the bottom reflector (A′′′B′′′E′′′F′′′) decreases. So, these effects have a trade-off relationship. A longer reflector length l_m causes a longer length l_5, so a longer reflector length l_m makes it possible to increase the reflector inclination θ_m. As a result, the inclinations of θ_s and θ_m can be increased to the point that the augmentation of reflected radiation, $Q_{sun,re}$, overcomes a decrease in the direct radiation $Q_{sun,dr}$ by increasing the still inclination θ_s from the optimum position of NS ($l_m/l_s = 0.0$).

The optimum still inclination θ_s and reflector inclination θ_m throughout the year are listed in Table 2. Here, to facilitate the ease of adjustment, the optimum inclinations θ_s and θ_m are assumed to be set at 5˚ steps. The decline of the daily amount of distillate with adjustments in θ_s and θ_m is listed in Table 2, from the results with adjustments to θ_s and θ_m shown in Fig. 7, is less than 1%. Therefore, the daily amount of distillate can be maximized approximately by setting the inclinations of θ_s and θ_m to be those listed in Table 2 for each month according to the ratio l_m/l_s at 30˚N.

The daily amount of distillate and increased ratio varying with the ratio l_m/l_s for four seasons (spring (February–April), summer (May–July), autumn (August–October) and winter (November–January)),

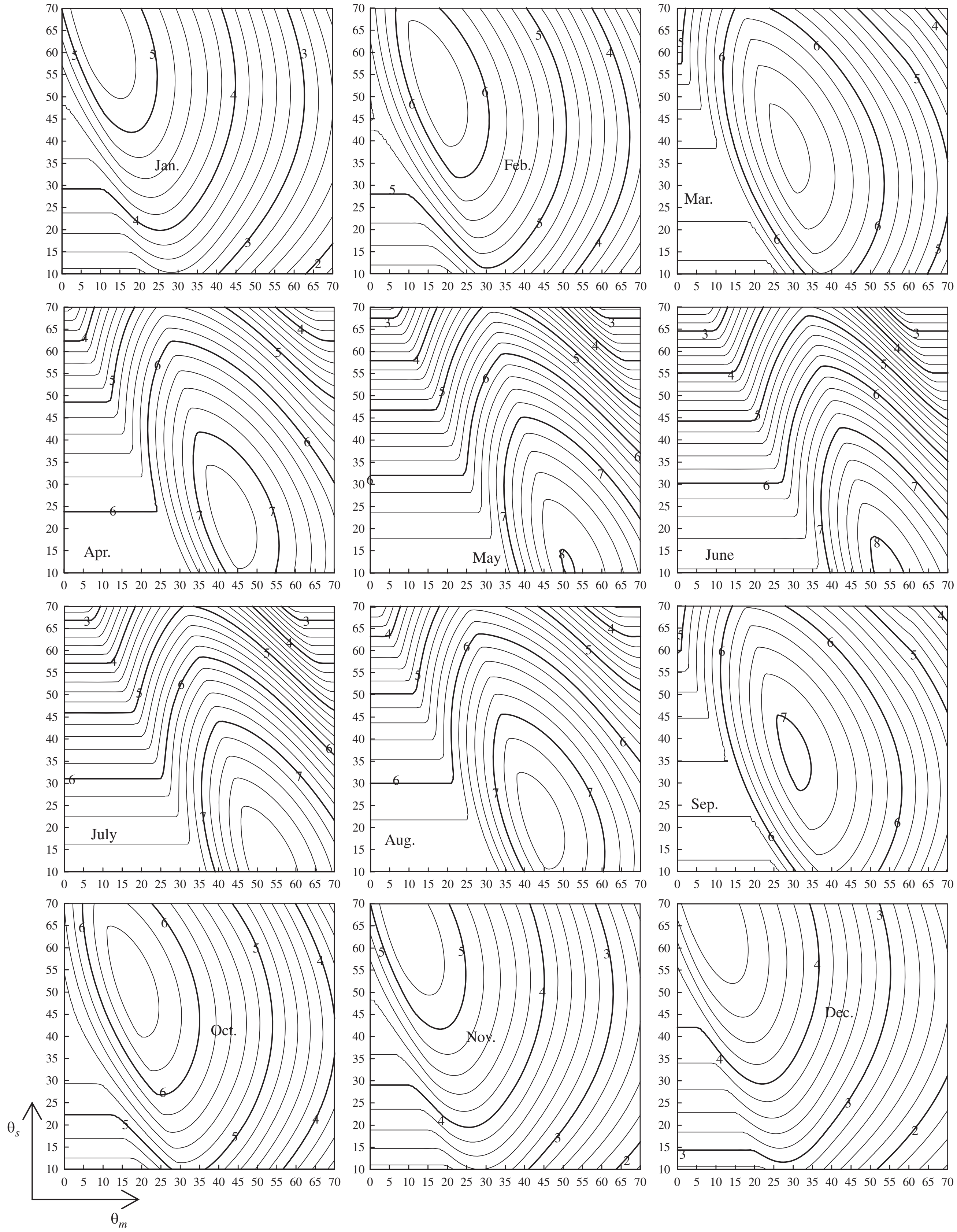

Fig. 6. Isometric diagrams of daily amount of distillate, kg/m^{2}day, from RS varying with still inclination, θ_s, and reflector inclination, θ_m, throughout the year at 30°N latitude.

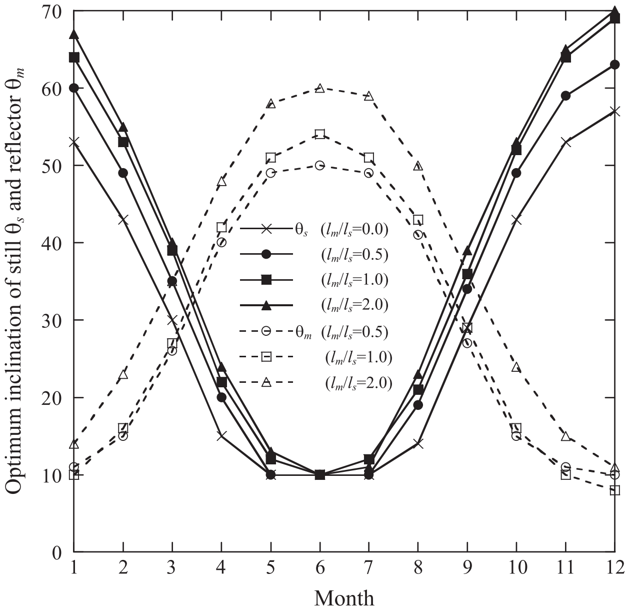

Fig. 7. Optimum inclination of still θ_s and reflector θ_m at the ratio of reflector and still length $l_m/l_s = 0.5$, 1.0 and 2.0 throughout the year at 30˚N.

and the average values for 12 months at 30˚N are shown in Fig. 8(a) and (b). Here, both the inclinations θ_s and θ_m are assumed to be set at the optimum angles listed in Table 2 for each month. $l_m/l_s = 0^*$ shows the results for a still without a reflector (NS) in which the inclination θ_s is fixed at 30˚ throughout the year, and $l_m/l_s = 0$ shows the results for the still without a reflector (NS) in which the inclination θ_s is set to the optimum position for each month as listed in Table 2. Increase ratio is defined as

$$\text{Increase ratio} = \frac{\text{Daily amount of distillate of NS or RS}}{\text{Daily amount of distillate of NS with } \theta_s = 30^\circ}$$

Table 2
Optimum inclinations of still θ_s and reflector θ_m throughout the year at 5˚ steps. $l_m/l_s = 0.0$ shows the still without reflector (NS)

Month	$l_m/l_s = 0.0$	$l_m/l_s = 0.5$		$l_m/l_s = 1.0$		$l_m/l_s = 2.0$	
	θ_s	θ_s	θ_m	θ_s	θ_m	θ_s	θ_m
December	55	65	10	65	10	70	10
January, November	55	60	10	65	10	65	15
February, October	45	50	15	55	15	50	25
March, September	30	35	25	35	30	40	35
April, August	15	20	40	20	45	20	50
May, July	10	10	50	15	50	15	55
June	10	10	50	10	55	10	60

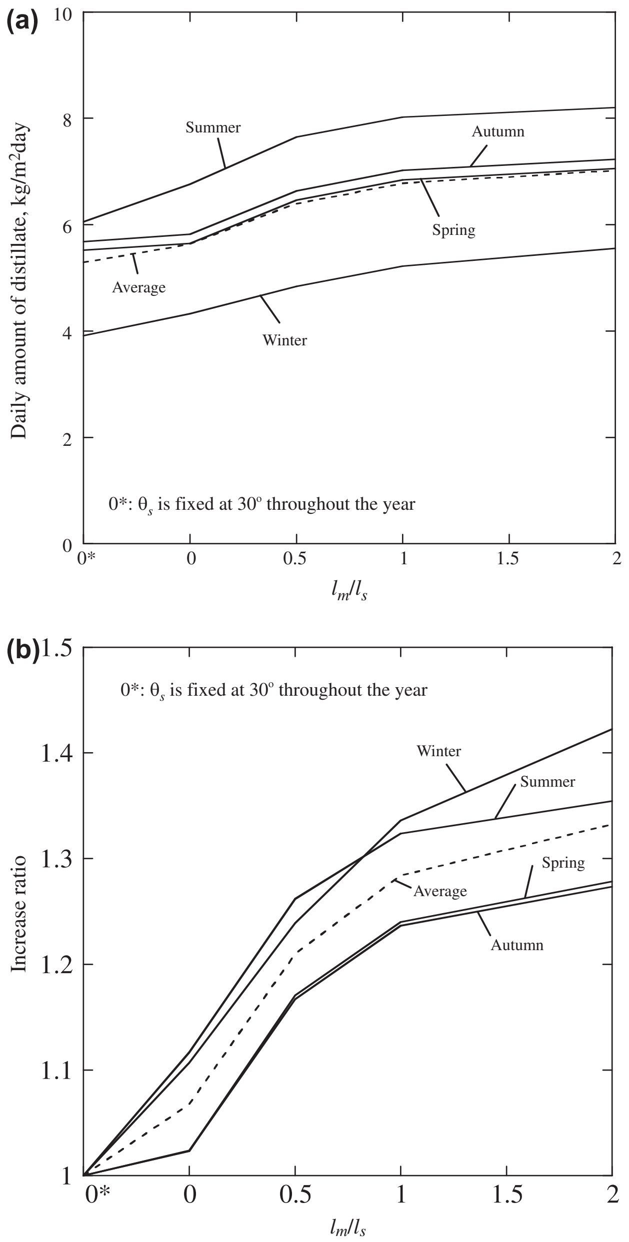

Fig. 8. (a) Daily amount of distillate and (b) increase ratio varying with the ratio of reflector length to still length, l_m/l_s, for four seasons and average values for 12 months at 30˚N.

The daily amount of distillate is highest in summer and lowest in winter, and in spring and autumn it is almost the same as the average values. The effect of the bottom reflector is greater in summer and winter than in spring and autumn. The daily amount of distillate produced by the still can be increased by using a bottom reflector and adjusting the inclination of θ_s and θ_m to the proper values. Compared with a conventional tilted wick solar still ($l_m/l_s = 0^*$: still without reflector and θ_s is fixed at 30°), the average daily amount of distillate throughout the year can be increased to about 7% by adjusting the still inclination θ_s to the proper values for each month ($l_m/l_s = 0$), and about 21, 28 and 33% by using a flat plate bottom reflector and adjusting the inclination of θ_s and θ_m to the proper values for each month at $l_m/l_s = 0.5$, 1.0 and 2.0.

4. Conclusions

We have performed a numerical analysis of a tilted wick solar still with a flat plate external bottom reflector extending from the lower edge of the still. We have determined the optimum inclination of both the still and the reflector throughout the year at 30°N latitude and investigated the effect of the length of the reflector on the daily amount of distillate of the still. In this paper, the still was assumed to be a square shape ($w = l_s = 1$ m). The numerical analysis to calculate the solar radiation absorbed on the wick would be valid even if the still was rectangular in shape if both the widths of the still and the reflector were the same. However, the optimum still and reflector inclinations would be different if the still was not square. The results of this work are summarized as follows:

(1) The daily amount of the distillate produced by a tilted wick solar still can be increased by using a flat plate bottom reflector.
(2) The optimum still inclination is higher in winter and lower in summer.
(3) The optimum reflector inclination is higher in summer and lower in winter.
(4) Both the optimum still and reflector inclination slightly increase with an increase in the ratio of the reflector length to still length l_m/l_s.
(5) An increase in the daily amount of distillate of the still over a conventional tilted wick solar still would average about 21, 28 and 33% throughout the year by using a flat plate bottom reflector at ratios of $l_m/l_s = 0.5$, 1.0 and 2.0, respectively and adjusting the inclination of both the still and the reflector to the proper angle according to month.

Nomenclature

G_{df}, G_{dr} — diffuse and direct solar irradiance on a horizontal surface, W/m^2
l_m, l_s — length of reflector and still, m
$Q_{sun,df}$, $Q_{sun,dr}$, $Q_{sun,re}$ — absorption of diffuse, direct, reflected solar radiation on wick, W
w — width, m
α_w — absorptance of wick
β — incident angle of sunray to glass cover
β' — incident angle of reflected sunray to glass cover
ϕ, φ — altitude and azimuth angle of the sun
θ_m, θ_s — inclination angle of reflector and still
ρ_m — reflectance of reflector
τ_g — transmittance of glass cover

References

[1] J.T. Mahdi, B.E. Smith, Solar distillation of water using a V-trough solar concentrator with a wick-type solar still, Renewable Energy 5(1) (1994) 520–523.
[2] A.A. Al-Karaghouli, A.N. Minasian, A floating-wick type solar still, Renewable Energy 6(1) (1995) 77–79.
[3] H. Tanaka, Y. Nakatake, Improvement of the tilted wick solar still by using a flat plate reflector, Desalination 216 (2007) 139–146.
[4] H. Tanaka, Y. Nakatake, One step azimuth tracking tilted-wick solar still with a vertical flat plate reflector, Desalination 235 (2009) 1–8.
[5] H. Tanaka, Y. Nakatake, Increase in distillate productivity by inclining the flat plate external reflector of a tilted-wick solar still in winter, Sol. Energy 83 (2009) 785–789.
[6] H. Tanaka, Increase in distillate productivity by inclining the flat plate reflector of a tilted-wick solar still in summer, Energy Sci. Technol. 1(2) (2011) 10–20.
[7] H. Tanaka, Tilted wick solar still with external flat plate reflector: Optimum inclination of still and reflector, Desalination 249 (2009) 411–415.
[8] H. Tanaka, Tilted wick solar still with flat plate bottom reflector, Desalination 273 (2011) 405–413.
[9] M.M. Elsayed, Comparison of transient performance predictions of a solar-operated diffusion-type still with a roof-type still, J. Sol. Energy Eng. Trans., ASME 105 (1983) 23–28.
[10] H. Tanaka, T. Nosoko, T. Nagata, A highly productive basin-type—multiple-effect coupled solar still, Desalination 130 (2000) 279–293.
[11] M.S. Sodha, A. Kumar, G.N. Tiwari, R.C. Tyagi, Simple multiple wick solar still: Analysis and performance, Sol. Energy 26 (1981) 127–131.
[12] K. Tanaka, T. Umehara, K. Watanabe, Improvement of the performance of the tilted wick type solar stills, Proceedings of the Eighth Biennial Congress of the International Solar Energy Society, August 1983, Perth, pp. 831–835.
[13] G.N. Tiwari, S.B. Sharma, M.S. Sodha, Performance of a double condensing multiple wick solar still, Energy Convers. Manage. 24(2) (1984) 155–159.
[14] S.K. Shukla, V.P.S. Sorayan, Thermal modeling of solar stills: An experimental validation, Renewable Energy 30 (2005) 683–699.