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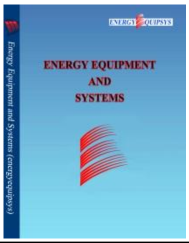

Theoretical and experimental investigation into incident radiation on solar conical collector

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ABSTRACT

The geometry of a collector is one of the important factors that can increase the incident radiation on the collector surface. In the present study, the incident radiation for a stationary collector with cone geometry, i.e. a conical collector, is theoretically and experimentally investigated. This type of collector is always stable and does not need a fixture to install. Moreover, it has a symmetric geometry, with all its sides facing the sun. The main advantage of this collector is its ability to receive beam, diffuse, and ground-reflected radiation throughout the day. The variation of the incident radiation is theoretically estimated by using an isotropic sky model based on the available data. The theoretical data are validated by an experimental test of a conical collector of a specific size. The results show that the conical solar collector is more operative in receiving total solar radiations than a horizontal plate such as a flat-plate collector and can be a suitable option for solar water heating. A calculation of the incident radiation shows that the incident radiation is maximized when the cone angle of the conical collector is equal to the latitude of the site test.

Keywords: Incident Radiation, Solar Collector, Conical Collector, Experimental Investigation, Theoretical Investigation, Isotropic Sky Model.

1. Introduction

Solar collectors are the most important part of solar thermal systems. A solar collector is a device that converts sunlight into useful energy [1]. Generally, solar collectors are divided into two: stationary solar collectors, which are firmly installed, and movable and tracking collectors.

Recently, researchers in the field of solar energy have attempted to enhance the efficiency of solar collectors and conversion systems [2–5]. The efficiency of solar collectors plays a key role in solar thermal systems. One of the important factors affecting the efficiency of a solar collector is the geometry of the collector.

Efficiency improvement can be achieved by using a suitable shape and good geometry of the collector to increase the incident radiation. With this rule in mind, many researchers have studied the collector geometry and attempted to increase the total incident radiation. Samanta and Balushi [6] estimated the incident radiation on a spherical solar collector and showed that their collector was more effective in receiving solar radiation than a flat-plate collector. Al-Sulaiman and Ismaili [7] investigated the average daily solar radiation for a month on a sloped surface using the isotropic sky model and reported the relationship between their theoretical predictions and experimental data. Pelece et al. [8, 9] studied the special

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geometry of a semi-spherical solar collector. They examined the surface temperature distribution and energy gain from the semi-spherical collector and suggested that this type of collector was appropriate for use in northern cold climates. In another study, Gaspar et al. [10] evaluated the global solar radiation received by a fixed spherical solar collector and compared the results with a flat-plate collector. The results revealed that spherical collectors can be more efficient than flat-plate collectors in receiving solar radiation. Kumar et al. [11] designed and tested a truncated pyramid type solar cooker/hot water system. They reported the benefit of this type of collector and showed that the maximum efficiency of their collector was ~54%. The truncated-pyramid geometry increased the performance of their solar system. Tian and Zhao [12] reported a comprehensive review of solar collectors and thermal-energy storage and explained the effect of the geometry of the stationary solar collector.

To estimate the incident radiation for a sloped plate or a solar collector with a special geometry, several methods have been proposed and are used by researchers throughout the world. These methods employ the following important components to calculate the total incident radiation: the beam and diffuse radiation, time and date of measurement, latitude, location, and surrounding conditions [13–21].

In the present study, a special type of stationary solar collector called the conical collector is proposed. It comprises a conical body (Fig. 1) with a glass cover, an absorbing surface, and working fluid. The collector is designed according to the natural geometry of trees such as pine and cypress, which is conical and suitable for receiving enough sunlight throughout the year. The special geometry of the conical collector appears to result in an increase in the solar energy received in the absorber of the collector.

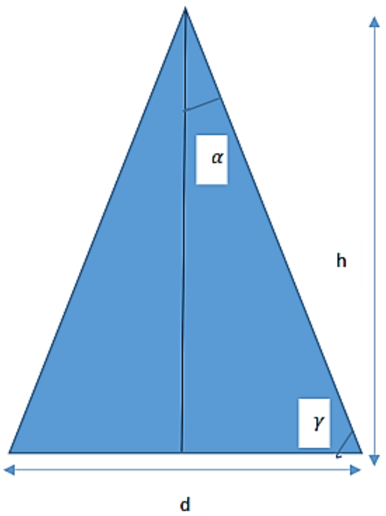

Fig. 1. Schematic of the solar conical absorber

Nomenclature

d	Cone width (m)
F_{c-s}	Radiation view factor from the sloped surface to the sky
F_{c-hz}	Radiation view factor from the sloped surface to the horizon
F_{c-g}	Radiation view factor from the sloped surface to the ground
h	Cone altitude (m)
I	Total radiation on a horizontal surface (MJ/m^2)
I_b	Beam radiation (MJ/m^2)
$I_{d,iso}$	Isotropic diffuse term (MJ/m^2)
$I_{d,hz}$	The circumsolar diffuse term (MJ/m^2)
$I_{d,cs}$	The contribution of the diffuse from the horizon from a band (MJ/m^2)
I_T	Total radiation on a sloped surface (MJ/m^2)
$G_{b,T}$	Beam radiation on titled surface (W/m^2)
G_b	Beam radiation on a horizontal surface (W/m^2)
$G_{b,n}$	Normal beam radiation (W/m^2)
R_b	Geometric factor

Greek parameter

α	Head angle of cone (degrees)
β	Sloped angle (degrees)
γ	Side angle of cone (degrees)
θ	Incident beam angle (degrees)
θ_z	Zenith angle (degrees)
δ	Declination angle (degrees)
ρ_g	Reflectance coefficient of ground
ϕ	Latitude angle of test area (degrees)
ω	Hour angle (degrees)

2. Materials and methods

The incident solar radiation on the Earth's surface has three components: the beam, diffuse, and ground-reflected radiation that are shown in Fig. 2 [2]. The diffuse component has three parts. The first—the isotropic part—is received uniformly from the entire sky dome. The second part—the circumsolar diffuse—results from the forward scattering of solar radiation and is concentrated on the part of the sky around the sun. The third part is concentrated near the horizon and is most pronounced in clear skies [2, 18].
The total incident solar radiation on a sloped surface is given as

$$I_T = I_b R_b + I_{d,iso} F_{c-s} + I_{d,cs} R_b + I_{d,hz} F_{c-hz} + I\,\rho_g F_{c-g} \quad (1)$$

In this equation, the first term is the beam contribution, the second is the isotropic diffuse term, the third is the circumsolar diffuse term, the fourth is the contribution of the diffuse radiation from the horizon from a band, and the fifth is the reflected radiation from the ground and surroundings. The ground surface is assumed to be a diffuse reflector. The variable R_b is called the geometric factor and is the ratio of the beam radiation on the titled surface to the beam radiation on a horizontal surface at any time

$$R_b = \frac{\text{beam radiation on titled surface}}{\text{beam radiation on a horizontal surface}} = \frac{G_{b,T}}{G_b} = \frac{G_{b,n}\cos\theta}{G_{b,n}\cos\theta_z} \quad (2)$$

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (3)$$

There are different methods to find the terms in Eq. (1). In the present study, the isotropic diffuse model is used, and the results are compared with experimental data that were obtained using a real conical collector.

3. Theoretical estimation of incident radiation on a conical collector

As previously mentioned, the total incident radiation on a sloped surface can be calculated using Eq. (1). The Perez model, the Hay-Davies-Klucher-Riendl model, and the isotropic sky model are the most commonly used theoretical models for estimating the total radiation on sloped surfaces [2, 22, 23]. In the isotropic sky model, all of the diffuse radiation is assumed to be isotropic. Accordingly, Eq. (1) takes the following form:

$$I_T = I_b R_b + I_d F_{c-s} + I\,\rho_g F_{c-g} \quad (4)$$

For a surface tilted at slope (β), the view factor to the sky F_{c-s} and the view factor to the ground F_{c-g} are given as (1+ cos β)/2 and (1- cos β)/2, respectively. If the surroundings have a diffuse reflectance of ρ_g for total solar radiation, the reflected radiation from the surroundings on the surface is $I\,\rho_g$ (1- cos β)/2. Consequently, Eq. (5) is obtained for the total solar radiation on the tilted surface for 1 h:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\,\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (5)$$

According to Eq. (2), we obtain

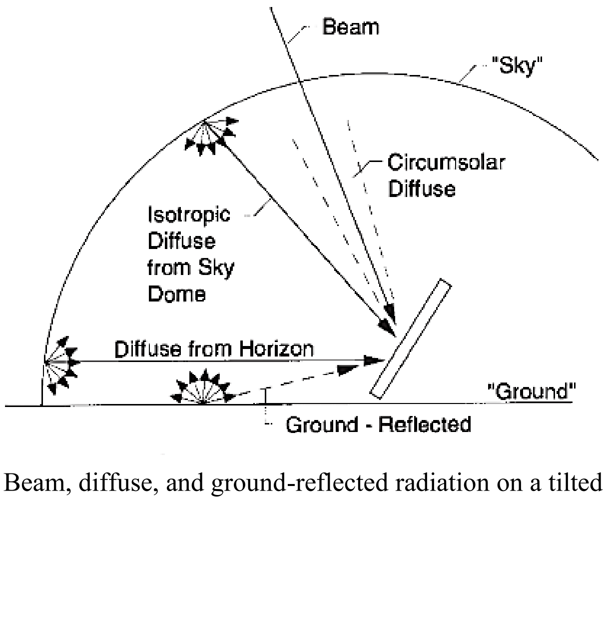

Fig. 2. Beam, diffuse, and ground-reflected radiation on a tilted surface [2]

$$R_b = \frac{\cos(\phi-\beta)\cos(\delta)\cos(\omega)+\sin(\phi-\beta)\sin(\delta)}{\cos\phi\cos\beta\cos\omega+\sin\phi\sin\delta} \tag{6}$$

To estimate R_b, the hour angle, slope angle, declination angle, and latitude and location of the conical collector are required. For this, a real conical solar collector is used, and its properties are shown in Table 1. To calculate R_b , we must determine ω and δ, i.e., the hour angle and declination angle, respectively. Using Table 1, we obtain

$$\delta = 23.45\, sin\left(360\frac{284+n}{365}\right) \tag{7}$$

$$\omega = (solar\ time - solar\ noon) \times 15° \tag{8}$$

Both the angles ω and δ angles are given in degrees. For example, when n = 37, δ = -15.8°. For $\omega_1 = 10AM, \omega_2 = 11AM$, and by introducing 12.00 as solar noon, we obtain
ω= [(midpoint time between 10–11 AM is 10.30 AM)-12.00] × 15°
The hour angle, ω, for the midpoint of the hour is -22.5°.

All the elements of the absorber plate in the cone collector have the same angle with the horizon. Thus, the angle between the cone collector and horizon, γ, is equal to the slope angle of the collector, β, i.e., the angle between the collector and Earth's surface (β = g).

Therefore, by using $\emptyset, \beta, \delta$, and ω, we can calculate R_b. Then, by using Eq. (5) and R_b, the final equation to calculate the total incident radiation on the conical solar collector is obtained as follows:

$$I_T = I_b\left(\frac{\cos(\phi-\gamma)\cos(\delta)\cos(\omega)+\sin(\phi-\gamma)\sin(\delta)}{\cos\phi\cos\beta\cos\omega+\sin\phi\sin\delta}\right) + I_d\left(\frac{1+\cos\gamma}{2}\right) + I\,\rho_g\left(\frac{1-\cos\gamma}{2}\right) \tag{9}$$

The calculation method to evaluate the total incident radiation on the conical solar collector is given by the flowchart shown in Fig. 3, which was developed using the software MATLAB 2014.

4. Experimental setup

The experimental setup was designed to investigate the incident radiation on the conical solar collector in the real condition. The solar radiation was recorded by a solar meter (TES). The conical collector was experimentally investigated at Behbahan, a southwestern city in Iran, (latitude 30° 36' 0" N and longitude 50° 15' 0" E). The specifications of the conical collector used in this investigation are presented in Table I. The tilt angle of the conical collector was always 90°; i.e., the collector was normal to the earth at every location and had a section on each side that was symmetric with respect to the sunrays.

5. Testing method

The conical collector has a symmetric geometry and can collect beam and diffuse radiation from every side. For measuring the total incident radiation, the conical geometry is modeled by the longitude and latitude on the conical surface. In this approach, the absorber of the conical collector is divided into 8 longitudinal sections and 10 latitudinal sections. Thus, the conical collector is divided into 80 pieces, with each piece being between two neighboring longitudes and latitudes. Each piece can be considered as a flat trapezoidal surface, as shown in Figs. 4–5.

Table 1. Specifications of the conical collector and test conditions for the theoretical calculation and experimental testing conditions

Specification	Dimension	Unit
Diameter of absorber (conical body)	0.6	m
Absorber altitude (h)	1.07	m
All side area (absorber area)	1.0	m^2
Date of test (day of year)	285th day of the year (October 12th)	-
Cone angle (γ)	72	Degrees
Time of test	Every 1 h, but the selected time for this calculation is 10 to 11 AM	-
Ground-reflection coefficient	0.7	
Latitude of test location (∅)	31	Degrees (north)
Measured direct radiation (average of I)	555	W/m^2

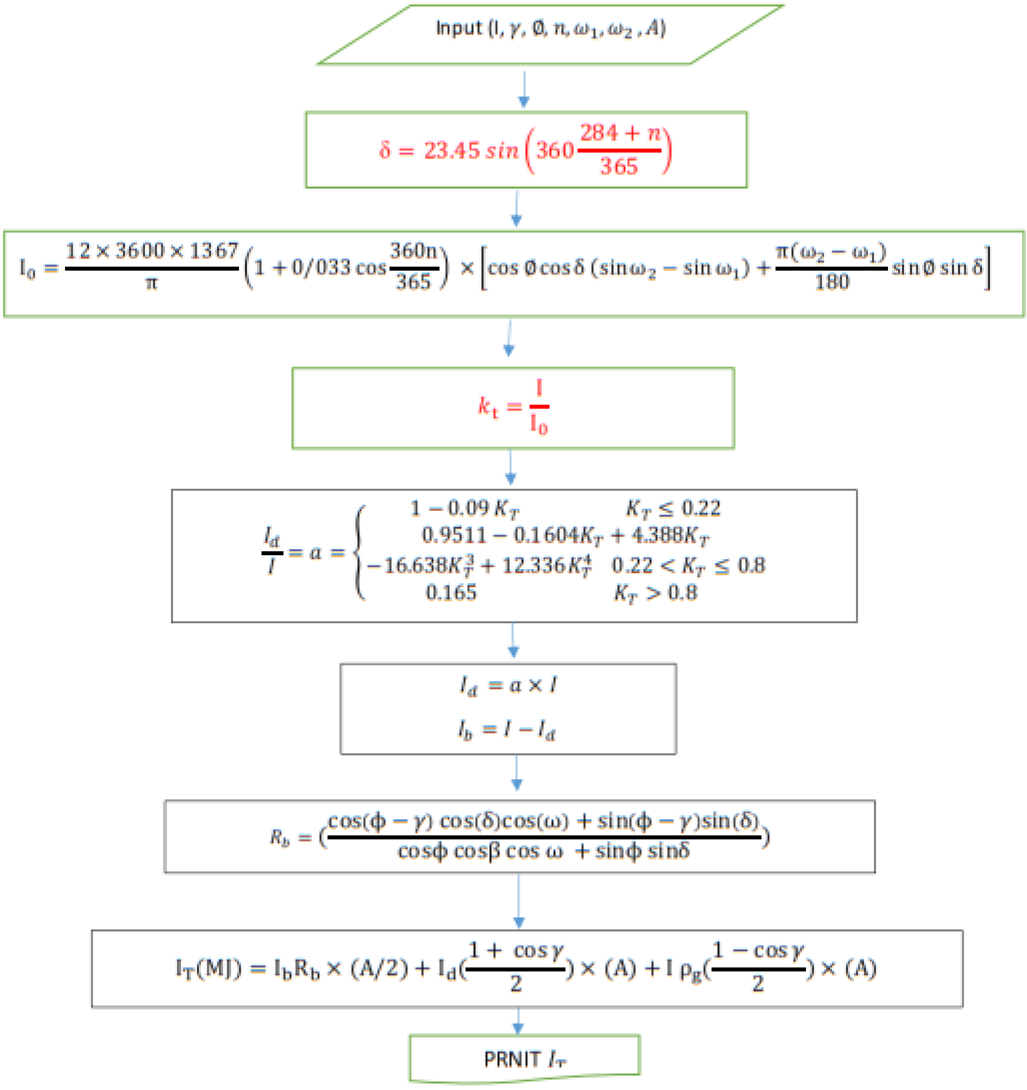

Fig. 3. Flowchart of step-by-step method to evaluate the total incident radiation on the conical solar collector

Fig. 4. Different parts of the conical absorber.

Fig. 5. Top view of the conical-absorber parts.

The experimental measurement of the total incident radiation on the conical collector, which is performed for 80 semi-flat parts, takes ~6 min. In this procedure, the solar meter is placed on each piece and records the incident radiation on that piece. After recording the incident radiation on all the pieces, the total incident radiation on the conical collector is calculated using Eq. (10).

$$\mathrm{I}_T = \sum_{k=0}^{80} \mathrm{A}_k \ I_k \quad (10)$$

Here, A_k and I_k are the area and incident radiation, respectively, for the k^{th} piece.

6. Results and discussion

6. 1. Investigation of the incident radiation

The incident radiation on the conical collector is theoretically and experimentally investigated. The experimental tests were performed several times on several days, and the best experimental data were chosen. The selected test was performed on an autumn day in southern Iran with a high range of solar radiation. The theoretical data for the total incident radiation on the conical collector are presented in Figs. 6 and 7 and were calculated according to the data shown in Table 1. Figure 6 shows the total incident radiation with respect to the cone angle (g). Here, the effect of the cone angle ranging from 0 to 90° on the total incident radiation is indicated. According to Fig. 6, the maximum incident radiation occurred when the cone angle was 31–32°, which is close to the latitude of the test place. This trend is similar to the results of Soulayman [24] and Morcos [25].

The estimated value of the diffuse radiation with respect to the cone angle is also shown in Fig. 7. For the diffuse-radiation measurement, the cone angle clearly increased when the diffuse incident radiation decreased, as a large cone angle caused the conical geometry to resemble vertical flat-plate geometry.

Figure 8 compares the theoretical values and experimental measurements of the total incident radiation on the conical collector. The theoretical value of the total incident radiation calculated by Eq. (9) matches the experimental data that were measured with solar meter and described in Section 5. The figure shows an acceptable agreement between the theoretical and experimental data. The simplification of the modeling may be the reason for the difference between the theoretical estimation and experimental measurements.

6.2.Comparison with flat-plate solar collector

The flat-plate solar collector is the most practical collector. For a suitable evaluation of the solar conical collector, the incident radiation is compared between the conical and flat-plate solar collectors. The flat-plate collector has an area of 1 m^2, and the incident radiation is horizontally measured. Figure 9 compares the solar radiation measured by the conical and flat-plate solar collectors on 9.12.2014. As indicated by the figure, the incident radiation on the conical collector was greater than that on the flat-plate collector in the morning and the evening.

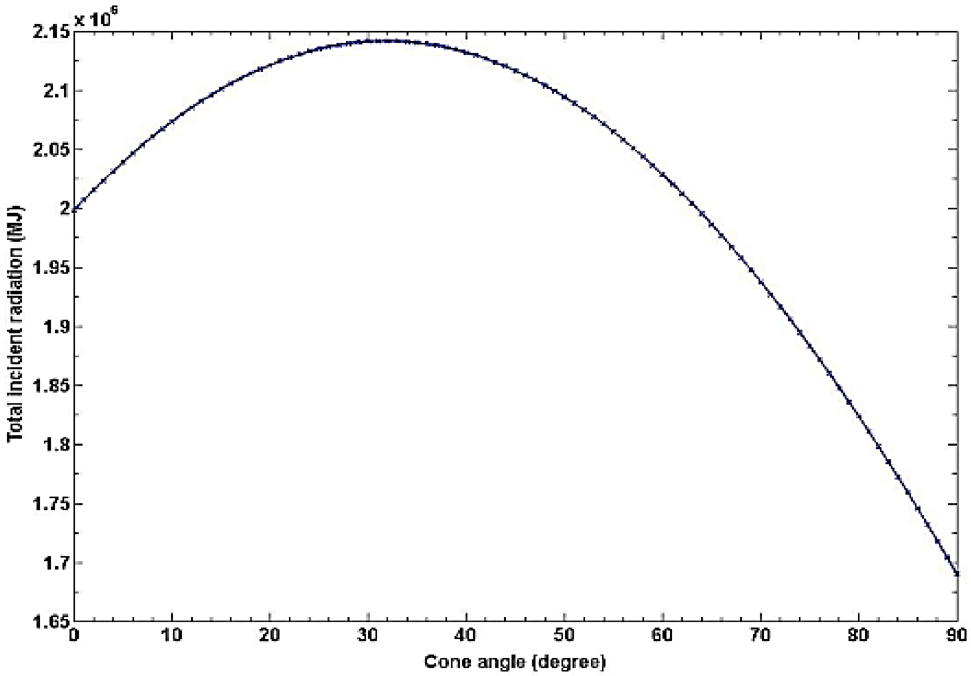

Fig. 6. Theoretical data for the total incident radiation on the conical collectors with respect to the cone angle (g).

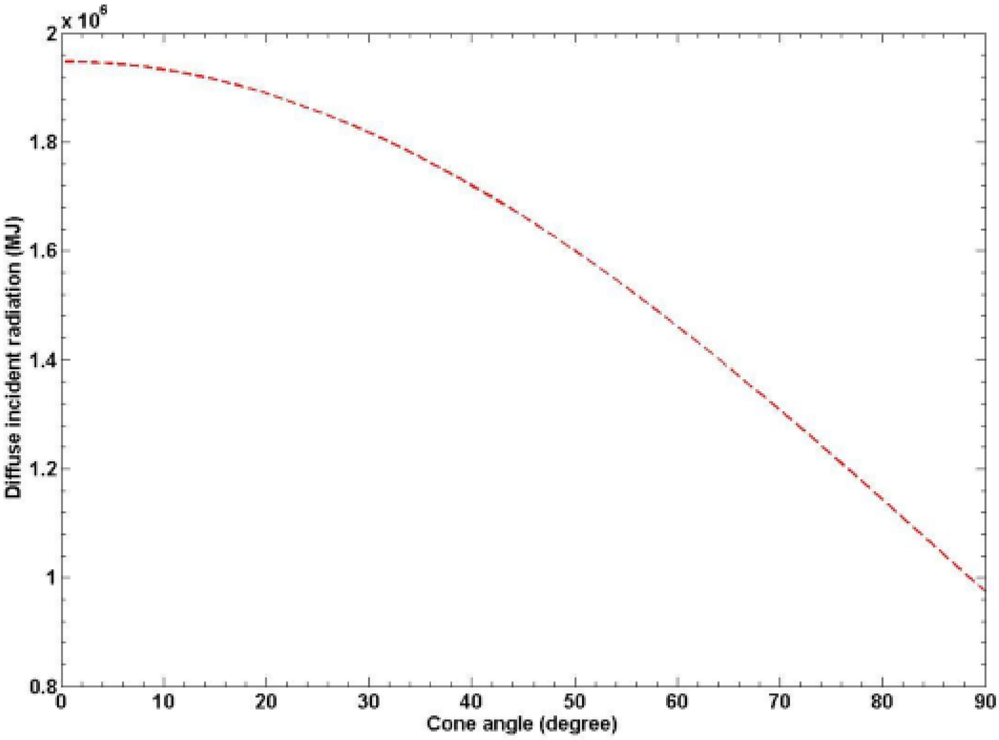

Fig. 7. Theoretical data for the diffuse radiation on the conical collectors with respect to the cone angle (g)

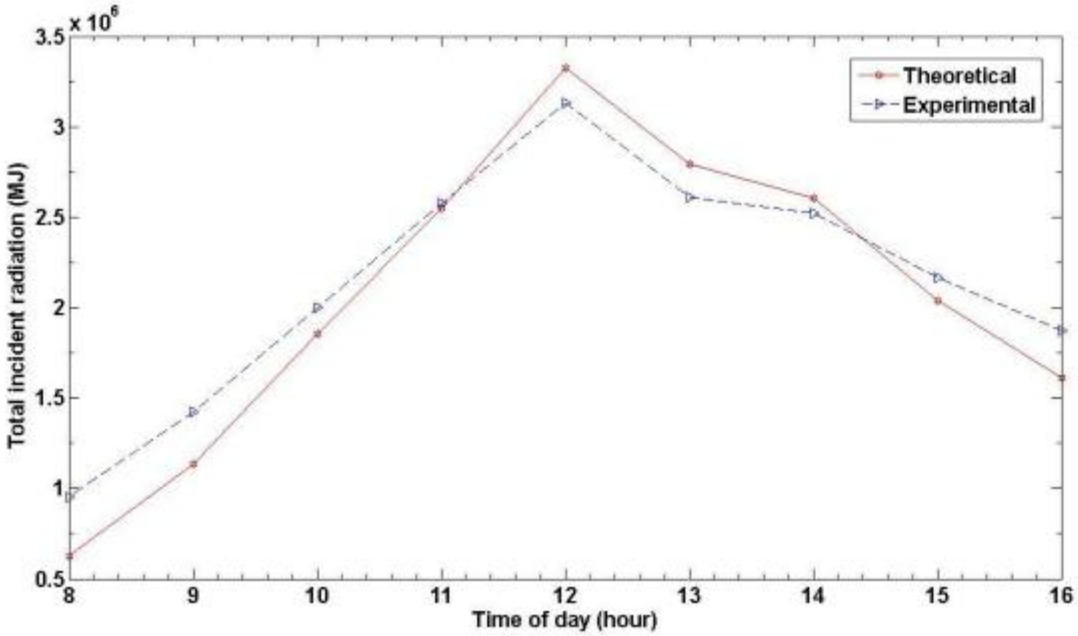

Fig. 8. Theoretical calculation and experimental measurement of the total incident radiation on the conical collector

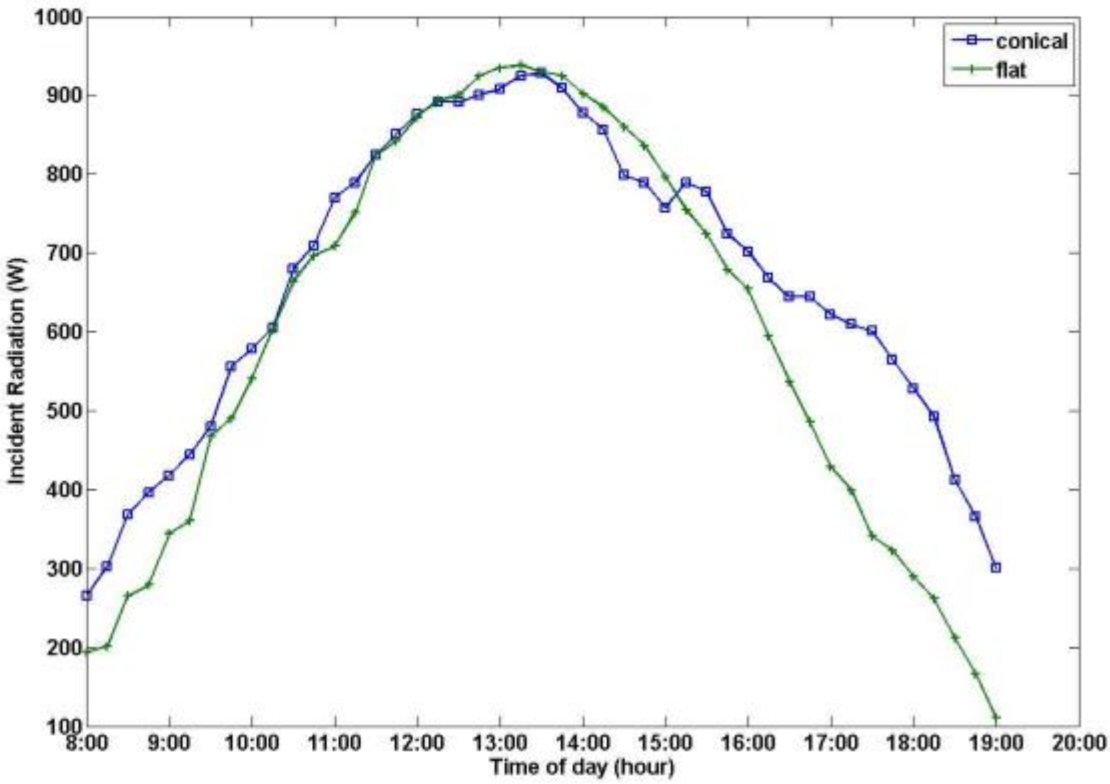

Fig. 9. Experimental data for the radiation on the flat and conical collectors (9.12.2014)

7. Conclusion

The solar conical collector is a stationary collector with a conical geometry. This collector is capable of receiving beam, diffuse, and ground-reflected radiation. The incident radiation on a solar conical collector with a specific size was theoretically and experimentally investigated in the present study. The isotropic sky model was used for theoretical estimations, and an experimental test was conducted in Behbahan, Iran. The results show good agreement between the theoretical and experimental data. They also reveal that the conical collector can receive a good amount of diffuse and ground-reflected radiation compared with a horizontal plate such as a flat-plate collector. Thus, the conical collector can be effectively used as a water heater because it can receive a suitable amount of radiation in early morning and the late evening. According to the results, the incident radiation is maximized when the cone angle of the conical collector is equal to the latitude of the site test.

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