Journal of Mechanical Engineering *Vol 20(2), 105-124, 2023*

Evaluation of Energy Production using Parabolic-Dish Solar Collector: A Case Study of Iraq

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ABSTRACT

The parabolic dish reflector solar collector is one of the significant and most efficient steam-producing solar concentrating systems in thermoelectric power plants and, furthermore, it's considered to be environmentally friendly (renewable energy). Iraq has vast land for installing solar collectors to generate steam and use for thermal power plants. However, no such application/power plant has yet been built. Therefore, the proposed study investigates opportunities for using PDR solar collectors, including all advantages and challenges. To implement and estimate the productivity and efficiency of the PDR in (Diyala City / Iraq), a PDR solar collector with a total area of 0.708 m^2 (including the glass pieces used as a reflective surface) was designed and fabricated. These glass pieces have been utilized to increase the reflection of solar rays by 80% when compared to a traditional case/setup. Two different systems (open and closed) were considered to investigate the performance of thermal power. The results show that the absorption temperature was increased from 34.6 to 95 °C. On the other hand, the coefficient of heat loss by convection increases by about (795.5 W). In addition, it was pointed out that the coefficient of total heat loss over time was increased by about 25 to 41% (closed and open systems). Furthermore, the experimental findings clearly demonstrate the usefulness of PDR solar heaters in Iraq. Hence, its confidently believed that this research will be useful in the future for this type of thermal power plant.

Keywords: *Environmentally Friendly; Parabolic Dish Reflector*

Nomenclature

Latin characters

a parabola depth, m

ISSN 1823-5514, eISSN 2550-164X

https://doi.org/10.24191/jmeche.v20i2.22057

Received for review: 2022-08-19
Accepted for publication: 2023-01-03
Published: 2023-04-15

h	diameter of the opening of the parabola, m
F	focus point, m
f	focal distance, cm
r_r	mean radius, m
r	outer reactor shell radius, m
d_{go}	outer dish diameter, m
a/2	radial displacement of focal point away from central axis, m
Gap	inner dish truncation diameter, m
A_r	solar reactor aperture area, m^2
A_a	dish aperture area, m^2
Q_s	incident radiant power, solar radiative power, W
Q_u	$\dot{Q}_{reactor}$, solar radiative power incident at calorimeter aperture, W
I_b	solar constant, assumed to be constant =1353 W/m^2
d_{ao}	inner diameter of the dish receiver, m

Greek characters

$\emptyset$	tracking offset,
$\emptyset r$	rim angle,
r_r	mean radius, m
r	outer reactor shell radius, m
σ_1	oversizing angle for secondary dish,
σs	oversizing angle for secondary dish,
2σ	angle between optical axis before and after reflection at secondary reflector

Introduction

The current estimated world consumption is 100 million barrels of oil per day, and recent studies indicated that this number may rise to reach about 123 million barrels per day by 2025 [1]. Based on this immoderate global demand for energy, since the industrial revolution, the excessive consumption/burning of these fossil fuels (oil, gas, coal) can cause many disasters in terms of global warming and the greenhouse effect [2]. This might lead to an unbalance of the environment and the depletion of the world's fossil fuel reserves.

Hence, the utilization of solar power (renewable energy) can preserve the wealth of future generations to come within the framework of the concept – of sustainable development. This evolution must be achieved in a way that guarantees the needs related to the development and those of the environment of present and future generations [2]. Iraq can be considered one of the developing countries in terms of building renewable power plants and merging with the global trend that seeks to reduce the consumption of fossil fuels via wind and solar power by the end of 2024 [3]. It should be pointed out that solar energy has priority in comparison with other sources to meet energy demands for human needs. In addition, it has an outstanding contribution to other energy activities due to its being environmentally friendly and it can be converted to other types of energy such as electrical, mechanical, and thermal energy. Recently, energy researchers witnessed the rapid expansion of applications in most world regions, including Arab countries, focusing on increasing and developing low efficiency. Figure 1 shows the extent of using renewable energy in the middle east, including Iraq.

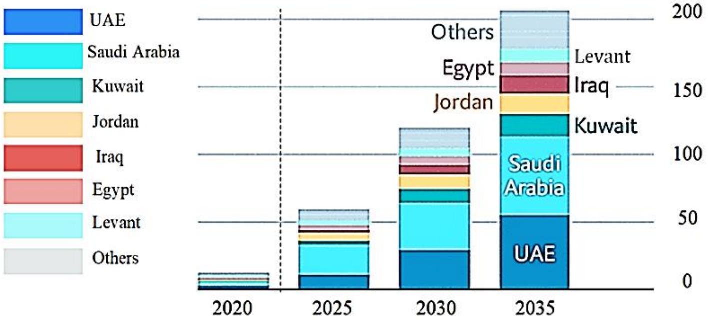
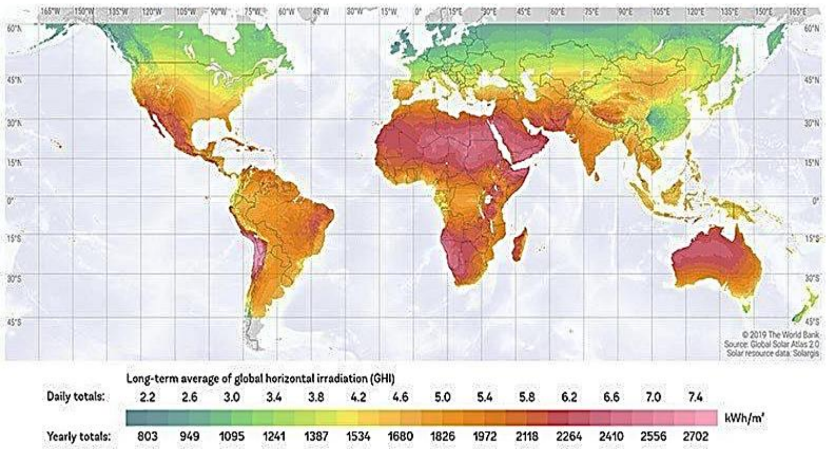


Figure 1: Middle East projects solar capacity (GW) [4]

In terms of solar energy, Iraq can be considered one of the blessed countries because of the advantage of getting sunlight almost during the whole year. There are two basic options when dealing with solar energy [5]. The first one is photovoltaic, and the second is solar thermal energy systems. The efficiency of photovoltaic systems is between (10-20%), while the solar thermal system has a noticeably higher efficiency to reach about 30% [1]. The present study attempts to take advantage of the intensity of solar thermal radiation by collecting it to be applied to the storage system of heating fluids. Solar energy can be harvested and concentrated in thermal form using a solar collector. The collected thermal energy can be transferred using working fluid in thermal applications such as heating space and domestic water heating [4]. Concentrating solar power plant (CSP) technology has the advantages of low cost, efficacy, and acceptability. It can be used in small applications (producing a few kilowatts, for instance, parabolic saucer (DP) Stirling system). It can also be centralized (producing a few megawatts, for example, parabolic cylindrical (PTC), solar towers (CRS), and Linear Fresnel Reflector (LFR) [6]. The solar activities available for investment in Iraq depend on many factors such as:

- The intensity of solar radiation: Iraq has the second level of solar radiation exposure (see Figure 2), the average daily solar radiation map in the world/Iraq, as shown in Figure 2. There are many potential areas for establishing large solar institutions on a large scale. In Iraq, the annual average of solar energy per day ranges between (4.5-5.4 kW/m^2) [5-7].

- Exposure to solar energy: the period of exposure in Iraq to solar energy is available for an extended period, as shown below. The familiarity with solar potential in Iraq is indispensable in developing solar power plant technology [8].



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Source: Global Solar Atlas 2.0
Solar resource data: Solargis

Figure 2: Areas of exposure to solar energy in the world [4]

Several researchers have employed concentrated solar dishes in many various applications for the purpose of energy generation. Studies by Iraqi researchers in this field have varied. For example, Hafez et al. [9] have fabricated a parabolic dish capable of generating steam to run a Stirling engine system to produce 10 kW from a 990 W/m^2 solar radiance. Al-Defiae have successfully desalinated the water through the operation of solar Stirling engine (heat rejection process) [10]. In a similar approach, Alahmer et al. [9]-[10] have made an advantage of a CPC (compound parabolic collector) to operate a solar-adsorption refrigeration system. In terms of solar energy, a considerable number of studies have provided useful discussions concerning concentrated solar systems, such as [10]-[11]:

- Solar dishes are combined with others to create hybrid systems.
- Solar dishes (concentrators) were combined with the use of gasification and micro gas-turbines (during the processes) [12]-[13].

This study is a complement to a series of studies conducted in Iraq, and it is the first of its kind in Diyala, which has suitable atmospheric factors for solar radiation up to 1700 kilowatts per square meter, making it a promising technology in power generation with an average efficiency of 40% and a regional efficiency of up to 80% despite the model's small size [14]. As a result, this study encourages the investment in PDR technology in Iraq to fulfill the growing demand for electricity. As a result, exergy analysis was performed on a parabolic-dish solar collector with a modified cavity receiver in this study, taking into account the energetic component of incident solar radiation. For this purpose, it is essential to know the amount of solar energy that impacts the country's terrestrial surface and its geographic advantages. The collector's parabola geometry is one of the technologies that is used to generate electricity. It has a promising future in the field of renewable energy [13]. It works to balance the absorbed solar radiation and the energy transferred to the fluid to generate steam by designing a heat exchanger with good efficiency. It can also be used to heat water and for heating purposes, including underground heating [1], [15]. Hence, this research conducted an experimental and analytical studies to assess the solar dish's suitability in central Iraq [16]-[19].

The present work has the advantages of building miniature rig (relatively small overall dimensions in comparison with others) along with its decent efficiency. In addition, it can be utilized for providing small residential buildings with hot water and minimizing the cost of electricity or gas bills. Furthermore, the unique design of the current solar concentrator (PDR) and using the closed system would decrease heat losses issues.

Mathematical Model

Solar concentrator (PDR) type concentrates solar radiation with high efficiency towards the heat exchanger. It receives radiation centered at the focal point of the dish complex. Such types of dishes may have different unique geometric designs. However, all revolve around the basic design shown in Figure 3.

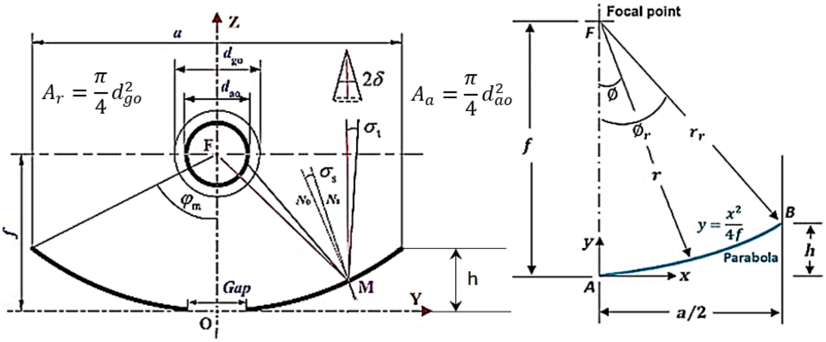


Figure 3: Parabolic-dish solar concentrator design [20]

The concentration ratio might be utilized to define the concentrated energy of the light for a defined collector. Dividing the area of the aperture of collector (A_a) by the surface area of receiver (A_r) is defined as geometric concentration ratio (CRg) (directly calculated, see Equation 1 [19], [21]:

$$CRg = A_a / A_\mathrm{r} \tag{1}$$

Equations 2 and 3 would be used to calculate (h) (the distance between the vertex and aperture) after both aperture diameter (d) and focal length (f) being [10]-[11]:

$$h = \mathrm{a}^2 / 16f \tag{2}$$

$$\frac{f}{a} = \frac{1}{4\tan\left(\frac{\Psi\mathrm{rim}}{2}\right)} \tag{3}$$

In the same manner, the rim angle (ψrim) can be expressed as follows:

$$tan\ \psi rim = 1 / [(\mathrm{a}/8h) - (2h/\mathrm{a})] \tag{4}$$

The exergy analysis of solar collectors is parametrically dependent on the thermal analysis, it should be noted. As a result, thermal analysis needs to be done first [22]. The ratio of the supplied (useful) to the incident energy, which can be computed using the equation below [22], may be used to define the thermal efficiency of the collector.

$$\zeta_c = \frac{Q_u}{Q_s} \tag{5}$$

The dish concentrator has an aperture area A_a equal to 0.708 m^2 and receives solar radiation at the rate of about 1488.3 W from the sun by using split type Lux Meter. Multiplying the area of the aperture of collector (Aa) by the (Ib) (incident solar radiation - per unit of concentration area gives (Qs: net transferred solar heat). This would be affected by the dish concentrator orientation, conditions of meteorological, geographical position on the earth, and finally the time during the day. For the current analysis, two conditions were imposed, which are steady state system and constant incident solar radiation (Ib) (see Equation 6) [22].

$$Q_s = I_b A_a \tag{6}$$

The beneficial heat energy (received from the solar collector) would be completely absorbed by the heat transfer fluid (equalized) when a steady-state conditions being imposed. This could be determined by the radiant solar energy (received by the receiver) after subtracting either indirect or direct heat lost by the receiver into the surrounding (as shown in Equation 7) [22].

$$Q_u = Q_r - Q_I \tag{7}$$

This beneficial heat gain can also be defined based on the temperature differences of the fluid (see Equation 8) [22].

$$Q_u = \dot{m}\, C_p (T_{out} - T_{in}) \tag{8}$$

Equation 9 represents the Hottel–Whillier equation for the actual heat gain Q_u of a concentrating solar collector system [22]:

$$Q_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L (T_{in} - T_a)\right] \tag{9}$$

The solar radiation absorbed by the absorbing tube (s); it is calculated from the following relationship [22]:

$$\mathrm{s} = \mathrm{I_b}(\rho_a \tau \alpha_r \gamma) \tag{10}$$

The heat removal factor (FR) is defined as follows [22]:

$$F_R = \frac{\dot{m} c_p}{A_r U_L}\left[1 - e^{-\left(\frac{A_r U_L \dot{F}}{\dot{m} C_P}\right)}\right] \tag{10}$$

Based on Equations 9 and 10, the actual heat gain might be given as follows [22].

$$Q_u = \frac{\dot{m} c_p A_a}{A_r U_L}\left(S - \frac{A_r}{A_a} U_L (T_{in} - T_a)\right)\left[1 - e^{-\left(\frac{A_r U_L \dot{F}}{\dot{m} C_P}\right)}\right] \tag{11}$$

where *S* is the absorbed flux ($\mathrm{I_b} \times$ optical efficiency ζ_o), and T_a represents the temperature of the ambient. The factor of heat removal relates to the temperature gradients within the receiver and permits for inlet fluid temperatures in the energy balance as shown in Equation 1. The temperature at the inlet is often identified which make it more convenient when dealing with the analyzing of a solar energy system [22].

$$A_r = \frac{\pi}{4} d^2 \tag{12}$$

The diameter of the cavity of the receiver (modified, for minimum heat loss) can be given as a function of its aperture [19], [22] (see Figure 4).

$$D = \sqrt{3}d \tag{13}$$

where D = Aperture diameter, and d = Cavity diameter.

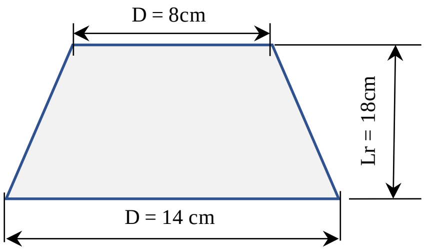


Figure 4: Schematic of cavity model-receiver

Equation 14 might be used to define the maximum angle about the aperture's diameter [23]:

$$\emptyset = 2\text{arctg}\,(d/4f) \tag{14}$$

The parabolic dish is the edge radius (rr) or maximum distance value existing between the focal point and the paraboloid extreme (see Equation 15):

$$\text{rr} = \frac{2\text{f}}{(1+\cos\emptyset)} \tag{15}$$

The total heat transfer coefficient (U_L) can be calculated from the following equation [24]:

$$U_L = h_w + h_{rad,r-sky} \tag{16}$$

h_w is defined as the coefficient of heat transfer by convection due to wind, which can be found in Equation 17, while $h_{rad,r-sky}$ is denoted by the coefficient of heat transfer by radiation from the absorbing tube to the outer periphery and is calculated by using Equation 18 [25].

$$h_w = 5.7 + 3.8V \tag{17}$$

$$h_{rad,r-sky} = \varepsilon_r . \sigma\left(T_r + T_{sky}\right)\left(T_r^2 + T_{sky}^2\right) \tag{18}$$

So, the sky temperature (T_{sky}) and the (T_r) temperature of the intake tube is calculated by the following equations as follows [26]:

$$T_{sky} = 0.055T_a^{1.5} \tag{19}$$

$$T_r = T_{m,f} + \frac{\dot{m}cp_r(T_{in} - T_a)}{h_{c,i}.A_{r,i}} \tag{20}$$

Specifically designed heat exchangers called solar energy collectors convert solar radiation energy into the internal energy of the transport medium. The solar collector is the most important part of any solar system. Incoming solar energy is absorbed by this device, which then transforms it into heat that should be delivered to a moving fluid (often air, water, or oil) through the collector. The solar energy must be transported from the circulating fluid to the space conditioning or hot water equipment to a thermal energy storage tank where it may be used later at night or on overcast days. Table 1 provides the intended dish's measurements.

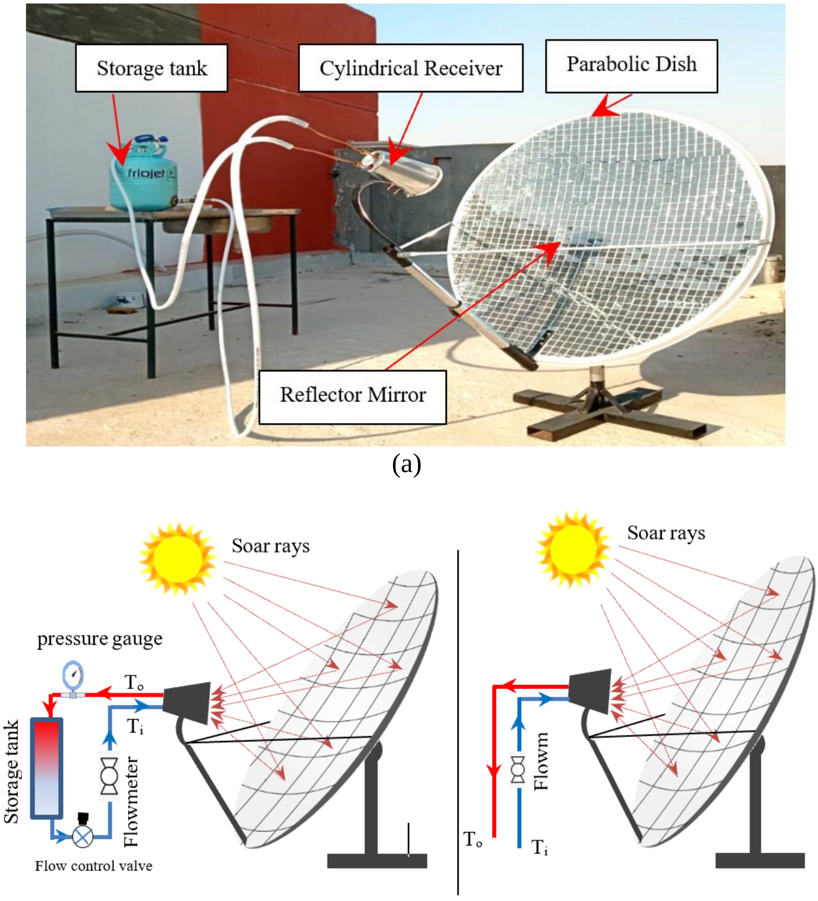
Table 1: Dimensions of the solar collector parabolic dish

Symbols	Value	Description
a	0.95 m	Diameter of the opening of the parabola
h	0.095 m	Parabola depth
A_a	0.708 m^2	The effective area of the reflector
f	0.76 m	Focal distance
ψrim	46°	Rim angle
f/d	0.56	Reflectivity of mirrors
$m^{\cdot}$	0.001 - 0.0067 kg/s	Mass flow rate
∅	34.7°	Rim angle degree
rr	0.834 m	Mean radius
C_p water & 15 °C	4.187 kJ/kg K	Specific heat at constant pressure.
A_r	0.5024 m^2	Receiver area
I_b	1353 W/m^2	Incident solar adiation
Qs	1488.3 W	Solar radiative power incident at solar dish aperture
S	1082.4 W/m^2	Direct normal beam irradiance.
Qu	795.5 W	Useful energy gain
ζc	53.4%	System efficiency

Experimental Setup and System Description

Parabolic dish

In the experimental setup, a parabolic/concave dish (made of aluminum and covered by pieces of glasses) was utilized. The method of a given focus and directrix has been employed in constructing the parabolic dish. The reflector plain mirror was cut into small rectangular pieces and fixed with adhesive with a reflectivity of 95%. The system was designed and built based on previous experiences and data (see Figure 5).



(a)

(b)

(c)

Figure 5: (a) Photographic view of the apparatus that located in the city of Diyala/Iraq, (b) schematic for the closed, and (c) open systems

Concentrator

The concentrator consisted of the following parts:

- Metal Structure: In order to reduce the cost of the fabrication and setup of the rig, an aluminum dish was utilized. It was designed with (1.20 m × 0.95 m). The oval/parabolic dish was mounted on a stand using bolts and nuts, while its free to move in both horizontal and vertical directions (see Figure 6). It should be pointed out that it was difficult to find a simple method for predicting the surrounding conditions. Most of the studies focus on the convection and radiation losses approximated by a simple equation at low operating temperatures. However, the convection losses are also relatively low to high temperatures. In addition, it was noted that the magnitude and the direction of the wind can significantly affect the number of heat losses. This heat loss becomes higher if the wind is parallel to the plane of the aperture and lower when facing it.
- Cylindrical Receiver: The cylindrical receiver was chosen for the current investigation because it has a small area towards the aperture window, which reduces reflection losses. Consequently, the design of this sort of receiver increases the likelihood that the internally reflected photons will be absorbed. Copper coil windings in an aluminum conical chamber make up the receiver. The components of the equipment were produced locally to reduce costs. The cylindrical chamber had an opening diameter of 170 mm and a depth of 180 mm. The coil had a 5 m length and produced ten smaller diameter windings. The tube's diameter was 12.5 mm. The constructed construction of the cylindrical receiver is shown in Figure 3. In the next part, the receiver's design will be discussed. The cylindrical receiver's aperture diameter was selected based on the focal diameter of the dish. Two thermocouples (Type-K) were used for measuring the inlet and the outlet temperatures of the heat transfer fluid (HTF) [27].

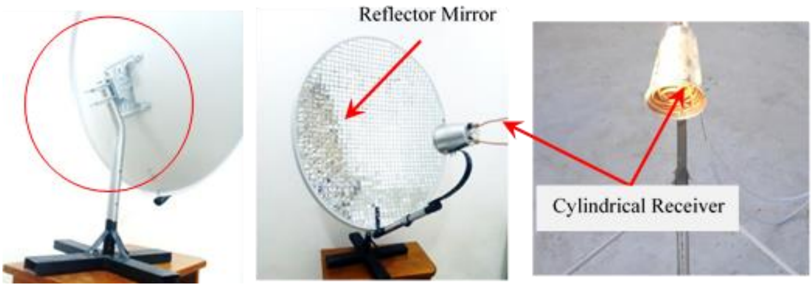


Figure 6: The structure of the solar system

- Connecting tubes: Two rubber tubes (for the inlet and outlet, as water begins to flow from the tank to the boiler) were used to handle the relatively internal high pressure as water turning into steam due to heating.
- Storage Tank: A 10-liter gas bottle was used for storage. It was modified to suit the work by adding two holes with fittings, one at the bottom for the liquid to exit and the other at the top where the liquid returns from the boiler in the form of steam and then adding a flow control valve for this process to control the water level outside the flow rate.

All the used thermocouples, gauges and flow meters are calibrated and the uncertainty of each was about ± 2, 5 and 7 %, respectively.

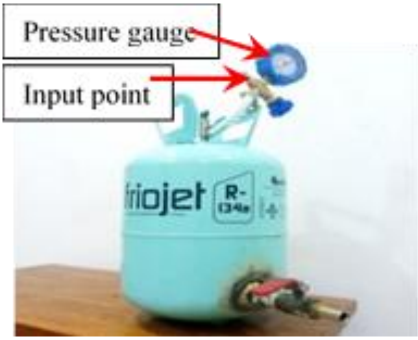


Figure 7: The used storage tank for the solar system

Results and Discussions

After fabricating all the necessary parts, the rig was assembled, and the center dish was directed towards the sunlight. The storage tank was filled with tap water and connected to the cylindrical receiver via the rubber pipes. Meanwhile, the solar radiation focused onto the boiler for about 10 minutes and the temperature was raised to reach almost 210 °C (with no water). The next step was to allow the water to flow between the receiver and storage tank. Both the inlet and outlet temperatures of the water were repeatedly recorded to calculate the heat transfer from the receiver to the hot tank. In the case of the open system of the current investigation, the amount of mass flow rate changes form 0.001 kg/sec (lowest value) up to 0.0067 kg/sec, whereas it was fixed to 0.0067 kg/sec during the experiments of the closed system.

To accurately analyze the system's overall performance, each experiment was repeated five times a day during four days. In general, the data indicated that the incident solar radiation increases with time and reaches its maximum at mid-afternoon and then decreases until sunset. This would be due to a change in the optical path of radiation through the atmosphere during the day which leading to a change in the amount of incoming solar radiation (mainly through the absorption and diffusion process). Consequently, the change in the intensity of solar radiation over-time causes a change in the temperature values, as shown in Tables 2 and 3.

Table 2: Experimental results for the PDC using the closed system

Time (hr.)	T_W °C	T_{in} °C	T_{out} °C	S.R (Lux)	S.R (w/m^2)	Useful energy (w)
08:00	32	17	35	121000	139.101	585
09:00	33.2	32	43	125000	143.7	640
10:00	35.1	39	51	130000	149.448	700
11:00	39.9	45	73	136000	156.345	750
12:00	44.1	66	85	141000	162.093	815
13:00	44.8	78.3	89.1	143000	164.392	980
14:00	45.4	82	91.2	141000	162.093	800
15:00	45.8	85	91.7	135000	155.196	675
16:00	46.1	86.2	92.5	132000	151.747	520

Table 3: Experimental results for the PDC using open system

Time (hr.)	T_W °C	T_{in} °C	T_{out} °C	S.R (Lux)	S.R (W/m^2)	Useful energy (W)
08:00	42	21	35	139000	159.794	490
09:00	42	24	39	139000	159.794	585
10:00	42.5	29	45	139000	159.794	610
11:00	43	32	51	139000	159.794	710
12:00	43	35	56	140000	160.944	755
13:00	43.5	36	64	140000	160.944	725
14:00	44	37.5	71	141000	162.093	620
15:00	45	40.5	77.5	143000	164.392	430
16:00	47	44	82	145000	166.692	380

The solar concentrated parabolic dish collector was designed for heating water in a storage tank for basic household needs. The equipment was tested on sunny days to see if it could provide the necessary heat. During two single days (in the middle of June and July 2021), the relationship between solar radiation and time in the city of Diyala/Iraq was established (see Figure 8). Iraq is considered as one of the most appropriate regions for solar applications (at the middle of the solar radiation zone) due to its geographical location. Figure 8 depicts the distribution of solar radiation in Diyala/Iraq based on the local time. It can be observed that the solar radiation increases from dawn until mid-afternoon in both June and July and then begins to drop until sunset.

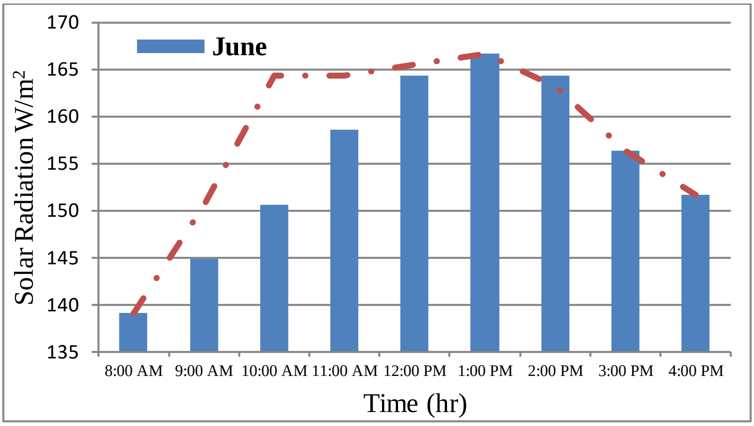


Figure 8: The relation between solar radiation and time in the city of Diyala/Iraq

Figure 9 shows the increase of the temperature during the time for the inlet and outlet temperatures of the water. It also shows the temperature of ambient and solar radiation during the day-time. The present results were recorded for a closed cycle between the storage tank and the boiler. It can be seen that both the inlet/outlet temperatures were increased with time until the sunset. Furthermore, it was noted that the outlet temperature was starting to be substantially higher than the input temperature between 10:00 and 01:00 PM, which might be attributable to an increase in solar radiation at this time of day. After that the difference between the two temperatures (Tin and Tout) becomes almost stable (maintaining same difference).

Figure 10 shows the increase of the temperature during the time for the inlet and outlet temperatures of the water and the temperature of ambient and solar radiation. These results were recorded for the open system. It can be noticed that the outlet temperature of the water is significantly higher when compared to the inlet temperature due to the effect of the open cycle.

Figure 11 represents the amount of energy generated as increases with increasing temperature and the amount of solar radiation falling on a unit area. In addition, it increases by increasing the amount of mass flow of the fluid to a certain extent and decreasing the concentration ratio to a certain extent.

Based on the current results, it can be pointed out that the percentage of improvement depends on the theoretical efficiency, which in turn depends on the percentage of concentration. The higher the concentration ratio, the higher the efficiency. However, practically, the efficiency was inversely proportional to the concentration ratio. This is due to the increase of the diameter of the supporting tube (lower concentration ratio) which led to the greater time of heat exchange between the absorbent tube and the fluid.

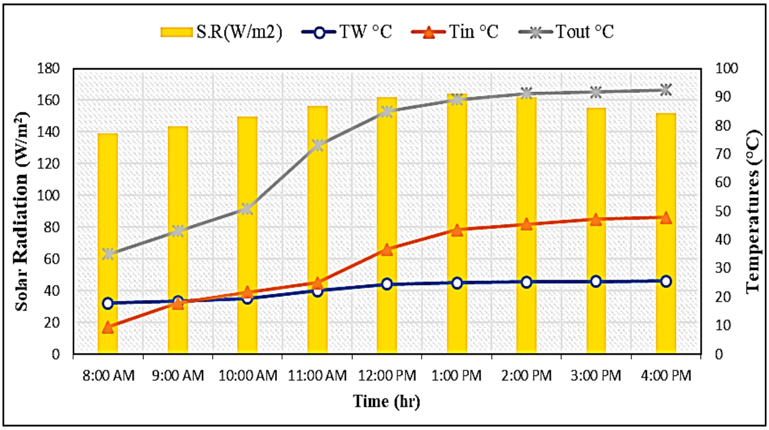


Figure 9: Relation between temperatures, solar radiation, and time (closed system)

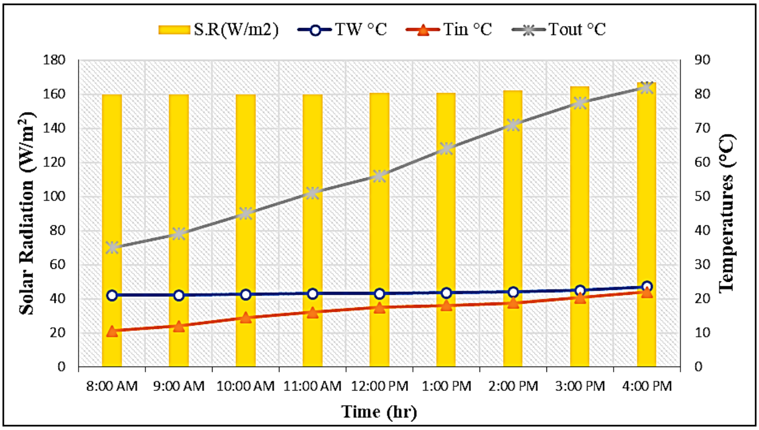


Figure 10: Relation between temperatures, solar radiation and time (open system)

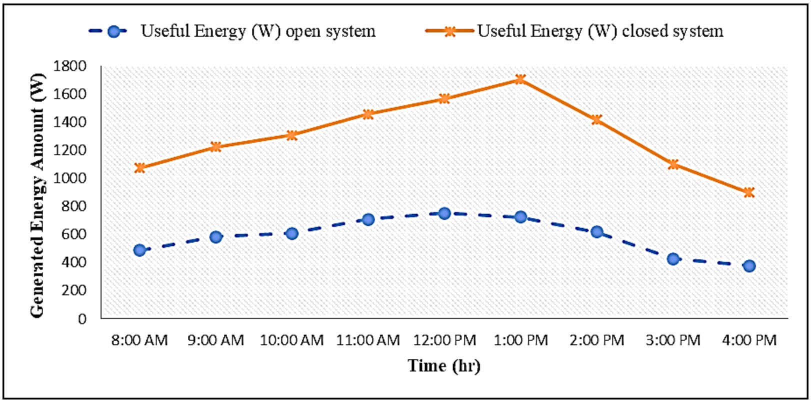


Figure 11: The amount of change in the energy produced by the solar collector with time, for open and closed systems

Conclusions

In this work, the heat losses coefficient with time has been studied for the parabolic-dish solar collector. It was concluded that the stored heat increases as solar radiation increases. The results were mainly obtained from two types of systems (open and closed). The closed system results showed that the maximum temperatures of the inlet and outlet water were 74.2 °C and 90 °C, respectively (differences of 16 °C). On the other hand, the open system showed a temperature difference of 38 °C (T_{in} = 44 °C and T_{out} = 82 °C, for the same time, i.e., at midnight). This is because the closed system uses circulating hot water and has a limited surface area (1 m^2), whereas the open system has reverse effect owing to water flow speed. This would explain the difference between temperatures in the (open and closed) systems. It was found that the coefficient of total heat loss over time was increased by about 25 to 41% (closed and open systems). This is due to the increase in the amount of water (increase in the Reynolds number) flowing through the collector for the open system, which helps to extract more heat from the solar collector. Based on the present shown results and efficiency, it can be said that the current design of the apparatus is decent enough for use in our daily lives. The current experiment provides good insight into the relationship between solar energy and its harnessing to generate thermal energy and the conclusion is as follows:

- It can help reduce the consumption of electrical energy, especially in the current situation in Iraq.
- The used energy for operating the systems is widely available (free).
- Low cost of the construction of the system with a very long lifespan.

- Maintenance-free (except for the cleaning process from dust from time to time).

For future work, it would be recommended to do the following steps. Firstly, the parabolic-dish concentrated-collector can be modified concerning focal length and dish diameter. Secondly, an automatic tracking system can be integrated for tracking the sun's direction. In addition, material opportunities were also considered while designing the dish with reflectivity and thermal conductivity. Thus, the parabolic dish solar collector system may be implemented in the future for air conditioning systems and other industrial heating applications.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

Funding

This work received no specific grant from any funding agency.

Conflict of Interests

All authors declare that they have no conflicts of interest.

Acknowledgment

The construction of all materials used in the current research is supported by University of Diyala (Mechanical Engineering Department).

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