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Theoretical analysis of solar thermal collector and flat plate bottom reflector with a gap between them

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ABSTRACT

Augmentation of solar radiation absorbed on a flat plate solar thermal collector by a flat plate bottom reflector was numerically determined when there was a gap between the collector and reflector. The inclination of both the collector and reflector was assumed to be adjustable according to the season. A mirror-symmetric plane of the collector to the reflector was introduced, and a graphical model was proposed to calculate the amount of solar radiation reflected by the reflector and then absorbed on the collector. The performance was analyzed for three typical days at a latitude of 30°N. Solar radiation absorbed on the collector can be increased by the bottom reflector even if there is a gap between the collector and reflector. The optimum inclinations of both the collector and reflector are almost the same while the gap length is less than the lengths of the collector and reflector. However, the range of inclination of the reflector that can increase the solar radiation absorbed on the collector decreases with an increase in gap length, and the solar radiation absorbed on the collector rapidly decreased with an increase in the gap length when the reflector and/or collector were not set at a proper angle.

1. Introduction

A booster reflector is an easy and inexpensive modification to add more solar energy to a solar thermal collector. Many studies have been performed to determine the optimum inclination angle of the top reflector (Rao et al., 1993; Hussein et al., 2000; Pucar and Despic, 2002), bottom reflector (McDaniels and Lowndes, 1975; Taha and Eldighidy, 1980; Arata and Geddes, 1986; Dang, 1986; Bollentin and Wilk, 1995; Hellstrom et al., 2003), and both the top and bottom reflectors (Chiam, 1982; Garg and Hrishikesan, 1988; Kostic et al., 2010a,b; Kostic and Pavlovic, 2012), where the top or bottom reflector extends from the upper or lower edge of the collector, respectively. Among them, Tanaka introduced graphical models to calculate the reflected radiation from the top (Tanaka, 2011a) or bottom (Tanaka, 2011b) reflector absorbed on the collector to determine the optimum inclination angle of both the collector and the top or the bottom reflector throughout the year at a 30°N latitude.

However, the collector–reflector systems that have been studied were only for cases in which the edges of the collector and reflector touched without a gap. Therefore, these models cannot be applied to the collector–reflector systems with a gap between the collector and reflector. However, there are many circumstances necessitating the installation of the booster reflector with a gap, especially to an already existing solar thermal collector, according to the limitations of the installation site.

Therefore, in this paper, the graphical model to calculate the solar radiation reflected from the bottom reflector and then absorbed on the collector when there is a gap between the collector and the bottom reflector is introduced. The analysis is performed for three typical days (spring equinox, summer solstice and winter solstice days) at 30°N latitude.

2. Theoretical analysis

2.1. Solar thermal collector and flat plate bottom reflector with a gap between them

A schematic diagram of the collector–reflector system with a gap analyzed in this paper is shown in Fig. 1. The solar thermal collector is assumed to be facing south, and the bottom reflector is placed on the southern side of the collector with a gap (l_g). The collector consists of a glass cover and absorbing plate. The bottom reflector is assumed to be made of a highly reflective material, such as a mirror-finished metal plate. The inclination angles of the collector and reflector from horizontal are θ_c and θ_m,

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Nomenclature

G_{df}, G_{dr}	diffuse and direct solar radiation on a horizontal surface, W/m^2
l_c, l_m	length of collector and reflector, m
l_g	gap length between collector and reflector, m
$Q_{sun,re}$	absorption of reflected solar radiation, W/m^2
$Q_{sun,df}, Q_{sun,dr}$	absorption of diffuse and direct solar radiation, W/m^2
s_d	area of shadow of collector, m^2
s_r	area of overlapping part, m^2
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
$(\tau_g)_{df}$	transmittance of glass cover for diffuse radiation

respectively, and the inclination angles of both the collector and reflector are assumed to be adjustable according to the season. Direct and diffuse solar radiation and also reflected radiation from the reflector transmit through the glass cover and are absorbed on the absorbing plate of the collector.

The design conditions and physical properties employed in this calculation are listed in Table 1. For simplification of the following calculations, the walls of the collector are disregarded, since the height of the walls (10 mm) is negligible in relation to the length (1 m) and width (1 m) of the collector.

Practically, solar radiation at lower levels cannot be utilized for the solar thermal collector due to heat loss. However, in this paper, it was assumed that solar radiation could be utilized even at lower levels.

2.2. Reflected radiation absorbed on the collector

The direct and reflected radiation concerning the collector–reflector system with a gap is shown in Fig. 2. The collector is shown as ABCD and the reflector is shown as EFGH. A distance between points A and E (or points B and F) is the gap length, l_g. The inclination angles of the collector and reflector from horizontal are θ_c and θ_m, and the length of the collector and the reflector is l_c and l_m, respectively. In this paper, the width of both the collector and reflector is determined to be the same as w. The altitude and azimuth angle of the sun is ϕ and φ, respectively. The direct radiation is shown as CC′, DD′, GG′ and HH′, and the reflected radiation is shown as GG″ and HH″. The reflected projection from the reflector casted on a horizontal surface is shown as EFG″H″. Not all of the reflected radiation could hit the collector, and a part of or all of the reflected radiation would escape to the ground without hitting the collector.

To calculate the amount of radiation reflected from the reflector and absorbed on the collector, a mirror-symmetric plane of the collector to the reflector is introduced and its side view is shown in Fig. 3. The amount of direct radiation that goes through the reflector and is then absorbed on the mirror-symmetric plane is exactly the same as that of the radiation that is reflected from the reflector and then absorbed on the collector. Here, from Fig. 3, the position of the top edge of the mirror-symmetric plane can be determined with length l_1 and l_2 as

$$l_1 = 2l_g \sin^2\theta_m \tag{1}$$

$$l_2 = l_g \sin 2\theta_m. \tag{2}$$

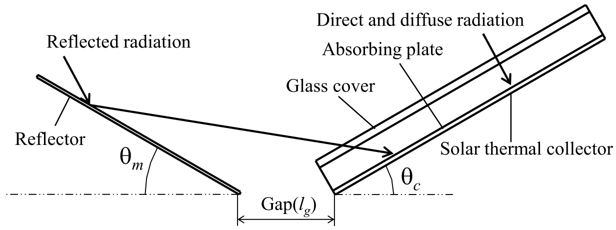

Fig. 1. Schematic diagram of collector–reflector system with a gap between the collector and reflector.

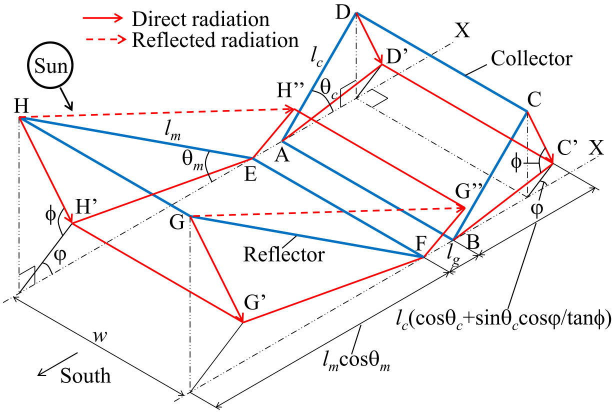

Fig. 2. Shadows of the collector (ABC′D′) and bottom reflector (EFG′H′) and reflected projection from the reflector (EFG″H″) on a horizontal surface caused by direct radiation.

Table 1
Design conditions and physical properties.

$w = 1$ m
$l_c = l_m = 1$ m
$\alpha_c = 0.9$, $\rho_m = 0.8$
$\tau_g(\beta)$ (Tanaka et al., 2000):
$\tau_g(\beta) = 2.642\cos\beta - 2.163\cos^2\beta - 0.320\cos^3\beta + 0.719\cos^4\beta$

The inclination angle of the mirror-symmetric plane from vertical is ω_1 and can be determined as

$$\omega_1 = 2\theta_m + \theta_c - \pi/2 \tag{3}$$

and Fig. 3 shows a case where angle ω_1 is positive ($\omega_1 > 0$). If ω_1 is negative ($\omega_1 < 0$), the length l_6 that is discussed below would be negative, but the following calculations are valid when l_6 has a negative value.

A schematic diagram to determine the amount of direct radiation that goes through the reflector and is then absorbed on the mirror-symmetric plane is shown in Fig. 4. The collector (ABCD) and reflector (EFGH) are exactly the same as those in Fig. 3, and the mirror-symmetric plane is shown as IJKL. The collector and reflector are placed on a horizontal surface (X), and the mirror-symmetric plane is placed on a virtual horizontal surface (X‴) that is $l_2 + l_3$ below from the horizontal surface (X). The shadows of the reflector and the mirror-symmetric plane caused by direct radiation on a virtual horizontal surface (X‴) are shown as E‴F‴G‴H‴ and I‴J‴KL, respectively. Therefore, the amount of direct radiation that goes through the reflector and is then absorbed on the mirror-symmetric plane, $Q_{sun,re}$, can be calculated by the area of the overlapping part of these shadows, s_r, in the form of a trapezoid I‴NG‴M as

$$Q_{sun,re} = G_{dr}\tau_g(\beta')\rho_m\alpha_c \times s_r \tag{4}$$

$$\cos\beta' = \sin\phi\cos\omega_1 + \cos\phi\sin\omega_1\cos\varphi$$
(Japan Solar Energy Soc., 1985) (5)