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Research Article

Utilization of a sun-tracking parabolic dish collector for water heating application

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ABSTRACT

In this study, it is aimed to obtain hot water through a parabolic dish mirror tracking the sun in two axes in climatic conditions of Diyarbakır, Turkey. A heat exchanger with copper spiral element was designed as an absorber on the focus point of the system. Water coming from network exits from the system by heated in the absorber. The experimental data was acquired from 10:00 a.m. to 16:30 p.m. o'clock. The effect of mass flow rate on efficiency was studied considering three cases of 0.00187, 0.00217 and 0.00345 kg/s. The results indicated that the highest useful heat amount and thermal efficiency were obtained at 0.00345 kg/s. The thermal efficiency values were determined as 32 to 39%. The exergy efficiency of the system was also evaluated as 5.7 to 6.3% according to the experimental data.

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Introduction

Solar energy is the most widely and easily found energy source. It is possible to obtain directly electricity by photovoltaic panels and heat energy by plane collectors from the sun. Future compact systems may provide more advantage from this environmentalist, economic and plenty energy source. Mahdi and Bellel [1] investigated optical and thermal performance of a solar concentrating system using spherical collector for middle and high temperature applications. Thermal efficiency was obtained as 60-70% for a wide temperature range up to 350°C. The results of study pointed out that spherical reflector could be used for heat requiring systems.

Sharma et al. [2] designed a parabolic dish collector with a solar tracking system. The effect of modification for spiral absorber geometry on outlet temperature was studied utilizing parabolic dish collector. Two types of absorber were used; one of them was helical coiled absorber without gap and the other one was helical coiled black coated absorber with gap. It was seen that maximum temperature difference was higher in the latter type by 43% compared to former case.

Pavlović et al. [3] performed optical and thermal analysis of a parabolic dish collector having a spiral absorber. Thermal efficiency was 4% to 15% depending on water inlet temperature energy efficiency was found as about 65%. Prado et al. [4] obtained fresh water for the daily requirement of at least two persons by desalination through a parabolic dish collector.

Thirunavukkarasu and Cheralathan [5] reviewed studies on parabolic dish solar collectors for low and middle temperature applications. Hijazi et al. [6] designed a low-priced parabolic dish collector to directly generate electricity. In order to have proper dimension of the dish, they investigated mechanical stresses due to wind and dish weight using a computer program. Pavlovic et al. [7] studied a simple, light and low-priced parabolic dish collector with a spiral absorber. Water was used as working fluid. Volumetric flow rate, inlet-exit temperatures, ambient temperature, air velocity and solar radiation values were measured in the study. The experimental measurements were used to verify validity of a numerical model evaluating three working fluids (water, thermal oil and air) under various operating conditions. Water was shown to be the most suitable working fluid for low temperature applications with respect to thermal analysis. Thermal oil was suggested as proper fluid for high temperature applications.

Depending on exergetic analysis, air was indicated to be the most suitable fluid for low-temperature applications while thermal oil was favourable for higher temperature cases. Stefanovic et al. [8] conducted a detailed parametric analysis using parabolic dish solar collector with a spiral absorber. Optimum operating conditions were determined and experimental results were also verified through a thermal model. Kumar et al. [9] recently conducted a detailed review study on exergy evaluation of parabolic solar collectors. The effects of various nanofluids and geometrical parameters on the exergy efficiency of solar parabolic collectors were comprehensively discussed.

The daily performance of a solar dish collector was investigated for various inlet temperatures [10]. They noted that the thermal and the exergy efficiencies were approximately constant during the daily operation. The inlet temperature was determined to be the most important parameter on the collector performance on a daily basis such that thermal efficiency was reduced but exergy efficiency was enhanced as inlet temperature increased. In the present work, thermal efficiency of parabolic dish collector is analysed.

Narasimha and Saivesh [11] computed thermal efficiency of parabolic dish collector with dome-cylindrical type cavity receiver for water mass flow rates ($\dot{m}$) of 0.0035 kg/s and 0.0065 kg/s. The results indicated that thermal efficiency was mainly depended on radiation intensity and temperature of the receiver. The average temperature of water at outlet was 21.1% higher for lower $\dot{m}$ case. The outlet temperature of water was increased with average receiver temperature. The heat loss was reduced hence overall thermal efficiency of the system was enhanced as $\dot{m}$ increased.

The investigations on the collectors with solar-tracking system can be found in the literature [12-16] to obtain results with better thermal efficiency of the solar collector. For example, Natarajan et al. [14] developed a two-axis tracking system for parabolic solar dish collector and experimentally determined the performance of the proposed system. Compared to the conventional solar photovoltaic panel, they found that the positioning accuracy of the solar tracking system improved the short circuit current by 86%. Consequently, the solar tracking system was suggested to be utilized in a parabolic dish with concentrating photovoltaic module as the focal point.

Parabolic solar collectors and potential receivers for these systems are seen to be interesting investigation topic for the researchers [17,18]. Various types of solar concentrating parabolic collectors were reviewed by Imadojemu [19]. The central receiver and dish systems with high temperature, which are mostly utilized to obtain electric power, are briefly discussed in the review study. Kaushika and Reddy [20] analysed performance characteristics of a solar parabolic dish concentrator to generate steam. Solar to steam conversion efficiency was determined as 70–80% at 450°C. Seo et al. [21] numerically studied the performance of the solar dish collector system. The influence of types of mirror arrays and receiver shapes on the performance of systems was considered in their investigation. The receiver shape of dome type was found to provide the best thermal performance. A solar concentrating parabolic dish was designed based on optimized flexible petals [22]. Experiments and finite element analysis were used to demonstrate the validity of the method. The new approach was determined to provide precision solar parabolic collectors considerably cheaper than conventional systems.

In the present study, design of a solar-tracking collector having parabolic dish mirror with 70 cm diameter was investigated for water heating application. It was aimed with this system to increase the temperature of water in ambient conditions. Three different mass flow rates were considered in the experiments and hence the effect of changing flow rate on exit temperature of fluid and thermal efficiency was investigated. The exergy efficiency of the system was also computed referring to the measured data.

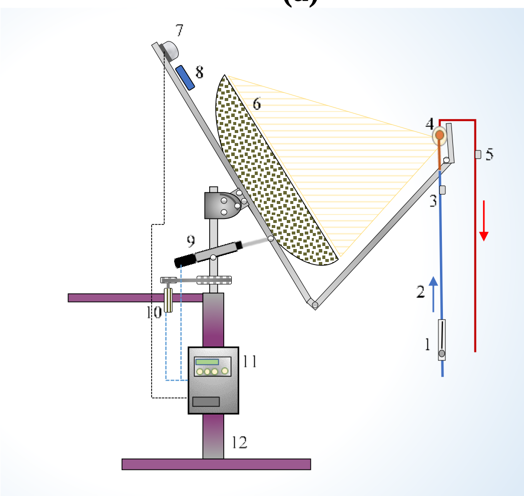
Material and method

The parabolic dish mirror collector shown schematically in Fig. 1 is 70 cm in diameter which tracks the sun in two axes (north-east and east-west) and concentrates the solar energy on an absorber located in the extension of mirror’s focus. Such type of collectors should continuously track the sun in order to reflect the possible highest solar radiation on thermal absorber. The absorber emits solar energy and transfers the heat energy to the fluid circulating inside the system. Then it can convert the heat energy to the electricity utilizing a generator directly coupled to the absorber. Parabolic dish collector systems may provide temperatures over 1500°C [23]. There are some significant advantages of parabolic dish solar collectors. There is less radiation loss due to their comparable small absorber surface. Since they continuously track the sun, they are also the most efficient systems among the collectors.

The motors provide the dish to track the sun depending on signals coming from photosensitive optical sensor. This signal is compared with a previously programmed reference amount and then proper current to the motors is provided with respect to the situation. Such tracking mechanism is a control system that could be utilized also for operation of photovoltaic solar energy units. A belt-pulley motor was used for east-west motion while a linear actuator was preferred for north-south movement of the parabolic dish.

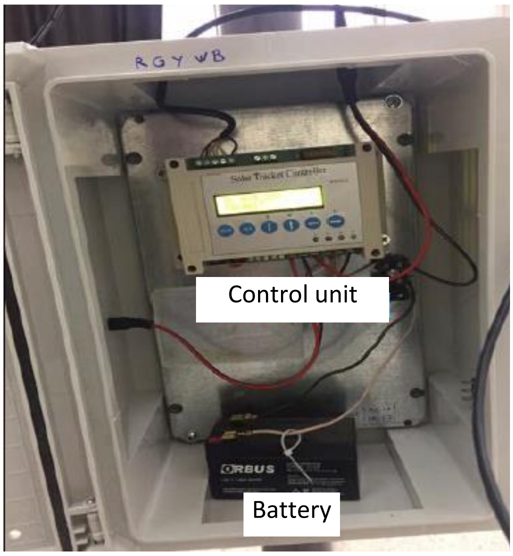
The focus supporter moves together with parabolic dish as shown in Fig. 1. The absorber is mounted to the free end of focus supporter. The absorber is a spiral copper tube with an inside diameter of 6.2 mm and the outside diameter of spiral element is 70 mm as demonstrated in Fig. 2. In order to reduce the effect of wind, the absorber is placed inside a silica glass tube resistant to high temperature as seen in Fig. 2. The pyranometer and optic sensor instruments are placed in back side of parabolic dish. There are control panel and 12 volt battery on support element of the system. The experimental work was carried at campus of Dicle University in Diyarbakır. The working fluid is water. The system is operating on open circuit basis and it is aimed to reach maximum possible temperature of water without reheating. The water is supplied to the system with three different amounts through a rotameter. The inlet and exit temperatures of water in the system are measured by digital thermometers. The focus point temperatures are measured with infrared thermometer.

(a)



(b)

1. rotameter
2. water inlet
3. thermocouple at absorber inlet
4. spiral heat absorber
5. thermocouple at absorber outlet
6. parabolic dish mirror
7. LDR (optic sensor)
8. pyranometer
9. north-south actuator
10. east-west gear motor
11. control box
12. support leg



(c)

Figure 1. Experimental set-up for the parabolic dish solar collector system (a) Photograph (b) schematic representation (c) control unit for solar-tracking system

Figure 2. The spiral absorber used in the experimental set-up.

The instant efficiency of collector η is the ratio of useful energy available in absorber to solar energy perpendicular to absorber area and it is computed as

$$\eta = \frac{Q_u}{IA} = \frac{\dot{m} C_p \Delta T}{IA} \tag{1}$$

where Q_u is useful energy rate received by collector (W), I is coming solar radiation (W/m^2), A is area of parabolic dish (m^2), C_p is specific heat of water (J/kg.K), ΔT is temperature difference between exit and inlet temperatures of absorber (°C) and $\dot{m}$ is mass flow rate of water (kg/s). Temperature, solar radiation and mass flow rate of water are measured using thermocouples, pyranometer and rotameter, respectively. Technical properties of instruments utilized for experimental measurements are given in Table 1.

Table 1. Technical properties of measuring devices

Instrument	Measuring range	Accuracy
J-type thermocouple	-100–700°C	±0.3°C
Pyranometer	300–1200 W/m^2	±1 W/m^2
Rotameter	0.1–1.0 l/min	±0.05 l/min

Only the first law efficiency of thermodynamics defined by Eq. (1) is not a measure for the energetic analysis of a system. Therefore, implementing the second law analysis of thermodynamics is also important in terms of evaluating qualitative reduction in the system, entropy generation and potentials of work performing of the system. Exergy efficiency of the system was computed assuming kinetic and potential energy changes are negligible, flow is steady and specific heat for the working fluid (water) is constant. Exergy efficiency (η_{ex}), in other words second-law efficiency of the system was determined as

$$\eta_{\text{ex}} = \frac{\dot{m}[(h_o - h_i) - T_e(s_o - s_i)]}{\left(1 - \frac{T_e}{T_{\text{sun}}}\right) Q_{\text{abs}}} \tag{2}$$

where h is enthalpy of water in kJ/kg, s is entropy in kJ/kg·K, subscripts o and i refer to outlet and inlet of the absorber, respectively, T_e is 293 K (i.e., dead state temperature), T_{sun} is surface temperature of the sun taken as 6000 K and Q_{abs} is absorbed solar energy by parabolic dish in W. More detailed expression on the calculations of exergy efficiency of the system can be found in the study by Devecioğlu et al. [24].

Results and discussion

The data provided in this paper cover results of an experimental work carried on July 16-18, 2018. The measurements were recorded from 10:00 to 16:30 at every half an hour. The variation of solar zenith angle with time is plotted in Fig. 3. It is clearly seen that solar zenith angle decreases up to noon, however it increases after 13:30 till sunset due to deviation of the sun from vertical axis.

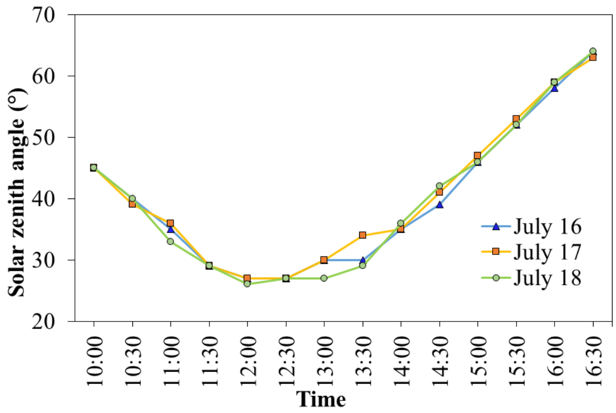


Figure 3. The distribution of solar zenith angle versus time

The distribution of solar altitude angle versus solar azimuth angle is demonstrated in Fig. 4. It can be seen that, solar azimuth angle is negative in the morning till noon and it is zero around noon. The parabolic dish mirror is exactly directed to the south at this time. Then solar azimuth angle takes positive value while the sun moves towards the west. Note that the sum solar altitude angle and solar zenith angle is considered as 90° according to the study by Kalogirou [23]. Therefore, solar altitude angle increases as solar zenith angle is reduced. Since the constructed system tracks the sun in two axes, sunbeam has been maintained to reach perpendicular as much as possible.

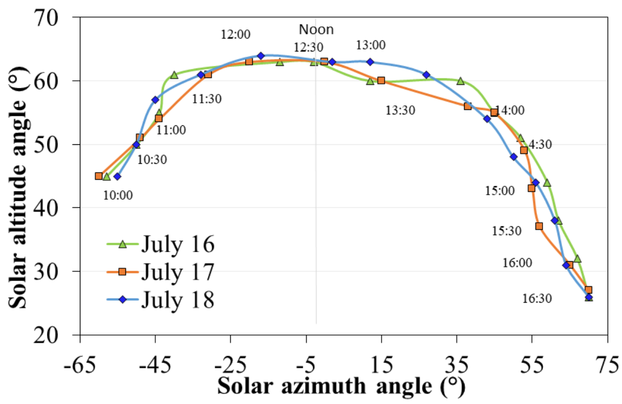


Figure 4. The variation of solar altitude angle with solar azimuth angle during the days

In the experimental investigation tap water of 28°C was used for the system feed. Mass flow rate, focus point temperature and temperatures of water at absorber inlet-exit sections were measured for determining absorbed energy. Intensity of solar radiation amount, I was measured by a pyranometer, hence energy coming from the sun was calculated. As a result, general efficiency of the system was computed using Eq. (1). Fig. 5 presents measured solar radiation magnitudes (I) on July 16-18, 2018 from 10:00 to 16:30 at every 30 minutes. It is clear that I value on July 18 is 1000 W/m^2 at 10:00 while it has a peak magnitude of 1040 W/m^2 at 13:30 o'clock. Note that there is a reduction in I about by 5% after 16:00. Similar behaviour for I distribution can be observed for other days as shown in Fig. 5. There is a difference of ±15W/m^2 between the measured I values at same times considering the other days.

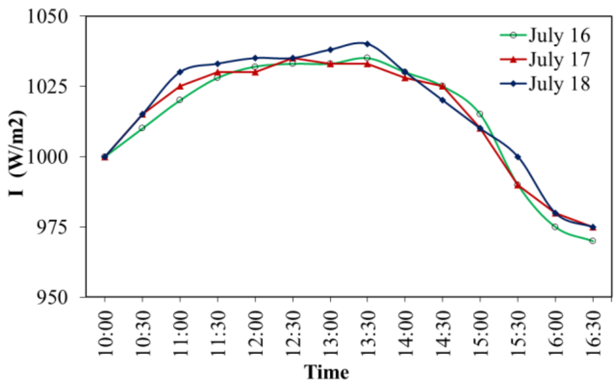


Figure 5. Time dependent distribution of solar radiation intensity

The temperature at outlet of absorber, T_o was measured during the investigation. The time dependent distribution of T_o for studied mass flow rate, $\dot{m}$ cases can be seen in Fig. 6. Note that temperature of water at inlet of the absorber is 28°C for the covered cases. As expected, T_o reaches the highest value around noon for all $\dot{m}$. Furthermore, T_o is reduced obviously as $\dot{m}$ increases such that average values of T_o can be determined from Fig. 6 as 44.9°C, 41.4°C and 37.7°C for $\dot{m}$ cases of 0.00187, 0.00217 and 0.00345 kg/s, respectively.

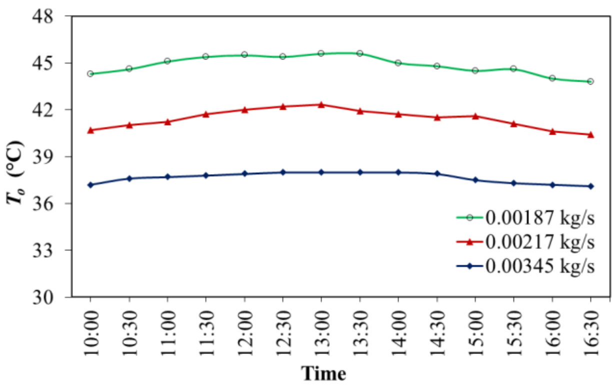


Figure 6. Time dependent distribution of temperature at outlet of the absorber

Water temperature difference between outlet and inlet of the absorber, ΔT is demonstrated in Fig. 7 for three cases of mass flow rates, $\dot{m}$. Similar to the behaviour observed in Fig. 6, ΔT is decreased as $\dot{m}$ increases such that average ΔT values are obtained as 16.9, 13.4 and 9.6°C for $\dot{m}$ values of 0.00187, 0.00217 and 0.00345 kg/s, respectively. Depending on measured data time, it can be seen that the difference between maximum and minimum values of ΔT is about 2°C for any case of $\dot{m}$. It should be noted also that ΔT decreases as I is reduced and it is maximum for the highest measured magnitude of I.

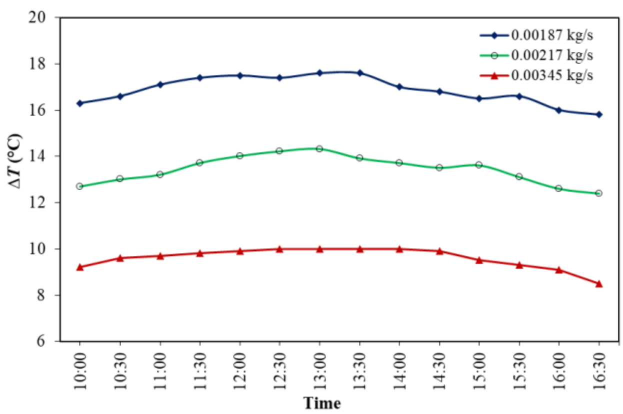


Figure 7. Time dependent distribution of temperature difference between outlet and inlet of the absorber

The solar energy captured by parabolic dish concentrator is not completely transferred to the water as a useful energy rate due to energy loss to surroundings. Therefore the rate of energy loss can be determined subtracting amount of useful energy from the solar energy (Eq. 1). As a result, the time dependent variations of solar energy rate, energy loss rate and useful energy rate are presented in Fig. 8 for the sample case of $\dot{m}$ = 0.00217 kg/s. Similar behaviours were observed for the other studied mass flow rate cases. It is evident that energy loss develops with a considerable amount such that about 65% of solar energy is not used in this case directly passing to the surrounds. The systems reducing these losses as much as possible should be designed in order to have the situations with improved efficiency.

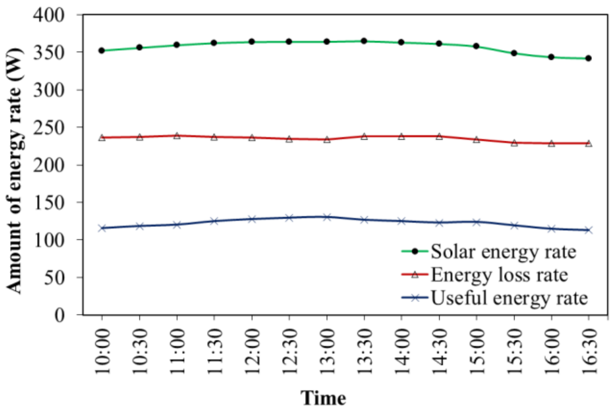


Figure 8. Time dependent distribution of rate of energy amounts for the sample case of $\dot{m}$ =0.00217 kg/s

The distribution of useful thermal energy amount (Q_u) transferred to water is presented in Fig. 9. As expected from Eq. (1), Q_u increases for higher values of both $\dot{m}$ and ΔT. Although average ΔT for $\dot{m}$ =0.00187 kg/s is greater than that for $\dot{m}$ =0.00345 kg/s as seen in Fig. 7, Q_u is the highest for the latter case as confirmed in Fig. 9 due to the fact that increase in $\dot{m}$ is higher compared to that in ΔT. Therefore, amounts of Q_u were determined nearly as 132, 122 and 139 W for $\dot{m}$ values of 1.87, 2.17 and 3.45 g/s, respectively. Furthermore, it should be noteworthy to recall that generally useful energy transferred to water is about 37% of coming solar radiation energy and remaining part is thermal heat loss to the surroundings.

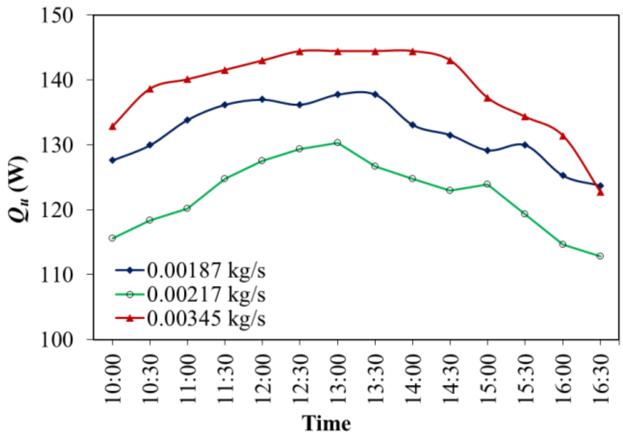


Figure 9. Variation of useful heat energy transferred to the water with time

The thermal efficiency of the system, η which is defined as the ratio of useful thermal energy to the solar energy on the parabolic dish, is calculated using Eq. (1). Time dependent distribution of η is given in Fig. 10. First of all, η is enhanced around noon and it is highest at this time. Moreover, the distributions observed for Q_u in Fig. 9 are the same those seen for η in Fig. 10 as far as the effect of $\dot{m}$ is considered. The highest efficiency values were obtained for $\dot{m}$ =0.00345 kg/s as about 38% while η values were found as nearly 36% and 34% for $\dot{m}$ values of 0.00187 kg/s and 0.00217 kg/s, respectively.
Although a parabolic dish collector with a comparable small size was used in present investigation, the efficiency of the system is satisfactory and reasonable referring to the results in the available literature. Usually, the computed efficiency values are known to be 30% to 50%. The size of reflector (i.e., parabolic dish collector) has not significant effect on efficiency; however, it plays a major role on required outlet fluid temperature.

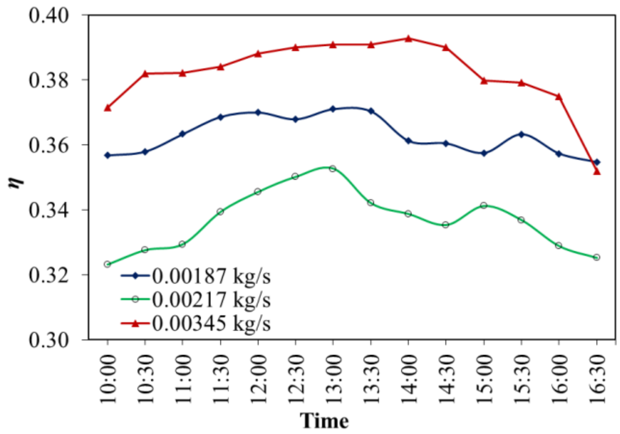


Figure 10. Time dependent distribution of the system thermal efficiency for covered $\dot{m}$ cases

The exergy efficiency of the system, (η_{ex}) was computed in the investigation using Eq. (2) and the distribution of η_{ex} versus time is shown in Fig. 11. Obviously, higher values of η_{ex} develop around noon time. In addition, η_{ex} is reduced as $\dot{m}$ increases such that average amounts of η_{ex} can be detected from Fig. 11 as 6.3%, 5.9% 5.7% for 0.00187, 0.00217 and 0.00345 kg/s, respectively.

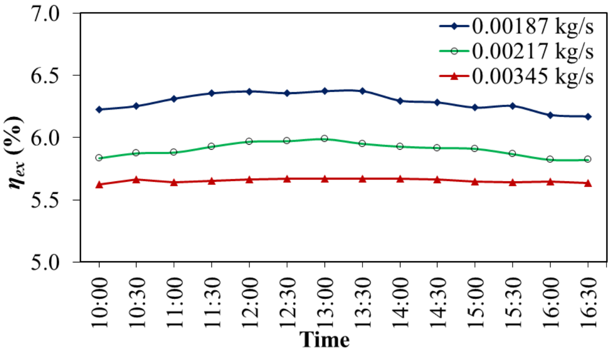


Figure 11. The behaviour of exergy efficiency over measurement period

3.1. Uncertainty analysis in the measurements

The area of parabolic dish collector, *A* and specific heat of water, C_p in Eq. (1) are constant parameters. Therefore, the uncertainty analysis in thermal efficiency of the system (U_η) is performed as a function of measured parameters of ΔT, I and $\dot{m}$ seen Eq. (1). Then, U_η is calculated as [24]

$$U_\eta = \left[\left(\frac{\Delta T}{I}U_{\dot{m}}\right)^2 + \left(\frac{\Delta T\dot{m}}{I^2}U_I\right)^2 + \left(\frac{\dot{m}}{I}U_T\right)^2\right]^{1/2} \quad (3)$$

where $U_{\dot{m}}$, U_I and U_T are uncertainties in rotameter, pyranometer and thermocouple instruments, respectively as provided in Table 1. Hence, uncertainty in efficiency of the system, U_η has been computed using Eq. (3) as 2.87% to 3.70% for the experimental work which can be considered as an acceptable error range for the engineering applications.

Conclusion

The present investigation is directed to obtain hot water through a new design of solar collector system consisted of a sun-tracking parabolic dish mirror and a spiral absorber element. Parabolic dish collector is a mirror having a comparatively small diameter of 70 cm. Water steadily flows through the system. The system efficiency values are calculated for 3 cases of $\dot{m}$ as 0.00187, 0.00217 and 0.00345 kg/s. The study is novel in term of designing a compact solar-tracking system of parabolic dish collector (mirror) and absorber element as well as different ambient conditions noted in literature. The basic results of the investigation can be recalled as follows:

- When solar radiation is 970 to 1040 W/m^2, average thermal power amount of 130 W was obtained by parabolic dish collector tracking the sun in two axes.
- It was experienced that temperature of 0.5 L water was increased about by 10°C in 145 seconds.
- ΔT was higher at lowest $\dot{m}$ case, but the heat energy amount transferred to water was maximum for greatest $\dot{m}$ studied herein.
- The thermal efficiency of system was computed as 32 to 39% for the covered mass flow rates and η was highest for 0.00345 kg/s while it was lowest for 0.00217 kg/s.
- Depending on $\dot{m}$, average exergy efficiency was calculated as 5.7 to 6.3% and η_{ex} is increased as $\dot{m}$ is reduced.

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