Design and Performance Analysis of a Novel Concentrating Solar Water Heater for Building Applications

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ABSTRACT

Flat plate solar collectors are widely used in residential applications. However, the collector's efficiency dramatically drops during the winter time when the hot water is mostly needed. This is due to the reason that the solar radiation hits the absorber plate collector at a lower angle.

This study aims to investigate a novel low/medium temperature non-tracking Parabolic Trough Collector (PTC). Such system is considered as a good alternative option to provide hot water and space heating compared to the conventional flat plate and evacuated tube collectors. Within the scope of this study, several related variables such as solar radiation, heat gain of the system and thermal efficiencies of PTC are tested under Mediterranean climate and compared to the previous studies.

The investigated system consists of a low temperature PTC collector, storage tank, flow meter and circulation pump. Experimental work has been carried out in the first and the third week of April in Famagusta during the early spring season where solar radiation was limited due to the rain and cloudy sky. Water is circulated between two storage tank and solar collector with two different flow rates which are 15 L/h and 20 L/h. Temperature sensors are installed tin the system to measure inlet and outlet temperatures of the collector as well as the tank and ambient temperatures. Furthermore, the intensity of the solar radiation is measured by the pyrometer and data is stored. According to the results, the overall thermal efficiency of the system with 15 L/h and 20 L/h was found 44% and 33% respectively. Furthermore, useful energy gain of the PTC is obtained as 285.24 W and 233.69 W, while the average

solar radiation is about 654.51 W and 723.31 W for the flow rates of 15 L/h and 20 L/h respectively.

Keywords: Solar Energy, Domestic Hot water, Water Heating, Parabolic Trough Collector, Flat Plate Collector, Evacuated Tube Collector.

ÖZ

Düz plakalı güneş kollektörleri konut uygulamalarında yaygın olarak kullanılmaktadır. Ancak, kollektörün verimliliği, sıcak suya en çok ihtiyaç duyulan kış mevsiminde önemli miktarda düşüş gösterir. Bu durum, güneş ışınımının düz plakalı kollektöre daha düşük bir açıda gelmesinden ve dolayısıyla absorbe edilebilen enerjinin azalmasından kaynaklanır.

Bu çalışma, düşük / orta sıcaklık aralığında çalışan yeni bir parabolik kollektör (PTC) sistemini araştırmayı amaçlamaktadır. İncelenen sistem, geleneksel düz plakalı ve vakum tüp kollektörlerine alternatif bir sıcak su ve mahal ısıtma sistemi olarak hedeflenmiştir. Bu çalışma kapsamında, güneş ışınımı, sistemin ısı kazanımı ve parabolik kollektörün ısıl verimi gibi çeşitli değişkenler, Akdeniz iklim koşullarında test edilmiş ve önceki çalışmalarla karşılaştırılmıştır.

İncelenen sistem düşük/orta sıcaklıkta çalışan düz plakalı güneş kollektörü, sıcak su depolama tankı, debimetre ve sirkülasyon pompasından oluşmaktadır. Deneysel çalışmalar, Nisan ayının ilk ve üçüncü haftasında, Gazimağusa'da (Kuzey Kıbrıs), yağmur ve bulutlu gökyüzü nedeniyle güneş ışınlarının sınırlı kaldığı dönemlerde gerçekleştirilmiştir. Deneysel çalışmada, 15 L/saat ve 20 L/saat olmak üzere, sistem iki farklı su sirkülasyon debisinde test edilmiştir. Bu yolla, su sirkülasyon debisinin sistem performansı üzerindeki etkisinin incelenmesi amaçlanmıştır. Sıcaklık sensörleri, kolektörün giriş ve çıkış sıcaklıklarını, ayrıca tank ve ortam sıcaklıklarını ölçmek için sisteme entegre edilmiştir. Ayrıca, güneş ışınımı yoğunluğu, güneş ışınımı ölçüm cihazı ile deneyler sırasında ölçülmüş ve kaydedilmiştir. Elde edilen

sonuçlara göre, sistemin ortalama ısıl verimi 15 L/saat ve 20 L/saat çalışma debileri için sırasıyla 44% ve 33% olarak hesaplanmıştır. Ayrıca, aynı çalışma debileri için, parabolik güneş kollektörünün faydalı ısıl enerji kazancı sırasıyla 285.24 W ve 233.69 W olarak elde edilirken, ortalama güneş ışınımı 15 L/s ve 20 L/s debileri için sırasıyla 654.51 W ve 723.31 W olarak ölçülmüştür.

Anahtar kelimeler: Güneş Enerjisi, Kullanım Sıcak Suyu, Su Isıtma, Parabolik Solar Kollektör, Düz Plakalı Solar Kollektör, Vakup Tüp Kollektör

To My Family

I thank you fo your love and support for my journey

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A_c [m^2]	Collector Area
Al_2O_3	Aluminum Oxide
A_r [m^2]	Receiver Area
C [-]	Concentration Ratio
CNC	Computer Numerical Control
C_p [kJ/kg.K]	Specific Heat Capacity of Water
CSC	Concentrating Solar Collectors
CuO	Copper Oxide
DHW	Domestic Hot Water
ETC	Evacuated Tube Collector
F [m]	Focal Length
FPC	Flat Plate Collector
HWST	Hot Water Storage Tank
I [w/m2]	Solar Radiation Intensity
LFR	Linear Fresnel Reflector
LPM	Litter Per Minute
$\dot{M}$ [kg/s]	Mass Flow Rate
N [-]	Number of Glass Cover
PSD	Parabolic Solar Dish
PTC	Parabolic Trough Collector
PVC	Polyvinyl Chloride
Q_o [W]	Heat Loss
Q_r [W]	Energy on the Collector Surface

Q_u [W]	Absorber Solar Energy
Q_u [W]	Useful Heat
SiO_2	Silicon Dioxide
T [˚C]	Temperature
T_amb	Ambient Temperature
T_incoll	Collector Inlet Temperature
T_outcoll	Collector Outlet Temperature
T_tank	Tank Temperature
TiO_2	Aluminum Oxide
W_a [m]	Aperture Width
WBS	Work Breakdown Structure
WO_3	Tungsten Trioxide
α [-]	Absorptivity
β [°]	Collector Tilted Angle
ε [-]	Emittance
η [%]	Efficiency
σ [%]	Total Uncertainty
τ [-]	Transmissivity
ω [-]	Uncertainty
Θ_r [-]	Rim Angle

Chapter 1

INTRODUCTION

1.1 Overview

Most of the world's energy is generated from the fossil sourced fuels. 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 of world population, World Energy Outlook 2018 indicated that the global energy demand will increase by more than 25% until the year of 2040 [1]. As a 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. The emission of CO_2 to the atmosphere will causing global temperature increase 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, CO_2 emission has increased by 1.7% from 2017 to 2018 [2].

The diminution of fossil fuels and their unstable prices have influenced many researchers to investigate other sustainable energy alternatives. Renewable energies such as solar, wind hydro-electric power and biomass are considered as better alternatives those are highly available and harmless to the environment. Accordingly, many cooperation and developing countries are hugely investing on technologies for effective utilization of such renewable source.

1.2 The Significance of the Study

In the last decades, solar water heating systems have been widely used in different parts of the world 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 plant. Consequently, residents are severing the higher costs of the electricity due to the rising fuel prices in international markets. For this reason many residential buildings have installed solar water heating systems which can overcome the electric costs of auxiliary heaters.

Flat plate collectors are the prominent solution for domestic hot water and heating applications. Good thermal efficiency, availability of materials, manufacturability, easy installment and low maintenance costs are promising advantages of the flat plate collectors. Although, flat plate collectors have contributed energy savings for long term, they also have drawbacks. Flat plate collector's efficiency dramatically drops during the winter time when the hot water is mostly needed. This is due to the reason that the solar radiation hits the absorber plate collector at a lower angle.

The alternative way to improve the performance of solar water heating 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 and heat is transferred directly to the working fluid. The concentrating collectors need a constant tracking system for incoming sun rays. Higher costs and geometric complexity caused by tracking systems have limited the usage of PTC systems. Such systems are mostly used in high temperature applications such as generation of superheated steam in solar thermal power plants.

In the last decade, low temperature PTC, which is a combination of FPC and high temperature PTC have been widely researched. This collector is basically consisting of multiple small scale concentrators on a flat surface and concentrates the solar radiation on to the absorber pipes to heat the water. As the aperture area of the concentrators is small, such collector type could be used without tracking the sun. Additionally, as the solar energy is concentrated to the pipe surface, it could provide higher sensible temperature increase of water at low solar radiation conditions when compared to FPC. Considering that the FPC's are widely used in buildings for water heating and they have limited utility in winter, new effective technologies to replace this water heating system could provide significant advantages such as cost savings and reduced fossil fuel usage. Accordingly, the purpose of this study is to design, develop and test a prototype low temperature PTC under Cyprus climate conditions. The outcomes of the presented research could considerably contribute to the development of low-temperature PTC systems for wide usage in building water heating applications.

1.3 Objectives

This study aims investigating a low temperature operating system of PTC for domestic hot water applications. The objectives of this study can be classified as follows:

- To design and develop a Parabolic Trough Collector.
- To perform experimental investigation on the developed prototype without a tracking system.

- To perform thermodynamic analysis on the experimental collector for the spring period operation under climate conditions of North Cyprus.
- To analyze the effect of mass flow rate of working fluid and incident solar radiation on the investigated collector performance.

1.4 Novelty of the Study

The performance of flat plate collectors decreases during the winter period therefore auxiliary power supply is needed to heat the water to the desired temperature level. Especially during peak hours, the price of electricity per kWh doubles which results a huge economic impact to the customers [3]. To overcome this problem, a specially designed low temperature operating PTC system is to be investigated. This system is non-tracking system which providing considerable temperature increase of water despite the radiation is not optimally striking on the collector. This improves the heat gain of the collector which enhances the thermal efficiency of this system even at the times when solar radiation is weak. It is also worthy to mention that no similar collector design has been investigated in the literature before.

1.5 Limitation of the Study

- The study will not cover a numerical investigation of the investigated PTC.
- Tracking system will not be used in this study.
- The study focuses on the thermal efficiency of the system during the winter spring period only. That means PTC performance in others seasons will not be investigated this study.
- Overall heat transfer coefficient will not be investigated in this study.

1.6 Organization of the Study

The current study is organized into 5 chapters;

- Chapter 1 covers the introduction, significance of the study, objectives, novelty of the study and the limitations.
- Chapter 2 presents the literature review and background research related with the performed study. The summary of the published researchs are illustared in Table 1.
- Chapter 3 is about design and development of the PTC system. Materials, relevent design parameters and thermodynamic analysis methodology also presented.
- Chapter 4 is about the experimental study of the system. Obtained experimental results and calculated performance parameters such as heat gain and collector efficiency are also presented. Furthermore, some relevant graphs are illustrated in this chapter to compare the obtained results with the results achieved in previous studies.
- Chapter 5 presents the key results obtained within the study. Recommendations and future work are also included in this chapter.

1.7 Work Breakdown Structure (WBS)

In Figure 1 below illustrates the breakdown structure of this research. The type of the collector investigated is PTC. Within the study; initially PTC design was carried out. Later on material selection and manufacturing stages of PTC is completed. In the following part of the study, experimental investigations on PTC were performed and thermodynamic analyses of the results were carried out. Finally based on the obtained outcomes, conclusions were drawn.

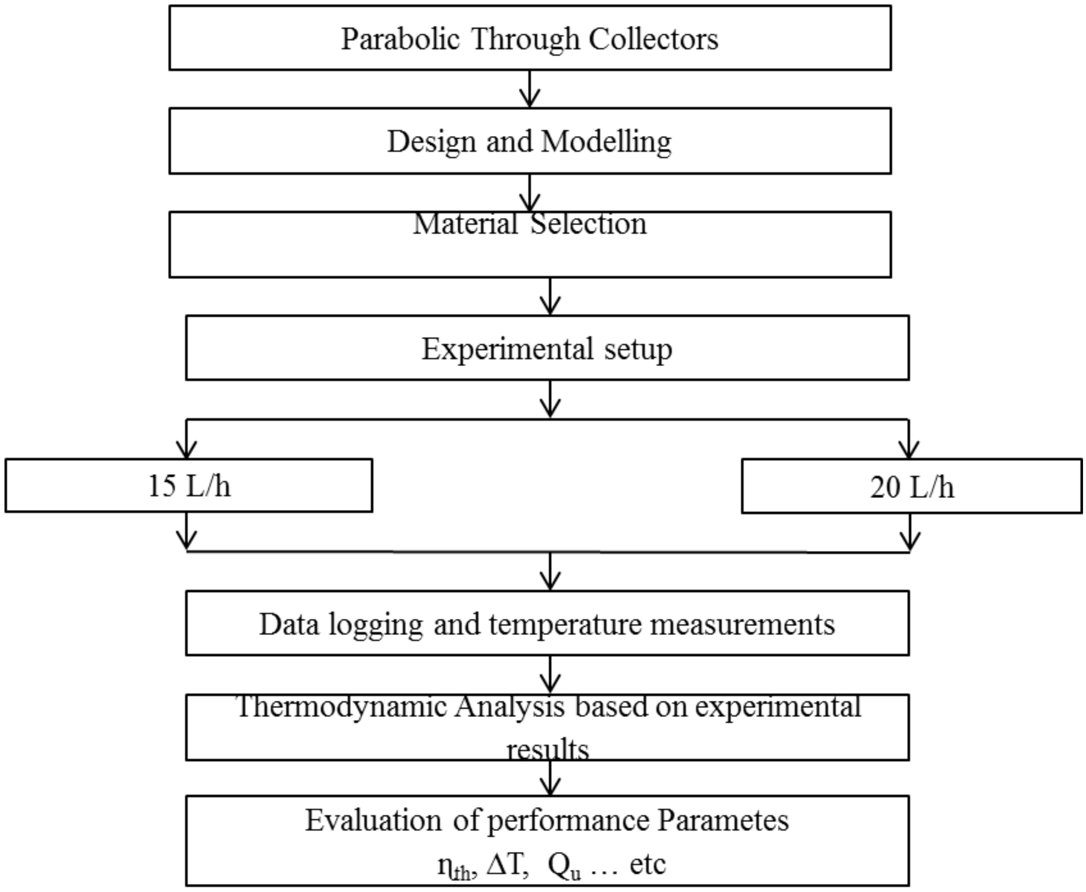

Figure 1: Work Breakdown Structure

Chapter 2

LITERATURE REVIEW

2.1 Solar Collectors

Solar collectors are special heat exchangers that convert the solar radiation into useful thermal energy. These systems are also the most widely used technology for solar thermal energy utilization. Based on the working principle, solar collectors can be classified in to two main categories which are concentrating and non-concentrating. The Figure 2 illustrates the classification of solar collectors. In below section, main categories and sub-categories of solar collectors are briefly discussed.

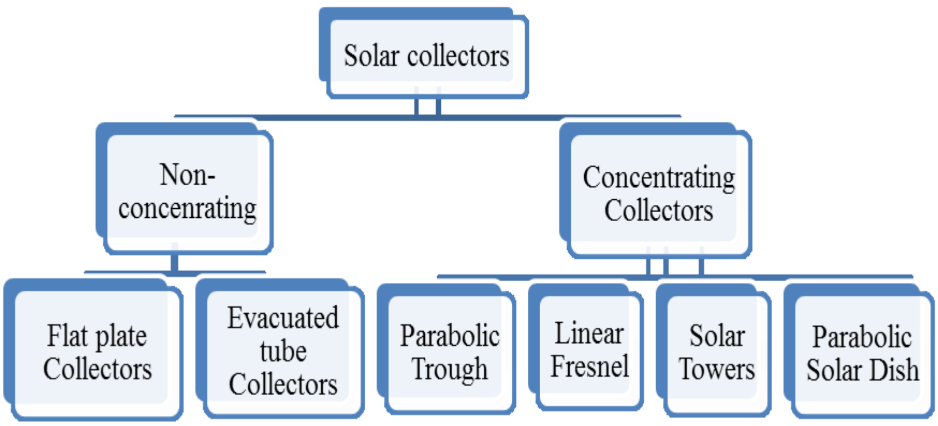

Figure 2: Types of Solar Collectors

2.1.1 Non-Concentrating Collectors

The non-concentrating solar collectors have flat and evacuated tubular absorber plates that are coated with a black color to absorb more radiation. This radiation is converted into heat and transferred through working fluid [4].The tracking systems are not needed in non-concentrating systems because the collectors can absorb both beam and diffuse radiations [5]. Flat Plate Collectors (FPC) and Evacuated Tube Collectors (ETC) are the main types of non-concentrating collectors and they will be discussed briefly.

FPC is special type of heat exchanger that converts solar radiant energy to heat. FPC is made up of absorber plate, working fluid, casing and transparent glass envelopes and working fluid. Each of these components have their own function. For the last 20 years, absorber plates have been made from copper sheets for higher conductivity purposes. The copper sheets have been replaced by aluminum due its lower costs [6]. To improve the efficiency of FPC, different types of coating is applied on the surface of the absorber plate [7]–[9].

Figure 3 illustrates flat plate collector. During the operation, A total solar radiation hits the glass cover of the collector. The aim of this cover is to minimize the convection heat losses from the collector absorber plate. Glazing materials are commonly used as result of the low iron glass fabrication. The glass can transmit about 90% of incoming solar radiation at normal incident angle. [5]

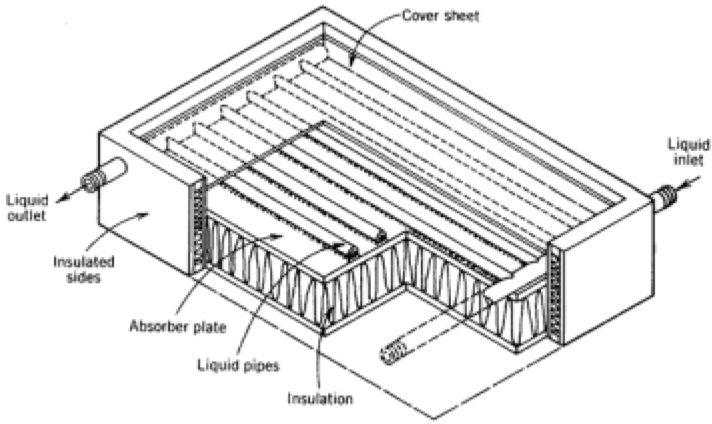

Figure 3: Schematic Diagram of a Flat Plate Collector

Evacuated Tube Collectors (ETC) is non-concentrating solar collectors which absorbs total radiation like FPC collectors. The main components of ETC are vacuum-sealed tubes where absorber surface is positioned into the inner glass tube. In comparison with FPC, the air between absorber and glass cover is removed so that the convection heat losses are eliminated [10].

A fused two-layered glass evacuated tube is shown in Figure 4. As seen, on the outer surface of the absorber tube, selective absorbing coating is deposited. The air between two glass tubes is removed to create vacuum. As a result of this vacuum, thermal losses become minimal due to lack of conduction and convection heat losses [11].

The non-concentrating system is mass-produced due to the low manufacturing costs, low temperature working application and no requirement for sun tracking mechanism [12][13].

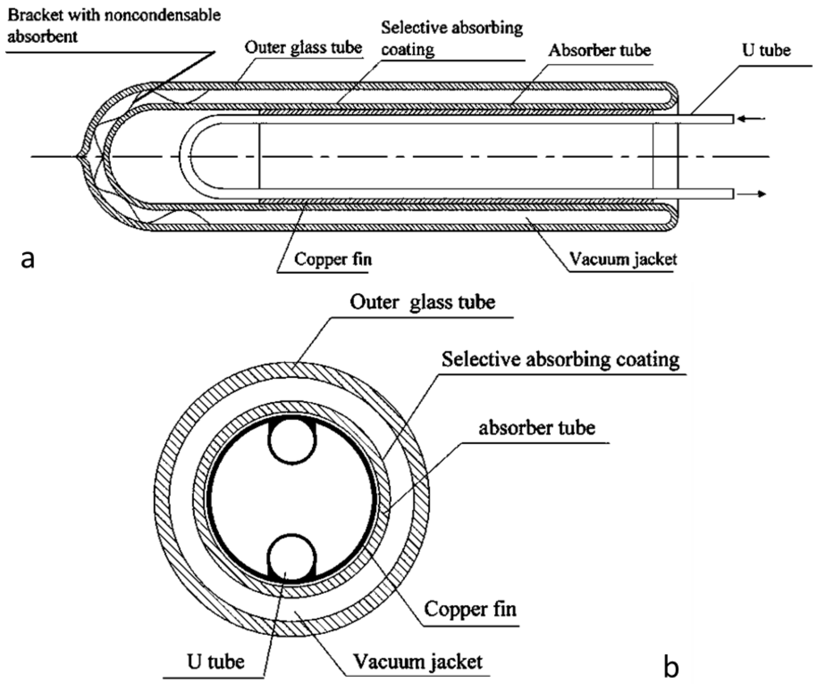

Figure 4: Evacuated Tube Collector a) Glass Evacuated Tube; b) Cross-section [11]

2.1.2 Concentrating Collectors

Concentrating Solar Collectors (CSC) have ability to operate at higher temperature levels compared to the non-concentrating solar collectors [14],[15]. CSC redirects the solar radiation from a reflective surface on to the receiver which is placed in a focal point or in a line [16][17]. The most commonly used CSC technologies are parabolic trough collectors (PTCs), linear Fresnel reflectors, solar towers and Parabolic Solar dish (PSD).

The receiver tube absorbs the reflected solar irradiation from the parabolas which is known as PTC. The location of the absorber tube should be designed carefully and aligned with the focal length of the parabolic collector. Working fluid in the receiver absorbs energy and circulated across a well-insulated heat storage tank. The PTC technology is one of the most widely applied systems for higher temperature applications. [18]. PTC has several types, which are illustrated in the Figure 5a.

Linear Fresnel Reflector (LFR) is linear concentrating collectors, which are consists of discrete mirrors those are close to the ground. The reflected solar radiation is absorbed by the receiver that is above the mirror level. Secondary absorber is attached at the top of absorber tube which reduces the thermal losses. LFR have single axis tracking system which enhances the efficiency of the system because the solar radiation is time dependent [19]. Scheme of Lear Fresnel Reflectors are shown in Figure 5b.

Solar Tower Collectors (STC) [20], [21] are the large individually tracking mirrors known as heliostats used to concentrate solar radiation on to a central receiver mounted on the top of a tower. A heat transfer medium in the central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy, which is used for the generation of superheated steam for turbine operation. A solar tower power plant is composed of heliostat, thermal storage, and power generation parts. The Figure 5c shows the diagram of the system.

In other type of CSC, solar radiation is concentrated in to the absorber which is adjusted at the focal point of the Parabolic Solar Dish (PSD) [22], [23]. The working fluid is heated up 750 ˚C by the concentrated beam radiation, which is absorbed by the receiver. This absorbed energy heats up working fluid which is then generating electricity through a Sterling engine that in mounted on the receiver as illustrated in Figure 5d.

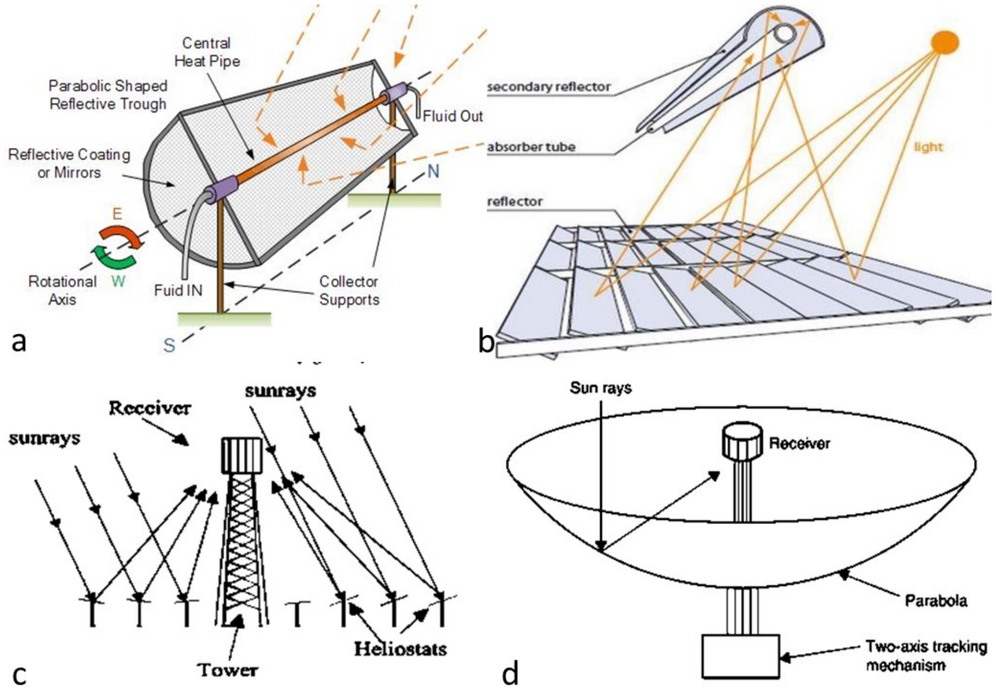

Figure 5: Classification of CSC from a) PTC [14], b) LFR from [24], c) STC from [14] and d) PSD from [25]

2.2 Low Temperature Solar Thermal Process

Low-temperature solar collectors transform the solar radiation to heat, which are directly used for hot water or space heating in residential, offices, and other buildings. Solar thermal systems can intensely decrease the amount of energy needed to buy from electric suppliers, because space and water heating are normally the largest uses of energy. Domestic Hot Water (DHW) and space heating solar thermal applications will be briefly reviewed in the following section.

2.2.1 Domestic Hot Water

The most common application of solar collectors around the world is domestic water heating. Solar radiation is converted into useful heat after being absorbed by the solar collector. A mixture of glycol-water or water is the core working fluids for the domestic solar water heaters. In such systems heat absorbing surfaces are used to gain solar heat and transfer it to the working fluid [26].

In domestic hot water systems (DHW), open or close loop water circulation system can be used. This means that water is heated from solar collector and stored directly to the storage while there is heat exchanger in close loop water heating. The heat transfer fluid is transported either naturally which is known as passive system or by forced circulation (active system). An active solar DHW system with a storage tank and pump is shown in Figure 6. Thermosyphoning occurs without a pump usage. This is to say when the fluid got hot the density of the fluid become slighter than the cold part of the liquid. As a result, the hot water goes at the up and replaced by cold water through convection heat process. On the other hand, a water pump is need for forced circulation systems [5].

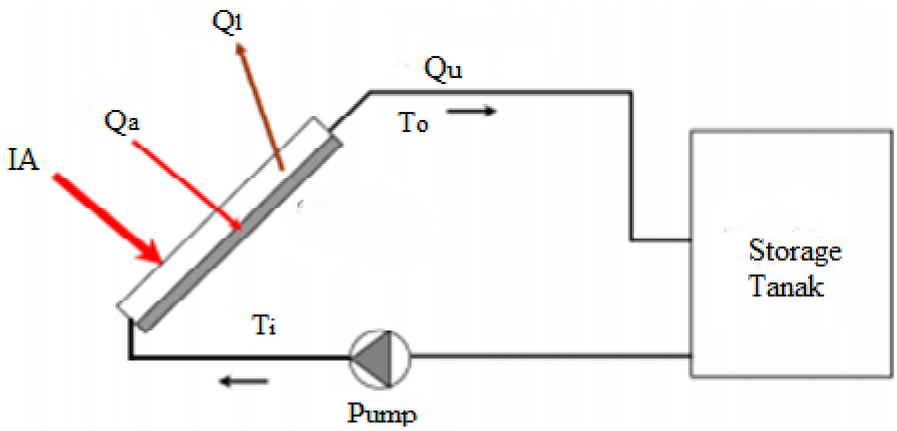

Figure 6: Typical Solar Water Heater [5]

2.2.2 Space Heating

Solar space heating can be used in combination with solar Domestic Hot Water (DHW) system or used separately. A traditional heating system such as underfloor heating or fan coil system can be supported by active solar system. In this case, system configuration again includes heat exchangers, storage tank and pumps. However, in the case separated water loops are required, one for heating and one for domestic hot water. The combination of water and space heating systems are commonly used in many counties and it can cover about 10% to 30% of the total heat demand [27]. Space heating can be achieved by heating the air directly and directing the hot air to the heating space.

2.3 Literature Review

Bellos & Tzivanidis [28] investigated the daily performance of an integrated system with flat plate collector analytically. The developed model was also validated with the realistic weather data of Athens. The investigation is carried out for twelve typical days for every one month. The yearly energy production was found 2171 kWh while the mean thermal efficiency and the payback period were 54.24% and 5.03 year respectively.

Zhang et al. [29] studied experimentally a dual function modified flat plate collector. Air heating, water heating and air-water heating modes were investigated. The experimental results of air and water heating showed that the average efficiency of the collectors were 51.3% and 51.4% with respect to the mass flow rate of 0.024 kg/s and 0.013 kg/s. In addition to that, average efficiency of air-water heating system reached to 73.4%. Zhu et al. [30] experimentally and numerically studied the performance of FPC with micro-heat pipe arrays. The system contains heat collection, transfer area, heat exchanger section and air ventilation section. Experimental results were validated with numerical simulation and its found that the average efficiency is 69% at the 290 m^3/h of volumetric flow rate of working fluid.

Jouybari et al. [31] experimentally tested flat plate collector with a metal porous foam filled channels. The working fluid was SiO_2/deionized water nano-fluid with volume fraction of 0.2%, 0.04% and 0.6%. 8.1% of thermal efficiency increase was achieved but the researchers observed that the porous materials and nano-fluid cause's dramatic pressure drop. Nikolić and Lukić [32] examined a double exposure flat plate water solar collector. Both experimental and mathematical model of each system were developed. The result shows that the thermal efficiency of the double exposure flat plate is significantly higher than the conventional flat plate by 18.44%. Fan et al. [33] has performed a comparison between the new V-corrugated absorber with multi-channels and applied for liquid flat plate collector in China. The absorptance is improved by extruded aluminum with specific triangular channels in the absorber. The thermal efficiencies of new collectors were found 84.9%, 69.4% while the conventional efficiency was obtained 69.1%. 58.6% under the mass flow rate of 10-90 kg/s. interestingly, this investigations show that the conventional collectors have higher pressure drop and pump power consumption than the new collector. Allouhi et al. [34] have investigated a forced-circulation flat plat collector integrated with heat pipe in Marocco and Turkey. Within the study simulations have been performed for performance analysis. In the analysis, coldest month of the year has been considered which has a mean daily temperature of 9.56 °C. The result is compared and validated with and existing experiment from the literature and a good agreement is obtained. The thermal efficiency and daily solar fraction of the coldest months of the year were 33% and 58% respectively. Ziyadanogullari, Yucel, and Yildiz [35] proposed three different nano-fluid flat plat collector in Turkey. The nano-fluids with 0.2%, 0.4% and 0.8% of concentration ratio were tested. The thermal enhancements of the mixture of Al_2O_3/water nanofluid were 71%, 63%, and 61.1% respectively. While the CuO/water nano-fluid were 87.8%, 84.6%, and 73.1%. Lastly, for the TiO_2/water nano-fluid, they were found to be 52.5%, 47.6%, and 35.7%, respectively. It is clear that CuO/water nano-fluid has the highest thermal efficiency among the three different nano-fluids that has investigated in this experiment. In addition to this, it is found that pressure drop and pump power consumption have increased due to the viscosity increase.

Balaji et al. [36] proposed a comparative study on convection effect of flat plat collectors with or without thermal improvers. Rod and tube were two types of thermal enhancers that have been attached to the solar absorber tubes. The overall thermal efficiency of the enhancer was 74% at the flow rate of 90 kg/h. Sharafeldin, Gróf, and Mahian [37] presented the effect of WO_3/water nano-fluids on the flat plate collector in Hungary. The researchers investigated three different types of volume fraction of nano-fluid particles as well as mass flow rates. The tested mass flow rates were 0.0156, 0.0183, and 0.0195 kg/s.m^2. The improved thermal efficiency of the collector was 17.8% under the volume fraction and mass flow rate of 0.0666% and 0.0195 kg/s m^2 respectively.

Jowzi et al. [38] investigated experimentally and mathematically a series connected four evacuated tube collector with cylindrical absorber in Greece weather climate. Ambient temperature, available irradiance, inlet temperature and mass flow rate are the examined parameters of this experimentation. The researchers concluded that the thermal solar collectors which are connected in series were working efficiently and its highest production is 5.6 kW. Kumar et al. [39] presented the evacuated tube collector which was employed with a heat pipe. Numerical simulation has been conducted during this research and compared with the other related works in the literature. Researchers found that the thermal efficiency is sensitive to external parameters like ambient temperature, solar radiation and the length of evaporator to condenser section. Xu et al. [40] designed and tested an evacuated tube under the mid-temperature operation in China's weather conditions. It is concluded that the collector thermal efficiency was 43 and 55% respectively. The impact of sun tracking in evacuated tube collector application was investigated by Teles et al. [41] for Brazil weather conditions. The numerical code was validated with the available experimental and simulation date in the literature. It was found that the tracking and non-tracking thermal efficiencies were 73 and 42% while the annual average of the collector as 61.5%. Jowzi et al. [42] studied the modified evacuated tube solar system experimentally and numerically in Iran's climate. Researchers optimized the diameter of the tube and it is found that thermal efficiency has increased about 11% while the heat gain of the modified collector was also 25% higher than the conventional collector under same conditions. Budihardjo and Morrison [43] carried out a comparative investigation between evacuated tube water collector and flat system in Sydney. It is found that the thermal performance of the evacuated tube has low sensitivity to the size of the storage tank. It is also found that the evacuated tube higher thermal performance compared to the flat plate collectors. Sharafeldin and Gróf [44] experimentally investigated an evacuated tube collector performance by using WO_3/Water nanofluid in the climate conditions of Budapest, Hungary. Researchers examined different concentration ratios and mass flow rates of the nano-fluid in the analysis. It is obtained that thermal efficiency increases with the increase of volume fraction ratio of the nano-fluid. The thermal-optical efficiency was also found 72.8%.

2.3.1 Summary of the Researchers

Table 1: Summary of the Research

No	Author	Year	Flow rate (kg/s)	η(%)	remarks
1	Budihardjo et al. [43]	2009	-	-	Comparative investigation between evacuated tube water collector and flate system.
2	Nikolić et al. [32]	2015	-	>18.44	Examined double exposure FPC water solar collector.
3	Zhang et al. [29]	2016	0.024 & 0.013	73.4	Dual function modified PFC-air-water heating mode.
4	Zhu et al. [30]	2017	290 m^3/h	69	FPC with micro-heat pipe arrays.
5	Jouybari et al.[31]	2017	0.2 & 0.04	> 0.6 & 8.1	PTC with a metal porous foam filled channels..
6	Sharafeldin et al.[37]	2017	0.0156, 0.0183 & 0.0195	17.8 improved	The effect of WO_3/water nanofluids on the flat plate collector.
7	Bellos et al. [28]	2018	-	54.24	Integrated system with flat plate collector
8	Şevik et al. [45]	2019	0.013, 0.03, 0.044	81.3	Comparative air collector with and without glazing.
9	Fan et al. [33]	2019	10-90	84.9 &69.4	Comparison between new V-corrugated absorber and conventional collector.
10	Allouhi et al. [34]	2019	-	33	Forced-circulation FPC integrated with heat pipe
11	Balaji et al. [36]	2019	0.008 to 0.025	74	Convection effect of FPC With or without thermal improves.
12	Xu et al. [40]	2019	-	43 &55	Evacuated tube under the mid-temperature operation in China's weather conditions.
13	Teles et al. [41]	2019	-	61.5	Comparison of tracking and non-tracking ETC.
14	Jowzi et al. [42]	2019	-	>11	Experimental and numerical investigation of modified evacuated tube solar system under Iran's climate conditions.
15	Sharafeldin et al. [44]	2019	-	72.8	Evacuated tube collector by using WO_3/Water Nanofluid in the clImate condition of Budapest, Hungary

2.3.2 Research Gap

Low/medium temperature non-tracking parabolic trough collectors are considered as a good alternative option to provide hot water and space heating compared to the flat plate and evacuated tube collectors. For the author’s best knowledge, it has been acknowledged that no recent research have been conducted on development and testing of a prototype non-tracking PTC under real climate conditions of Mediterranean climate.

This research will elaborate the performance of a new PTC under climate conditions of North Cyprus. In the literature, researchers have investigated large scale conventional PTCs with sun tracking systems where those type of PTCs are suitable only for power plant applications. However, the PTC with small-sized parabolas and with no-tracking system for space/water heating has not been investigated in the literature before. For this reason, an innovative design of small-sized stationary PTC is developed and tested under the North Cyprus climate and the results are compared and validated with flat plate collectors.

Chapter 3

DESIGN AND METHODOLOGY

3.1 Proposed Design Configuration

A modular small-sized PTC system was developed as it is shown in Figure 9. The system consists of an innovative non-tracking PTC, well-insulated how water storage tank (HWST), circulation pump and pipe connections. Five parabolas with a central receiver pipe are connected to produce a modular PTC. The total aperture width of the collector is 800 mm which makes each section of the collector to 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 reflective index.

Beside the high reflective index, stainless steel is available in the market and can easily be manufactured. For the manufacturing processes, CNC machine were 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, bending machine was used in order to curve the stainless steel sheet. This process must be done carefully and the reason is this, in concentrating collectors, the reflected solar radiation from the reflector should hit and absorbed by the receiver tube 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 of the collector are main parameters of the designing 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 axis and a line from the focus to the edge of the physical concentrator is known as the rim angle as it is shown in Figure 7 [46]. In this study the rim angle is taken as 90˚ [47] while the aperture width of each parabola is 160 mm.

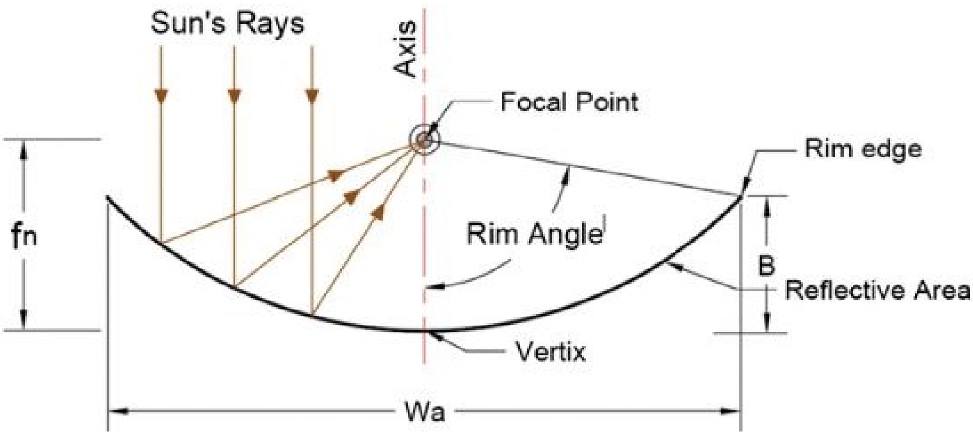

Figure 7: Cross Section of PTC [46]

The focal length of the system can be obtained [48] as follows;

$$f = \frac{Wa}{4\, tan \times \left(\frac{\theta r}{2}\right)} \tag{1}$$

Where the Wa is aperture width and θr is rim angle.

The geometric concentration ratio is the ratio of the receiver to that collector reflector area [49]. This expression can be written as:

$$\mathrm{C} = \frac{\mathrm{Ar}}{\mathrm{Ac}} \tag{2}$$

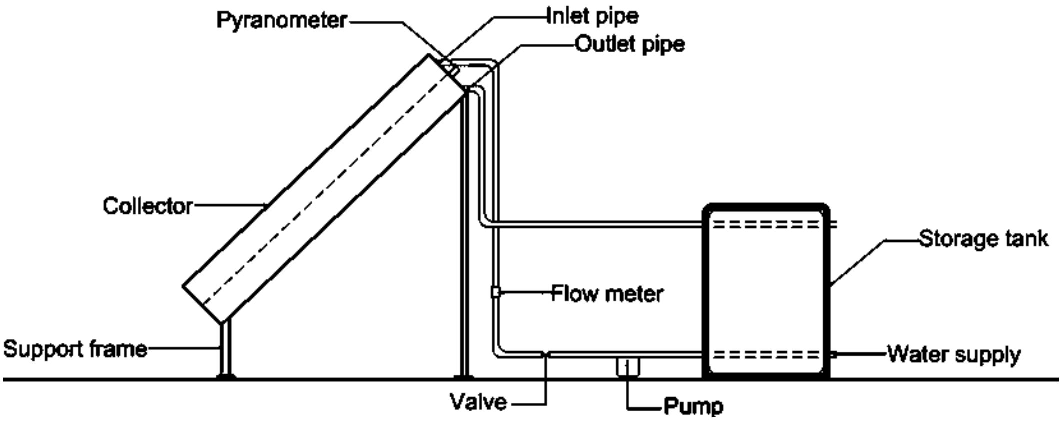

Figure 8: Schematic Diagram of Solar Collector

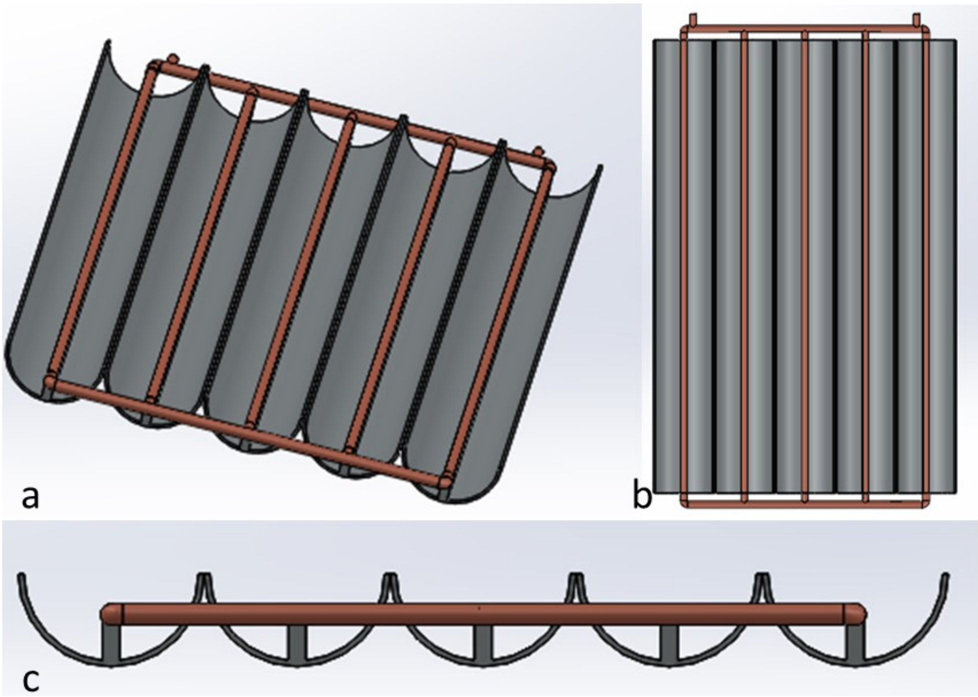

Figure 9: Proposed Design: a) Side View b) Top View c) Front View

Figure 8 illustrates the whole typical solar collector of PTC. Stored water in the tank is pumped to the collector inlet and passes through the copper pipes which are attached at the focal point of the reflectors and then it goes back to the storage tank in Figure 9a. The temperature of water inlet increases as the water absorbs heat energy from the solar collector. The process will continue until the tank temperature comes to equilibrium with collector outlet temperature.

Figure 9a, b and c demonstrates 3D model of the parabolic section of the system's side, top and front views respectively. The model is designed by using Solid Work software which is friendly to the users. The side and top views clearly displays 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 exact location of the absorber tubes on the collector.

In addition to the design, for manufacturing and calculation of the concentration ratio and focal length of reflector, a good selection of material and a proper positioning on the focal axis of the receiver tube is needed. In this project, an EN1057 Type X copper pipe is selected because the copper has high thermal conductivity. Furthermore, the receiver is coated with black paint in order to increase the absorption of the incoming solar radiation from both the reflector and direct sun radiation. The diameters of the receiver tube and the header and other dimension of the concentrating collector are displayed in a Table 2. In this prototype, rectangular glass cover is used rather than conventional circular envelop cover. The flat glass cover has small thickness for having good transmittance coefficient. To avoid the thermal heat loss of the system, the collector is well air-tightened, well-insulated and minimized the gap between the absorber tube and the glass cover.

Table 2: PTC Specifications

Item	**Value**
Aperture width (W_a)	5x0.16 m= 0.8 m
Collector length (L)	1.2 m
Absorber diameter D	0.15 m
Rim angle	90˚
Concentrating ratio C	5 x3= 15
Focal distance f	0.04 m
Glass transmittance	0.9
Reflector reflectance	0.9
Collector materials	Stainless Steel
Tank material	Stainless 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 in case to avoid the convection heat loss. An aluminum sheet of 1300 mm length, 860 mm width and 180 mm height is used to case the collector as illustrated in Figure 10. Glass wool materials are used to insulate the system and it is placed in between the parabolic reflectors and back and sides of the collector. The top section of the collector is attached the glass cover which prevents the top heat losses of the system.

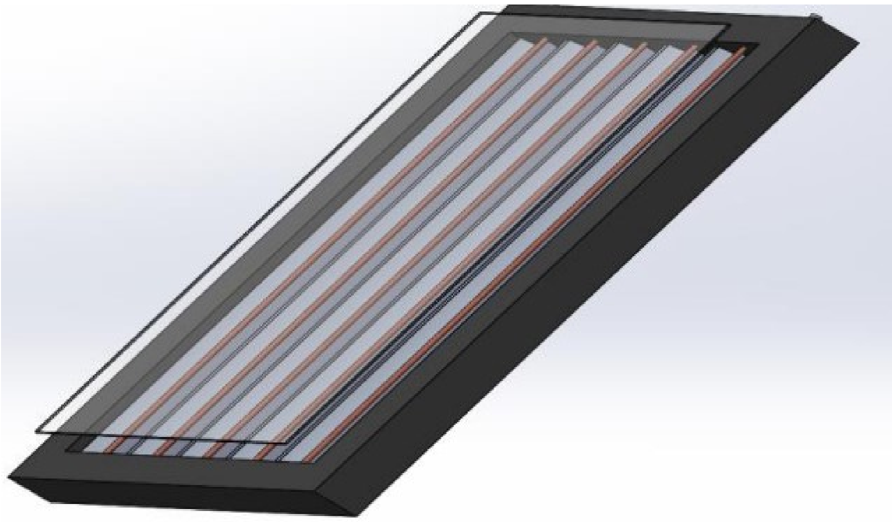

Figure 10: Assembled Parabolic Solar Collector

3.2 Design Component

3.2.1 Data Logger

Temperature readings at the inlet and the exit of collector, ambient temperature and tank temperature changes with time are closely monitored during this study. PCE-T 390 digital thermometer is a useful tool to counter this challenge. This data logger has four channels can be connected to the different type of thermocouples (K/J/T//E/R/S). The data logger has a microcomputer circuit that provides intelligence functioning and high accuracy of the data. 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. Figure 11 shows a PCE-T 390 digital thermometer used in this experiment. The temperature sensors are able to measure temperatures in the range of -50°C to approximately 100 °C with accuracy of ±0.4%+0.5 °C with resolution of 0.1 °C [50].

Figure 11: PCE-T390 Digital Thermometer [50]

3.2.2 Pyranometer

To conduct this experiment, it is essential to have accurate solar radiation data. This data can be found in meteorological offices in the cities or can be directly measured by using pyranometer instrument. The pyranomer is attached on the solar collector as it is shown in Figure 16. The pyranomer has ability to measure the total radiation with the scope of 180 degrees. The data is recorded in voltage and later converted into energy per unit area. The pyranomer is connected to the data acquisition system in the Solar Energy Lab in EMU Mechanical department [51].

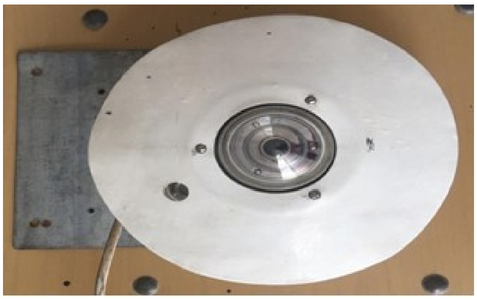

Figure 12: Pyranometer

3.2.3 Water Pump

The wet rotor pump is designed for the circulation of hot water for both domestic and residential buildings. The shaft of the pump can manually change. The pump can operate in-between 0.6 to 3.7 m^3/h with head pump of 6 meter. The working pressure of the pump is 10 bars while the temperature ranges of the liquid in between -10 °C to 110 °C. Calcium concentration in the pump can be avoided by limiting the maximum operating temperature below 65 °C [46].

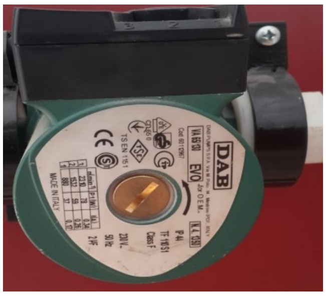

Figure 13: Water Pump

3.2.4 Storage Tank

Solar hot water storage tank stores heat energy that is obtained from solar collectors. As a regulation of solar water heating processes, storage tanks are well insulated and wrapped with metal sheet to avoid heat losses. Tanks are wrapped with glass wool for heat insulation to reduce energy consumption, speed up the heating process, and maintain the desired operating temperature. Thicker thermal insulation reduces standby heat loss. In this experiment, tank is made from two concentric stainless steel cylinders and 2 cm thickness of glass wool insulation material inserted in between the steel layers. The bottom and top surfaces of the tank are also insulated. Figure 14 illustrates the inlet and outlet of the tank and the sensor position.

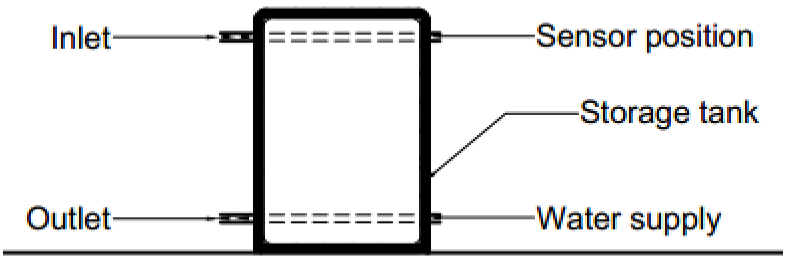

Figure 14: Storage Tank from Solid Work

3.2.5 Data Logging and Sensor Position

In this study PCE-T 390 data logger with four channels of K-type thermocouples were adjusted to record the temperature of the water and atmospheric air in every two minutes. The thermocouple positions are shown in Figure 15.

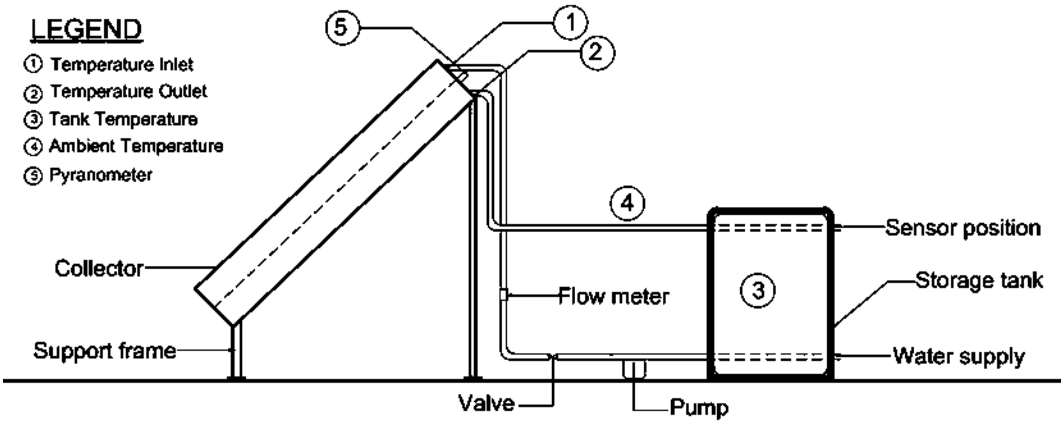

Figure 15: Thermocouples Position in the Collector System

The thermocouples are inserted at specific locations of the collector and the tank. These recorded data is essential for analysing the thermodynamic parameters. The thermocouple positions are clearly indicated on the figure above and described as fellows;

- Thermocouple 1 (T_1): at the input of the collector after water is pumped from the tank.
- Thermocouple 2 (T_2): at the exit of the collector after water passes through the PTC modulus.
- Thermocouple 3 (T_3): At the inside of the storage tank.
- Thermocouple 4 (T_4): measures the ambient temperature.
- Measurement 5: recording solar radiation.

3.3 Experimental Setup

This experiment was conducted in Mechanical Engineering Department of EMU which is located in Famagusta, TRNC. The latitude and the longitude of the city are 35.125° N 33.95°E respectively. The collector was tilted 45° to minimize the incident angle [31]. Two different flow rate were tested in six various days in April.

Figure 16: Experimental Setup.

The detailed testing procedure is given as follows:

- The tank was refilled every experiment.
- Data logger and Pyranometer were installed in the system and allowed to stabalise.
- The experiment is started at 9:00 am in each day of testing.
- The temperature sensors are connected different position of the system.
- The solar radiation was recorded every 20 mins while the temperature reading at T_1, T2, T3 and T_4 was recorded every 1 mins and later was taken average of 20 min.
- The flow rate was measured manually.
- The experiment is carried out for 7 hrs. daily, and the final data were stored.

3.4 Thermodynamics Analysis

The main aim of this experiment is to design, test and thermodynamically analyse of PTC system performance based on the experimental data. In this regard, it is essential to apply first law of thermodynamics' energy balance. The data is obtained from the conducted experimentation [51]. To develop the energy balance of this system, some assumptions are needed to be considered:

- The PTC system operates in unsteady state condition.
- The water properties such as specific heat capacity and density are considered constant during the experimentation.
- Energy stored in the glass cover is neglected.
- Dust particles on the glass cover are neglected.

The power intensity of the solar radiation that hits on the collector surface (w/m^2) is obtained:

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

Where, Q_r is thermal power of the solar radiation on the collector surface, I is the solar radiation and A is the collector aperture area. The fraction of the solar radiation is reflected back to the sky by the glass cover. Other portion is absorbed by the glass cover which is neglected in this case and the remaining is transmitted to the parabolic reflectors where the reflected ratio is being absorbed by the receiver tube. The absorbed energy (Q_a) by the receiver is the transmittance-absorptance product and the intensity of the solar radiation on surface of the collector [52]:

$$Q_a = \tau \times \alpha \times I \times A_c \tag{4}$$

Where τ and α are the transmissivity and absorptivity ratio respectively.

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

$$Q_u = \dot{m} \times C_p(T_{outcoll} - T_{incoll}) \tag{5}$$

Where $\dot{m}$ is the mass flow rate of the fluid, C_p is the specific heat of the fluid and T_{out} and T_{in} are the outlet and inlet temperature of the collector.

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

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

3.5 Uncertainty Analysis

The accuracy of the experimental performance of the PTC can be proved by uncertainty analysis method. 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 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:

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

Equation 6 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.

$$\eta = f(T_{outcoll}, T_{incoll}, \dot{m}, I) \quad (8)$$

Total uncertainty for overall system efficiency can be expressed as;

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

Based on the equations 7-8, the uncertainty of the PCT system that is affecting the thermal efficiency is computed. The total uncertainty (σ) of the efficiency was found 2.3%. The experimental device accuracies and their ranges of operation are displayed in Table 3 below.

Table 3: 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

Chapter 4

RESULTS AND DISCUSSION

This chapter will represent the experimental data and thermodynamic analysis results of the PTC system. The system is composed from solar collector, water pump, flow meter, storage tank and connecting pipes. The main objective of the experiments is to evaluate the thermal efficiency of the system by recording four different temperatures and solar radiation. Energy gain by the collector is calculated by using thermodynamic equations presented in Chapter 3.

4.1 Results Analysis

Tests have been conducted for six days of the beginning and the ending of the April 2019. The test were evaluated under two different water flow rate 15 L/h and 20 L/h. Based on that the following parameters were evaluated:

1. Temperatures
2. Solar radiation
3. Energy gain
4. Thermal efficiency of the system.

4.1.1 Temperatures

The temperature variation of the PTC system with flow rate of 15 L/h was presented in Figure 17-18-19 respectively. As it is seen in Figure 17 the outlet and tank temperatures show a fluctuating pattern during the day1 of experimentation. This is due to the rain and cloudy sky of that particular day. The maximum temperature is 63

°C while the average outlet and tank temperatures are 45.75 °C and 39.72 °C respectively.

Figure 18-19 of day2 and day3 of experimentation shows a good performance of outlet and tank temperature compared to the result in Figure 17. The graphs clearly illustrate a linear pattern. This is due to the reason that those testing days were clear sky from 9:30 to 13:00. The daily average of outlet and tank temperature of day2 were 56.42 °C and 49.99 °C while in day3 these values were 52.75 °C and 46.49 °C respectively.

The inlet temperature is always lower than the tank temperature. This is due to the stratification of fluid. That is to say that the fluid in the tank is not fully mixed so the water of the upper part of the tank is higher temperature than the water at the bottom of the tank.

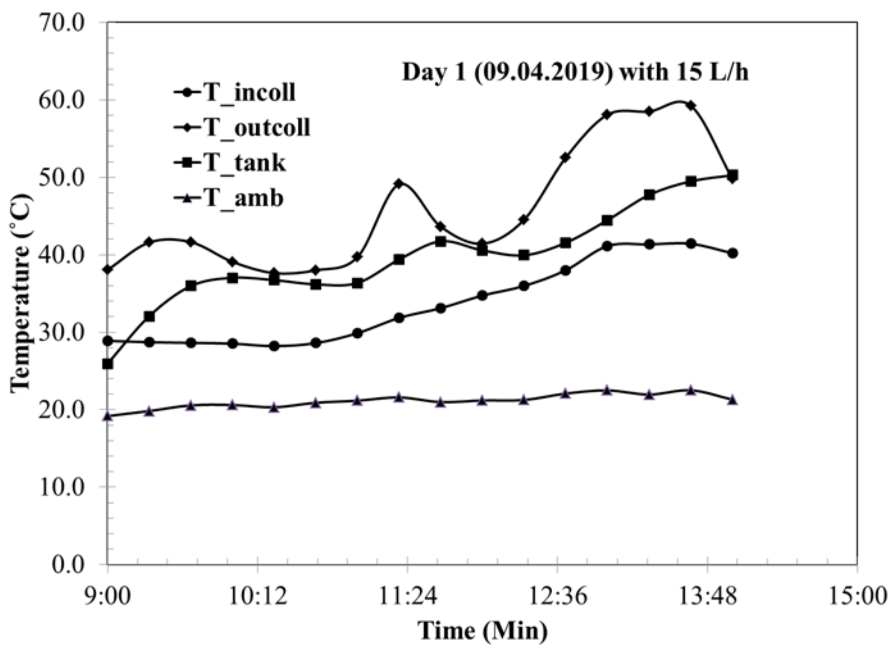

Figure 17: Temperature Variation of Water on Testing Date of 09.04.2019

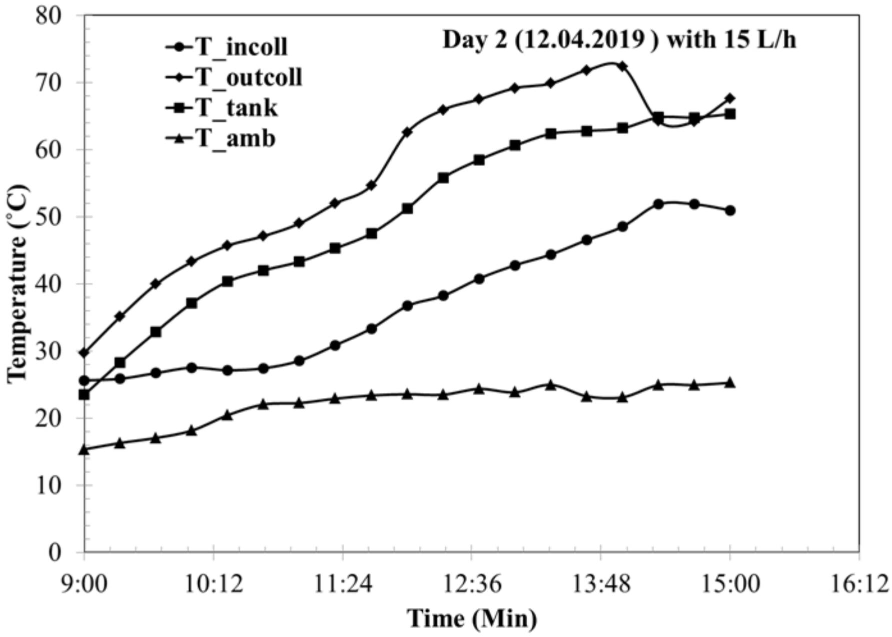

Figure 18: Temperature Variation of Water on Testing Date of 12.04.2019

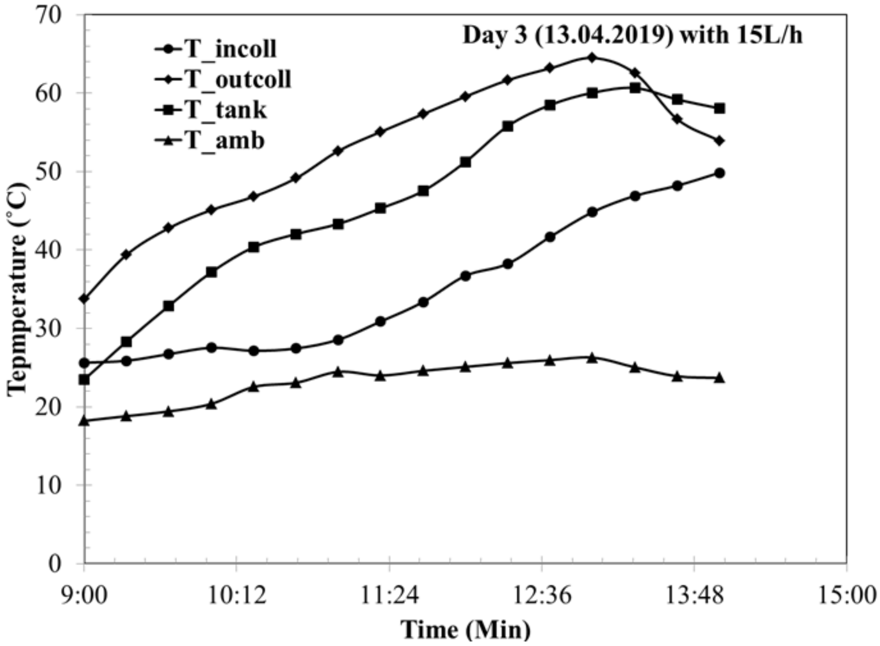

Figure 19: Temperature Variation of Water on Testing Date of 13.04.2019

Figure 20-21-22 shows the temperature measurement for the last three different days of testing with flow rate of 20 L/h. The graphs illustrate that inlet, outlet and tank temperatures increase due to the increase of solar radiation. Interestingly, it is clear that at some point the water temperature is becoming uniform inside storage tank.

This is due to the drop of outlet temperature from the collector because the sky is partially getting cloudy or the flow rate is higher so there is more fluid circulation between the storage tank and the collector. Interestingly, it is noticed that the outlet temperature in Figure 21 has dropped for short time of period and then increased gradually. This is due to shading from clouds that are preventing the incoming solar radiation. The overall average of the outlet and tank temperature is found 53.51 °C and 48.94 °C.

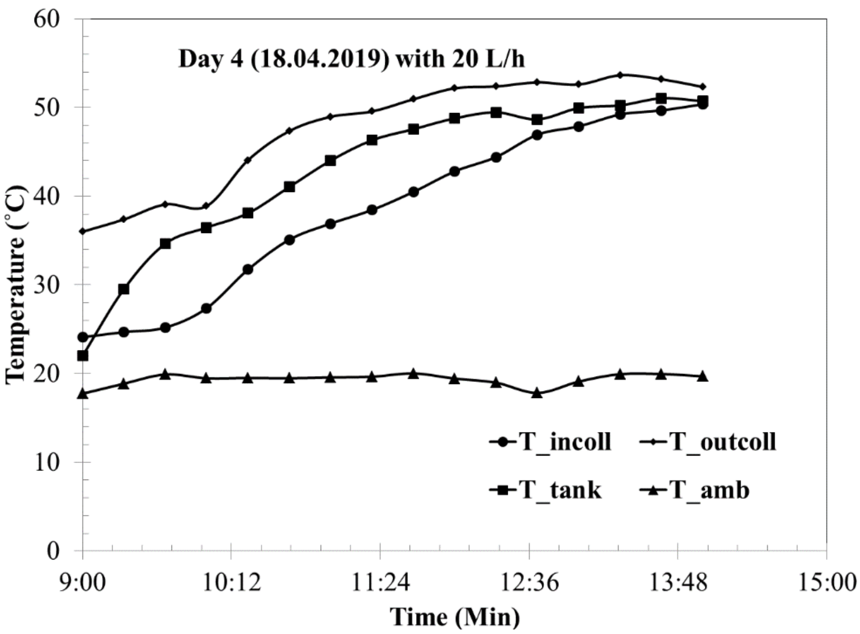

Figure 20: Temperature Variation of Water on Testing Date of 18.04.2019

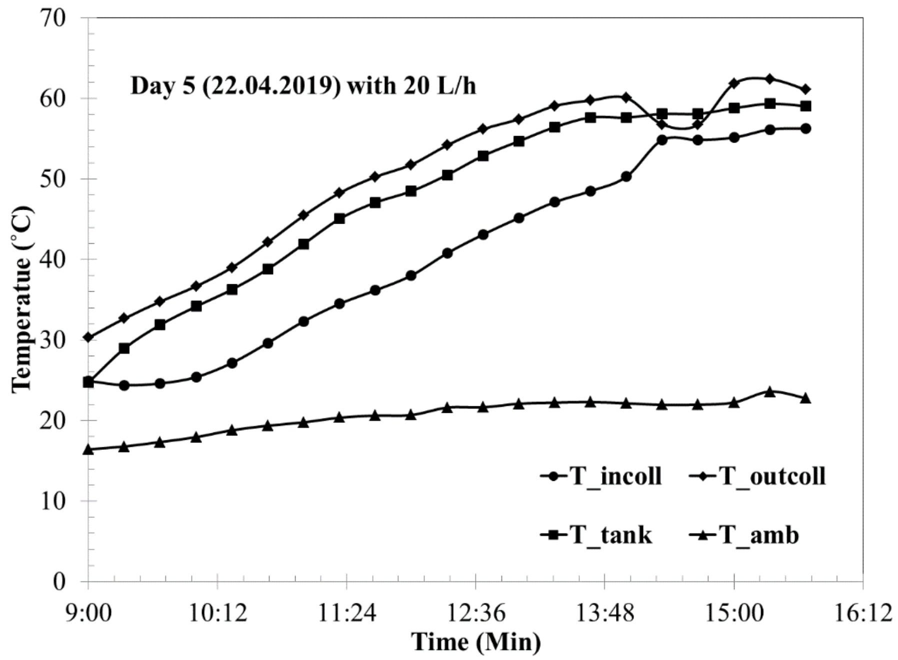

Figure 21: Temperature Variation of Water on Testing Date of 22.04.2019

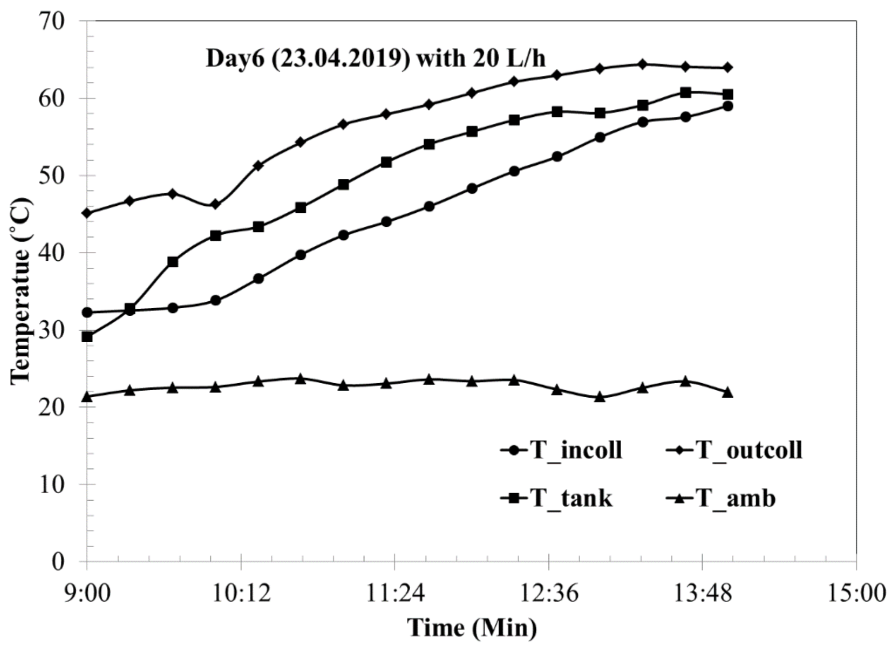

Figure 22: Temperature Variation of Water on Testing Date of 23.04.2019

4.1.2 Solar Radiation

Figure 23-24 shows the total radiation that is striking on the surface of PTC system for second and the third week of April. Day1 and day4 of both graphs have shown considerable fluctuation because the sky was partially cloudy for these days which are affecting the available solar radiation on earth surface.

Day2 and day3 in Figure 23 indicates the dramatic increase of the solar radiation from 9:30 am -10:30 am which also shows a gradual increase between10:30-12:30. The main reason of this change is that, as the incident angle which is angle between the beam radiation on a surface and the normal to that surface decreases, the solar radiation increases and vice versa. The overall average of solar radiation of the first three days of experimentation is found 654.51 W while the remaining days is 723.31 W. It is observed that the solar radiations of day1 and day4 have been dramatically fluctuating throughout the day as it is shown in Figure 23 and Figure 24 respectively. This fluctuation is caused by frequency clouds which were completely or partially covering the solar radiation. As result of this, the intensity of the radiation has changed from 200 W/m^2 to 1000 W/m^2 within thirty minutes or an hour.

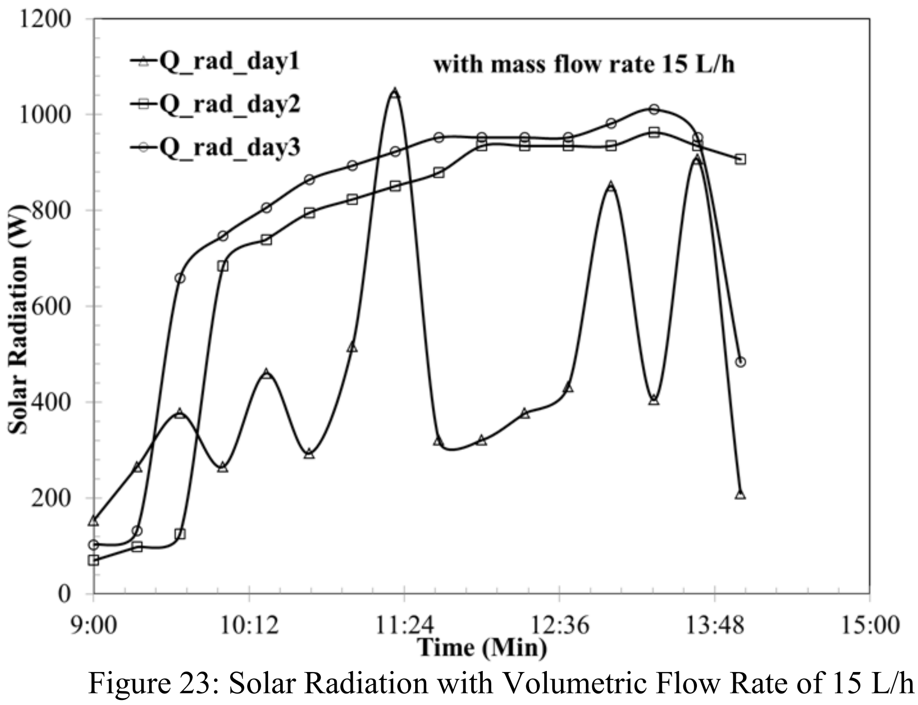

Figure 23: Solar Radiation with Volumetric Flow Rate of 15 L/h

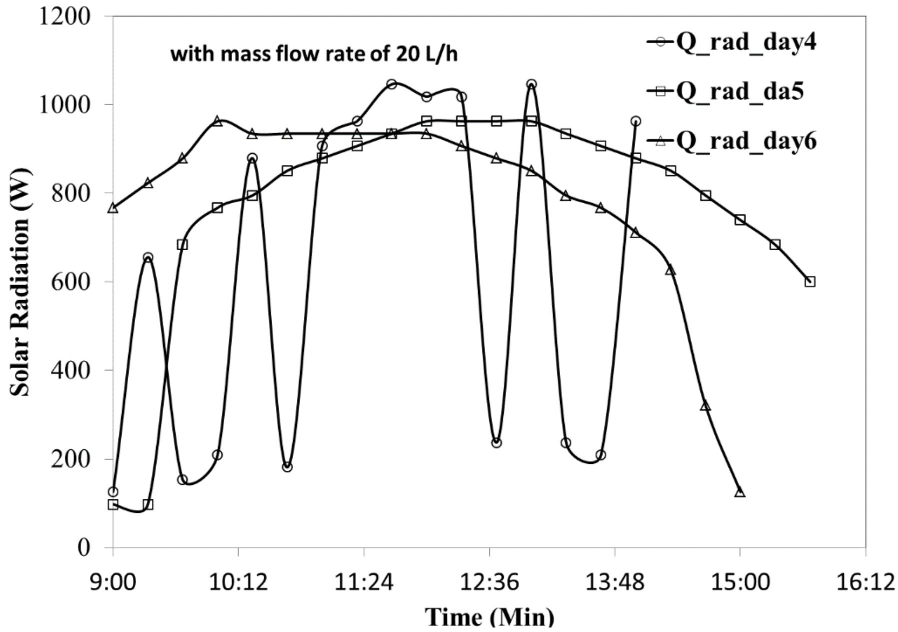

Figure 24: Solar Radiation with Volumetric Flow Rate of 20 L/h.

4.1.3 Energy Gain

Figure 25-26 shows useful energy gain for the PTC with two different flow rates. It is obvious that the energy gain of both day1 and day4 have the minimum value which is 210.85 W and 210.0 W respectively. These days had low intensity solar radiation as we can see from Figure 23-23. Day2 and day3 in Figure 25 are giving the maximum energy gains which are 335.42 W and 309.4 W while the energy gain in day6 for Figure 26 is 271.37 W.

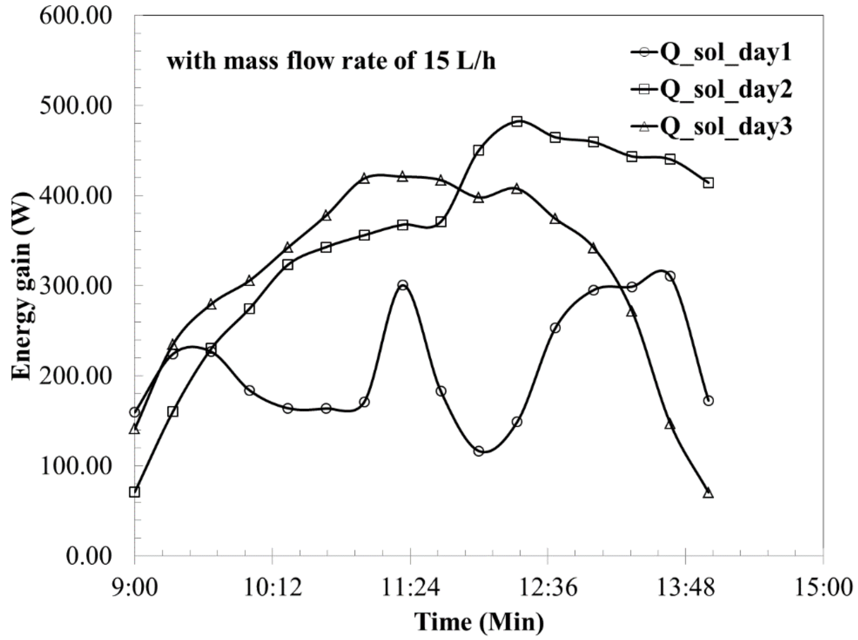

Figure 25: Energy Gain with Volumetric Flow Rate of 15 L/h

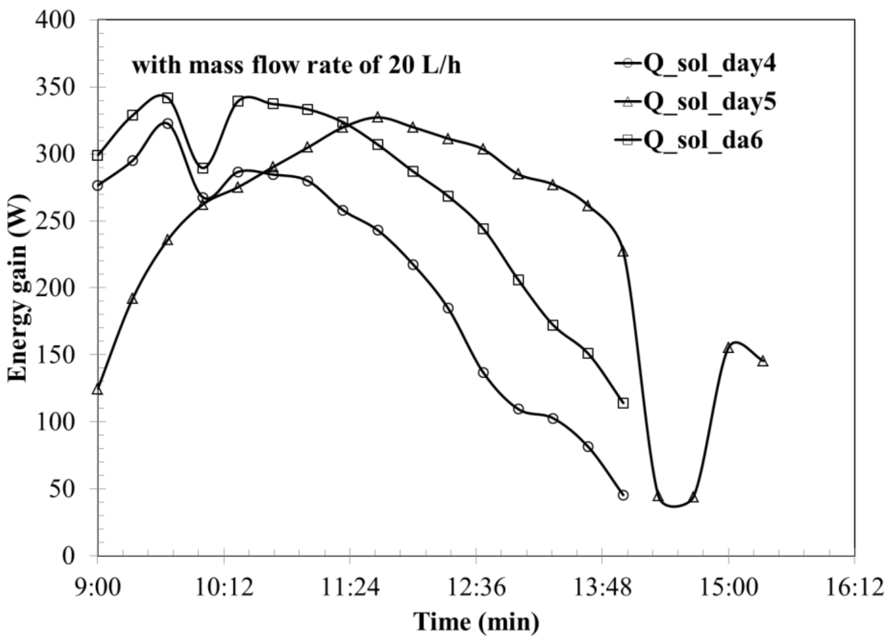

Figure 26: Energy Gain with Volumetric Flow Rate of 20 L/h

4.1.4 Thermal Efficiency

One of the most important parameter to conduct this experiment it to justify where the system is efficient to use water heating application or not. Most heat transferred to the working fluid is gained from the solar collector. The efficiency of this system depends on solar radiation and the performance of the collector. The daily efficiency of the PTC with 15 L/h were found 47%, 45% and 40% while the efficiency of the remaining three days with volume flow rate of 20 L/h were 34%, 30% and 34% . The efficiency variations of the experimented days are displayed in Figure 27-28.

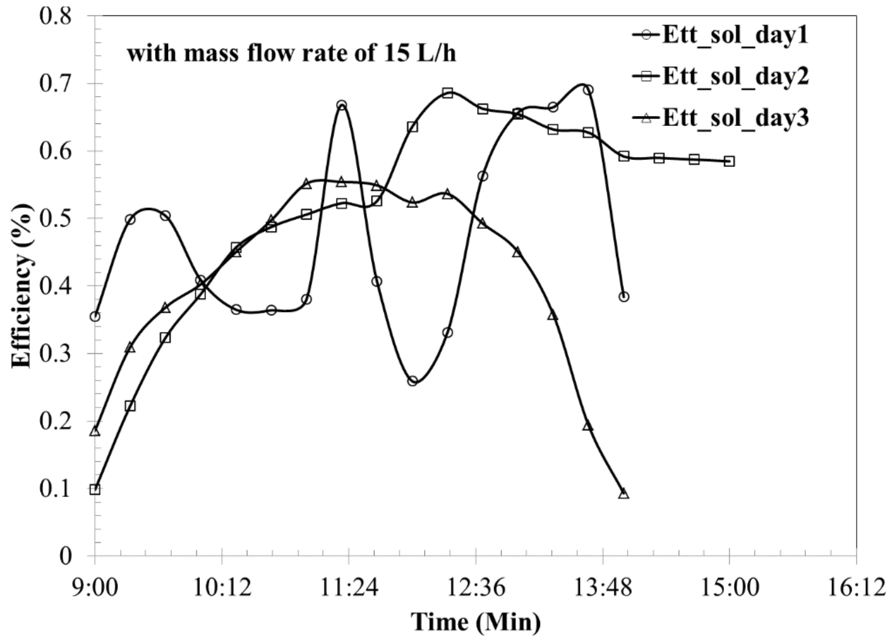

Figure 27: Thermal Efficiency for Volumetric Flow Rate of 15L/h

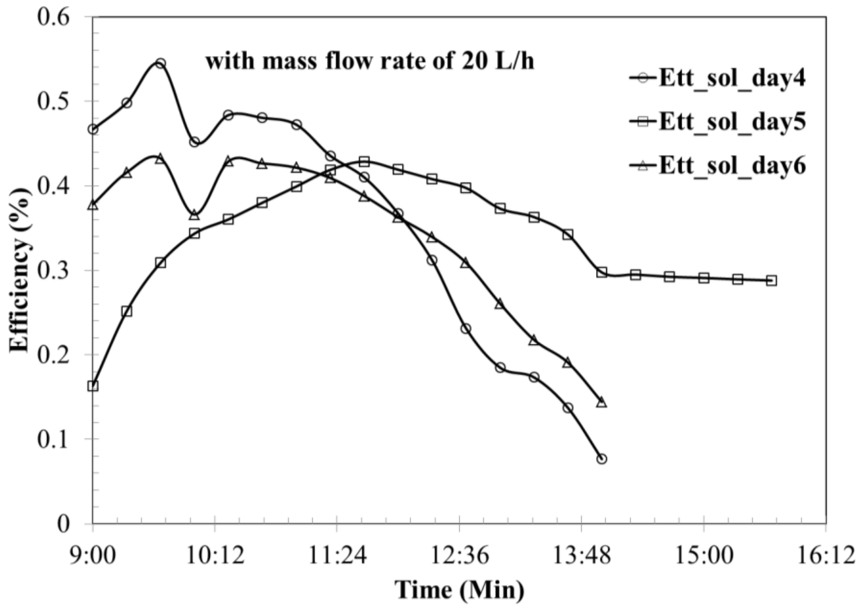

Figure 28: Thermal Efficiency for Volumetric Flow Rate of 20L/h

The efficiency of the PTC system also depends on the incoming solar radiation, incident angle, and reflective index of the reflector, type of absorber tube and collector area. The overall average efficiency during the test period for flow rate of 15 L/h and 20 L/h are 44% and 33%. Table 4 displays the summary of the experiment.

Table 4: Experimental Summary

Mass (kg/s)	**No. of days**	**T_incol (˚C)**	**T_outcol (˚C)**	**T_tank (˚C)**	**T_amb (˚C)**	**Q_sol (W)**	**Q_rad (W)**	**η_{th} (%)**	**σ (%)**
15 L/h	9.4.19	33.71	45.79	39.72	21.12	210.84	449.92	47	2.50
	12.4.19	37.16	56.42	49.99	22.10	335.42	740.89	45	2.31
	13.4.19	34.98	52.75	46.49	23.20	309.45	772.72	40	2.05
Average		**35.28**	**51.65**	**42.51**	**22.14**	**285.24**	**654.51**	**44**	**2.29**
20L/h	18.4.19	38.46	47.58	43.03	19.325	210.0	615.59	34	2.13
	22.4.19	46.82	56.27	54.01	21.78	219.67	763.51	30	2.07
	23.4.19	45.00	56.67	49.77	22.73	271.39	790.82	34	2.37
Average		**43.43**	**53.51**	**48.94**	**22.28**	**233.69**	**723.31**	**33**	**2.19**

Chapter 5

CONCLUSION

A low/medium temperature non-tracking Parabolic Trough Collector (PTC) is considered a promising technology that can be used for domestic hot water and space heating applications instead of using conventional flat plate collectors. This kind of study has not been investigated recently under North Cyprus weather conditions.

During spring period, two different flow rates have been tested in six different days in April. It is observed that the average solar irradiation of those days ranged between 680.7 W/m^2 – 749.49 W/m^2. The useful energy gain of the collector was 285.24 W for flow rate of 15 L/h and 233.69 W for flow rate of 20 L/h while the outlet temperature ranges from 51.65 ˚C -53.51 ˚C. Furthermore, the overall thermal efficiency of the system with 15 L/h and 20 L/h was found 44% and 33% respectively.

According to results, it is observed that the thermal efficiency of the first flow rate is higher than the second flow rate, while having lower solar radiation. One of the reasons is that, working fluid had enough time to pass through absorber tubes. As a result, the working fluid absorbs more useful energy. Secondly, daily individual solar radiation of the first flow rate was better the second flow rate because, two of the three testing days were sunny so that their solar radiation was not varying a lot.

The study concludes that, using medium temperature CPT system in domestic hot water and space heating applications in a Mediterranean climate could be potential because when there is low incoming solar radiation, the PCT systems have higher superior than conventional FPC.

5.1 Future Work

The performance of the PTC system can be further improved by investigated the following parameters:

- To obtain more accurate results from the study, more experiments and repetitions are needed. Also tests could be performed during different periods of the year.
- Simulation investigations on the developed prototype with numerous variables such as nano-fluid particles with different concentration ratio, different type of piping materials, and various types of coating materials are required.
- Applying optimization methods such as Genetic Algorithm and ANN.
- To test the unit with different flow rates and also in natural circulation mode to determine optimum operational conditions.
- To perform numerical simulations for optimizing the parabola configurations and dimensions.

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