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Evaluation of Global Solar Radiation Received by a Spherical Solar Collector

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Abstract. In the paper the global solar radiation incident on a fixed spherical solar collector is evaluated and compared to a south oriented with 46 grade tilt angle fixed flat plate solar collector. Mean daily and hourly solar radiation are calculated from existing data for Cluj-Napoca, Romania. The results show that depending on the equivalent absorbing surface area taken into account, spherical collectors can be more efficient in receiving solar radiation than flat plate collectors.

Keywords: solar radiation, spherical solar collector, flat plate solar collector, absorbing surface.

INTRODUCTION

In household solar water heating flat plate and evacuated tube solar collectors are the most commonly used. The heat gain from a solar collector is directly influenced by its orientation and tilt angle with the horizontal plane.

A solar collector positioned at its optimal tilt angle will receive up to 1.3 times more global radiation over a year than a horizontal fixed one. The yearly optimal tilt angle for collectors varies with the latitude angle (ϕ) of the given location. For a location in the northern hemisphere with $\phi \leq 65^{o}$, such as Cluj-Napoca, the yearly optimal tilt angle for a solar collector proposed by Chang (2009) is $0.764 \cdot \phi + 2.14^{o}$. Also, a general rule adopted in this domain says, the tilt angle equal to the latitude is the best for increased annual energy gain from fixed solar collectors (Duffie and Beckman, 1991).

For maximizing the incident global radiation for a surface, solar tracking mechanisms can be used (Mousazadeh *et al.,* 2009). This can increase the yearly solar radiation gain up to 1.45 times more compared with an optimal tilted solar collector (Lave and Kleissl, 2011). Such tracking mechanisms are complicated and costly to operate and their use in domestic solar water heating is not economically justified.

Eliminating the tracking mechanism and keeping its benefits is possible by using spherical surfaces, by considering that for any position of the Sun on the sky dome a hemisphere of the sphere is always irradiated.

Estimation of solar radiation incident on spherical shape solar collector has been carried out by Oztekin (2006) and Samanta and Rajab Al Balushi (1998). Pelece et al. (2008) estimated the total solar energy received by a semi-spherical solar collector. In all cases good results have been obtained, when comparing these spherical collectors with flat plate solar collectors.

The objective of this paper is to evaluate the global solar radiation incident on a spherical solar collector, taking into account its whole absorbing surface area. Such a spherical solar collector, with 0.35 meter radius, was designed and built by the author (Fig. 1). A similar solar collector was developed by Pelece (2010), but in semispherical shape.

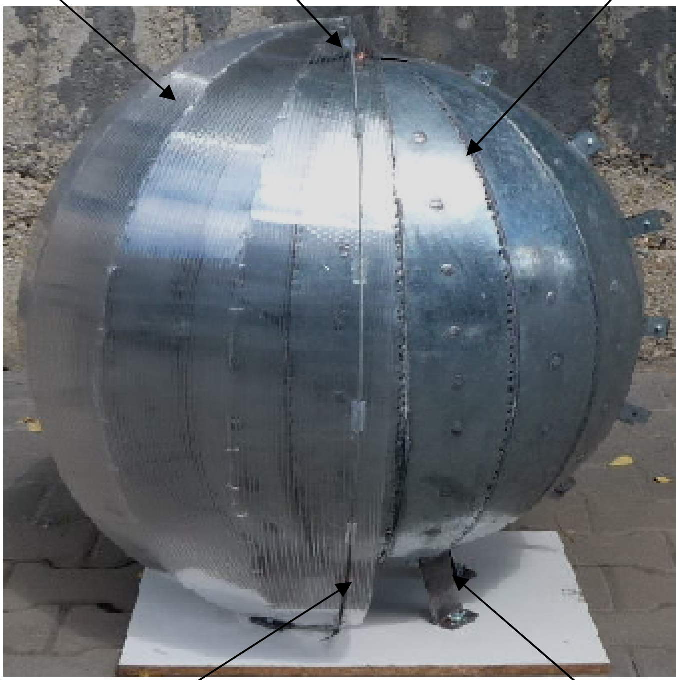

Fig. 1. Spherical solar collector with 0.35 meter radius.

Evaluation is based on the global monthly mean, direct (beam) and diffuse solar radiation measured over a 28 months period (August 2007 - September 2009) for horizontal surface, at the Technical University of Cluj-Napoca (Bălan et al., 2008).

MATERIALS AND METHODS

The monthly mean daily global solar radiation $\bar{H}_i$ for a horizontal surface in Cluj-Napoca averaged from the 28 months of measurement and its components ($\bar{H}_{b_i}$ - beam and $\bar{H}_{d_i}$ -diffuse) are given in Table 1 with the ground reflection coefficient ρ_{g_i} considered for each month.

Tab. 1
The monthly mean global solar radiation on a horizontal surface and its beam and diffuse components

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
$\bar{H}_i$	4.4	7.76	10.45	18.19	22.76	23.5	24.24	20.39	14.17	8.78	5.37	3.2
$\bar{H}_{b_i}$	3.17	5.57	7.56	14.39	16.93	16.68	17.85	16.24	11.32	6.74	3.97	2.16
$\bar{H}_{d_i}$	1.33	2.08	2.89	3.8	5.82	6.82	6.39	4.15	2.85	2.04	1.4	1.04
ρ_{g_i}	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4

The monthly mean daily global solar radiation $\bar{H}_{T_i}$ (1) for a tilted surface with the tilt angle $\beta = 46^{\circ}$ is given in terms of global solar radiation on a horizontal surface and its beam, diffuse and ground reflected components:

$$\bar{H}_{T_i} = \bar{H}_{b_i} \cdot \bar{R}_{b_i} + \bar{H}_{d_i} \cdot \left(\frac{1+\cos\beta}{2}\right) + \bar{H}_i \cdot \rho_{g_i} \cdot \left(\frac{1-\cos\beta}{2}\right), \tag{1}$$

where $\bar{R}_{b_i}$ is the geometric factor and represents the ratio of the monthly mean daily beam radiation on the tilted surface to that on the horizontal plane and is given by the equation (2):

$$\bar{R}_{b_i} = \frac{\cos\theta}{\cos\theta_z}. \tag{2}$$

The angle θ_z is the incidence angle of the beam radiation on the horizontal plane with respect to its normal and the incident angle of the beam radiation for a tilted plane surface θ are given according to the latitude angle ϕ, sunset hour angle ω'_{s_i} and declination δ_i as follows:

$$\bar{R}_{b_i} = \frac{\cos(\phi-\beta)\cdot\cos\delta_i\cdot\sin\left(\omega'_{s_i}\right) + \omega'_{s_i}\cdot\sin\left(\phi-\beta\right)\cdot\sin\delta_i}{\cos\phi\cdot\cos\delta_i\cdot\sin\left(\omega'_{s_i}\right) + \omega'_{s_i}\cdot\sin\phi\cdot\sin\delta_i}, \tag{3}$$

where

$$\omega'_{s_i} = \min[\cos^{-1}\left(-\tan\phi\cdot\tan\delta_i\right),\ \cos^{-1}\left(-\tan\left(\phi-\beta\right)\cdot\tan\delta_i\right)], \tag{4}$$

and "min" means the smaller of the two items in the brackets.

The declination angle δ_i for any day (i) of the year can be obtained as follows:

$$\delta_i = 23.45\cdot\sin\left(360\cdot\frac{\pi}{180}\cdot\frac{284+n_i}{365}\right). \tag{5}$$

For a spherical collector the monthly mean daily global radiation can be written as follows:

$$\bar{H}_{s_i} = \bar{H}_{b_i}\cdot\bar{R}_{bs_i} + \bar{H}_{d_i}\cdot f_{sd} + \bar{H}_i\cdot\rho_{g_i}\cdot f_{sg}. \tag{6}$$

The corresponding geometric factor, $\bar{R}_{bs_i}$, (suffix s refers to spherical collector) is obtained from the fact that the incident beam radiation is always normal to the projection of the irradiated hemisphere and it can be written as:

$$\bar{R}_{bsi} = \frac{f_s\cdot\cos\theta}{\cos\theta_z}. \tag{7}$$

For a surface that is continuously tracking the sun, the incident angle is zero and the geometric factor for a spherical surface after integration from sunrise to sunset is given by:

$$\bar{R}_{bs_i} = \frac{f_s\cdot\omega'_{s_i}}{\cos\phi\cdot\cos\delta_i\cdot\sin\left(\omega'_{s_i}\right) + \omega'_{s_i}\cdot\sin\phi\cdot\sin\delta_i}, \tag{8}$$

where f_s is the view factor of the beam radiation to the irradiated semispherical surface and is obtained from integration of an elemental area (dA) over the irradiated hemisphere and reported to the total surface of the sphere (9):

$$f_s = \frac{1}{4 \cdot \pi \cdot R^2} \int_0^{2\pi} \int_0^{\pi/2} \cos\beta \cdot R \cdot \sin\alpha \cdot d\beta \cdot R \cdot d\alpha = \frac{1}{4}. \tag{9}$$

It means, for beam radiation, the sphere acts as a tracking solar collector with an effective absorbing surface equal to one fourth of the total surface of the spherical collector.

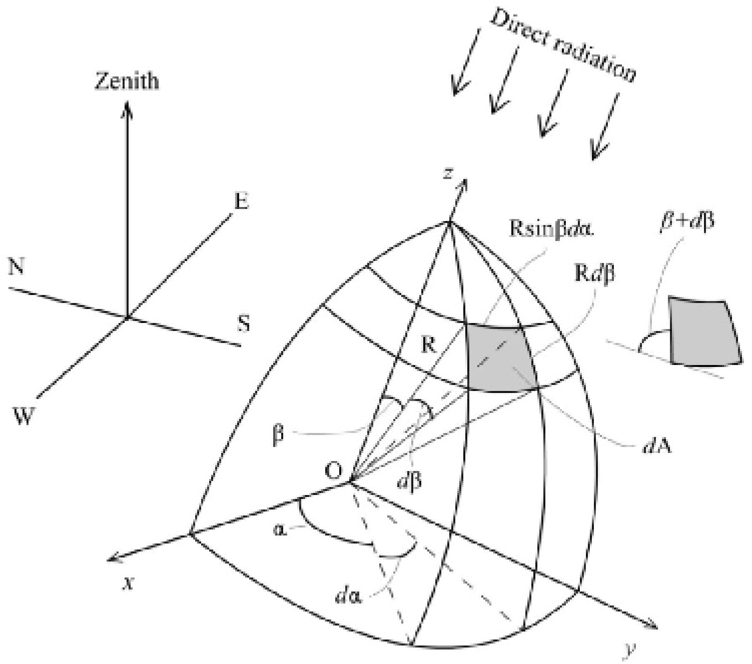

Fig. 2. An elemental area on the spherical solar collector.

Similarly, the view factors to the sky and the ground can be determined by integration of an elemental area (dA) on the total surface of the spherical collector (Fig. 2) and reported to the total surface of the irradiated sphere as follows:

$$f_{sd} = \frac{1}{4\pi R^2} \int_0^{2\pi} \int_0^{\pi} \left(\frac{1+\cos\beta}{2} \right) \cdot R \cdot \sin\alpha \cdot d\beta \cdot R \cdot d\alpha = \frac{1}{2}, \tag{10}$$

$$f_{sg} = \frac{1}{4\pi R^2} \int_0^{2\pi} \int_0^{\pi} \left(\frac{1-\cos\beta}{2} \right) \cdot R \cdot \sin\alpha \cdot d\beta \cdot R \cdot d\alpha = \frac{1}{2}. \tag{11}$$

This means, that for diffuse radiation the spherical collector behaves like a horizontal surface equal to half of the total surface of the spherical collector.

The monthly mean hourly radiation on a flat-plate collector at a latitude ϕ with a tilt angle β can similarly be obtained for isotropic sky condition (12) (Duffie and Beckman, 1991):

$$\bar{I}_{T_{ij}} = \left(\bar{H}_i \cdot r_{t_{ij}} - \bar{H}_{d_i} \cdot r_{d_{ij}} \right) \cdot \bar{R}_{b_i} + \bar{H}_{d_i} \cdot r_{d_{ij}} \cdot \left(\frac{1+\cos\beta}{2} \right) + \bar{H}_i \cdot \rho_{g_i} \cdot r_{t_{ij}} \cdot \left(\frac{1-\cos\beta}{2} \right). \tag{12}$$

The factors $r_{t_{ij}}$ and $r_{d_{ij}}$ given as follows:

$$r_{t_{ij}} = \frac{\pi}{24} \cdot \left(a_i + b_i \cdot \cos\omega_{ij}\right) \cdot \frac{\cos\omega_{ij} - \cos\omega_{s_i}}{\sin\omega_{s_i} - \frac{\pi}{180} \cdot \omega_{s_i} \cdot \cos\omega_{s_i}}, \tag{13}$$

$$r_{d_{ij}} = \frac{\pi}{24} \cdot \frac{\cos\omega_{ij} - \cos\omega_{s_i}}{\sin\omega_{s_i} - \frac{\pi}{180} \cdot \omega_{s_i} \cdot \cos\omega_{s_i}}, \tag{14}$$

where the coefficients a_i and b_i are given by:

$$a_i = 0.409 + 0.5016 \cdot \sin\left(\omega_{s_i} - 60\right), \tag{15}$$

$$b_i = 0.6609 - 0.4767 \cdot \sin\left(\omega_{s_i} - 60\right). \tag{16}$$

The hour angle ω_{s_i} is given by:

$$\omega_{s_i} = \cos^{-1}\left(-\tan\phi \cdot \tan\delta_i\right). \tag{17}$$

RESULTS AND DISCUSSIONS

All the above-mentioned relations are programmed in MATCAD (***, 1999) and results are obtained for Cluj-Napoca ($\phi = 46.47^{\circ}$ N). Figure 3 shows the monthly variation of mean daily global incident solar irradiation on both types of collectors.

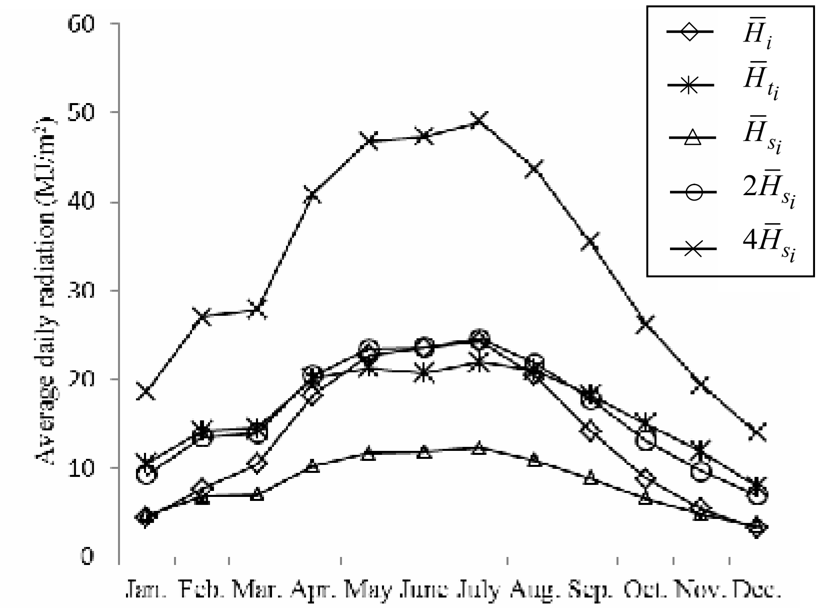

Fig. 3. Monthly mean daily solar radiation for tilted and spherical solar collectors.

The plotted curves are the monthly mean daily global solar radiation measured on a horizontal plane $\bar{H}_i$, on a tilted plane $\bar{H}_{t_i}$ with one square meter area and for spherical surfaces with one, two and four square meter of total area $\bar{H}_{s_i}$, $2\bar{H}_{s_i}$ respectively $4\bar{H}_{s_i}$.

The annual average of the daily global incident solar irradiation on the spherical collector for the three above situations are 8.25 MJ/m ^{2}, 16.49 MJ/m ^{2} and 32.98 MJ/m ^{2}. To benefit the self tracking feature of the spherical solar collector, the total area of the sphere should be at least twice of the flat plate solar collectors absorbing area, in which case the annual average of the daily global solar radiation incident on the spherical collector is 6% higher than on a flat-plate collector (16.41 MJ/m^2).

The monthly mean hourly variation of global incident radiation is calculated for the average days of each month for one hour intervals for a spherical collector (Tab. 2) with total area twice as the flat plate collector (Tab. 3).

Tab. 2

The monthly mean hourly global solar radiation on a spherical surface $2\overline{I}_{s_{ij}}$, (MJ/m^2)

Hours / Month	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18
Jan.	0.00	0.00	0.49	1.01	1.44	1.68	1.68	1.44	1.01	0.49	0.00	0.00
Feb.	0.00	0.18	0.69	1.29	1.83	2.14	2.14	1.83	1.29	0.69	0.18	0.00
Mar.	0.03	0.58	1.06	1.49	1.83	2.01	2.01	1.83	1.49	1.06	0.58	0.03
Apr.	0.05	0.41	0.99	1.64	2.19	2.51	2.51	2.19	1.64	0.99	0.41	0.05
May	0.11	0.54	1.14	1.78	2.33	2.63	2.63	2.33	1.78	1.14	0.54	0.11
June	0.13	0.57	1.15	1.76	2.27	2.55	2.55	2.27	1.76	1.15	0.57	0.13
July	0.12	0.57	1.19	1.85	2.39	2.70	2.70	2.39	1.85	1.19	0.57	0.12
Aug.	0.07	0.47	1.06	1.71	2.26	2.58	2.58	2.26	1.71	1.06	0.47	0.07
Sep.	0.02	0.31	0.85	1.47	2.02	2.33	2.33	2.02	1.47	0.85	0.31	0.02
Oct.	0.00	0.45	1.00	1.49	1.86	2.06	2.06	1.86	1.49	1.00	0.45	0.00
Nov.	0.00	0.05	0.53	1.05	1.48	1.72	1.72	1.48	1.05	0.53	0.05	0.00
Dec.	0.00	0.00	0.23	0.65	1.06	1.30	1.30	1.06	0.65	0.23	0.00	0.00

Tab. 3

The monthly mean hourly global solar radiation on a tilted flat plate surface $\overline{I}_{T_{ij}}$, (MJ/m^2)

Hours / Month	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18
Jan.	0.00	0.00	0.54	1.14	1.64	1.92	1.92	1.64	1.14	0.54	0.00	0.00
Feb.	0.00	0.17	0.68	1.33	1.91	2.26	2.26	1.91	1.33	0.68	0.17	0.00
Mar.	0.01	0.60	1.09	1.55	1.91	2.11	2.11	1.91	1.55	1.09	0.60	0.01
Apr.	0.02	0.35	0.93	1.58	2.15	2.47	2.47	2.15	1.58	0.93	0.35	0.02
May	0.03	0.42	0.99	1.60	2.11	2.41	2.41	2.11	1.60	0.99	0.42	0.03
June	0.05	0.43	0.95	1.51	1.98	2.24	2.24	1.98	1.51	0.95	0.43	0.05
July	0.05	0.45	1.01	1.62	2.13	2.42	2.42	2.13	1.62	1.01	0.45	0.05
Aug.	0.02	0.39	0.97	1.62	2.17	2.48	2.48	2.17	1.62	0.97	0.39	0.02
Sep.	0.00	0.28	0.83	1.48	2.06	2.40	2.40	2.06	1.48	0.83	0.28	0.00
Oct.	0.00	0.51	1.14	1.71	2.14	2.37	2.37	2.14	1.71	1.14	0.51	0.00
Nov.	0.00	0.06	0.64	1.28	1.82	2.13	2.13	1.82	1.28	0.64	0.06	0.00
Dec.	0.00	0.00	0.25	0.73	1.20	1.49	1.49	1.20	0.73	0.25	0.00	0.00

The differences between the results for the two types of collectors are shown in Figure 4. The values calculated for the spherical solar collector ($2\overline{I}_{s_{ij}}$) are higher than for the tilted flat plate collector ($\bar{I}_{T_{ij}}$) for sunrise and sunset hours in spring - autumn period.

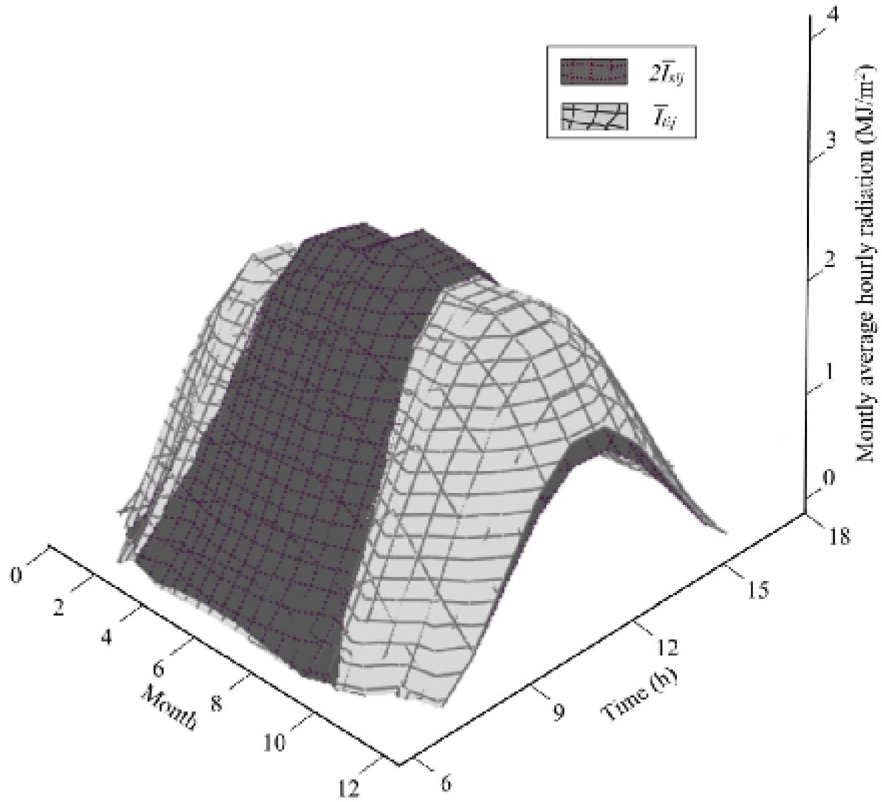

Fig. 4. Monthly mean hourly solar radiation on a tilted flat plate and spherical solar collector.

CONCLUSIONS

The evaluated monthly mean daily global solar radiation received by the spherical solar collector, with the absorber surface area equal to an optimal tilted flat plate solar collector's absorbing surface area, is smaller for each month of the year than for a flat plat collector. In this case the annual average of the global daily solar radiation incident on the spherical collector is about 50% smaller than on a flat plate one for Cluj-Napoca's conditions.

For a spherical collector with absorbing surface area twice of an equivalent flat plate solar collector, the monthly mean daily solar radiation received is higher for summer months compared with the flat plate collector, also the annual average daily global solar radiation incident on the spherical collector is about 6% higher than on a flat plate one. The six percent gain of the incident solar radiation is mainly due to diffuse and ground reflected component of the solar radiation on the larger surface of the spherical collector.

Evaluation of the monthly mean hourly variation of global incident radiation shows higher values for the spherical collector for sunrise and sunset hours.

The spherical solar collector has an advantage over the optimum tilted flat plate collector if its absorber area is at least twice of the flat plate one.

Based on these results, experimental testing of the spherical solar collector presented in Figure 1 is proposed for further work.

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