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Experimental Analysis of a Parabolic Trough Collector Performance Under Mediterranean Climate Conditions

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Abstract: In this study, a novel non-tracking parabolic trough collector (PTC) is developed and experimentally investigated under North Cyprus climate conditions for residential water heating applications. Within the study, the impact of solar radiation (SR) and water volumetric flow rate (VFR) on the system performance is evaluated based on the testing results. Experiments were performed in the first and third weeks of April in Famagusta, in which SR is limited due to the rain and cloudy sky. The system is tested with water VFRs of 15 L/h and 20 L/h. During the tests, collector inlet/outlet temperatures also water tank, and ambient temperatures were measured. Furthermore, the solar intensity was also measured and recorded. Average SR on PTC surface, during the testing with 15 L/h and 20 L/h, was determined as 654.5 W and 723.3 W respectively. Study results showed that the useful heat gain from PTC was 285.2 W and 233.7 W, for the same order of VFRs. Moreover, the average thermal efficiency of the system was found as 44% and 33% for the VFRs of 15 L/h and 20 L/h respectively.

Keywords: Water heating, solar energy, parabolic trough collector, experimental, thermal efficiency

Parabolik Bir Güneş Kollektörünün Akdeniz İklim Koşullarında Deneysel Olarak İncelenmesi

Öz: Bu çalışmada, konutlarda sıcak su üretimi amaçlı, hareketsiz tip parabolik kollektör geliştirilmiş ve Kuzey Kıbrıs iklim koşullarında deneysel olarak incelenmiştir. Çalışma kapsamında güneş ışınımı miktarının ve sirkülasyon suyu debisinin sistem performansına etkisi deneysel sonuçlardan faydalanarak analiz edilmiştir. Deneyler, bulut ve yağış etkisinin güneş ışınımı etkinliğini azalttığı Nisan ayının birinci ve üçüncü haftasında Gazi Magusa'da gerçekleştirilmiştir. Sistem, su hacimsel debisinin 15 L/s ve 20 L/s olduğu koşullarda test edilmiştir. Deneyler sırasında, kollektör giriş/çıkış sıcaklıkları, tanktaki su sıcaklığı ve çevre sıcaklığı ölçülmüştür. Ayrıca güneş ışınımı ölçülmüş ve kayıt edilmiştir. 15 L/h ve 20 L/h çalışma koşulları altında parabolik kollektör yüzeyindeki ortalama güneş ışınımı miktarı 654.5 W ve 723.3 W olarak belirlenmiştir. Çalışma sonuçlarına göre parabolik kollektörden elde edilen ortalama ısı kazancı aynı çalışma koşulları için 285.2 W ve 233.7 W olarak hesaplanmıştır. Buna göre, 15 L/h ve 20 L/h su hacimsel debilerinin kullanıldığı koşullar için parabolik kollektör ortalama ısıl verimi 44% ve 33% olarak hesaplanmıştır.

Anahtar Kelimeler: Su ısıtma, güneş enerjisi, parabolik kollektör, deneysel, ısıl verim

1. Introduction

In the current day, the majority of the global energy consumption is satisfied by fossil fuels [1]. In this context, the scarcity of fossil fuels, rising oil prices, and global warming are primary concerns of many world decision-makers. Due to the increase in world population, World Energy Outlook 2018 indicated that the global energy demand will increase nearly 30% until the year 2040 [2]. As a

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result of the rising energy demand, more fossil fuels will be burned, which could also considerably increase the release of greenhouse gases, such as CO_2, to the atmosphere [3]. The emission of CO_2 into the atmosphere could increase the global temperature that could result melting of icebergs and eventually could cause severe floods in low land areas. Based on a report from International Energy Agency 2018, energy-related CO_2 emissions have increased by 1.8% from 2017 to 2018 [4]. The diminution of fossil fuels and their unstable prices have influenced many researchers to investigate other sustainable resources including solar, wind, and biomass [5, 6]. Accordingly, many countries are hugely investing in new technologies to efficiently benefitting from such renewable sources [7].

As one of the key renewable energy technologies, solar sourced water heaters are commonly used to minimize the operating costs of auxiliary heaters in both domestic and industrial applications. In small countries like North Cyprus, heavy fuel is imported and used to generate electricity by using conventional fossil-sourced power plants. Consequently, residents are severing the higher costs of electricity due to the rising fuel prices in international markets. For this reason, many residential buildings have installed water heaters driven by solar energy, which can overcome the electric costs of auxiliary heaters.

Flat plate collectors are the prominent solution for space and water heating applications. Good thermal efficiency, availability of materials, manufacturability, easy installation, and low maintenance costs are promising advantages of flat plate collectors. Although flat plate collectors contribute energy savings for the long term, they also have drawbacks. Flat plate collector's efficiency drops dramatically during the winter time when hot water is most needed. This is due to the reason that the SR hits the absorber plate of the collector at a lower angle. The alternative way to enhance solar water heating (SWH) performance is to use concentrating solar collectors mainly Parabolic Trough Collector (PTC). PTC's absorber area is much smaller than the gross and aperture area of the collector, therefore it enables water heating even at low SR conditions through the concentration method. In that regard, recently, several studies have been performed on PTC systems.

Ktistis et al. investigated a PTC system integrated with concrete heat storage for industrial applications in Cyprus [8]. It is obtained that the developed system could store daily 107.3 kWh of thermal energy. In another research, Bernard et al. investigated the performance enhancement of PTC with the use of carbon nanotube fluid in comparison with water. Researchers found that the use of carbon nanotube fluid enhances the heat gain between 5.2-7.3% for different mass flow rates (MFR) [9]. Lamrani et al. numerically investigated a PTC system integrated with latent heat storage. Different phase change materials were investigated within the study. It is concluded that the system could provide a maximum water temperature of 85 °C and 63 °C for daytime and nighttime operation [10]. Soudani et al. investigated the performance of a PTC integrated with a thermochemical heat pump. According to the study results, for PTC length of 3m, in Algerian Sahara winter climate conditions, the system can produce 164.5 L/day hot water [11]. Donga et al. investigated the impact of receiver position error on thermal and optical efficiency in PTC systems. Researchers found that the collector thermal efficiency drops by 14% for the position error of 1.63% from the focal point [12]. Afsharpanah et al. numerically investigated the impact of using different types of twisted tapes in PTC systems for performance enhancement. Results demonstrated that utilizing dual square-cut twisted tapes provides a performance increase between 12-16% in comparison with plain tube absorber [13]. Balotaki et al. experimented a multifunctional collector for simultaneous water and air heating. The total collector efficiency was found between 58-74%, while individual water and air heating efficiency ranges were 43-19% and 31-45% respectively [14]. Bhusal et al. performed technical and economical investigations on a PTC using an evacuated tube absorber. Based on the study results, the developed collector provides a maximum thermal efficiency of 51% at 100 °C. Additionally, the thermal energy production cost of the collector was found as 2.9 cents/kWh [15]. Qui et al. performed experimental and numerical investigations on the impact of integrating different types of reflectors to flat plate collectors. Results revealed that flat-plate, parabolic, and polyline reflectors enable 19.8% 27.7%, and 40.3% increase of SR on collector surface respectively [16]. Haran and Venkataramaiah investigated a PTC with different absorber configurations and different working fluids. The highest efficiency is obtained with the use of copper absorber and CuO-water nanofluid at 68.1% [17]. Similarly, the impact of configuration and type of heat transfer fluid in stationary PTC systems is investigated by Barbosa et al. Average efficiency of PTC system integrated with concentrator was found in the range of 17.4-24.2% and 14.6-17.5% with the use of water and oil as working fluid, respectively [18]. Ercoskun et al. investigated double-grooved type PTC unit under Tarsus (Turkey) climate conditions. System had an aperture area and rim angle of 90 cm and 83° respectively. Study results showed that the efficiency of the system varies between 37.59-50.6%, where the average efficiency value was obtained as 43.03% [19]. In another study, Caglar and Talay theoretically investigate the impact of glass cover diameter also the impact of wall thickness, diameter and material of absorber tube on the PTC performance. It is found that glass cover diameter and absorber wall thickness do not have any major impact on PTC performance. However impact of absorber tube material and diameter were found significant [20].

As presented above, PTCs made up of a single large-scale parabola, mostly with sun-tracking systems, have been widely investigated in the literature. However, research on modular non-tracking PTC design, consisting of multiple small-sized parabolas for domestic water heating applications, is limited in the literature. In that regard, in the present study, an innovative design of small-sized stationary PTC is developed and tested under North Cyprus climate conditions. The outcomes of the presented study could contribute to the further development of efficient domestic SWH systems.

2. Methods

2.1. Proposed Design Configuration

The investigated system consists of an innovative non-tracking PTC, a well-insulated cylindrical tank for storing hot water, a circulation pump, and pipe connections as illustrated in Figure 1. During the system operation, water is pumped from the tank to the collector inlet and passes through the copper pipes which are attached at the focal point of the reflectors, and then circulates back to the tank. Water temperature increases between the inlet-outlet as it absorbs thermal energy from the PTC. The process will continue until the tank temperature comes to equilibrium with the PTC outlet temperature.

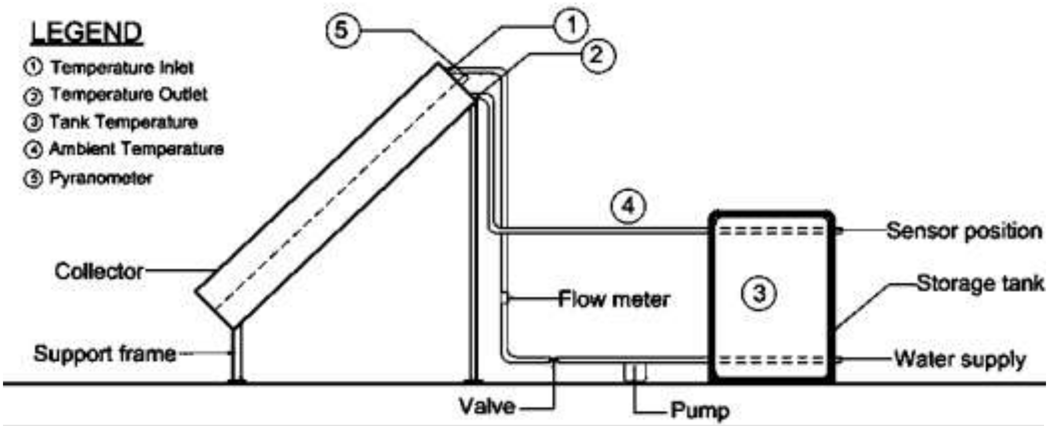

Figure 1. Schematic illustration of the investigated PTC based SWH system

Five parabolas with central receiver pipes are connected to produce the modular PTC. The total aperture width of the collector is 800 mm which makes each section of the collector have an aperture width of 160 mm and 1200 mm length. Based on the reflection index of different metal sheets, it has been chosen stainless steel which has 90% of the reflective index. Besides the high reflective index, stainless steel is available in the market and can easily be manufactured. For the manufacturing processes, a CNC machine was used to cut the desired dimension of the parabolic part of the collector because the accuracy of the design parameter is highly essential. After, rectangular metal sheets are prepared; a bending machine was used to curve the stainless steel sheet. This process must be done carefully and the reason is this, in concentrating collectors, the reflected SR from the reflector should hit and absorbed by the receiver tubes which are perfectly placed at the focal point of the reflector. If this is not the case, the concentration idea is lost and the efficiency of the system drops.

During the manufacturing process of the parabolic section, geometric concentration ratio and focal distance are the main parameters for the design of PTC. To calculate the dimension of the PTC, it is essential to consider the rim angle of the collector. The angle in between the y-axis and a line from the focus to the edge of the physical concentrator is known as the rim angle as is shown in Figure 2 [21]. In this study, the rim angle is taken as 90˚ [22] while the aperture width of each parabola is 160 mm.

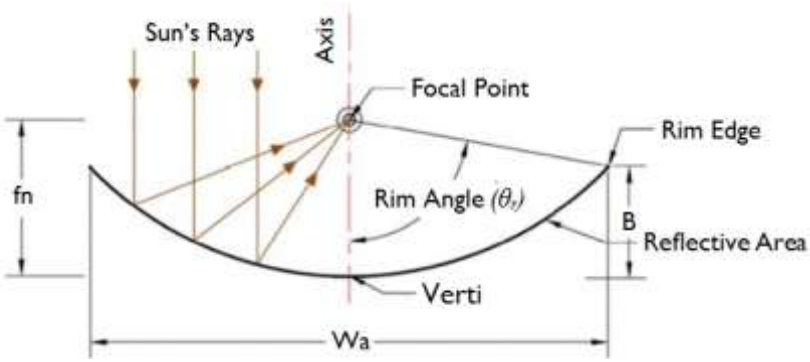

Figure 2: Cross Section of PTC [21]

The focal length of the system can be obtained [23] as follows;

$$f = \frac{W_a}{4.tan\left(\frac{\theta_r}{2}\right)} \tag{1}$$

Where W_a and θ_r illustrate the aperture width and rim angle respectively.

The geometric concentration ratio is the ratio of the receiver to that collector reflector area [24]. This expression can be written as:

$$\mathrm{C} = \frac{A_r}{A_c} \tag{2}$$

Figure 3a, b, and c show a 3D model of the parabolic section of the system's side, top and front views respectively. The model is designed by using SolidWorks software. The side and top views display the absorber tubes that are attached to the parabolic modulus. The front view shows both the header that is soldered and connected by the copper pipes and the exact location of the absorber tubes on the collector.

In the study, EN1057 type copper pipe is used as an absorber due to its effective thermal conductivity. Furthermore, it is coated with black paint for increasing the absorption of the incoming SR to the PTC surface. The diameter of the absorber tubes also the dimensions of other parameters of PTC and storage tank are displayed in Table 1.

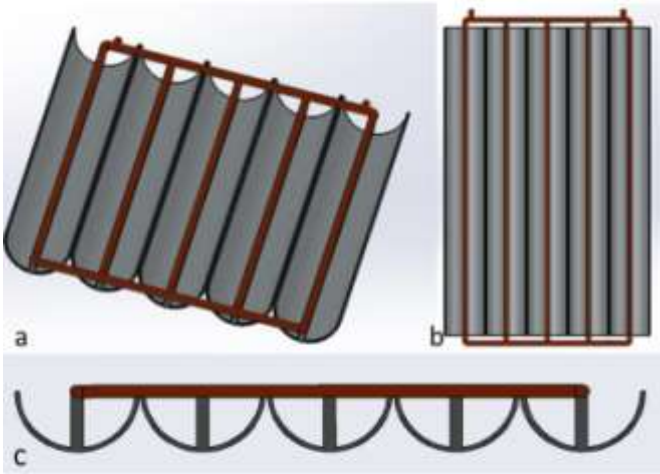

Figure 3. Proposed design: a) Side view b) Top view c) Front view

Table 1. PTC Specifications

Item	Value
Total aperture width ($W_{a,t}$)	5x0.16 m= 0.8 m
Collector length (L)	1.2 m
Absorber diameter (D)	0.015 m
Rim angle (θ_r)	90˚
Concentrating ratio (C)	5x3= 15
Focal distance (f)	0.04 m
Height of parabola (B)	0.04 m
Glass transmittance	0.9
Reflector reflectance	0.9
Collector material	Stainless steel
Tank material	Galvanized steel
Tank insulation material	Glass wool
Tank storage	50 L

After designing the parabolic section and selecting a good absorber tube and a glass cover, the system needs to be well-insulated to minimize heat loss. An aluminum sheet of 1300 mm length, 860 mm width, and 180 mm height is used as a collector casing. Glass wool material is used to insulate the system. It is placed in between the parabolic reflectors and back casing of the collector. Furthermore, the collector is well air-tightened. Schematic drawing and the frontal picture of the manufactured PTC are illustrated in Figures 4a and 4b respectively.

In investigated system, a 50 L hot water tank was utilized to store thermal energy gained by PTC. The storage tank is insulated with 20 mm thick glass wool and wrapped with a metal sheet to avoid heat losses. The bottom and top surfaces of the tank are also insulated.

PTC inlet (T_1) and exit (T_2) temperatures, tank temperature (T_3), and ambient temperature (T_4) are recorded during the tests. For that purpose, PCE-T 390 temperature data logger with K-type thermocouples having an accuracy of ±0.5 °C were utilized [25]. All temperature measurement points are illustrated in Figure 1.

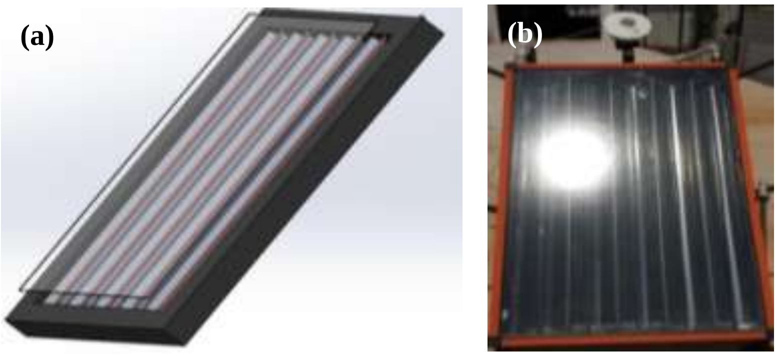

Figure 4. a) Schematic view and b) Frontal picture of the assembled PTC

For conducting the experiments, it is essential to have accurate SR data. To measure the instantaneous SR during the experiments, a CM22 type pyranometer is used. The pyranometer is attached on the top side of the PTC, parallel to the absorber surface. The measurements were taken in volts and then converted to power per meter square.

2.2. Experimental Procedure

The experiments were conducted in the Mechanical Engineering Department of EMU which is located in Famagusta, TRNC. The latitude and the longitude of the city are 35.125° N and 33.95° E respectively. The collector was tilted 45° to minimize the incident angle [26]. Two different VFRs were tested over six days in April.

The applied experimental testing methodology is given as follows:

- The tank was refilled before every experiment.
- Data logger and pyranometer were installed in the system and allowed to stabilize.
- The experiment is started at 9:00 am on each day of testing.
- The temperature sensors are connected to different positions of the system.
- The SR was recorded every 20 mins while the temperature reading at T_1, T_2, T_3, and T_4 were recorded every 1 min and later was taken on an average of 20 min.
- During the study, three consecutive tests with low (15 L/h) and high (20 L/h) VFRs were performed.
- The duration of each experiment was 7 hours.

2.3. Thermodynamic Analysis

The main aim of the study was to design, test, and thermodynamically analyze a PTC system performance based on the experimental data. The main parameters investigated in the study are defined in this section.

The solar power that hits the collector surface (W) is obtained via Equation 3;

$$Q_r = I.A \tag{3}$$

Where *I* and *A* are instantaneous SR and collector aperture area respectively.

The absorbed energy (Q_a) by the receiver is the transmittance-absorptance product ($\tau\alpha$) and the intensity of the SR on the surface of PTC [27]:

$$Q_a = I.(\tau\alpha).A_c \tag{4}$$

The useful heat (Q_u) that is transmitted to the fluid which is water in our case is calculated numerically as follows:

$$Q_u = \rho.\dot{V}.c_p.(T_{outcoll} - T_{incoll}) \tag{5}$$

Where ρ, $\dot{V}$ and c_p represents the density, VFR, and specific heat of the fluid. Here multiplication of density and VFR gives the MFR ($\dot{m}$) of circulation water.

The thermal efficiency of PTC is the most important factor in this study. Thermal efficiency (η) is the useful energy gain of fluid divided by the product of the solar intensity (I) and the collector area (A):

$$\eta = \frac{Q_u}{I.A_c} \tag{6}$$

The accuracy of the experimental performance of the PTC can be proved by applying uncertainty analysis. Measurement uncertainties and the sensitivity of the equipment are the two main sources of error. Two different types of sensors were used in this experiment. One type of sensor is to measure T_{incoll} and $T_{outcoll}$ while the other type of sensor is used to measure the solar irradiance (I). Then, the general form of uncertainty w_R is expressed [28, 29]:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \left(\frac{\partial R}{\partial x_3}w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_4}w_4\right)^2\right]^{1/2} \tag{7}$$

Equation 6 is used to evaluate the system efficiency (η). Efficiency is the function of temperature T, $\dot{V}$ and I. Those parameters were measured during the experiment.

$$\eta = f\left(T_{outcoll}, T_{incoll}, \dot{V}, I\right) \tag{8}$$

Total uncertainty for overall system efficiency can be expressed as;

$$w_R = \left[\left(\frac{\partial \eta}{\partial T_{outcoll}}w_T\right)^2 + \left(\frac{\partial \eta}{\partial T_{incoll}}w_T\right)^2 + \left(\frac{\partial \eta}{\partial \dot{V}}w_{\dot{V}}\right)^2 + \left(\frac{\partial \eta}{\partial I}w_I\right)^2\right]^{1/2} \tag{9}$$

Based on equations 8-9, the uncertainty of the PCT system that is affecting the thermal efficiency is computed. The total uncertainty (σ) of the efficiency was found 2.94%. The experimental device accuracies and their ranges of operation are displayed in Table 2 below.

Table 2. Accuracies and ranges of measurement equipment

Equipment	Parameters	Accuracy	Range
Data logger	Temperature	±0.5 °C	-50 ÷ 100
CM22 Pyranometer	SR	± 20W/m^2	0 ÷ 4000 W/m^2
Flowmeter	Flow rate	±0.8 L/h	10-100 L/h

3. Results and Discussion

Tests have been conducted for six days in April 2019. The tests were performed under two different water VFRs of 15 L/h and 20 L/h. During the experiments, temperature variations of water across the solar collector and water temperature change inside the tank were measured. Additionally, instantaneous SR was also recorded throughout the testing period. According to the obtained experimental data, solar heat gain by the PTC, amount of heat stored in the tank, and system efficiency were determined.

3.1. Solar Intensity Variations

Figures 5-6 show the total radiation that is striking on the surface of PTC during the tests with 15 L/h and 20 L/h respectively. It is obtained by multiplying the available SR and the total aperture area of PTC as presented in Equation 3.

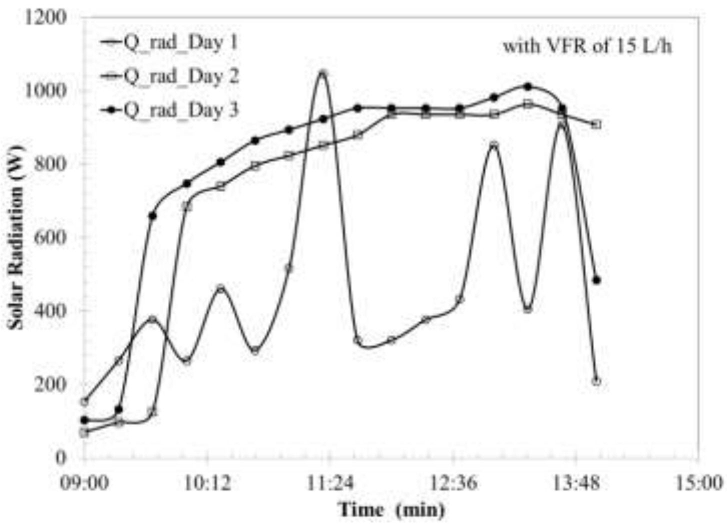

Figure 5. Total SR on PTC surface during testing with VFR of 15 L/h

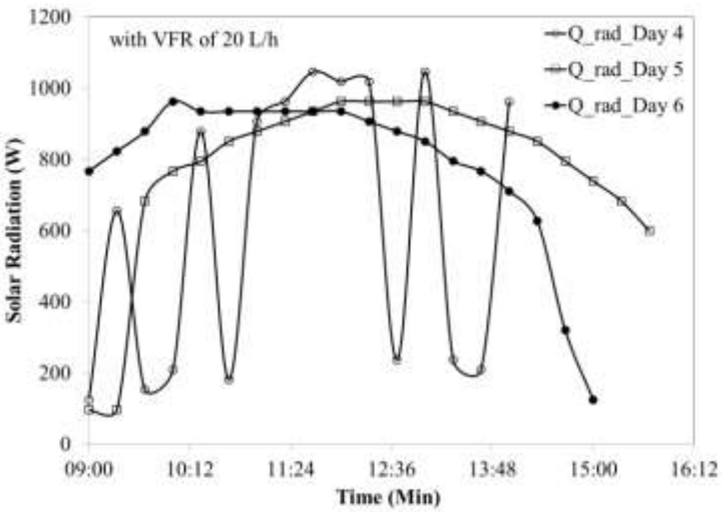

Figure 6. Total SR on PTC surface during testing with VFR of 20 L/h

As seen from the figures, on Day 1 and Day 4, a considerable fluctuation was observed due to the partial cloud effect, which was affecting the available SR on the earth's surface. Day 2 and Day 3 in Figure 5 indicate the dramatic increase of the SR from 9:30 am -10:30 am which also shows a gradual increase between 10:30-12:30. The main reason for this change is that, as the incident angle decreases, the SR increases and vice versa. The overall average of SR of the first three days of experimentation with VFR of 15 L/h is found 654.51 W, while the remaining three days with a VFR of 20 L/h is determined as 723.31 W.

3.2. Temperature variations

During the experiments, it was proposed to investigate the PTC performance at low and high VFR's. The low VFR is determined by setting the pump to minimum VFR and the high VFR is determined by setting the pump to maximum flow rate. These flow rates were corresponding to 15 L/h and 20 L/h. Three repeating tests were performed with VFR of 15 L/h and 20 L/h. In this section, single day clear sky testing results with 15 L/h and 20 L/h are provided. Overall testing results of all testing days are presented in Table 3.

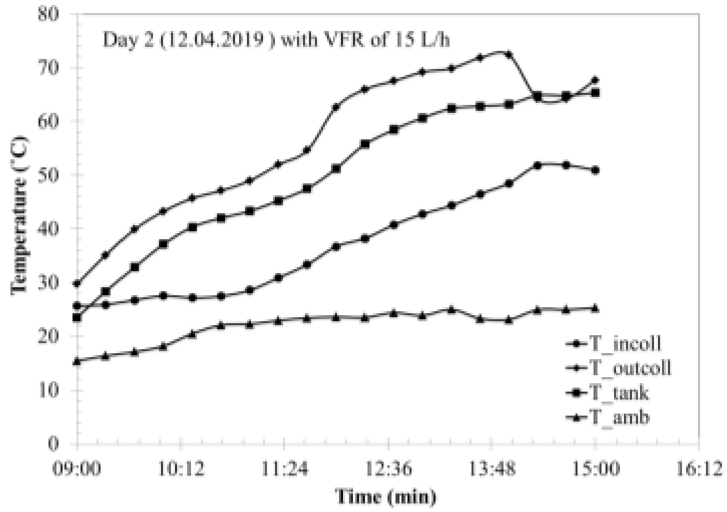

Figure 7. Temperature variation of water on testing date of 12.04.19

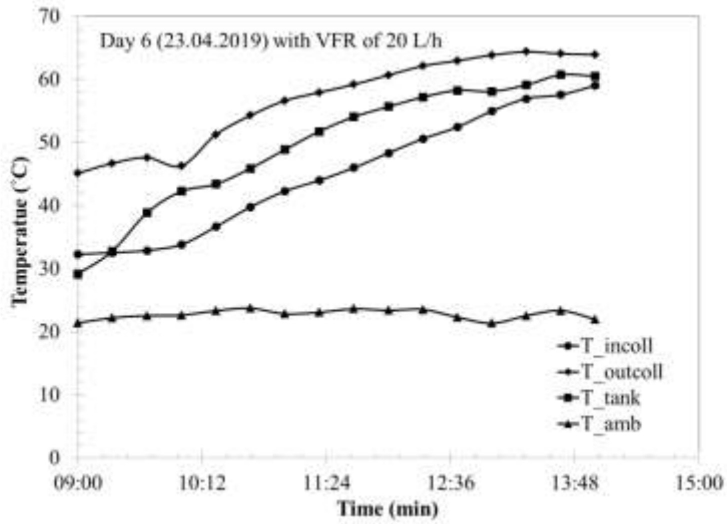

Figure 8. Temperature variation of water on testing date of 23.04.19

The temperature variation of water across the PTC also tank and ambient temperatures during the experiments with VFR of 15 L/h and 20 L/h were presented in Figure 7 and Figure 8 respectively. The graphs clearly illustrate a linearly increasing pattern. This is due to the reason that those testing days were clear sky from 9:30 to 13:00. With VFR of 15 L/h, maximum collector outlet temperature and tank temperature were reached to 72.9 °C and 65.0 °C respectively (Figure 8). The daily average of collector outlet and tank temperature on that day were also 56.4 °C and 49.9 °C.

With VFR of 20 L/h, maximum collector outlet and tank temperatures were achieved as 64.1 °C and 61.9 °C. Accordingly, average collector outlet and tank temperatures were determined as 56.6 °C and 49.7 °C respectively. Results showed that, with VFR of 15 L/h, the peak collector outlet and tank temperatures were higher when compared to VFR of 20 L/h. However in terms of achieved daily average temperatures, there was no substantial difference between the two different flow rates.

It is also found that the PTC inlet temperature is always less than the water temperature inside the tank. This is due to the stratification of fluid. That is to say that the fluid in the tank is not fully mixed so the tank's upper part has a higher temperature than the bottom part of the tank.

3.3. Energy Gain Variations

Figures 9-10 show the useful energy gain of the PTC with two different VFRs. The energy gain of both Day 1 and Day 4 has the minimum value at 210.85 W and 210.0 W respectively.

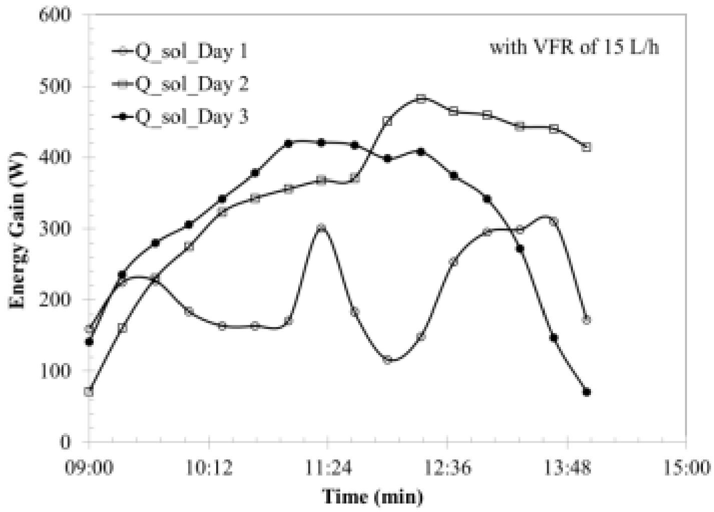

Figure 9. Energy gain with VFR of 15 L/h

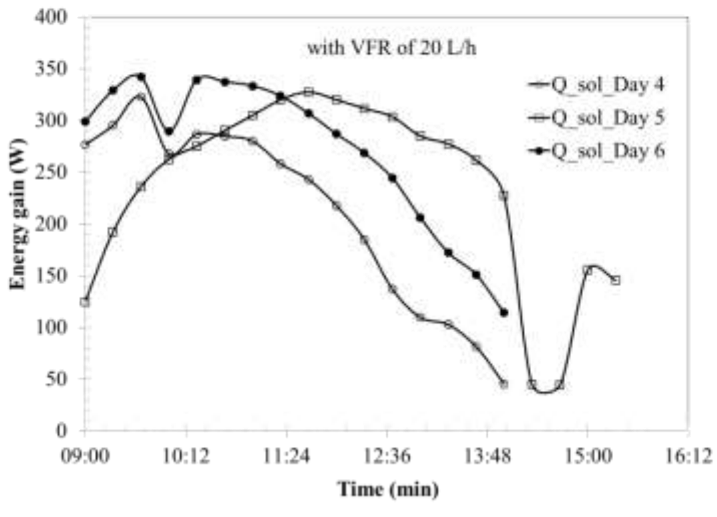

Figure 10. Energy gain with VFR of 20 L/h

These days had relatively lower SR (Figures 5-6). On the other hand in Day 2 and maximum energy gains of 335.42 W and 309.4 W were obtained, while the energy gain in Day 6 was 271.37 W.

3.4. Thermal Efficiency Variations

A key parameter for performance evaluation of PTC systems is thermal efficiency. The efficiency variations of the experimented days are displayed in Figures 11-12. The daily efficiencies of the PTC with 15 L/h were found 47%, 45%, and 40%, while the efficiency of the remaining three days with VFR of 20 L/h were 34%, 30%, and 34%.

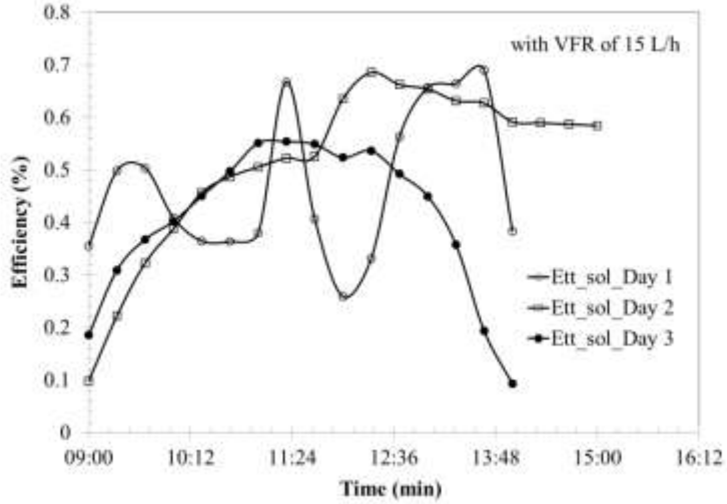

Figure 11. Thermal efficiency for VFR of 15L/h

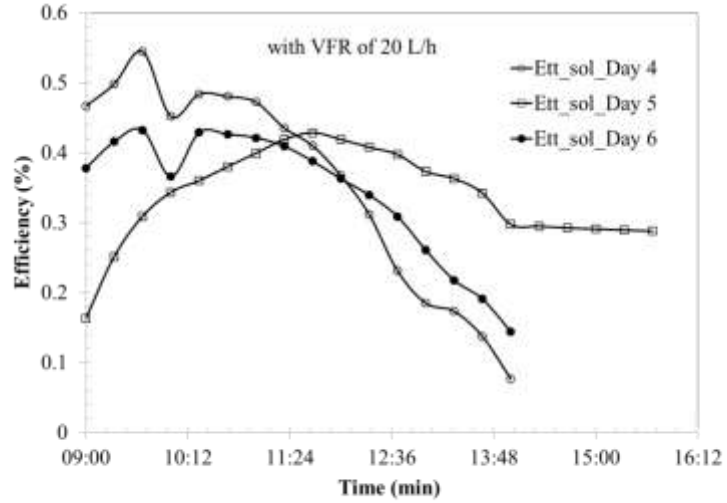

Figure 12: Thermal efficiency for VFR of 20L/h

The efficiency of the PTC system also depends on the incoming SR to its surface, incident angle, reflective index of the reflector, type of absorber tube, and collector area. The overall average efficiency during the test period for VFR of 15 L/h and 20 L/h were 44% and 33%. Table 3 displays the summary of the experimental results. As seen from the table, the highest efficiency is obtained with the lowest SR (449.9 W) and lower VFR (15 L/h) on Day 1. On the other hand, the lowest efficiency is obtained with a high average SR (763.5 W) and high VFR (20 L/h). Results showed that the PTC performance is indirectly proportional to the VFR and SR.

Table 3. Summary of the experimental results

Mass (kg/s)	Testing days	T_{incoll} (˚C)	$T_{outcoll}$ (˚C)	T_{tank} (˚C)	T_{amb} (˚C)	Q_u (W)	Q_r (W)	η_{th} (%)
15 L/h	09.4.19	33.71	45.79	39.72	21.12	210.84	449.92	47
	12.4.19	37.16	56.42	49.99	22.10	335.42	740.89	45
	13.4.19	34.98	52.75	46.49	23.20	309.45	772.72	40
Average		**35.28**	**51.65**	**42.51**	**22.14**	**285.24**	**654.51**	**44**
20L/h	18.4.19	38.46	47.58	43.03	19.325	210.0	615.59	34
	22.4.19	46.82	56.27	54.01	21.78	219.67	763.51	30
	23.4.19	45.00	56.67	49.77	22.73	271.39	790.82	34
Average		**43.43**	**53.51**	**48.94**	**22.28**	**233.69**	**723.31**	**33**

4. Conclusion

Low/medium temperature non-tracking PTC is considered a promising technology that could be utilized for domestic water and space heating applications as an alternative to conventional flat plate collectors. Accordingly, this study aims experimental investigation of a PTC performance under North Cyprus climate conditions.

Within the study, two different VFRs have been tested on six different days in April. It is obtained that the average SR of those days (on collector surface) ranged between 449.9 –790.8 W. The average useful heat gain of PTC was 285.24 W for the VFR of 15 L/h and 233.69 W for the VFR of 20 L/h. The average PTC outlet temperatures were also determined as 51.65 ˚C (15 L/h) and 53.51 ˚C (20 L/h). Furthermore, the overall PTC efficiency with 15 L/h and 20 L/h was found 44% and 33% respectively. Compared to the previous studies in the literature, obtained efficiencies were found slightly lower than expected. Possible reasons of this could be slight shifting of absorbers from the focal point due to the shrinkage of metal during the manufacturing of PCT. In addition, there could be some losses do to the non-tracking feature of the PTC. Despite the system is designed with multiple small parabolas to eliminate the tracking requirement, solar energy could not be totally focused on absorber at some periods of the day. Further studies could be performed to optimize the diameter of parabolas and absorber pipe for enhancing the efficiency. Also system could be tested with wider range of VFR to investigate the impact of this parameter in more detail.

Authors' Contributions

MYA and DA designed and carried out the work. They are wrote up the article. Both authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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