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PERFORMANCE ANALYSIS OF A MEDIUM TEMPERATURE SOLAR CONCENTRATOR FOR DOMESTIC WATER HEATING

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ABSTRACT

In the last decade, solar energy technologies are gaining attention due to their potential for reducing environmental emissions and enhancing sustainability in residential and industrial applications. In this regard, solar collector systems are widely used for hot water production in buildings. Currently, flat plate collectors are mostly used collector type; however, their efficiency dramatically drops in winter period when the hot water demand is at its peak. Consequently, present study is concerned with the design and development of a parabolic dish collector as an alternative to flat plate collectors. The proposed collector consists of a parabolic dish, a receiver made up of a black painted spiral coil tube heat exchanger and a glass glazing. In the system, a 50 L water tank is also used and the water is circulated between the collector and the water tank by employing a water pump.
System is tested on the coldest days of the year (10-13 December 2018) and highest water temperature of 42 ℃ is achieved. The average and maximum instantaneous thermal efficiencies of collector were obtained as 48% and 76% respectively.

Keywords: solar energy, parabolic dish, water heating, thermal energy analysis, efficiency

1. INTRODUCTION

With the growing emphasis on energy conservation, renewable energy sources have received increasing attention [1]. The term "renewable energy" is not a new concept to the environment, but rapidly it continues to emerge as an alternative to fossil fuels and all other deleterious energy resources. Solar energy, which is one of the most abundant renewable source have the potential to meet the total global energy demand. However, only 0.02% of that energy is utilized in the present day [2]. Nevertheless, since the initial implementation of solar systems, numerous projects have been completed and the developments in the field of solar energy are ongoing. Among all renewable sources, solar energy is considered as one of the most economic and efficient alternative.

Solar systems are basically converts solar irradiation into useful form of energy such as heat or electricity. In solar thermal applications, solar collectors or concentrators are used to gather the solar radiation. The radiation energy can then be used for space/water heating and for producing process heat in residential and industrial applications [3]. In the literature, several studies investigating different type of solar collector performances have been completed previously. Bellos & Tzivanidis studied flat plate collector performance experimentally and numerically under Athens conditions. Average efficiency of the investigated system was found 54.2% [4].

Zhang et al. investigated a multi-purpose flat place solar collector for air and water heating. The overall efficiency of the collector in combined air-water heating mode reached to 73.4% [5].

Nikolić and Lukić studied a double exposure flate plate collector for water heating. Results showed that double exposure collector provides an efficiency enhancement of 18.4% when compared to conventional flat plate collector [6]. Fan et al. investigated a novel solar collector with V-corrugated multi-channel absorber. Thermal efficiency of the new collector was found in the range of 69-74%, while the efficiency of conventional solar collectors is determined as 58-69% for the same operating conditions [7].

Jowzi et al. investigated evacuated tube collector performance with cylindrical absorbers in Greece. It is obtained that; four evacuated tube collectors connected in series can produce a maximum of 5.6 kW thermal energy [8]. Xu et al. carried out experimental studies on evacuated tube collector performance under China climate conditions. Thermal efficiency of the developed collector was found between 43-55% [9].

Teles et al. numerically investigated the performance enhancement with the use of sun-tracking in evacuated tube solar collector applications in Brazil climate. The efficiencies of tracking and non-tracking evacuated tube collector were found 73% and 42% respectively [10]. In another study, Budihardjo and Morrison performed comparative investigations between vacuum tube and flat plate collector in Sydney. The thermal performance of the vacuum tube collector was found higher while its sensitivity to the size of the storage tank was found lower compared to the flat plate collector [11].

Despite several studies have been performed on flat plate and vacuum tube collectors, research on dish type concentrating solar water heaters is very limited in the literature. Such type of solar systems is mostly investigated for high temperature applications such as in solar thermal power plants. Different than the previous research, in present study, a dish type concentrating solar water heater using spiral coil tube heat exchanger is investigated for residential applications under North Cyprus climate conditions.

2. METHODS

2.1. System Design and Operation

The proposed parabolic dish solar water heating unit consists of four main components namely; solar dish, copper coil receiver, support frame and water tank, as illustrated in Figure 1. In the system, receiver is made up of a horizontally aligned copper coil which is fitted inside a cylindrical glass glazing. With such design, it is targeted to enhance the receiver area to eliminate the tracking requirement and to enhance the heat transfer rate to the water across the copper coil heat exchanger. During the system operation water is circulated between the water tank and receiver by using a water pump. Mass flow rate of water across the system is also controlled by using a water valve as illustrated in Figure 1.

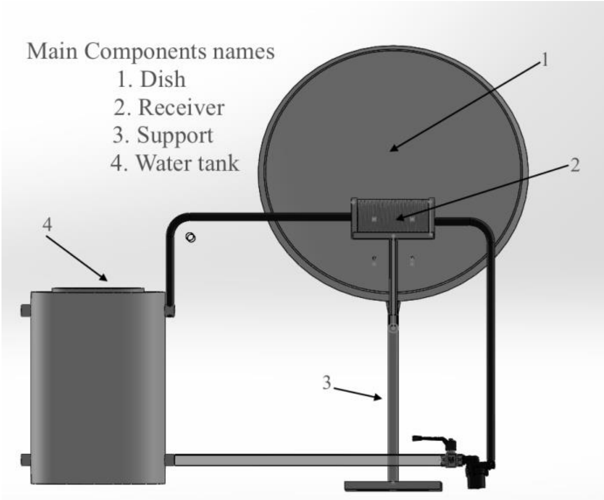

Figure 1. CAD design of solar dish water heating system

Parabolic dish is the main component of the design that is made up of aluminum sheet metal. It is covered with reflective aluminum tape for enhancing the reflected radiation on to the receiver. The parabolic dish is of 800 mm diameter (*Dc*) with a depth (*h*) of 80 mm and a focal length (*F*) of about 500 mm as shown in Figure 1.

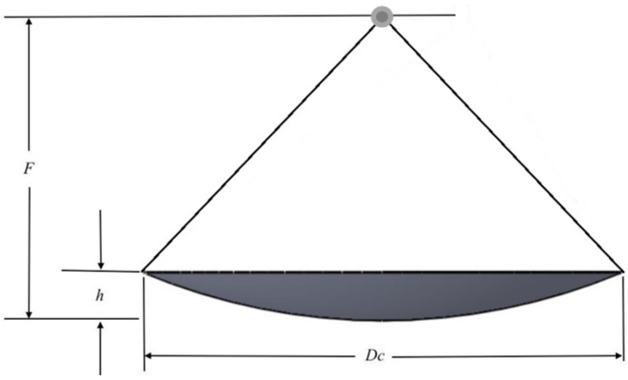

Figure 2. Design of parabolic dish unit

The manufactured and assembled solar dish water heating system is illustrated in Fig. 3-a. During the experimental testing, dish is faced to south and system is operated between 10:00-14:30 hours. The detailed view of the copper coil heat exchanger (receiver) is presented in Fig. 3-b. The copper pipe is processed in turning machine to obtain the coil type configuration and the final product is painted to black for enhancing the absorptivity of the coil. The coil is placed inside a transparent cylindrical glass glazing and placed horizontally at the focal point of receiver. As the receiver is aligned in horizontal direction, the change of the focal point of dish in horizontal direction, due to the movement of sun, is tolerated and the focal point remained on the coil heat exchanger during the testing.

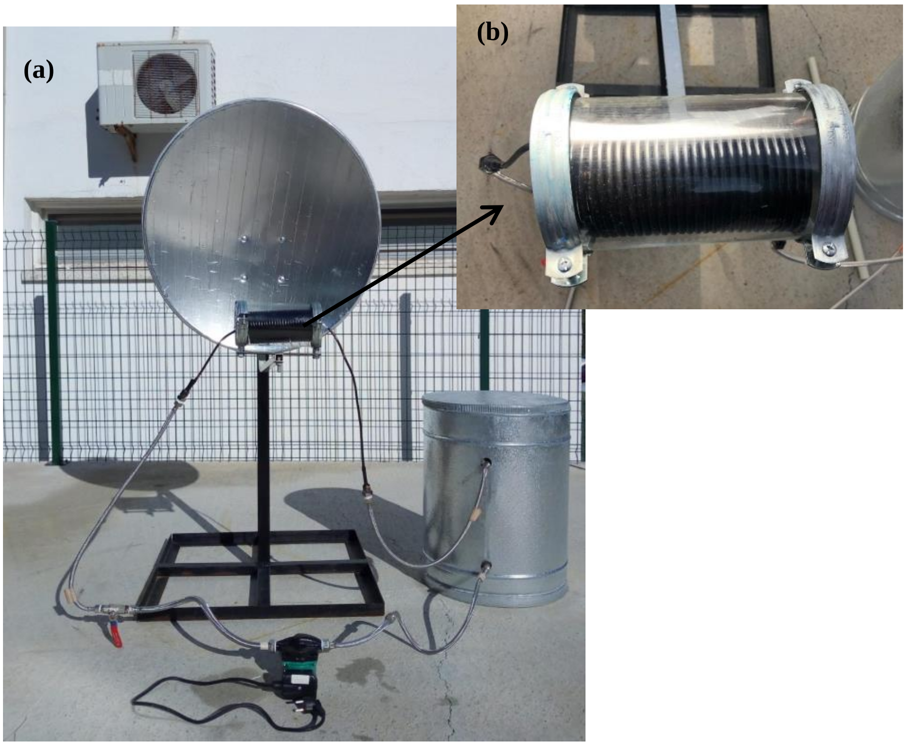

Figure 3. (a) Assembled solar dish water heating system (b) Detailed view of copper coil receiver

2.2. Experimental Measurement and Data Logging

Temperature readings at the inlet and the exit of the collector, ambient temperature and tank temperature changes with time were closely monitored during the study. PCE-T 390 digital thermometer (Figure 4-a) is used for this purpose. This data logger has four channels and can be connected to different type of thermocouples (K/J/T//E/R/S). The instrument is powered by UM3/AA (1.5V) x 6 batteries or DC 9V adapter or it can be easily connected the PC computer interface. The temperature sensors are able to measure temperatures in the range of -50°C to approximately 1000 °C with an accuracy of ±0.4% + 1 °C. During the experiments solar radiation was also measured by using a pyranometer (Figure 4-b). It can measure the total radiation with a scope of 180 degrees. The data is recorded in voltage and later converted into energy per unit area.

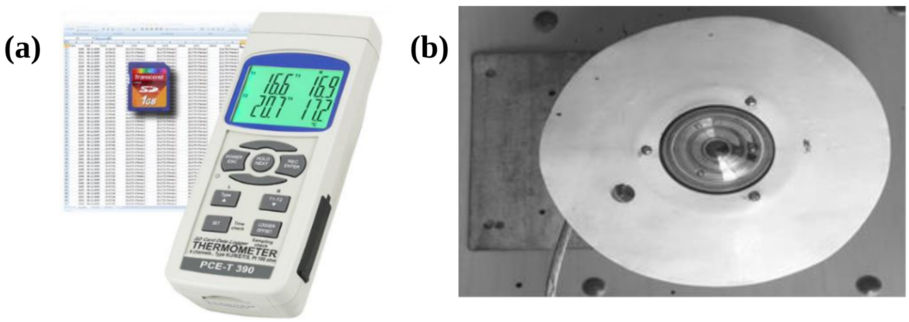

Figure 4. (a) Image of PCE-T390 Digital Thermometer, (b) Pyranometer

Three different experiments were performed and temperatures were recorded during the tests. The tank is filled with water and outlet water temperature form the tank (at the bottom) is assumed to be equal to the inlet temperature to the collector (T1). T2 is the water temperature in the tank, T4 is the water outlet temperature from the collector receiver and T3 is the ambient temperature. Figure 5 shows the schematic of the sensor positions in the system. The mass flow rate of water during the first two experiments is set to 0.00525 kg/s and in the last experiment it is set to 0.00277 to investigate the impact of water mass flow rate on system efficiency.

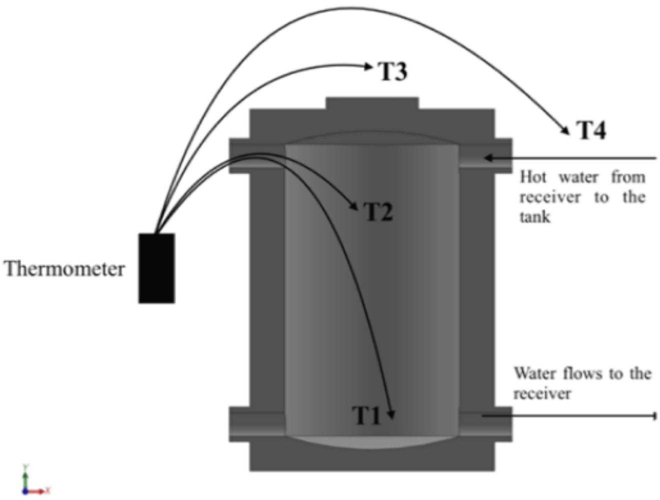

Figure 5. Schematic view of the water tank and illustration of sensor positions

2.3. Design Parameters of the Solar Dish Collector

A mathematical analysis was performed based on the dish dimensions to calculate the values that satisfy the need for the design criteria.

The concentration ratio index (C) is defined as the ratio of aperture area (A_c) to the area of the receiver (A_r). This concentration index indicates that the higher the ratio, the higher the temperature to be reached with the concentrator. Among the rest of the collectors, parabolic dish is considered as one of the best collector type with high concentration ratio. C is defined in Equation (1).

$$C = \frac{Ac}{Ar} \quad (1)$$

The collector area A_c can be calculated by the following equation:

$$A_c = \frac{\pi D_c{}^\wedge 2}{4} \quad (2)$$

While the receiver area is the surface area of the cylindrical receiver and is given by:

$$A_r = \pi D l \quad (3)$$

Where D is the diameter of the cylinder with a value of 0.12m, and it has a length l of 0.21m. Therefore $A_c = 0.503\ m^2$ and $A_r = 0.0792\ m^2$, then;

$$C = \frac{0.503}{0.0792} = 6.34$$

The half acceptance angle [12,13] is given by:

$$\emptyset = \sin^{-1}\sqrt{\frac{1}{C}} = 23.40° \quad (4)$$

The optimum rim angle [12,13] is given by:

$$\psi = 90 - \emptyset = 66.6\,° \quad (5)$$

2.4. Thermodynamic Analysis of the Solar Dish Collector

The available solar energy that can be obtained from the reflection can be calculated by:

$$Q_s = I_g . A_c \quad (6)$$

While the total amount of heat from the parabolic dish reflected to the receiver aperture area can be defined as the optical efficiency by the available solar energy is defined by Equation (7) below:

$$Q_{abs} = \eta_{opt} . I_g . A_c \quad (7)$$

Where, η_{opt} is the optical efficiency of the dish collector, A_c is the dish collector aperture area and I_g is the solar irradiation intensity. The optical efficiency for most solar collectors is 60 - 70 % [13]
The estimated useful energy is calculated by:

$$Q = m_w . c_p . \Delta T \quad (8)$$

Where, m_w mass flow rate of water, c_p is the specific heat capacity of water and ΔT is change in the final and initial temperature. While the thermal efficiency of the collector can be calculated by Equation (9) and is defined as the ratio of the useful delivered energy to the incident energy falling to the concentrator surface [12];

$$\eta_{c,therm} = \frac{Q}{Q_{abs}} \quad (9)$$

The energy balance over the absorber leads to Eq. (10). According to the equation, absorbed heat by the receiver is equal to the total of heat gain by water and the heat losses.

$$Q_{abs} = Q + Q_{loss} \quad (10)$$

The efficiency (η) of most solar collectors' is between 40-60% (Alarcón et al. 2013). Gained useful energy can be calculated by:

$$Q = \eta . I_g . A_c \tag{11}$$

This shows that Equations (8) and (11) are equal and yield:

$$Q = \eta . I_g . A_c = m_w . c_p . \Delta T \tag{12}$$

The instantaneous thermal efficiency is given by;

$$\eta = \frac{Q}{I_g . A_c} \tag{13}$$

2.5. Uncertainty Analysis

The accuracy of the experimental performance of the solar dish collector can be proved by uncertainty analysis method [14,15]. Measurement uncertainties and the equipment sensitiveness are the two main source of the error. Two different types of sensors were used in this experiment. One type of sensor is to measure while the other type of sensor is used to measure the solar irradiance (I). Then, the general form of uncertainty w_R is expressed:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \left(\frac{\partial R}{\partial x_3} w_3 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_4} w_4 \right)^2 \right]^{1/2} \tag{14}$$

Equation 13 is used to evaluate the efficiency (η) of the system. Efficiency is the function of temperature (T), mass flow rate (ṁ) and irradiance (I). Those parameters were measured during the experiment.

$$\eta = f(T_1, T_4, \dot{m}, I) \tag{15}$$

Total uncertainty for overall system efficiency can be expressed as;

$$w_R = \left[\left(\frac{\partial \eta}{\partial T_4} w_T \right)^2 + \left(\frac{\partial \eta}{\partial T_1} w_T \right)^2 + \left(\frac{\partial \eta}{\partial \dot{m}} w_{\dot{m}} \right)^2 + \left(\frac{\partial \eta}{\partial I} w_I \right)^2 \right]^{1/2} \tag{16}$$

The uncertainty of the solar dish collector system thermal efficiency is computed based on the equations 14-15. The total uncertainty (σ) of the efficiency was found 2.3%. The experimental device accuracies and their ranges of operation are displayed in **Hata! Yer işareti başvurusu geçersiz.** below.

Table 1. Accuracies and Ranges of the Experimental Devices

Instruments	Measured parameters	Accuracy	Range
Data logger	Temperature	±0.5 °C	-50 ÷ 100
CMM22 Pyranometer	Solar irradiation	± 20W/m^2	0 ÷ 4000 W/m^2
Flow meter	Mass flow rate	± 0.02	0 ÷ 100 L

3. RESULTS and DISCUSSIONS

This section presents the results obtained from the performed experiments. The testing was conducted in three different days; Dec 10, Dec 11 and Dec 13. On the first two days, mass flow rate of water is set to 0.00525 kg/s and in the final day of testing it is set to 0.00277 kg/s. By applying high and low water flow rates, it was aimed to analyze the impact of flow rate on the solar dish efficiency.

3.1. Results for 10th December 2018

The system was tested for almost 4.5 hours of that day, which is from 10:00 to 14:30. During the experiments four different sensor locations were used. T1 (collector inlet temp) is the temp of the water inlet to the heat exchanger and it is also assumed equal to the bottom temperature in the tank, while T4 (collector outlet temp) represents the hot water temperature at the exit of the dish receiver. T2 (water tank temp) is the surface water temperature inside the tank, and T3 is the ambient temperature.

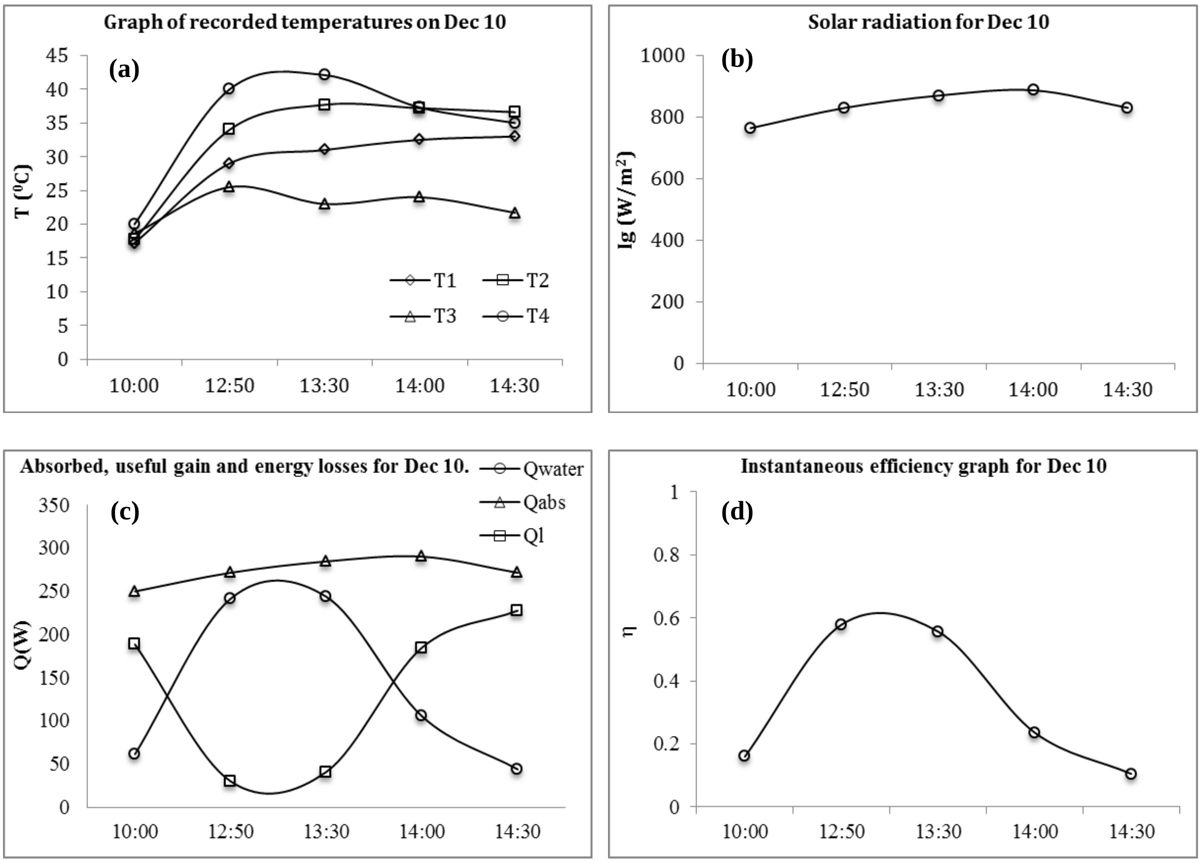

Figure 6. Variation of (a) Temperature, (b) Solar radiation, (c) Absorbed, useful and lost energy, and (d) Efficiency during the experiment on 10th December

Figure 6 a-d represents the temperature, solar radiation, energy and efficiency variations obtained during the experiment. The average temperature increase of water across the dish was determined as 6.3 °C whereas maximum water temperature inside the tank was reached to 37.7 °C from the initial temperature of 17.7 °C (See: Figure 6-a). As shown in Figure 6-b, solar radiation varied between 764 and 887 W/m^2 while average heat transfer rate to the water was calculated as 139.1 W (Figure 6-c). Accordingly, based on the data presented in Fig 6-d, average efficiency of the dish was found 32.7% during the operation.

3.2. Results for 11th December 2018

On 11th December, system is tested under similar operating conditions to validate the results obtained in initial testing. Temperature, solar radiation, energy and efficiency variations of the second day testing were illustrated in Fig. 7. The average temperature increase and rate of heat gain across the dish were found 9.1°C (See: Figure 7-a) and 199.7 W (See: Figure 7-c), which were higher than the values obtained in the first day of testing. On the other hand average solar radiation is measured as 811 W/m2 (See: Figure 7-b) on the second they which was slightly less than the average solar radiation in first day. As a result, as presented in Figure 7-d, efficiency of the dish varied in the range of 24.5%→58.3% and the average efficiency is obtained as 48.3% on that day.

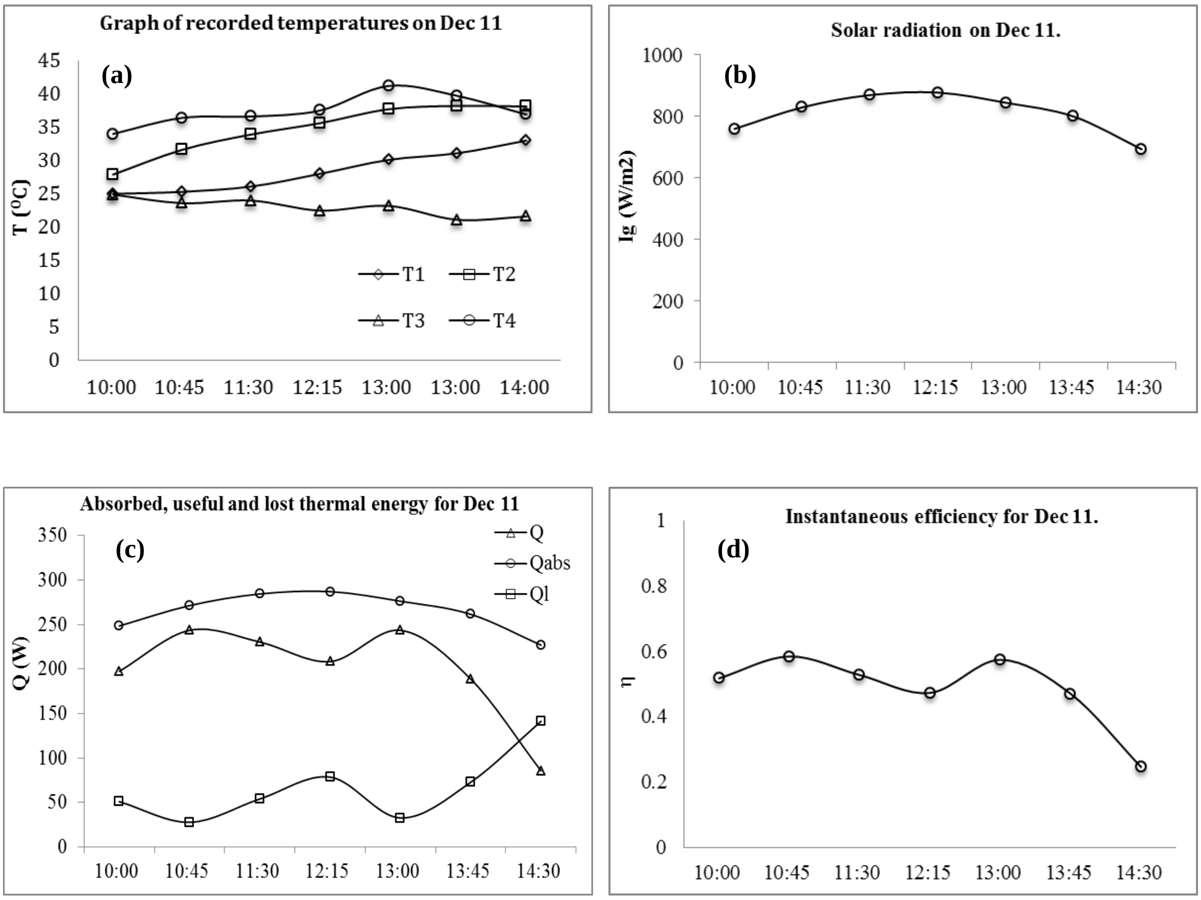

Figure 7. Variation of (a) Temperature, (b) Solar radiation, (c) Absorbed, useful and lost energy, and (d) Efficiency during the experiment on 11th December

3.3. Results for 13th December 2018

In the last day of testing, mass flow rate of water is reduced to 0.00277 kg/s to see the impact of flow rate on solar dish water heater performance (See: Figure 8). Besides, in this testing, receiver temperature was also measured to demonstrate the highest temperature obtained with spiral coil heat exchanger. According to the testing results average temperature lift and rate of heat gain of water across the dish were achieved as 7.1 °C (Figure 8-a) and 153.9 W (Figure 8-b) respectively, while the maximum receiver temperature reached to 116 °C at around 11:45 am (Figure 8-e). During the experiments average solar intensity is measured as 810.1 W/m^2 (Figure 8-b), and it was in close approximation with the intensity on the second day of testing. Accordingly, efficiency of the dish water heater is obtained as 37.3% (Figure 8-d), which was higher than the first day but lower than the second day of testing.

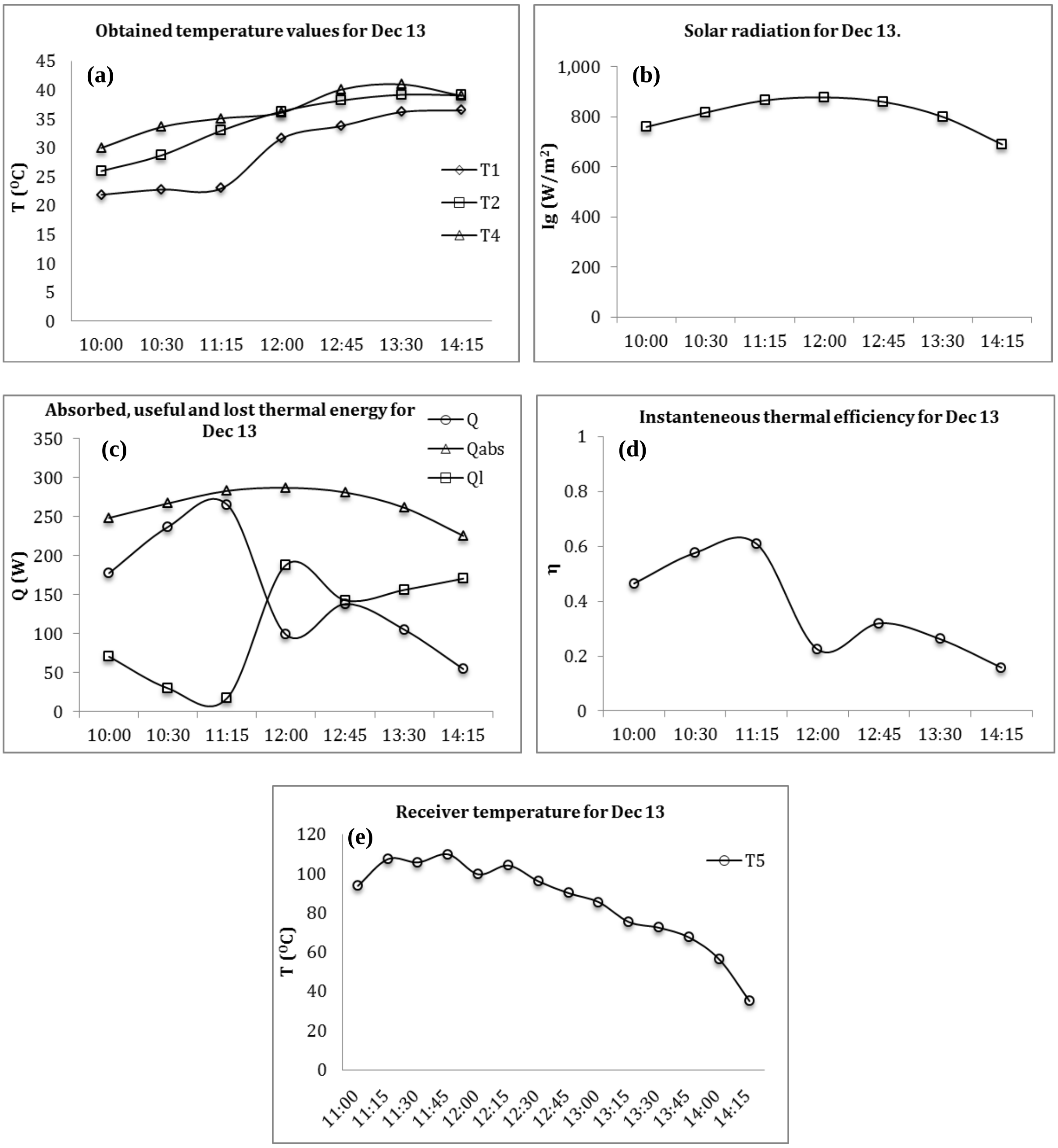

Figure 8: Variation of (a) Temperature, (b) Solar radiation, (c) Absorbed, useful and lost energy, (d) Efficiency, and (e) Receiver temperature during the experiment On 13th December

4. CONCLUSION

In this study, a solar dish unit with copper coil receiver is designed and experimentally investigated for residential water heating applications. System is tested under different solar radiation and water mass flow rate conditions. The summary of the testing results are presented in Table 2. According to the study results, maximum hot water temperature inside the tank is achieved in the first day of testing, while maximum rate of heat gain is obtained in the last day.

However, the highest average of heat gain across the dish is achieved in Day 2. Results showed that both solar radiation and mass flow rate of water significantly effects the system performance. More specifically, it could be stated that; dish system provides higher efficiency at lower solar radiation conditions ($\eta_{day3} > \eta_{day1}$) and higher mass flow rates ($\eta_{day2} > \eta_{day3}$). However further studies are required for optimizing the operating parameters (mass flow rate, dish size, receiver configuration, water tank volume etc.) of the investigated solar dish system.

Table 2. Summary of the testing results

	Dec 10	Dec 11	Dec 13
m_w (kg/s)	0.00525	0.00525	0.00277
I_g (W/m^2)	836.2	811.4	809.1
$T1_{ave}$ (^{O}C)	28.5	33	29.4
$T2_{ave}$ (^{O}C)	32.6	34.7	34.3
$T4_{max}$ (^{O}C)	42.1	41.2	40.1
$T4_{ave}$ (^{O}C)	34.8	37.3	36.4
Q_{max} (W)	243.5	243.5	265.5
Q_{ave} (W)	139.1	200	153.9
η	0.33	0.48	0.37

As the investigated non-tracking solar dish system is low cost, efficient, easy to operate and require less space compared to flat plate collectors, it demonstrates a good potential to be employed in building water heating applications in the future. However deep research on numerical modelling, experimental validation through pilot applications and economic feasibility analysis of such systems is required to bring them to the market level.

REFERENCES

[1] Tian Y., Zhao CY. A review of solar collectors and thermal energy storage in solar thermal applications. Applied Energy 2013; 104: 538-553.

[2] Devabhaktuni V, Alam M, Depuru SSSR, Green II RC, Nims D. Near C. Solar energy: Trends and enabling technologies. Renewable and Sustainable Energy Reviews 2013; 19: 555-564.

[3] Mekhilef S, Saidur R, Safari A. A review on solar energy use in industries. Renewable and Sustainable Energy Reviews 2011; 15(4): 1777-1790.

[4] Bellos E, Tzivanidis C. Development of an analytical model for the daily performance of solar thermal systems with experimental validation. Sustain. Energy Technol. Assessments 2018; 28: 22–29.

[5] Zhang D, Li J, Gao Z, Wang L, Nan J. Thermal performance investigation of modified flat plate solar collector with dual-function. Applied Thermal Engineering 2016; 108: 1126–1135.

[6] Nikolić N, Lukić N. Theoretical and experimental investigation of the thermal performance of a double exposure flat-plate solar collector. Solar Energy 2015; 119: 100–113.

[7] Fan M, et al. A comparative study on the performance of liquid flat-plate solar collector with a new V-corrugated absorber. Energy Conversion and Management 2019; 184: 235–248.

[8] Jowzi M, Veysi F, Sadeghi G. Novel experimental approaches to investigate distribution of solar insolation around the tubes in evacuated tube solar collectors. Renewable Energy 2018; 127: 724–732.

[9] Xu L.-C, Liu Z-H, Li S-F, Shao Z-X, Xia N. Performance of solar mid-temperature evacuated tube collector for steam generation. Solar Energy 2019; 183: 162–172.

[10] Teles MPR, Ismail KAR, Arabkoohsar A. A new version of a low concentration evacuated tube solar collector: Optical and thermal investigation. Solar Energy 2019; 180: 324–339.

[11] Budihardjo I, Morrison GL. Performance of water-in-glass evacuated tube solar water heaters. Solar Energy 2009; 83: 49–56.

[12] John GA, Nidhi MJ. Design and simulation of parabolic dish collector for hot water generation. 2015.
Retrieved December 13, 2018 from http://troindia.in/journal/ijcesr/vol2iss9/20-24.pdf

[13] Alarcón JA, Hortúa JE, Lopez A. Design and construction of a solar collector parabolic dish for rural zones in Colombia. Tecciencia 2013; 7(14): 14-22.

[14] Moffat, R. J. Describing the uncertainties in experimental results. Experimental Thermal and Fluid Science 1988; 1(1): 3-17.

[15] Taylor JR. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, second ed., University Science Books, Sausalito, CA, 1997.