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EXPERIMENTAL SETUP OF SOLAR DISH COLLECTOR WITH CHANGEABLE STRUCTURE

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واحد آزمایشی کلکتور بشقابی خورشیدی با ساختار متغیر

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ABSTRACT

This paper proposes the design, construction and testing of a solar dish collector with changeable structure and evaluates its overall thermal conversion performance. The changeable parameters of the parabolic dish collector are as follows: focal length of the dish (f), aperture diameter of dish (D), dish rim angle (φ), area of the receiver (A) and concentration ratio (C_R). Results show that the solar dish collector system could reach a power output of 1973 W in a typical setup. Using the mentioned setup, 1 kg of water will be boiled in 2.5 minutes, which is enough to produce 192 kg boiling water per day that will be used at night for greenhouse heating.

چکیده

این مقاله طراحی، ساخت و آزمون یک کلکتور بشقابی خورشیدی را با ساختار متغیر ارائه داده و عملکرد تبدل حرارت کلی آن را ارزیابی می نماید. مشخصه‌های متغیر گیرنده بشقابی سهموی بصورت مقابل هستند: فاصله کانونی بشقاب (f)، قطر دهانه بشقاب (D)، زاویه دهانه بشقاب (φ)، مساحت گیرنده (A) و نسبت تراکم (C_R). نتایج نشان می‌دهد که سیستم کلکتور بشقابی خورشیدی قابلیت دستیابی به توان خروجی 1973 وات در یک نمونه برپا شده را دارا می‌باشد. با استفاده از نمونه برپا شده مذکور، 1 کیلوگرم آب در 2/5 دقیقه به جوش خواهد آمد که برای تولید 192 کیلوگرم آب جوش در روز کافی است که در شب برای گرمایش گلخانه استفاده خواهد شد.

INTRODUCTION

Solar dish collectors (SDC) offer the highest thermal and optical efficiencies of all the current concentrator options *(Lovegrove et al., 2011)*. Solar dish collector (SDC) have been widely used to concentrate solar radiation and convert it into medium or high temperature heat, including solar cooker *(Abu-Malouh et al., 2011; Kumar et al., 2012)*, solar hydrogen production (*Furler et al., 2012*), and Dish–Stirling system to generate electricity *(Mancini et al., 2003; Mills, 2004)*. Coventry and Andraka (2017) reviewed parabolic dish technology and focused on the evolution of dish design, by examining features such as mode of tracking, structure and mirror design. The review includes a brief summary of power generation options as well as a discussion about options for storage and hybridisation.

Sun is not a point source of light and 0.32° non-parallelism of natural sunlight and imperfections of the collector can provide a reduction in the solar radiation intercepted by the receiver *(Stine and Harrigan, 1985)*. Hence, improving the optical performance is the main step to optimize the SDC *(Li et al., 2013)*.

Considerable theoretical and experimental works on SDC for a large range of industrial applications have been carried out in recent years *(Cui et al., 2003; Li et al., 2011; Lovegrove et al., 2011; Reddy and Kumar, 2009; Shuai et al., 2008; Wang and Siddiqui, 2010; Wu et al., 2010a, 2010b; Wua et al., 2010)*.

Solar dishes are very attractive due to their high concentration ratios and versatility *(Poullikkas et al., 2010)*. High concentration ratios allow to control the thermal losses and therefore to obtain high conversion efficiencies *(Andraka and Powell, 2008)*. Also, conversion efficiencies severely depend on the optical properties of the reflective surfaces. Errors affect the intercept factor, which is defined as the ratio of the energy intercepted by the receiver to the energy reflected by the reflector *(Sodha et al., 1984)*. The ideal optical configuration for the dish concentrator is a paraboloidal mirror which is very expensive to fabricate, its costs increase rapidly with aperture area. However, in practice, it is easier to fabricate a dish concentrator from small elementary mirrors. The elementary components are known as reflecting petals or facets *(Kaushika and Reddy, 2000)*.

During the last decade, several innovations in the design and materials of dish technology have been reported: Glass-metal, Aluminized film, Silver-polymer/silver-steel and Stretched membrane technology. Silvered mirror was adopted as reflective material as it combines both high reflectance and good mechanical properties *(Poullikkas et al., 2010)*. Compared with other mirror types, it is preferred for its high reflectance, good specularity and durability. *Rafeeu and Ab Kadir, (2012*) presented three experimental models with various geometrical sizes and diameter of about 0.5 m of SDC to analyse the effect of geometry on a solar irradiation and temperature and in maximizing the solar fraction.

According to the effects of optical and geometrical parameters on thermal performance of the concentrating collectors, the aim of this work is to design and manufacture a solar dish collector as an experimental setup with changeable geometrical and optical structure to investigate various parameters which it is impossible with prevalent unchangeable collectors and also to carry out the performance analysis of SDC to heat the water located at the focal point of the concentrator and finally heating a typical greenhouse.

MATERIAL AND METHODS

SOLAR DISH COLLECTOR DESIGN

A common SDC is mainly composed of a parabola provided with an absorber placed by some arms at the focal position. A reflector embedded in a nacelle rotatable around two axes: the horizontal axis (elevation angle) from the support sustained by a mast and the second is the vertical axis (azimuth angle). The SDC is fixed to the ground (

Fig. 1) and is constructed from small elementary mirrors of square form (

Fig. 1 and Fig. 2). As indicated in

Fig. 1 the main frame supports the aluminium frame and the optical units have translational movement along aluminium frame to adjust distance between mirrors. Also, the aluminium frame is expandable to provide various aperture diameter of dish for different research applications.

Fig. 1 shows a row of optical units mounted on the aluminium frame and fixed in appropriate position by a typical holder.

As illustrated in Fig. 2 the optical unit consists of three main parts with mirror dimension of 50×50 mm, the arm length varying in the range of 50-400 mm and it is made of wood covered with impermeable layer. The joint connects mirror and arm by two screws and also provide rotational degree of freedom (DOF) along two axes. The optical unit has 5 degrees of freedom that provide precision in adjustment of mirror position (Fig. 3) and contrary to constant connection, installing errors were reduced. Also, it is possible to change the number of installed optical units on the main frame, which subsequently results in changing the aperture area of the dish in a wider range.

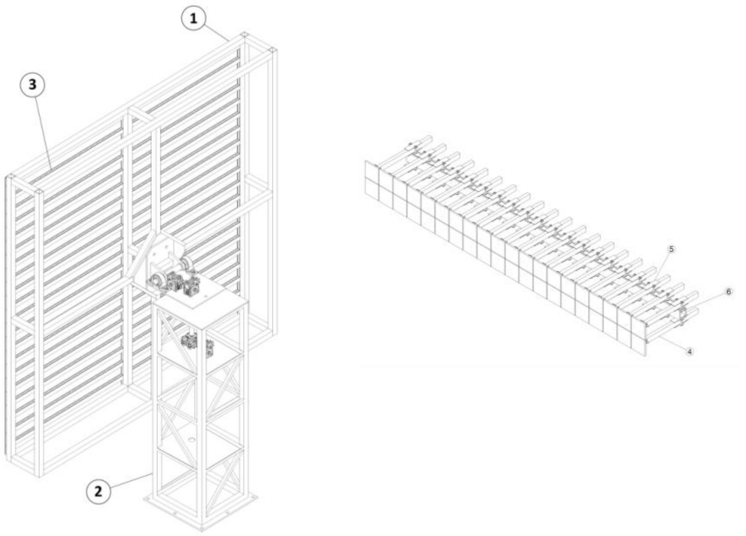

Fig. 1 - Components of SDC

1-main frame; 2- mast; 3- aluminium frame; 4-optical unit; 5-holder; 6-aluminum profile

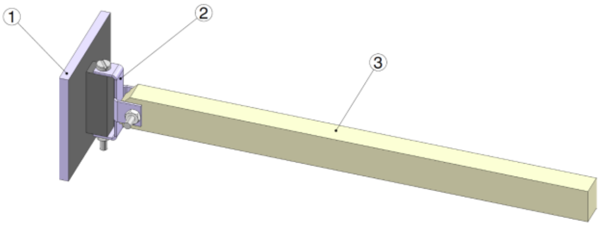

Fig. 2 - Optical unit

1- mirror; 2-joint; 3-arm

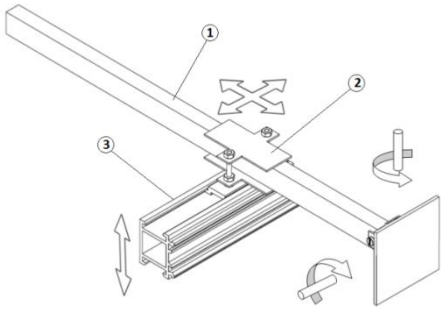

Fig. 3 - Degree of freedom of each unit

1-optical unit; 2-holder; 3-aluminum profile

The characteristics of the SDC (aperture diameter of dish, Depth of the dish and Focal distance) which are changeable are indicated in Table **1**. These ranges are enough for an extensive application such as heat and electricity production, researches, etc.

Table 1

Changeable characteristics of the SDC

Parameters	Range
Focal distance (f)	500-2500 (mm)
Aperture diameter of dish (D)	500-4000 (mm)
Depth of the Dish (d)	50-500 (mm)
Aperture area of the dish (A_a)	0.25-16 (m^2)
Entrance aperture area of receiver (A_r)	176.7-706.8(cm^2)
Number of mirrors	100-6400 (unit)

In Fig. 4, a pilot model of the assembled SDC illustrates the arrangement of 100 mirrors on main frame with 500 mm dish aperture diameter, 750 mm focal distance and 65 mm of the dish depth.

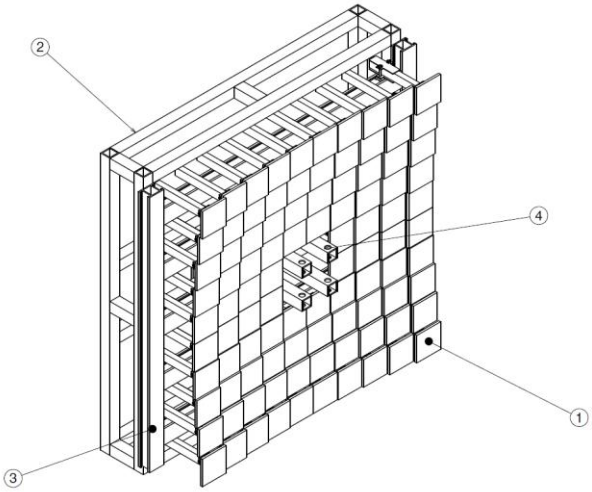

Fig. 4 - Pilot model of changeable collector
1-optical unit 2-main frame 3-aluminium profile 4-receiver joints

SOLAR TRACKING SYSTEM

Basics of solar geometry can be found in several texts on solar energy *(Duffie and Beckman, 2013).* Two most commonly used configurations in two-axis sun-tracking system are azimuth-elevation and tilt-roll (or polar) tracking system. In an optical mirror mount, azimuth-elevation system is the most popular sun-tracking system used in various solar energy applications *(Mousazadeh et al., 2009; Beltran et al., 2007; Georgiev et al., 2004; Luque and Andreev, 2007, Hafez et al., 2017)*. In the azimuth-elevation tracking, the collector must be free to rotate about the zenith-axis and the axis parallel to the surface of the earth.

The tracking angle about the zenith-axis is the solar azimuth angle and the tracking angle about the horizontal axis is the solar elevation angle *(Stine and Harrigan., 1985)*. The sun altitude or elevations (γ) and sun azimuth (α) define the position of the sun as shown in Fig. 5. The sun altitude is defined as the angle between the centre of the sun and the horizontal seen by the observer. The azimuth angle of the sun describes the angle between geographical north and the vertical through the centre of the sun *(Quaschning, 2005)*.

Many fast algorithms for the calculation of the solar position, used in engineering application, can be found in the literature. All these algorithms work correctly for limited periods of time. There are high-precision astronomical algorithms, such as the numerical algorithm proposed by Meeus (1988), which has been reviewed in a form suitable for solar application by Reda and Andreas (2004) and is known as SPA (solar position algorithm). This algorithm has a maximal error smaller than 0.0003º for a very long period of time (2000 b.C.–6000 a.C.), but it requires a large amount of calculations.

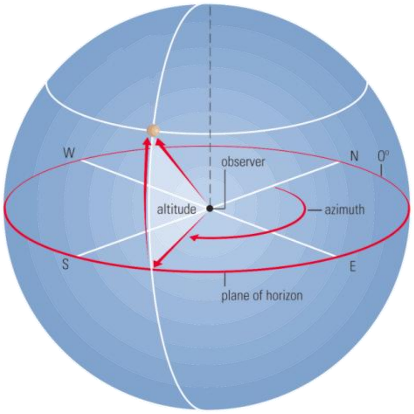

Fig. 5 - Position of the sun

- **Solar azimuth angle**

For a specific longitude and altitude the sun begins a race from east to west. This is the angle between the line that points to the sun and south. The angle is negative to the east and positive to the west. This angle is 0° at noon. It is probably close to -90° at sunrise and 90° at sunset, depending on the season. The azimuth angle is calculated according to the following equation *(Chassériaux, 1979*):

$$\sin\alpha = \frac{\cos\,\delta\,\sin\,\omega}{\cos\,h} \tag{1}$$

- **Solar altitude angle**

The solar altitude angle is the angle between the line that points to the sun and the horizontal. It is the complement of the zenith angle. This angle is 0° at sunrise and sunset. The altitude angle is calculated using to the following equation *(Chassériaux, 1979).*

$$\sin h = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \tag{2}$$

Two axes sun tracking system

The solar tracking system consists of four parts: mechanical design, electrical design, electronic design and a control program. In this work an algorithm for the computation of the solar position with high precision (maximal error 0.0027° over the period 2003–2023) and of small complexity are used which are presented by *Grena (2008).* This precision is enough for a wide range of solar applications.

FOCAL RECEIVER

The focal absorber receives the concentrated solar radiation and transforms it to thermal energy to be used in a subsequent process *(Kaushika and Reddy, 2000)*. The basic feature of a receiver is to absorb the maximum amount of the reflected solar energy and transfer it as heat, with minimum losses, to the working fluid. A cavity receiver is used to accomplish this purpose. The position of cavity receiver should be varying to achieve the preferred performance of collector in different setups. Hence, a cavity receiver with a glass window or not is studied and mounted on a rail to provide transitional motion in direction of collector axis (Fig. 6).

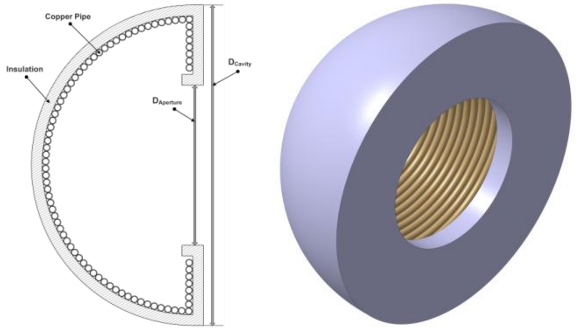

Fig. 6 - Cavity receiver

EXPERIMENTAL SETUP

The changeable parameters of the parabolic dish collector system are as follows: focal length of the dish (*f*), aperture diameter of dish (*D*), dish rim angle (φ), area of the receiver (*A*) and concentration ratio (C_R). The fundamental parts of the experimental SDC are: the solar concentrating system, the absorber (solar heat exchanger), the data acquisition system, instrumentation and solar tracking system (Fig. 8).

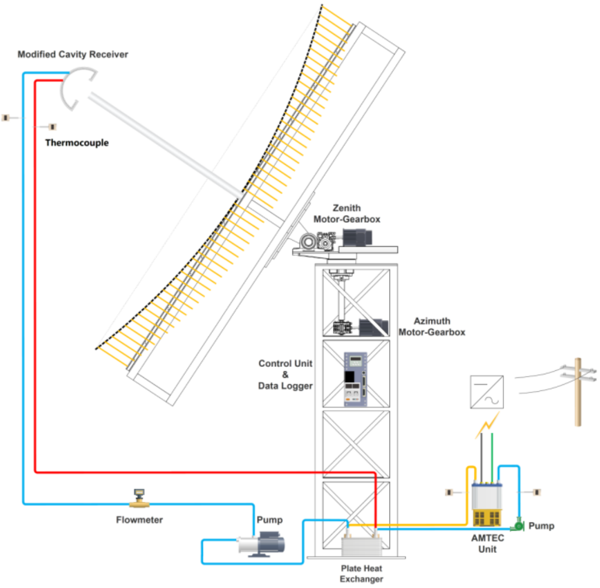

Fig. 7 - Schematic of experimental setup of changeable solar dish collector

OPTICAL CALIBRATION

The diode technique, a simple and cheap method, consists of a laser diode that emits a narrow beam that is made to be incident onto the reflecting surface of the dish. The diode emits light in the wavelength range of 640–660 nm. *Mlatho et al. (2010)* showed that a laser diode technique, which is relatively cheap when compared to the radiometer technique, can be used to determine the spatial extent of the focal point with fairly good accuracy. In this study laser beam is used to be assured that reflected ray incident on focal point. For this purpose, a laser beam source placed parallel to collector axis and the entire mirrors adjusted manually and fixed in appropriate position by two screws. This method not only provides a changeable structure but also increases the precision of concentration.

RESULTS

The concentration ratio (C) is defined as the ratio of the aperture area (A_a) to the entrance aperture area of receiver or absorber area (A_r); *(Duffie and Beckman, 2013)*. The area concentration ratio is:

$$C_R = \frac{A_a}{A_r} \tag{3}$$

The results showed that the concentration ratio in the range of 3.5-800 is achievable. It is possible by changing the receiver area through different dimension of cavity aperture.

The useful heat delivered by a solar collector system was prepared according to the procedure used by *Wu et al. (2010a)* under steady state conditions and is equal to the energy absorbed by the heat transfer fluid, which is determined by the radiant solar energy falling on the receiver minus the direct or indirect heat losses from the receiver to the surroundings. That is,

$$\dot{Q}_\mathrm{u} = \dot{Q}_\mathrm{r} - \dot{Q}_\mathrm{l} \tag{4}$$

Where $\dot{Q}_\mathrm{u}$ is the rate of useful heat gain, $\dot{Q}_\mathrm{r}$ and $\dot{Q}_\mathrm{l}$ are radiation falling on the receiver and total heat loss rate of the receiver respectively.

The radiant solar energy falling on the receiver can be defined as:

$$\dot{Q}_{\mathrm{r}} = \eta_0 \dot{Q}_{\mathrm{s}} \tag{5}$$

Where η_0 is the optical efficiency of concentrator and is defined by *Wu et al. (2010a)* as:

$$\eta_0 = \Gamma \tau \alpha \rho \gamma \cos\theta \tag{6}$$

where Γ is the factor of un-shading, ρ is dish reflectance, $\tau\alpha$ is transmittance–absorptance product, γ is the intercept factor of receiver, which is defined as the ratio of the energy intercepted by the receiver to the energy reflected by the focusing device, i.e. parabola dish, θ is angle of incidence. As the solar parabolic dish concentrator maintains its optical axis, always pointing directly towards the sun to reflect the beam, which means the incidence angle of solar beam into the dish is zero degree, and the cosine loss equals to zero *(Palavras and Bakos, 2006)*. That is:

$$\eta_0 = \Gamma \tau \alpha \rho \gamma \tag{7}$$

A clean mirror made of low-iron glass with a silver back-coat should provide a reflectivity (ρ) of 90–94% *(Kribus et al., 2006)*. In this study, a transparent window is placed at the receiver entrance to reduce heat losses, hence the transmission–absorption loss of the receiver is assumed to have about 6–12% loss.

$$\Gamma = \frac{A_a - A_r}{A_a} \tag{8}$$

Based on the analysis above, the optical efficiency used in the current study, including all of these losses, is then assumed as a value of 0.847, which is close to the representative value of 0.85 reported in *(Kribus et al., 2006; Feuermann and Gordon, 2001; Wu et al., 2010a)*.

The net solar heat transferred Q_s is proportional to A_a, and the direct normal insolation (DNI) per unit of collector area I_s:

$$\dot{Q}_{\mathrm{s}} = I_s A_a \tag{9}$$

Substituting Eq. (6 and 5) into Eq. (4):

$$\dot{Q}_{\mathrm{u}} = \dot{Q}_{\mathrm{r}} - \dot{Q}_{\mathrm{l}} = \eta_0 \dot{Q}_{\mathrm{s}} - \dot{Q}_{\mathrm{l}} = \Gamma \tau \alpha \rho \gamma I_s A_a - \dot{Q}_l \tag{10}$$

The total heat loss rate includes three parts and can be expressed as:

$$\dot{Q}_l = \dot{Q}_{lk} + \dot{Q}_{lc} + \dot{Q}_{lr} \tag{11}$$

where $\dot{Q}_{lk}, \dot{Q}_{lc}, \dot{Q}_{lr}$ are Conduction, Convection and Radiation heat loss, respectively.

Researches show that the conductive loss is normally insignificant compared to the convection and radiation losses *(Wu et al., 2010a)*. Therefore, $\dot{Q}_{lk} = 0$. convection heat loss is a major contributor to the total energy loss. Hence, its characteristic has been extensively investigated and various models have proposed to predict convection heat loss of cavity receivers *(Le Quere et al.,1981, Koenig and Marvin1981, Siebers and Kraabel,1984, Clausing, 1987*, *Stine and McDonald,1989*, *Paitoonsurikarn et al., 2004, Azzouzi et al., 2016)*. As in this study, a transparent window is installed at the receiver aperture, thus natural convection heat loss becomes the dominant loss. Finally, the equations applied by *Paitoonsurikarn et al. (2004)* and *Wu et al., (2010a)* are used to evaluate convective and radiation heat loss from the receiver. Finally, for a typical setup the following results were obtained (Table 2):

Table 2

Changeable characteristics of the SDC and achieved results

Parameters	**value**
Focal distance (f)	1250 (mm)
Aperture diameter of dish (D)	2000 (mm)
Depth of the Dish (d)	190 (mm)
Aperture area of the dish (A_a)	3.68 (m^2)
Entrance aperture area of receiver (A_r)	314.16(cm^2)
Number of mirrors	1600 (unit)
I_s	700 (w/ m^2)
$\dot{Q}_s$	2576 (w)
η_0	0.847
$\dot{Q}_{\mathrm{r}}$	2183 (w)
$\dot{Q}_{\mathrm{l}}$ **(max)**	210 (w)

$\dot{Q}_u$	1973 (w)

It results from table 3 that the obtained value of $\dot{Q}_u$ is high enough to boiling water with a rate of 0.397 kg/min. In other words, with the mentioned setup we can produce 1 kg hot water (100℃) in 2.5 minutes.

APPLICATION IN GREENHOUSE

The easiest and most common way to even out the temperature of greenhouse is to use thermal mass, also called a heat sink. The size of the thermal mass depends on the heat capacity of the material and it's mass. The most common way to use thermal mass is water, because it has such a high heat capacity (4.18 J/cm^{3}K at 77 F). Using the designed Collector, we were able to control the greenhouse temperature in recommended range during April to October in West Azerbaijan, Urmia. In this study, a 250m^2 greenhouse with twin-wall polycarbonate considered (Fig. 8). The recommended temperature in greenhouse is 22°C.

Fig. 8 - Spanish design greenhouse, Urmia University, Agricultural Faculty

According to 10 years metrological data of Urmia, the monthly average temperatures are presented in Table 3. Also, the solar power incident on a surface averages 700 W/m^2 and 10 years average 8.5 sun hours. It is shown in this table that during April to October the average temperature is about 10 degrees below the recommended temperature in greenhouse. So, the calculation is based on ΔT=10°.

Table 3

Monthly average temperature, Urmia

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	0.4	1.8	7.8	9.9	14.8	20.4	22.1	23.2	18.4	13.3	5.9	-2.6
2005	-2.7	-2.1	6.5	12.2	15.2	20.3	24.8	23.6	18.9	12.3	5.3	2.4
2006	-2.7	0.8	7	12.2	16.3	23.1	23.5	24.7	18.7	13.2	3.6	-2.7
2007	-4.2	0.6	4.9	9	17.4	21.1	23.3	23.3	19.8	13	6.5	-0.4
2008	-7.3	-2.7	9.9	14.3	15.9	21.3	24.4	24.4	18.9	12.3	5.6	0.2
2009	-2.4	3.5	5.9	9.5	16.2	19.6	23.3	21.5	16.9	12.9	5.9	2.9
2010	2.8	3.8	8.5	11	15.5	22.7	25.3	23.3	20.5	14.6	6.2	2.3
2011	-2.8	0.9	5.4	11.6	15.6	21.2	24.9	22.8	18.1	11	1.3	-1.7
2012	-1.1	-0.6	2.6	12.9	17.5	22	23.9	24.6	18.9	13.4	7.6	0.6
2013	-0.4	3.8	7.4	12.2	15.4	20.9	24	22.8	19	11.2	7.3	-5.9
2014	-2.5	0.8	8	12.6	17.3	21.8	24.9	25	20.1	11.4	4.4	2.2

Considering 250m^2 greenhouse, a gas heater consumes 6 m^3/h fuel, that its annual amount will be 25920 m^3 gases. Taking into account the cost of the gas as 0.072\$/m^3 in Iran, the annual cost will be 1866 \$. However, the total cost estimate of the proposed experimental setup of collector is 1750 \$. The results obtained from the preliminary calculations of useful heat delivered by a solar collector system are presented in Table 2. For 8.5 hours received solar energy is:

$700\ W/m^2 \times 8$ hours $= 5600\ Wh/m^2 = 5.6\ kWh/m^2 = 5.6$ PSH (Peak Sun Hours)

According to results we produced 192 kg boiling water that will be used at night. It starts releasing that energy, thereby ‘heating’ the greenhouse.

CONCLUSIONS

This project was undertaken to design an experimental setup to investigate the effect of geometrical parameters on optical and thermal performance of a solar dish collector and evaluate its application. The characteristics of the SDC such as aperture diameter of dish, depth of the dish, focal distance and cavity area are changeable. This experimental setup has assembly and disassembly capability and can act as a research tool to investigate different configurations of SDC systems. Also different type of receivers, parabolic dishes and other type of collectors can be tested by the experimental setup and it can be used as a main structure for any type of collectors for solar applications. The major limitation of this study is the mirror sizes, which limited to 5×5cm mirrors. Useful heat delivered by solar collector system is 1973 W which is enough to produce 192 kg boiling water per day. Produced water will store in thermal mass that will be used at night for heating the greenhouse. This research will serve as a base for the future studies and for domestic solar thermal applications like indoor solar cooking and indoor solar water heating or electricity generation. This device can be used for different applications like desalination, pasteurization, detoxication and vapour production by adjustment of the working fluid flow through receiver. Taken together, these wide ranges of investigations suggest that the cost of experimental setup in comparison with its applications is justifiable. This would be a fruitful area for further works.

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