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Theoretical Analysis of Solar Thermal Collector with a Flat Plate Bottom Booster Reflector

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Abstracts

A theoretical analysis of a solar thermal collector with a flat plate bottom reflector is presented. The bottom reflector extends from the lower edge of the collector. The variations of daily solar radiation absorbed on the collector with inclinations from horizontal for both the collector and reflector throughout the year were predicted, and the optimum inclinations of the collector and reflector which maximize the daily solar radiation absorbed on the collector were determined for each month at 30°N latitude. The effects of the size of the collector and reflector on the daily solar radiation absorbed on the collector were also investigated. The optimum collector inclination is lower in summer and higher in winter, while the optimum reflector inclination is higher in summer and lower in winter. The average daily solar radiation absorbed on the collector throughout the year can be increased about 20%, 27% and 33% by using a bottom reflector if the ratio of reflector length to collector length is 0.5, 1.0 and 2.0, respectively, when the collector's length is equal to its width.

Key words: Solar energy; Solar thermal collector; Bottom reflector; Collector-reflector; Optimum inclination

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Nomenclatures

G_{df}, G_{dr}: diffuse and direct solar irradiance on a horizontal surface, W/m^2

l_c, l_m: length of collector and reflector, m

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

w: width of collector and reflector, m

α_c: absorptance of absorbing plate

β: incident angle of sunrays to glass cover

β': incident angle of reflected sunrays to glass cover

ϕ, φ: altitude and azimuth angle of the sun

θ_c, θ_m: angle of collector and reflector from horizontal

ρ_m: reflectance of reflector

τ_g: transmittance of glass cover

INTRODUCTION

For a solar thermal collector, a booster reflector can be a useful and inexpensive modification to increase the solar radiation incident on the collector. A top reflector extends from the upper edge of the solar collector and is inclined slightly from vertical, while the bottom reflector extends from the lower edge of the solar collector and is inclined from horizontal. The effects of the top reflector[1-3], the bottom reflector[4-9] and both the top and bottom reflectors together[10-13] on a solar thermal collector have been studied experimentally and theoretically.

The optimum inclination of a conventional solar thermal collector without booster reflectors and located on a single site varies according to the seasons (or months), and can be easily determined. However, the optimum inclination for a solar collector with booster reflectors (top, bottom or both top and bottom together) may differ from that of a conventional solar collector. Further, the optimum inclination of the booster reflectors would also vary with the seasons. So the optimum inclination of the collector as well as the optimum inclination of the booster reflector should be determined by considering the combination of these inclinations to maximize the solar radiation incident on the solar thermal collector. However, studies to determine these optimum inclinations have only been done in limited cases, and a detailed analysis to determine the optimum inclination of both the collector and reflector taking into account their combination has not been presented in spite of the fact that many studies have been done as mentioned above.

Therefore, in a previous paper[14], we have added to this research by performing a graphical analysis using a geometrical model to evaluate the effect of a flat plate top reflector on a solar thermal collector. We determined the optimum inclination of the collector and the top reflector for each month, and found that the top reflector can increase the daily solar radiation absorbed on the absorbing plate of the solar thermal collector about 19%, 26% and 33% throughout the year when the ratio of the top reflector and collector length is 0.5, 1.0 and 2.0 respectively and both the collector and reflector are adjusted to the proper inclination at 30^{o}N latitude.

A flat plate bottom reflector as shown in Fig. 1 would also be able to increase the solar radiation incident on the solar thermal collector as reported earlier[4-13], but detailed and a quantitative analysis has not been presented. Recently, we have performed numerical analysis of a tilted wick solar still with a flat plate bottom reflector. The tilted wick solar still consists of a glass cover and black wick cloth. We presented a geometrical model to calculate solar radiation reflected by a bottom reflector and then absorbed onto the wick[15]. A geometrical model for a top reflector that calculates the solar radiation reflected by the top reflector and then absorbed onto the solar collector cannot be applied to the bottom reflector. But the geometrical model of the tilted wick solar still with bottom reflector can be applied to the solar thermal collector with bottom reflector since the tilted wick solar still is also a flat plate system as is the solar collector. Therefore, in this paper, we determine the optimum inclination angle of the collector as well as the bottom reflector according to each month at 30^{o}N latitude by a graphical analysis using a geometrical model to calculate the solar radiation reflected by the bottom reflector and then absorbed onto an absorbing plate of the solar thermal collector.

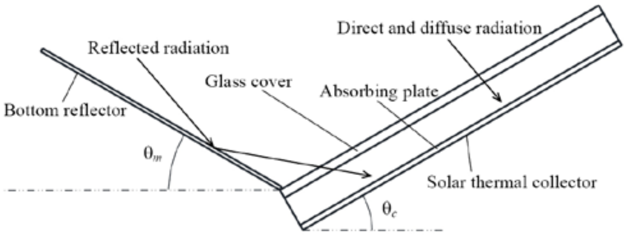


Figure 1
Schematic Diagram of a Solar Thermal Collector and Bottom Reflector System

1. THEORETICAL ANALYSIS

1.1 Solar Thermal Collector with Flat Plate Bottom Reflector

The proposed solar thermal collector and reflector system is shown in Fig. 1. The solar collector consists of a glass cover and an absorbing plate, and a flat plate bottom reflector is assumed to be made of highly reflective material. Direct and diffuse solar radiation and also the reflected solar radiation from the bottom reflector are transmitted through the glass cover and then absorbed onto the absorbing plate. The reflector is inclined upwards from horizontal.

To simplify the following calculations to determine the absorption of solar radiation on the absorbing plate of a solar collector, the walls of the solar collector are disregarded, since the height of the walls (10 mm) is negligible in relation to the collector length (1 m or 2 m) and width (1 m). In this calculation, the solar collector and reflector are assumed to be facing due south to maximize the solar radiation absorbed on the absorbing plate. The design conditions and physical properties employed in this calculation are listed in Table 1.

Table 1
Design Conditions and Physical Properties

w=1m
α_c=0.9
ρ_m=0.8
$\tau_g(\beta)$[17]: $\tau_g(\beta)=2.64^2\cos\beta-2.163\cos^2\beta-0.320\cos^3\beta+0.719\cos^4\beta$

Practically, for a collector with heat loss, solar radiation at lower levels cannot be utilized. However, in the calculations, it was assumed that solar radiation can be absorbed and utilized even at lower levels.

1.2 Radiation Reflected by Bottom Reflector and Absorbed on Absorbing Plate

Numerical models, such as vector analysis[5-7,11], graphical analysis[1-4,8] and two dimensional analysis[13] have been presented to calculate the solar radiation reflected by the reflectors and then absorbed onto the absorbing plate. A new geometrical model presented in this paper to calculate the solar radiation reflected by the bottom reflector and then absorbed onto the absorbing plate is basically the same as the graphical analysis for a solar collector reflector system[1-4, 8].

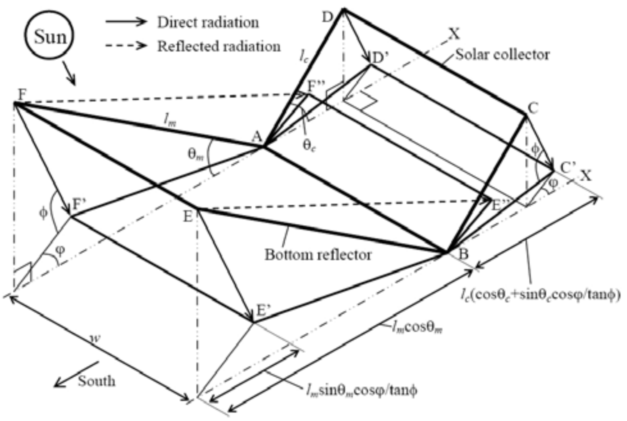
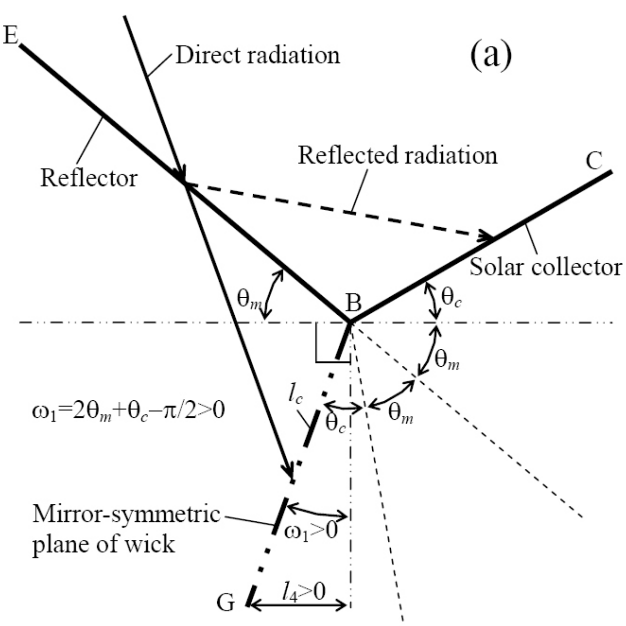


Figure 2
Shadows of the Solar Collector and Bottom Reflector and Reflected Projection from the Reflector on a Horizontal Surface

Fig. 2 shows a schematic diagram of shadows produced by the collector and the bottom reflector as well as the projection of the reflected sunlight from the bottom reflector on a horizontal surface caused by direct solar radiation. Here, the shadows of the glass cover and the absorbing plate of the collector would be exactly the same since the walls of the collector are disregarded as mentioned above. l_c or l_m is the length of the collector (shown as ABCD) or the bottom reflector (shown as ABEF), and θ_c or θ_m is the inclination from horizontal of the collector or the reflector, respectively. w is the width of both the collector and the reflector. φ and ϕ are the azimuth and altitude angle of the sun, respectively. The shadow of the collector and the bottom reflector, and the reflected projection from the reflector on a horizontal surface caused by direct solar radiation are shown as ABC'D', ABE'F' and ABE''F'', respectively.



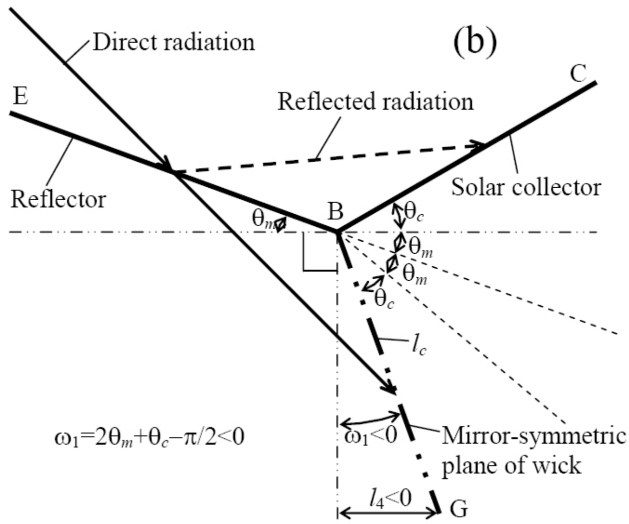


Figure 3
The Mirror-Symmetric Plane of the Solar Collector to the Reflector and Its Angle ω_1 from Vertical (a) $\omega_1>0$ and (b) $\omega_1<0$

Not all of the reflected solar radiation from the bottom reflector can be absorbed by the collector, and part of or all of it would escape to the ground or the surroundings without hitting the collector. To calculate the solar radiation reflected by the bottom reflector and absorbed on the collector, a mirror-symmetric plane of the collector to the bottom reflector is introduced as shown in Fig. 3. The incident point and incident angle of the reflected radiation which is reflected by the bottom reflector and reaches the collector 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 on the collector can be calculated by determining the amount of direct radiation which goes through the bottom reflector and is absorbed on the mirror-symmetric plane. Here, ω_1 is the angle between the mirror-symmetric plane and a vertical line, and is determined as shown in Fig. 3 as

$$\omega_1=2\theta_m+\theta_c-\pi/2 \quad (1)$$

If $\omega_1 > 0$, the length l_4 ($= l_c\sin\omega_1$) would be positive (Fig. 3a), and if $\omega_1 < 0$, the length l4 would be negative (Fig. 3b).

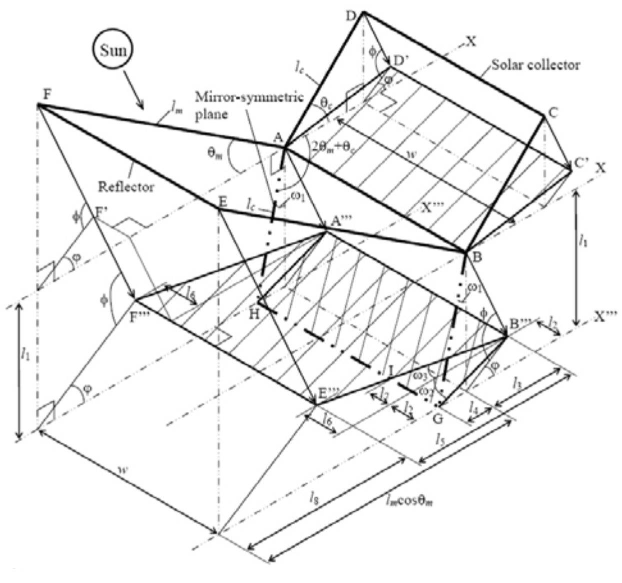


Figure 4
Shadows of the Reflector and the Mirror-Symmetric Plane of the Solar Collector on a Horizontal Surface X''' to Calculate the Reflected Radiation Absorbed on the Absorbing Plate.
$l_1=l_c\cos\omega_1$, $l_2=l_1\sin|\varphi|/\tan\phi$, $l_3=l_1\cos\varphi/\tan\phi$, $l_4=l_c\sin\omega_1$, $l_5=l_m(\cos\theta_m - \sin\theta_m\cos\varphi/\tan\phi)$, $l_6=l_m\sin\theta_m\sin|\varphi|/\tan\phi$, $l_7=(l_3+l_4)\tan\omega_3$, $l_8=(l_1+l_m\sin\theta_m)\cos\varphi/\tan\phi$
$\omega_1=2\theta_m+\theta_c-\pi/2$, $\tan\omega_2=l_2/(l_3+l_4)$, $\tan\omega_3=l_6/l_5$

A geometric diagram to calculate the amount of solar radiation reflected by the bottom reflector and absorbed onto the collector is shown in Fig. 4. Only the geometric diagram for the case when ω_1 and $l_4 > 0$ is shown, but the following calculations are valid even if ω_1 and $l_4 < 0$. In Fig. 4, the solar collector (ABCD) and the bottom reflector (ABEF) are exactly the same as those in Fig. 2. ABGH is a mirror-symmetric plane of the collector to the bottom reflector whose angle from vertical is ω_1. The collector (ABCD) and bottom reflector (ABEF) are placed on a horizontal surface, X, and the mirror-symmetric plane (ABGH) is placed on a virtual horizontal surface, X''', where the horizontal surface, X''', is l_1 ($= l_c\cos\omega_1$) below the horizontal surface, X. The shadow of the bottom reflector and the mirror-symmetric plane on the horizontal surface X''' caused by direct solar radiation is shown as A'''B'''E'''F''' and A'''B'''GH, respectively. The amount of solar radiation reflected from the bottom reflector is A'''B'''E'''F'''. The portion of the reflected radiation from the bottom reflector which can be absorbed on the collector can be determined as the overlapping area of these shadows (a trapezoid A'''B'''IH), and the residue would escape to the ground or the surroundings. Therefore, the solar radiation reflected from the bottom reflector and absorbed on the collector, $Q_{sun,re}$, can be determined as

$$Q_{sun,re}=G_{dr}\tau_g(\beta')\rho_m\alpha_c\times(l_3+l_4)\{w-0.5(l_2+l_7)\} \quad (2)$$

where G_{dr} is the direct solar irradiance on a horizontal surface, τ_g is transmittance of the glass cover, ρ_m is reflectance of the bottom reflector, α_c is absorptance of the absorbing plate of the collector, and β' is incident angle of reflected sunrays to the glass cover as[16]

$$\cos\beta'=\sin\phi\cos\omega_1+\cos\phi\sin\omega_1\cos\varphi \quad (3)$$

The term $(l_3+l_4)\{w-0.5(l_2+l_7)\}$ is the overlapping area of shadows of the bottom reflector and the mirror-symmetric plane. The length in Eq. (2) can be calculated with the lengths (l_1 to l_8) and angles (ω_1 to ω_3) as shown in Fig. 4.

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

1. When $l_8 > l_m\cos\theta_m+l_3$, $Q_{sun,re}$ is zero.
2. When $\omega_1 < 0$ and $l_3+l_4 < 0$, $Q_{sun,re}$ is zero (here, l_4 is negative when $\omega_1 < 0$).
3. During the months of April to August, when the sun moves north, that is, the absolute value of the azimuth angle of the sun, $|\varphi|$, is larger than $\pi/2$ in the morning and evening, $Q_{sun,re}$ should be calculated by determining length l_3 in Fig. 4 to be negative ($l_3 < 0$).
4. When $l_8 > l_m\cos\theta_m-l_4$ as shown in Fig. 5, the overlapping area is A'''B'''E'''J, so the area $(l_3+l_4)\{w-0.5(l_2+l_7)\}$ in Eq. (2) should be substituted with

$$l_5\{w-0.5l_5(\tan\omega_2+\tan\omega_3)\} \quad (4)$$

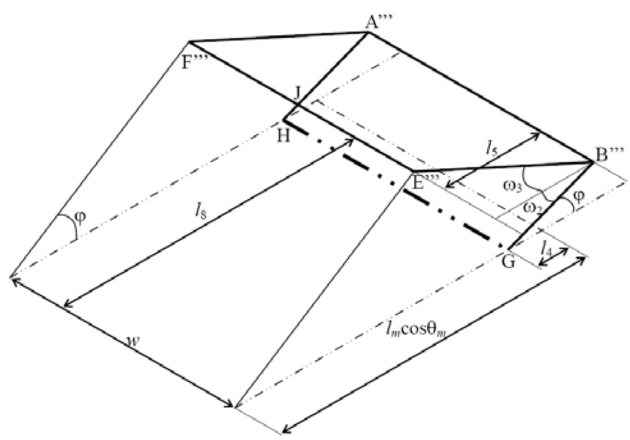


Figure 5
The 4th Exception when $l_8 > l_m\cos\theta_m - l_4$

5. When the overlapping area forms a triangle A'''B'''K (l_2+l_7 in Fig. 4 or $l_5(\tan\omega_2+\tan\omega_3)$ in Fig. 5 is larger than the collector width w) as shown in Fig. 6, the area in Eq. (2) should be replaced by

$$\frac{1}{2}w^2\frac{\sin(\pi/2-\omega_2)\sin(\pi/2-\omega_3)}{\sin(\omega_2+\omega_3)} \quad (5)$$

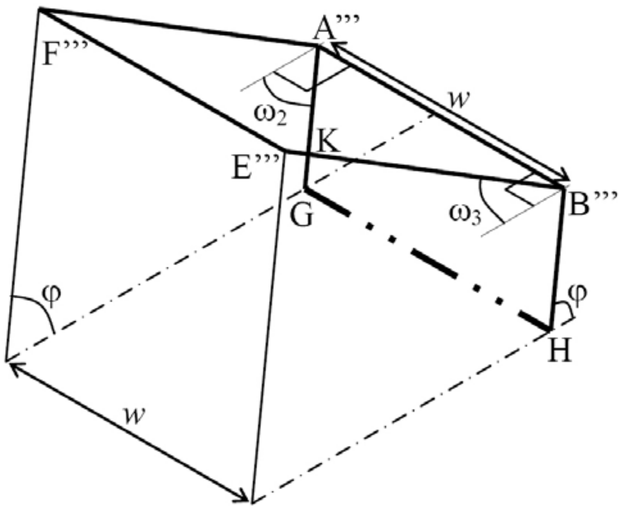


Figure 6
The 5th Exception when the Overlapping Area is a Triangle

1.3 Direct and Diffuse Radiation

The way to calculate direct and diffuse solar radiation absorbed on the absorbing plate of the solar collector, $Q_{sun,dr}$ and $Q_{sun,df}$, was described in our previous paper in detail[14], and may be expressed as

$$Q_{sun,dr}=G_{dr}\tau_g(\beta)\alpha_c\times wl_c(\cos\theta_c+\sin\theta_c\cos\varphi/\tan\phi) \quad (6)$$

$$Q_{sun,df}=G_{df}(\tau_g)_{df}\alpha_c\times wl_c \quad (7)$$

where G_{df} is diffuse solar irradiance on a horizontal surface, β is the incident angle of sunrays to the glass cover, and $(\tau_g)_{df}$ is transmittance of the glass cover for diffuse radiation, which is a function of the inclination of the collector, θ_c, and is calculated by integrating the transmittance of the glass cover for diffuse irradiance from all directions in the sky dome.

Direct and diffuse solar irradiance on a horizontal surface, G_{dr} and G_{df}, was also described in our previous papers in detail[14,15].

1.4 Effect of Shadow of Reflector

In the morning and evening, the altitude angle of the sun ϕ would be so small that the bottom reflector would shade a part of the collector as shown in Fig. 7. In the calculations, the effect of the shadow is taken into consideration. In Fig. 7, ABC'D' and ABE'F' are the shadows of the collector and the reflector on a horizontal surface caused by direct solar radiation, and the area ABLF' shows the shadow of the reflector on the collector. Therefore, when the reflector shades the collector (or $l_m\sin\theta_m\cos\varphi/\tan\phi > l_m\cos\theta_m$), $Q_{sun,re}$ is zero, and the area in Eq. (6) for $Q_{sun,dr}$ should be replaced by

$$wl_s(\cos\theta_s+\sin\theta_s\cos\varphi/\tan\phi)-l_9\{w-0.5(l_{10}-l_{13})\} \quad (11)$$

where the term $-l_9\{w-0.5(l_{10}-l_{13})\}$ represents the effect of the shadow of the reflector on the collector.

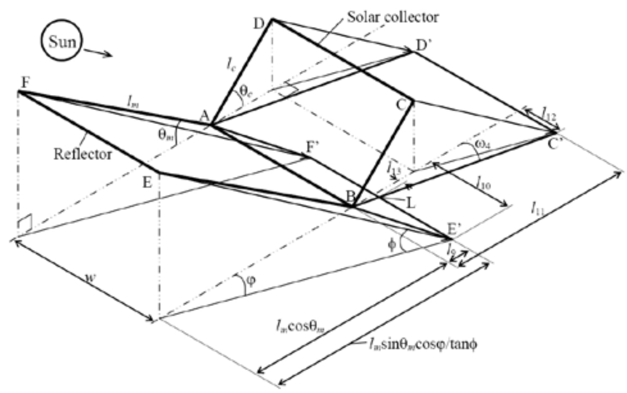


Figure 7
The Shadow of the Reflector and the Absorbing Plate on a Horizontal Surface when the Solar Altitude Angle is Low ($l_m\sin\theta_m\cos\varphi/\tan\phi>l_m\cos\theta_m$).
$l_9=l_m(\sin\theta_m\cos\varphi/\tan\phi-\cos\theta_m)$, $l_{10}=l_m\sin\theta_m\sin|\varphi|/\tan\phi$, $l_{11}=l_c(\cos\theta_c+\sin\theta_c\cos\varphi/\tan\phi)$, $l_{12}=l_c\sin\theta_c\sin|\varphi|/\tan\phi$, $l_{13}=l_9\tan\omega_4$, $\tan\omega_4=l_{12}/l_{11}$

2. RESULTS

In this paper, the daily solar radiation absorbed on the solar collector was calculated for the 23rd of each month since the equinox and solstice days are around 23rd. The azimuth and altitude angle of the sun and direct and diffuse solar irradiance on a horizontal surface were calculated for 600 seconds time steps from sunrise to sunset to determine the solar radiation absorbed on the collector for each day.

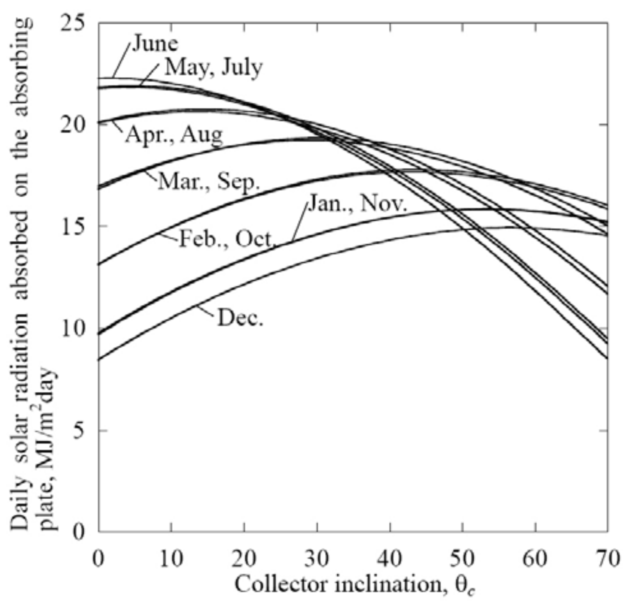


Figure 8
The Daily Solar Radiation Absorbed on the Absorbing Plate Without a Reflector Varying with Collector Inclination θ_c Throughout the Year at 30°N

The daily solar radiation absorbed on the collector without a reflector varying with the collector inclination θ_c throughout the year at 30°N is shown in Fig. 8. In this paper, the daily solar radiation is defined as that per unit effective glass cover area through which the solar radiation transmits. The daily solar radiation has a gentle peak on each month, and the collector inclination θ_c which maximizes the daily solar radiation is smaller in summer and larger in winter, since the solar altitude angle is high in summer and low in winter. The daily solar radiation in five pairs of months (January and November, February and October, March and September, April and August, and May and July) would be almost the same, since the loci of the sun would be similar in each pair of months.

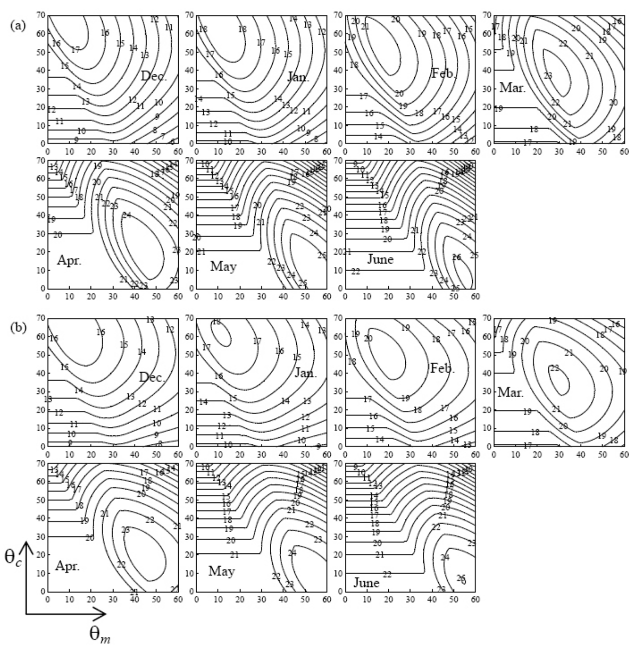


Figure 9
Isometric Diagrams of Daily Solar Radiation (MJ/m^2 day) Absorbed on the Absorbing Plate of the Collector with a Bottom Reflector; Varying with Collector Inclination θ_c and Reflector Inclination θ_m Throughout the Year at 30°N when the Ratio of Collector Length and Width, l_c/w = (a) 1.0 and (b) 2.0, and the Reflector Length is the Same as the Collector Length, $l_m = l_c$

Isometric diagrams of the daily solar radiation (MJ/m^2 day) absorbed on a solar collector with a bottom reflector varying with the collector inclination θ_c and reflector inclination θ_m for seven months (December to June) at 30°N is shown in Fig. 9. In Fig. 9, the ratio of the collector length to the width, l_c/w, is 1.0 (Fig. 9a) and 2.0 (Fig. 9b) and the reflector length is the same as the collector length, $l_m = l_c$. The daily solar radiation absorbed on the collector was calculated at 1° steps for both inclinations θ_c and θ_m, so 70×60 = 4200 calculations were done to investigate the effect of both inclinations for each month at each ratio l_c/w. The results from July to November were omitted here, but the results for each month of these months is approximately the same as for the opposite month in the pairs of months mentioned above, since the loci of the sun is similar in each pair of months.

The combination of the optimum inclinations θ_c and θ_m, that maximize the daily solar radiation absorbed on the collector, would vary considerably according to month, and be slightly affected by the ratio l_c/w. The optimum collector inclination θ_c is lower in summer and higher in winter for the same reasons as in the results for a collector without a reflector. The daily solar radiation increases first, peaks and then decreases with an increase in reflector inclination θ_m on each month at each collector inclination θ_c. The reason is as follows. As the reflector inclination θ_m increases, angle ω_1 (=$2\theta_m+\theta_c-\pi/2$) as well as length l_4 increases so the shadow area of the mirror-symmetric plane (A'''B'''GH in Fig. 4) increases, while length l_5 decreases so the shadow area of the bottom reflector (A'''B'''E'''F''' in Fig. 4) decreases, as shown in Figs. 3 and 4. Therefore, these effects have a trade-off relationship, and the reflector inclination θ_m has its optimum value when the overlapping area of these shadows, that is, the absorption of reflected radiation on the collector is maximized.

When both the inclinations are small (bottom left region of each isometric diagram), the daily solar radiation remains constant as the reflector inclination θ_m increases, since the all of the reflected radiation escapes to the surroundings without hitting the collector in this region.

The daily solar radiation is slightly larger for l_c/w = 1.0 (Fig. 9a) than for l_c/w = 2.0 (Fig. 9b), since the larger amount of reflected solar radiation is absorbed on the lower part of the collector.

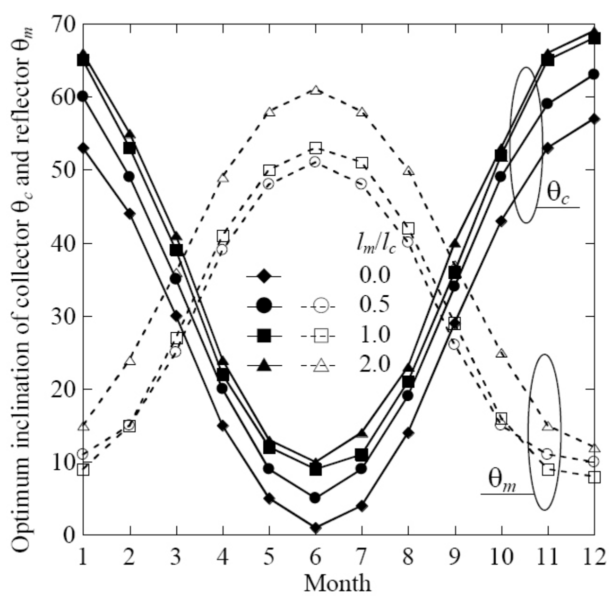


Figure 10
Optimum Inclination of Collector θ_c and Reflector θ_m with Ratio of Reflector and Collector Length, l_m/l_c=0.0, 0.5, 1.0 and 2.0 when l_c/w = 1.0 Throughout the Year at 30°N

The optimum inclination for the collector θ_c and bottom reflector θ_m at ratios l_m/l_c = 0.0, 0.5, 1.0 and 2.0 throughout the year when the collector length l_c is same as the collector width w, l_c/w = 1.0, is shown in Fig. 10. Here, both the optimum inclinations of θ_c and θ_m at ratios l_m/l_c= 0.5 and 2.0 were determined by performing the same calculations as for Fig. 9 at each ratio respectively, and l_m/l_c = 0.0 shows the results of a collector without a bottom reflector. Both the optimum inclinations θ_c and θ_m increase slightly with an increase in ratio l_m/l_c. The reason for this can be explained using Fig. 4 as follows. A longer reflector length l_m causes a longer length l_5, so both the inclinations θ_m and θ_c can be increased to enlarge the overlapping area (A'''B'''IH) of shadows cast by the reflector and mirror-symmetric plane. On the other hand, the direct solar radiation absorbed on the collector, $Q_{sun,dr}$, decreases with an increase in inclination θ_c from the optimum position for l_m/l_c = 0.0 (a collector without a reflector). Therefore, the inclinations θ_c and θ_m can be increased with an increase in the reflector length l_m to the point that the augmentation of the reflected radiation $Q_{sun,re}$ overcomes a decrease in the direct radiation $Q_{sun,dr}$.

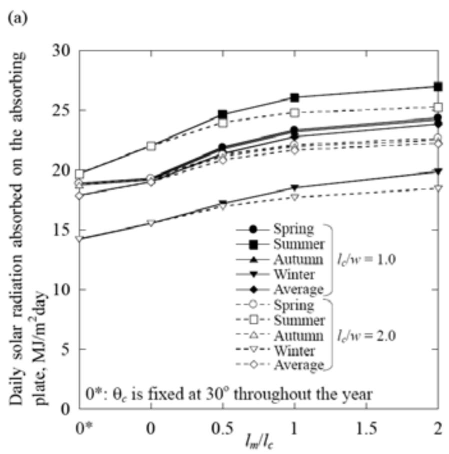
The optimum collector inclination θ_c and reflector inclination θ_m, that maximize the daily solar radiation absorbed on the collector, throughout the year when l_c/w = 1.0 are listed in Table 2. Here, to facilitate ease of adjustment, the optimum inclinations θ_c and θ_m are assumed to be set at 5^o steps. The decline of daily solar radiation with the adjustments in θ_c and θ_m listed in Table 2 from the results of the adjustments to θ_c and θ_m shown in Fig. 6 is less than 1%. Therefore, the daily solar radiation can be maximized approximately by setting the inclinations θ_c and θ_m to be those listed in Table 2 for each month according to the ratio l_m/l_c at 30^{o}N. Further, the optimum inclinations θ_c and θ_m are slightly affected by the ratio of collector length and width, l_c/w, and the optimum inclinations for l_c/w = 2.0 are slightly different than one for l_c/w = 1.0 (Fig. 9). However, for l_c/w = 2.0, the decline of daily solar radiation with the adjustment in θ_c and θ_m listed in Table 2 from the results of the adjustments in optimum inclinations θ_c and θ_m for l_c/w = 2.0 is less than 1%. Therefore, the daily solar radiation can be maximized approximately by setting the inclinations θ_c and θ_m to be those listed in Table 2 even at l_c/w = 2.0.

Table 2
Optimum Inclinations of Collector and Reflector when Collector Length is the Same as Collector Width, l_c=w Throughout the Year at 5 Degree Steps. l_m/l_c=0 Shows the Collector Without a Reflector

Month	l_m/l_c=0	l_m/l_c=0.5		l_m/l_c=1.0		l_m/l_c=2.0	
	θ_c	θ_c	θ_m	θ_c	θ_m	θ_c	θ_m
Dec.	55	65	10	65	10	70	10
Jan., Nov.	55	60	10	65	10	65	15
Feb., Oct.	45	50	15	55	15	50	25
Mar., Sep.	30	35	25	35	30	40	35
Apr., Aug.	15	20	40	25	40	20	50
May, July	5	10	50	15	50	15	55
June	0	5	50	5	55	10	60

The daily solar radiation absorbed on the collector and increase ratio varying with the ratio l_m/l_c when the ratio l_c/w = 1.0 and 2.0 for four seasons (spring (February – April), summer (May – July), autumn (August – October) and winter (November – January)), and the average values for 12 months at 30^{o}N are shown in Fig. 11a and b. Here, both the inclinations θ_c and θ_m are assumed to be set at the optimum angles listed in Table 2 for each month and for each ratio l_c/w. l_m/l_c = 0* shows the results for a collector without a reflector in which the inclination θ_c is fixed at 30^o throughout the year, and l_m/l_c = 0 shows the results for the collector without a reflector in which the inclination θ_c is set to the optimum position for each month as listed in Table 2. The increase ratio is defined as

$$\text{Increase ratio} = \frac{\text{Daily solar radiation with optimum inclination(s)}}{\text{Daily solar radiation } (l_m / l_c = 0^*)}$$



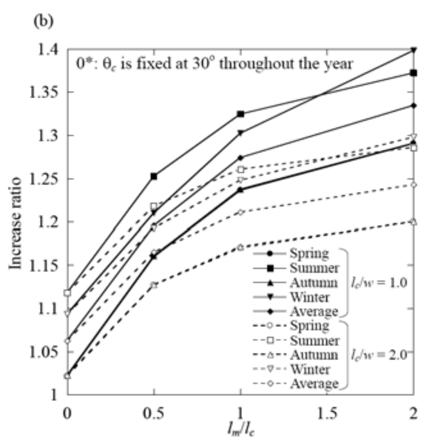


Figure 11
(a) Daily Solar Radiation Absorbed on the Absorbing Plate and (b) Increase Ratio Varying with the Ratio of Reflector Length to Collector Length, l_m/l_c, for Four Seasons and Average Values for 12 months at 30^{o}N

The daily solar radiation absorbed on the collector is highest in summer and lowest in winter, and in spring and autumn it is almost the same as the average values. The increase ratio is greater in summer and winter than in spring and autumn. The daily solar radiation and the increase ratio are greater for l_c/w = 1.0 than for l_c/w = 2.0. The daily solar radiation can be increased by using a bottom reflector and adjusting the inclinations of θ_c and θ_m to the proper values. Compared with a conventional solar thermal collector (l_m/l_c = 0*: collector without reflector and its inclination θ_c is fixed at 30^o throughout the year), the average daily solar radiation absorbed on the collector throughout the year can be increased about 6% by adjusting the collector inclination to the proper values for each month (l_m/l_c = 0), and about 20%, 27% and 33% at l_c/w = 1.0 and 17%, 21% and 24% at l_c/w = 2.0, respectively, by using a flat plate bottom reflector and adjusting the inclination of θ_c and θ_m to the proper values for each month at l_m/l_c = 0.5, 1.0 and 2.0.

CONCLUSIONS

A solar thermal collector with a flat plate bottom reflector extending from the lower edge of the collector has been analyzed theoretically. We have determined the optimum inclination of both the collector and reflector throughout the year at 30^{o}N latitude. The investigations to determine the effect of the size of the collector and reflector on the daily solar radiation absorbed on the collector has also been done. The results of this work are summarized as follows:

(1) The solar radiation absorbed on the collector can be increased by using a flat plate bottom reflector.

(2) The optimum collector inclination is lower in summer and higher in winter, while the optimum reflector inclination is higher in summer and lower in winter.

(3) The optimum inclinations of both the collector and reflector are slightly affected by the ratio of collector length to width, and increases with an increase in the ratio of reflector length to collector length.

(4) The daily solar radiation absorbed on the collector per unit effective glass cover area decreases with an increase in the ratio of collector length to width, and increases with an increase in the ratio of reflector length to collector length.

(5) Compared with a conventional solar thermal collector, the average daily solar radiation absorbed on the collector throughout the year can be increased about 20%, 27% and 33% by using a bottom reflector with ratio of reflector length to collector length of 0.5, 1.0 and 2.0, respectively, when the collector length is the same as the collector width.

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