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Increase in Distillate Productivity by Inclining the Flat Plate Reflector of a Tilted-Wick Solar Still in Summer

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Abstract: A tilted-wick solar still with a flat plate reflector inclined backwards is theoretically analysed to predict the distillate productivity of the still on a summer solstice day at 30°N latitude. We are proposing a new geometrical model to calculate the solar radiation reflected by the inclined reflector and then absorbed onto an evaporating wick. Using this method, we performed a numerical analysis of heat and mass transfer in the still in order to determine the effectiveness of the inclination of the reflector. We found that the benefit of a vertical flat plate reflector is negligible, while an inclined reflector can increase the distillate productivity of the still, and that the reflector angle should be set at about 20° backward from vertical on a summer solstice day. The benefit of the inclined reflector is less in summer than in winter, but the daily amount of distillate can be increased about 9% or 6% by using an inclined reflector when the length of the reflector is a half of the still's length and the still's angle is 10° or 30°.

Key words: Solar still; Solar distillation; Solar desalination; Tilted-wick; Reflector; Inclined; Summer

Nomenclature

G_{dr}: direct solar radiation on a horizontal surface, W m^{-2}

l_m: length of reflector, m

l_s: length of still, m

$Q_{sun,df}$, $Q_{sun,dr}$: absorption of diffuse and direct solar radiation, W

$Q_{sun,re}$: absorption of reflected radiation from reflector, W

w: width of still and reflector, m

α_w: absorptance of wick

β: incident angle of sunrays to glass cover

ϕ, φ: altitude and azimuth angle of the sun

ϕ', φ': altitude and azimuth angle of reflected radiation from reflector

ρ_{re}: reflectance of reflector

τ_g: transmittance of glass cover

1. INTRODUCTION

An external reflector can be a useful modification to increase the distillate productivity of single-effect stills, and the study on the external reflector for a basin type still [1-3] and a tilted-wick till [2] have already been reported, but a detailed and quantitative analysis of the effect of an external reflector on both the basin type still and the tilted-wick still had not been presented.

Therefore, we have added to this research by presenting a geometrical model for a basin type still [4] and a tilted-wick still [5] to evaluate the effect of a vertical flat plate reflector on the distillate productivity of both the stills at 30°N latitude. We found that the vertical flat plate reflector can remarkably increase the distillate productivity of both stills during the spring and autumn seasons. But during the summer and winter seasons, the effect of the external reflector would be less than during spring and autumn, or would even be negligible.

In summer, a vertical reflector would not effectively reflect the sunrays onto the basin liner or the evaporating wick around noon since the sunrays would be nearly vertical. Further, during the morning and evening, the external reflector would shade the basin liner or the evaporating wick as the sun moves north, and this would cause a slight decrease in the amount of direct solar radiation on the basin liner or the evaporating wick. In winter, the benefit of the external reflector would decrease with an increase in the angle of the glass cover from horizontal, and when the glass cover angle exceeded about 35°, the benefit of the vertical reflector would be negligible for both the stills. This is because the solar altitude angle decreases in winter and most of the reflected sunrays from the vertical reflector would escape to the ground without hitting the basin liner or the evaporating wick. Therefore, the arrangement of the external reflector has to be changed from vertical in the summer and winter seasons for both types of stills.

During the winter season, an external reflector inclined slightly forward would be able to make the reflected radiation hit the basin liner or the evaporating wick even when the solar altitude angle is small. Therefore, we have presented an additional analysis for the basin type still [6] and the tilted-wick still [7] to calculate the solar radiation reflected from the external reflector inclined forward and then absorbed onto the basin liner or the evaporating wick. We found that an external reflector inclined forward can increase the distillate productivity of both the stills at any angle of the glass cover. The external reflector angle should be set at a forward angle about 15° from vertical. This would produce approximately a 15% increase in distillate over a basin type or tilted-wick still with a vertical reflector when the reflector was half as long as the basin liner or the evaporating wick.

During the summer season, since the sunrays are nearly vertical around noon, a vertical reflector would not be able to reflect the sunrays onto the basin liner or the evaporating wick, while a reflector which is inclined slightly backward would effectively reflect the sunrays as shown in Fig. 1. This may cause an increase in the distillate productivity of both stills even during the summer season. Khalifa and Ibrahim [8] performed outdoor experiments of a basin type still with internal and external reflectors over the 7 months from June to December. The external reflector was inclined forward during the experimental period. They reported that increase in distillate productivity achieved by internal and external reflectors in outdoor experiments is in a reasonable agreement with the theoretical results in our previous paper [6], except for June and July. The results show that external reflector should be inclined backward during summer season.
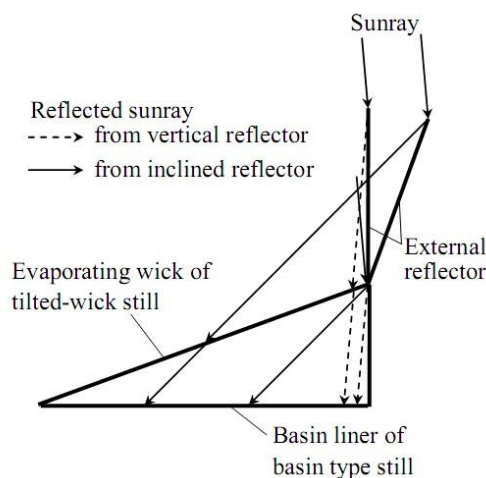

Fig. 1: Reflected Sunrays from Vertical and İnclined Reflector of a Basin Type and Tilted-Wick Stills

In this paper, we present a new geometrical model to calculate the solar radiation reflected from a flat plate reflector inclined backwards and then absorbed on the evaporating wick of the tilted-wick still. The geometrical model presented in this paper differs significantly from the one for the vertical reflector [5] and differs slightly

from the one for the forwardly inclined reflector [7]. We also numerically analyze the effect of the inclination of the reflector on the distillate productivity of a tilted-wick still on a summer solstice day at 30°N latitude.

2. THEORETICAL ANALYSIS

The proposed still is shown in Fig. 2. The still consists of an evaporating wick, a glass cover, a bottom insulation and a flat plate reflector of highly reflective materials such as a mirror-finished metal plate extending from the back wall of the still and tilted backwards. Direct and diffuse solar radiation as well as the reflected solar radiation from the reflector are transmitted through the glass cover and then absorbed on the wick.
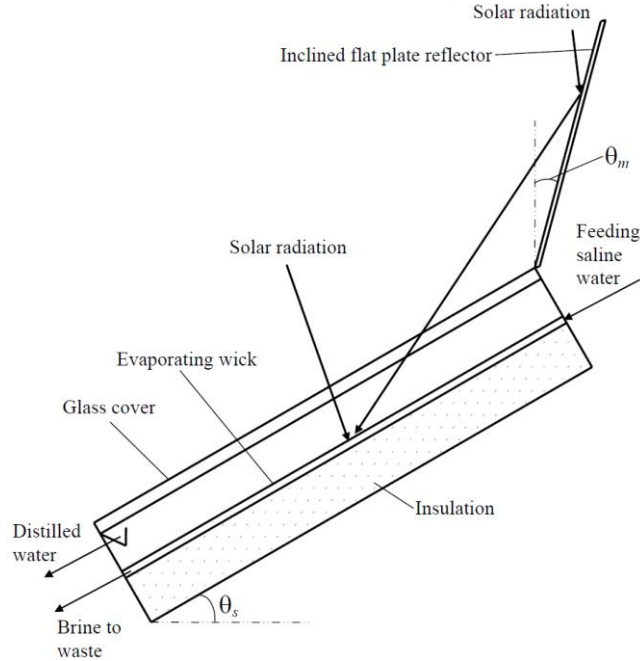
Fig. 2: Schematic Diagram of a Tilted-Wick Still with a Backwardly İnclined Flat Plate Reflector

To simplify the following calculations to determine the absorption of solar radiation on the wick, the walls of the still are disregarded since the height of the walls (10mm) is negligible in relation to the still's length (1m) and width (1m).

$$\omega_1 = \tan^{-1}\frac{l_5}{l_4}$$

$$\omega_2 = \tan^{-1}\frac{l_6}{l_s\cos\theta_s - (l_7 + l_9)}$$

$$l_6 = l_7\tan\omega_1$$

$$l_8 = l_s\sin\theta_s\frac{\cos\varphi}{\tan\phi}$$

$$l_9 = l_s\sin\theta_s\tan\theta_m$$

$$l_7 = l_s\sin\theta_s\{\tan(\omega_3 + 2\theta_m) - \tan\theta_m\}$$

$$l_3 = l_1\tan\omega_2$$

$$l_2 = l_1\tan\omega_1$$

Fig. 3: The Shadow of the Still And the Shadow and Reflected Projection of the İnclined Reflector

Figure 3 shows a schematic diagram of the shadows of the still and the inclined reflector as well as the projection of the reflected sunrays from the inclined reflector on a horizontal surface caused by direct solar radiation. Here, the shadows of the glass cover and the evaporating wick would be exactly the same since the walls are disregarded as mentioned above. l_s is the length of the still (shown as ABCD), l_m is the length of the reflector (shown as ABEF) and w is the width of both the still and the reflector. θ_s is the angle of the still from horizontal, and θ_m is the tilt angle of the inclined reflector from vertical. φ and ϕ are the azimuth and altitude angles of the sun. In this calculation, the still is assumed to be facing due south.

The direct solar radiation absorbed on the wick, $Q_{sun,dr}$, can be determined as the product of the direct solar radiation on a horizontal surface, G_{dr}, the shadow area of the still on a horizontal surface shown as parallelogram A''B''CD, transmittance of the glass cover, $\tau_g(\beta)$, and absorptance of the wick, α_w, and this may be expressed as

$$Q_{sun,dr} = G_{dr}\tau_g(\beta)\alpha_w \times wl_s(\cos\theta_s + \sin\theta_s\cos\varphi/\tan\phi) \tag{1}$$

Fig. 4: (a) Isometric and (b) Side Views of an İnclined Reflector Placed Directly on a Horizontal Surface

The shadow and reflected projection of the inclined reflector (ABEF) on a horizontal surface are shown as A''B''E''F'' and A'B'E'F', respectively. The reflected sunrays from the reflector cannot all hit the wick, and some portion of the reflected sunrays would escape to the ground. Assuming that the radiation with the same azimuth and altitude angles as the reflected radiation from the reflector hits the whole surface of the still, the shadow of the still would be an area shown as A'B'CD. The portion of the reflected radiation from the reflector which would be able to be absorbed on the wick can be determined as the overlapping area of the reflected

projection of the reflector (A'B'E'F') and the shadow of the still caused by the reflected radiation (A'B'CD) shown as trapezoid A'B'GF', and the residue shown as triangle B'E'G would escape to the ground. Since the reflected radiation from the inclined reflector would be concentrated or diluted, the intensity of the reflected radiation from the inclined reflector on a horizontal surface can be determined as $G_{dr} \times l_4/l_1$. Therefore, the solar radiation reflected from the reflector and absorbed on the wick, $Q_{sun,re}$, can be determined as the product of the intensity of the reflected radiation, $G_{dr} \times l_4/l_1$, the overlapping area of the reflected projection of the reflector and shadow of the still shown as A'B'GF', reflectance of the reflector, ρ_{re}, transmittance of the glass cover and absorptance of the wick, and this may be expressed as

$$Q_{sun,re} = G_{dr} \frac{l_4}{l_1} \tau_g(\beta)\rho_{re}\alpha_w \times l_1 \left\{ w - \frac{1}{2}(l_2 + l_3) \right\} \tag{2}$$

To calculate Eq. (2), the lengths of l_1, l_4 and l_5 and the angles of ω_1 to ω_3 have to be determined. Therefore, isometric and side views of an inclined flat plate reflector (ABEF) which is directly placed on a horizontal surface are shown in Figs. 4a and b. The shadow (ABE''F'') and the reflected projection (ABE'F') of the reflector on a horizontal surface shown in Fig. 4a would be in exact accordance with those shown as A''B'E''F'' and A'B'E'F' in Fig. 3. Since the incident angle and reflected angle of the sunrays for the reflector would be the same as $\omega_3+\theta_m$ as shown in Fig. 4b, the length of the reflected projection of the inclined reflector, l_1, can be determined as follows with the angle ω_3 $(=\tan^{-1}(\cos\varphi/\tan\phi))$

$$l_1 = l_m\{\cos\theta_m \tan(\omega_3 + 2\theta_m) - \sin\theta_m\} \tag{3}$$

By drawing an additional vertical line from point E to a horizontal surface to Fig. 4a, the length of l_4 and l_5 can be determined as follows

$$l_4 = l_m\left(\sin\theta_m + \cos\theta_m \frac{\cos\varphi}{\tan\phi} \right) \tag{4}$$

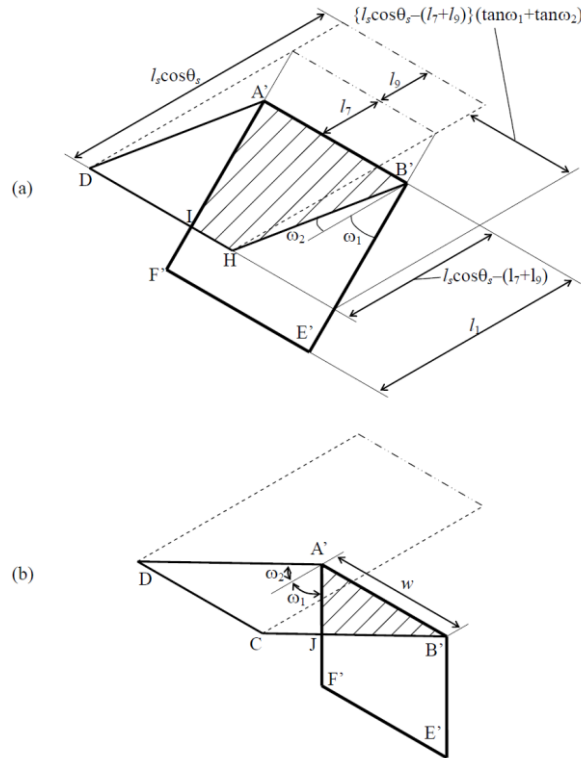$$l_5 = l_m \cos\theta_m \frac{\sin|\varphi|}{\tan\phi} \tag{5}$$

Fig. 5: The Overlapping Area of the Reflected Projection of the Reflector and the Shadow of the Still when the Overlapping Area is: (a) a Trapezoid and (b) a Triangle

Therefore, $Q_{sun,re}$ can be determined with lengths of l_1 to l_{11} and angles of ω_1 to ω_3 shown in Figs. 3 and 4.

When $Q_{sun,re}$ is calculated, there are three exceptions as follows:

a.   When $l_7+l_9>l_s\cos\theta_s$, all of the reflected sunrays would escape to the ground and $Q_{sun,re}$ would be zero.

b.   When $l_1+l_7+l_9>l_s\cos\theta_s$ and the overlapping area of the reflected projection of the reflector and the shadow of the still is a trapezoid A'B'HI as shown in Fig. 5a, $Q_{sun,re}$ may be expressed as

$$Q_{sun,re} = G_{dr}\frac{l_4}{l_1}\tau_g(\beta)\rho_{re}\alpha_w \times \left\{l_s\cos\theta_s - (l_7+l_9)\right\}\times$$
$$\left[w - \frac{1}{2}\left\{l_s\cos\theta_s - (l_7+l_9)\right\}(\tan\omega_1 + \tan\omega_2)\right] \tag{6}$$

c.   When the overlapping area of the reflected projection and the shadow forms a triangle A'B'J as shown in Fig. 5b, $Q_{sun,re}$ may be expressed as

$$Q_{sun,re} = G_{dr}\frac{l_4}{l_1}\tau_g(\beta)\rho_{re}\alpha_w \times \frac{1}{2}w^2\frac{\sin(90°-\omega_1)\sin(90°-\omega_2)}{\sin(\omega_1+\omega_2)} \tag{7}$$

On a summer solstice day, the sun moves north in the morning (from sunrise until about 9:13 a.m.) and evening (from about 2:48 p.m. until sunset). The shadows of the still and the reflector caused by the direct solar radiation on a horizontal surface when the sun moves north is shown in Fig. 6. The reflector obstruct the sunrays and shade the evaporating wick, and the shaded area is shown as A'B'GF'. Therefore, $Q_{sun,re}$ and $Q_{sun,dr}$ when the sun moves north can be determined as

$$Q_{sun,re} = 0 \tag{8}$$

$$Q_{sun,dr} = G_{dr}\tau_g(\beta)\alpha_w \times \left[wl_s\left(\cos\theta_s - \sin\theta_s\frac{\cos\varphi}{\tan\phi}\right) \right.$$
$$\left. -\left\{wl_m\left(\cos\theta_m\frac{\cos\varphi}{\tan\phi} - \sin\theta_m\right) - \frac{1}{2}l_m^2\cos\theta_m\frac{\sin|\varphi|}{\tan\phi}\left(\cos\theta_m\frac{\cos\varphi}{\tan\phi} - \sin\theta_m\right)\right\} \right] \tag{9}$$

where the term of

$$-\left\{wl_m\left(\cos\theta_m\frac{\cos\varphi}{\tan\phi} - \sin\theta_m\right) - \frac{1}{2}l_m^2\cos\theta_m\frac{\sin|\varphi|}{\tan\phi}\left(\cos\theta_m\frac{\cos\varphi}{\tan\phi} - \sin\theta_m\right)\right\} \tag{10}$$

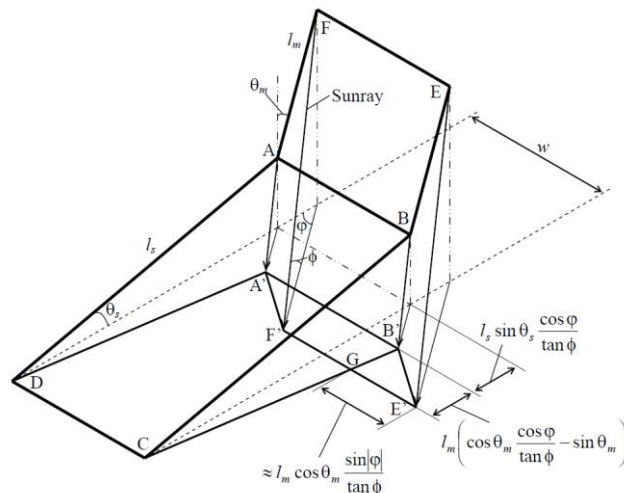represents the effect of the shadow of the reflector on the evaporating wick.

Fig. 6: The Shadows of the Still and the Reflector when the Sun Moves North

In Eqs. (1), (2), (6), (7) and (9), the incident angle of sunrays to the glass cover, β, can be expressed as [9] for Eq. (1) and (9)

$$\cos \beta = \sin \phi \cos \theta_s + \cos \phi \sin \theta_s \cos \varphi \qquad (11)$$

for Eqs. (2), (6) and (7)

$$\cos \beta = \sin \phi' \cos \theta_s + \cos \phi' \sin \theta_s \cos \varphi' \qquad (12)$$

where φ' and φ' are the azimuth and altitude angles of the reflected sunrays from the inclined reflector, and can be expressed with φ* shown in Fig. 4a as

$$\varphi' = 180° - \varphi* \qquad (13)$$

$$\phi' = \tan^{-1} \frac{l_m \cos \theta_m \cos \varphi*}{l_1 + l_m \sin \theta_m} \qquad (14)$$

$$\varphi* = \tan^{-1} \frac{l_2}{l_1 + l_m \sin \theta_m} \qquad (15)$$

The details for calculating the diffuse solar radiation absorbed on the wick, $Q_{sun,df}$, was described in our previous paper [5].

Heat and mass transfer in the still was also described in our previous paper in detail [5], which was basically the same in content as one by Elsayed [10] and Tanaka et al. [11]. The equations for the respective solar radiation ($Q_{sun,dr}$, $Q_{sun,df}$ and $Q_{sun,re}$), the energy balance for the evaporating wick and the glass cover, and the equations of properties were solved together to find the distillate production rate throughout the day. The weather and design conditions are listed in Table 1.

Tab. 1: Design and Weather Conditions

w = 1 m, l_s = 1 m, l_m = 0.5 m
Diffusion gap between wick and glass cover = 10 mm
α_w = 0.9, ρ_{re} = 0.85
$\tau_g(\beta) = 2.642\cos\beta - 2.163\cos^2\beta - 0.320\cos^3\beta + 0.719\cos^4\beta$ [11]
Ambient air temperature = 30 $^{\circ}$C
Wind velocity = 1 m/s
Thermal conductivity and thickness of bottom insulation = 0.04 W/mK and 50 mm
G_{dr}: Bouguer's equation with transmissivity of atmosphere is 0.7 and 30°N latitude [12]
G_{df}: Berlage's equation with the solar radiation incident on the atmosphere of 1370 W/m^2 at 30°N latitude [12]

3. RESULTS

Theoretical predictions of hourly variations of the global solar radiation on a horizontal surface (Global), and the distillate production rates of a still without a reflector (called NS) and one with a reflector (called RS) on a summer solstice day at 30°N latitude (daily global solar radiation is 30.3 MJ m^{-2} day^{-1}) when the angle of the still θ_s is 10° are shown in Fig. 7. In this paper, the distillate production rate and the daily amount of distillate of the still are defined as those per unit effective glass cover area. The distillate production rates of RS with $\theta_m = 0^{\circ}$ to 30° are larger than that of NS around noon, but is slightly smaller than NS when the sun moves north (from sunrise until about 9:13 a.m. and from about 2:48 p.m. until sunset) since the reflector shades the evaporating wick as shown in Fig. 6. The daily amounts of distillate of RS with $\theta_m = 0^{\circ}$ (the still with a vertical reflector) and NS (the still without reflector) are 6.70 and 6.66 kg m^{-2} day^{-1}, respectively, so the benefit of the vertical reflector on a summer solstice day would be negligible. This is because an increase in distillate production rate by the vertical reflector around noon would be all but cancelled by a decrease in distillate production rate caused by the shadow of the reflector onto the evaporating wick when the sun moves north shown as Fig. 8. However, the distillate production rate of RS can be increased by inclining the reflector, and the daily amounts of distillate of RS with $\theta_m = 10^{\circ}$ to 30° are larger than those of NS and RS with $\theta_m = 0^{\circ}$, so the inclination angle of the reflector θ_m should be optimized.
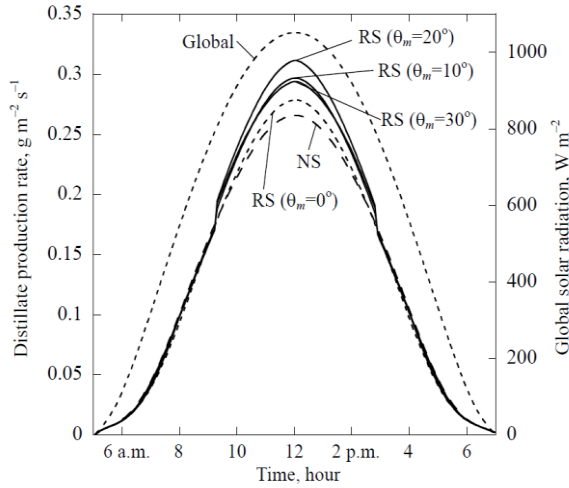
Fig. 7: Hourly Variation of Global Solar Radiation on a Horizontal Surface and Distillate Production Rate of NS and RS ($\theta_m = 0^o$ to 30°) when the Still'S Angle $\theta_s = 10^o$ on the Summer Solstice at 30^oN Latitude.

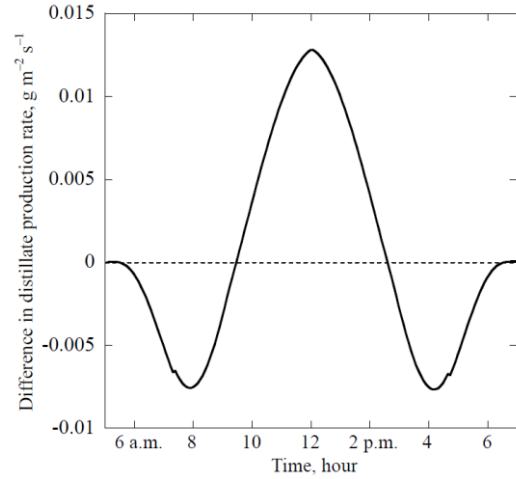**Fig. 8: Hourly Variation of Difference in Distillate Production Rate of RS ($\theta_m = 0^o$) and NS when $\theta_s = 10^o$ on the Summer Solstice at 30^oN Latitude.**

The variations in the cumulative daily amount of reflected radiation absorbed on a 1 m^2 evaporating wick area, $\Sigma Q_{sun,re}$, as well as the ratio of the cumulative daily amount of reflected radiation to the amount of direct and diffuse radiation, $\Sigma Q_{sun,re}/(\Sigma Q_{sun,dr} + \Sigma Q_{sun,df})$ with the angle of the reflector θ_m are shown in Fig. 9. The cumulative reflected radiation as well as the ratio, $\Sigma Q_{sun,re}/(\Sigma Q_{sun,dr} + \Sigma Q_{sun,df})$, increase with an increase in the angle θ_m, but peaks at around $\theta_m = 15^o$ to 25° and decreases with an increase in θ_m after the peak. This is because the total amount of reflected radiation from the reflector would increase with an increase in the angle θ_m (or the length of l_4 shown in Fig. 3 and Fig. 4a would increase with an increase in θ_m), but on the other hand, a larger inclination angle of θ_m causes lengths l_1, l_7 and l_9 in Fig. 3 to increase, and the reflected projection (shown as A'B'E'F' in Fig. 3) exceeds the still's shadow (shown as A'B'CD in Fig. 3). The ratio of the amount of the reflected radiation which can be absorbed on the wick to the total amount of the reflected radiation from the reflector decreases with an increase in θ_m after the reflected projection exceeds the still's shadow (or $l_1+l_7+l_9 > l_s \cos\theta_s$ as shown in Fig. 5a).
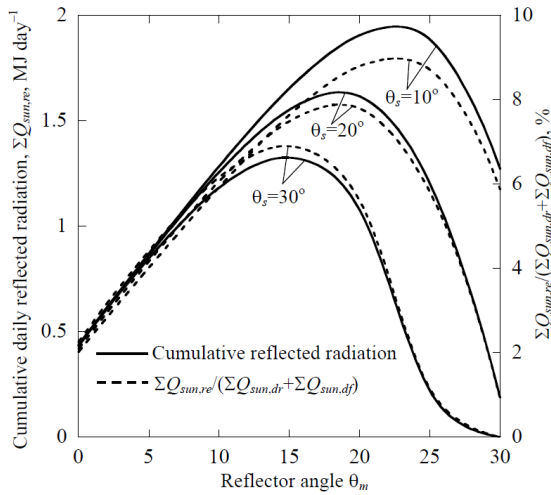

Fig. 9: The Variation of the Cumulative Daily Reflected Radiation, $\Sigma Q_{sun,re}$, and the Ratio of $\Sigma Q_{sun,re}/(\Sigma Q_{sun,dr}+\Sigma Q_{sun,df})$ with a Reflector Angle θ_m on the Summer Solstice at 30^oN Latitude
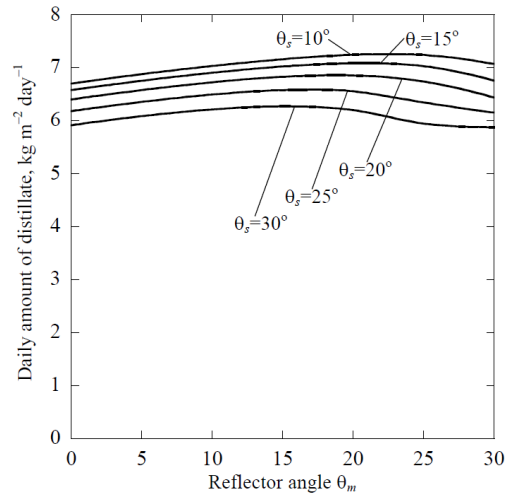
Fig. 10: Daily Amount of Distillate of RS Varying with the Reflector Angle θ_m and Angle of Still θ_s on the Summer Solstice at 30^oN Latitude

The cumulative reflected radiation as well as the ratio, $\Sigma Q_{sun,re}/(\Sigma Q_{sun,dr} + \Sigma Q_{sun,df})$, are larger for the still with a smaller still's angle θ_s at any reflector angle θ_m. This is because a smaller still's angle θ_s causes shorter lengths of

l_3, l_7 and l_9 in Fig. 3, and this causes a larger ratio of the amount of the reflected radiation which can be absorbed on the wick to the total amount of the reflected radiation from the reflector.

The variations in the daily amount of distillate from a still with a reflector angle of θ_m when the still's angle θ_s is 10° to 30° are shown in Fig. 10. The daily amount of distillate is larger for a still with a smaller still's angle at any reflector angle θ_m, since the direct solar radiation as well as the reflected radiation from the reflector and absorbed on the wick increase with an decrease in the still's angle θ_s. The daily amount of distillate peaks at around $\theta_m = 20^o$, and the increase in daily amounts of distillate achieved by inclining the reflector from vertical ($\theta_m = 0^o$) to $\theta_m = 20^o$ would be about 8% and 5% at $\theta_s = 10^o$ and 30°.

The variation of the daily amount of distillate with the still's angle θ_s for NS (a still without a reflector) and RS (a still with a reflector) are shown in Fig. 11. The results of RS are shown for a reflector angle of $\theta_m = 0^o$ and a reflector length of half of the still's length ($l_m = 0.5l_s$), $\theta_m = 0^o$ and $l_m = l_s$, $\theta_m = 20^o$ and $l_m = 0.5l_s$, and $\theta_m = 20^o$ and $l_m = l_s$. The daily amount of distillate produced by each still increases with a decrease in the still's angle θ_s. The daily amount of distillate produced by RS with $\theta_m = 0^o$ and $l_m = 0.5l_s$ is almost the same as that of NS at any still's angle θ_s. This is because an increase in the distillate production rate achieved by the reflector around noon would be almost cancelled by the shadow of the reflector during the morning and evening as mentioned above.
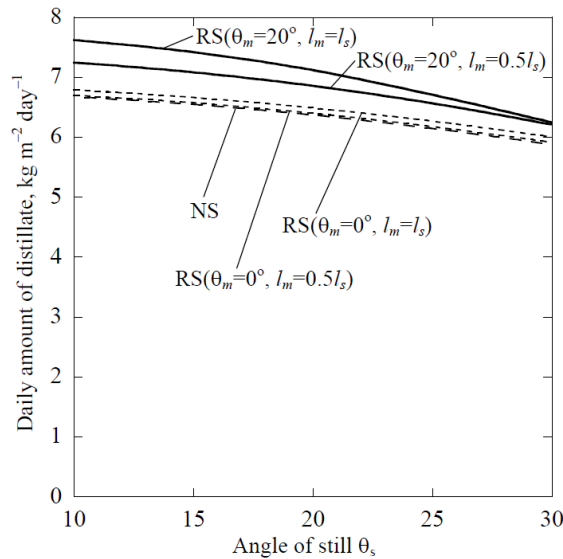

Fig. 11: Daily Amount of Distillate of NS and RS Varying with the Angle of Still θ_s on the Summer Solstice at 30°N Latitude

The daily amount of distillate from RS with an inclined reflector ($\theta_m = 20^o$) and $l_m = 0.5l_s$ or $l_m = l_s$ would be about 9% or 14% more than that of NS when $\theta_s = 10^o$, and about 6% and 6% more when $\theta_s = 30^o$. On a winter solstice day, the daily amount of distillate of a tilted-wick still ($\theta_s = 40^o$) with a forwardly inclined flat plate reflector, with an inclination angle of 15° and a length of half of or the same as the still's length, is about 18% or 26% more than that of a still without a reflector[7]. This indicates that the augmentation of the daily amount of distillate achieved by using an inclined flat plate reflector is less in summer than in winter. However, the distillate productivity of the tilted-wick still can be increased by using an inclined flat plate reflector at the proper angle and increasing the reflector's length even in summer.

4.   CONCLUSIONS

We theoretically analyzed the solar radiation absorbed on an evaporating wick of a tilted-wick solar still with a flat plate reflector extending from the back wall of the still and inclined backward, and predicted the distillate productivity of the still on a summer solstice day at 30°N latitude. The results of this work are summarized as follows:

a.   The benefit of a vertical flat plate reflector is negligible, while a backwardly inclined reflector can increase the distillate productivity of the still on a summer solstice day.

b.   When the angle of the still θ_s is in the range of 10° to 30°, the reflector angle θ_m should be set at about 20° to maximize the daily amount of distillate.

c.   When the angle θ_s is 10°, the daily amount of distillate of a still with an inclined reflector ($\theta_m = 20^o$) and l_m (length of the reflector) $= 0.5 \times l_s$ (length of the still) or $l_m = l_s$ would be about 9% or 14% more than that of a still without a reflector.

d. When the angle θ_s is 30°, the daily amount of distillate of a still with the inclined reflector ($\theta_m = 20^o$) and $l_m = 0.5l_s$ or $l_m = l_s$ would both be about 6% more than that of a still without reflector.

e. The benefit of the inclined reflector is less in summer than in winter for the tilted-wick still.

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