Mathematical Modeling and Thermal Analysis of Evacuated Flat Plate Collector in Pakistan

By

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Reg # 00000277510

Session 2018-2021

Supervised by

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National University of Sciences and Technology (NUST)

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THESIS ACCEPTANCE CERTIFICATE

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Certificate

This is to certify that work in this thesis has been carried out by **Mr. Zohaib Hassan** and completed under my supervision in, US-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

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Abstract

Energy plays a vital role in the development of a country. In the industrial sector water heating applications of different temperature ranges from low to medium use a major portion of final energy consumption. The Energy Sector is now facing a demand-supply gap that must be bridged, as well as an improvement in the energy mix for lower-cost supply. Solar energy is, without a question, one of the most suitable and broad solutions to the present increasing energy demand and resulting economic and environmental challenges. Conventional solar systems, on the other hand, suffer unbeatable hurdles that compromise their technical performance and economic viability. To address these issues, more emphasis is being placed on the use of solar thermal collectors as a cost-effective heat transmission technique. This paper describes an evacuated flat plate collector with a surface area of 4 m^2 using a water-glycol mixture is a working fluid that circulates inside the copper tubes with mass flow rates of 0.03, 0.0336, and 0.0504 kg/s. Vacuum is created inside the enclosure of the collector by using a vacuum pump for the reduction of convective losses between absorber and glass cover. Program code developed in MATLAB was simulated with design conditions of the EFP collector model and input climatic data obtained from MHP equipment positioned at USPCAS-E, NUST, Islamabad, Pakistan. The current study also comprises parametric sensitivity analysis and model validation of EFP collectors. Using EFP collector results in 15°C rises of the absorber temperature and 8°C rises in fluid outlet temperature when compared to the FP collector without vacuum. The maximum thermal efficiency of evacuated flat plate collector observed is 0.78.

Keywords: Renewable energy, Solar thermal collector, EFP Collector, numerical modeling, Experimental validation of collector.

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1. **Zohaib Hassan, Mariam Mahmood, Adeel Waqas, Majid Ali, Naveed Ahmed** *"Mathematical Modeling and Thermal Analysis of Evacuated Flat Plate Collector in Pakistan"* International Conference on Emerging Power Technologies, April 2021, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology Topi, Swabi.

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Nomenclature

Variables

$h_{r,p-c}$	Radiation from plate to cover (W/m^2K)
$h_{r,c-a}$	Cover to ambient radiation (W/m^2K)
T_p	Absorber plate temperature (°C)
T_c	Glass cover temperature (°C)
T_{fout}	Fluid outlet temperature (°C)
T_a	Ambient temperature (°C)
h_w	Convective heat transfer due to wind
ε_c	Emissivity of glass cover
ε_p	Emissivity of absorber plate
σ	Stefan Boltzmann constant
$\dot{m}$	Mass flow rate of working fluid (kg/s)
F_R	Heat removal factor
F'	Collector efficiency factor
H	Solar radiations (W/m^2)
S_1	Absorbed radiations by cover
S_2	Absorbed radiations by plate

Abbreviations

EFP	Evacuated Flat Plate
FP	Flat Plate collector
ETC	Evacuated tube collector
RMSE	Route Mean Square Error
MAPE	Mean Absolute Percentage Error
EIA	Energy Information Administration
MHP	Metrological High Precision

Chapter 1

Introduction

1.1. Climate Change

The increasing energy demand for the fossil fuels day by day led it to the limitation of the fossil energy. The main reason for energy crises in Pakistan is the dependency on fuels like oil, coal, and natural gas which are very expensive and limited. Climate change and global warming are the main reasons, which will affect industrial sector as well as having a greater impact in increasing health problems. According to World health organization (WHO) survey 2010 deaths of 160,000 per year occurs due to the climate change [1]. Every industry, farm, and household emit greenhouse gas emissions, which affect many aspects of nature, human health, and agriculture. The consequences of climate change in less developed countries are very worst. Climate change is one of the complex and more uncertain problems than any other big environmental issue. To reduce greenhouse gas emissions, it is very important to create an awareness platform for improving energy efficiency and replacement of traditional energy resources with renewable energy [2]. According to the Energy Information Administration (EIA) survey 2012, between the years 1980 and 2010 there is a huge increase in the world natural gas consumption from 50 trillion cubic feet to115 trillion cubic feet and will be increased from 115 in 2010 to 186 trillion cubic feet in 2040 by EIA 2013 survey [3]. As industrial sector is a greater contributor to energy used globally, so by replacing fossil fuels with renewable will results in saving of 33% of energy consumption and about 38% of the carbon dioxide (CO_2) emissions. Also, it will increase energy efficiency of the industry from 18-25% and reduction of carbon dioxide [4]. An average of about 35% total energy of the world consumed in commercial sector having higher impact on the country economy and production of greenhouse gas emissions [5]. Energy resources from fossil fuels are depleting because of climate change, while energy demand is rising. Climate change and GHG emission drive us to substitute energy derived from renewable resources such as energy from solar thermal collectors for energy derived from non-renewable energy sources such as fossil fuel.

1.2. Solar Energy Potential

Pakistan receives a plenty of solar radiation, which necessitates its effective use for a variety of reasons. Because of Pakistan's geographical position, southern areas of Punjab, mostly parts of Baluchistan, mostly area of Sindh, and southern regions of Khyber Pakhtunkhwa gains a lot of solar radiation and has a lot of potential for solar energy. During summer, the duration of the day is 12-h to 14-h, while during the winter season 8-h to 10-h in Pakistan. In Pakistan all over the year normally 10-h to 12-h time span of the day was observed. Throughout the year, solar radiation in Pakistan, especially in the Sindh region, Baluchistan area, and mostly areas of Punjab, are observed in the range of 1500 W/m^2/day up to 2750 W/m^2/day [6].

Pakistan's annual energy consumption is increasing by 9%, and it is expected to grow by a factor of eight by 2030 and a factor of twenty by 2050 [7]. Pakistan generates 17 GW of electricity and demand of electricity is 23 GW, which leads to 6 GW of deficit, and by 2030 it will increase up to 25 GW [8]. According to International Energy Agency, globally solar PV had the capacity of 402 gigawatts (GW) by 2017 and will increase to 580 (GW) by the near future [9]. Pakistan having a grater solar potential of 1600,000 MW [10].

For proper utilization of solar thermal potential, it is very important to invest in the public and private sector [11]. Regarding energy crises, solar thermal is the best option For tackling all the challenges [12][13].

The applications of photovoltaic and solar thermal for different purposes are observed to be very limited as compared to the available potential energy from the sun. On smaller scale solar energy potential has been correctly utilized to some extent from the recent decades, but on the larger scale solar thermal energy has very limited shares in industries. In Pakistan SNGPL is the best utilizer for solar thermal energy. Several departments are paying its attention towards the solar thermal energy utilization for the generation of electricity and thermal applications. According to a report published by the International Energy Agency (IEA), solar energy would supply roughly 45 percent of global energy demand by 2050 [1]. The heat energy from the sun is very useful and can be used for different purposes like water heating, cooking, drying, and energy generation. Such type of technologies will be of low cost, more efficient, more feasible and highly adaptable.

Using of solar energy for water heating is a solar thermal technology and considered to be very established, but in our country this energy utilization is very limited up to now because of its capital cost. In Pakistan textile industry has a greater impact on the total exports of the country, as cotton is produced in abundant amount. In textile industry steam and hot water is consumed in large amount for fabric preparation through process washing, drying, heating, bleaching, wet processing etc. In Pakistan mostly boilers are used for hot water and steam generation, which consumes electricity or natural gas in a large quantity. From year 1971 to 2004 total energy consumed in textile side has been increased from 47 EJ/year to 90 EJ/year in the world, which shows that energy consumption is almost doubled that will have a greater impact in energy crises [14]. If we replace these boilers with solar thermal collectors, or use solar thermal collectors during day Time, it will be more feasible, economical, and will save the energy from natural gas or electricity. Evacuated tube and flat plate collectors are normally used for domestic hot water applications. EFPC is a new technology, which is designed by creating vacuum within the space of the flat plate collector through which losses through convection from absorber to the glass cover has been dramatically reduced. Schematic diagram shown in **Figure 1.1** presents EFPC system for process heat.

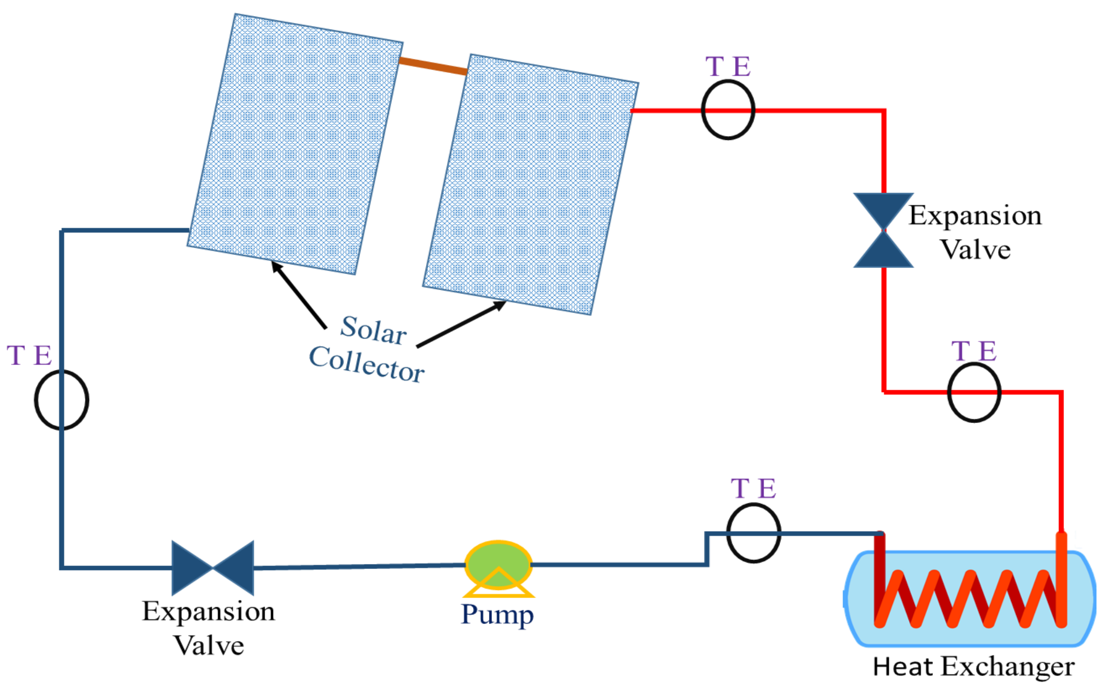

Figure 1.1 Schematic diagram of EFPC system for process heat

1.3. Problem Statement

The Energy Sector is facing a demand-supply gap that must be bridged, as well as an improvement in the energy mix for lower-cost supply. Solar energy is, without a question, one of the most suitable and broad solutions to the present increasing energy demand and resulting economic and environmental challenges. EFP is a new solar thermal technology having very less contribution in the market on commercial and industrial side, because of designing a model on large scale. The main parameters its selective absorber, a perfect vacuum, and working fluid are very crucial for designing which needs further research for selecting a material having maximum absorbing capacity, a good vacuum and type of working fluid to enhance the fluid output temperature. To address these issues 1-D model is developed in MATLAB with design conditions of the EFP collector system and performed transient analysis under climatic conditions of Islamabad, Pakistan, followed by the experimental validation of EFP collector model.

1.4. Study Objectives

In reference to the current energy crises and limitation of fossils fuel in Pakistan, it is very important to accomplish research study of solar thermal collectors and its potential for commercial and industrial applications. For achieving desired goals and solving this issue, research study has been accomplished for the following purposes.

- Mathematical modeling of EFP Collector
- Model validation with literature and experimental results
- Sensitivity investigation of the collector
- Comparison of Evacuated with non-evacuated Flat Plate Collector

EFP collector. MATLAB is used for numerical modeling and simulations by using climate conditions of USPCAS-E, NUST located at Islamabad, Pakistan. The study comprises of sensitivity investigation of the EFPC using MATLAB programming to better understand different settings. The simulations results generated through MATLAB are then compared with the FP collector having same conditions for design parameters, and results are plotted. Also, experimentation of EFP collector is carried out under the same climatic condition of Islamabad, Pakistan. MATLAB simulations are validated against the reference study as well as the experimental results of real model. **Figure 1.2** shows the Temperature variation graph under Islamabad weather conditions.

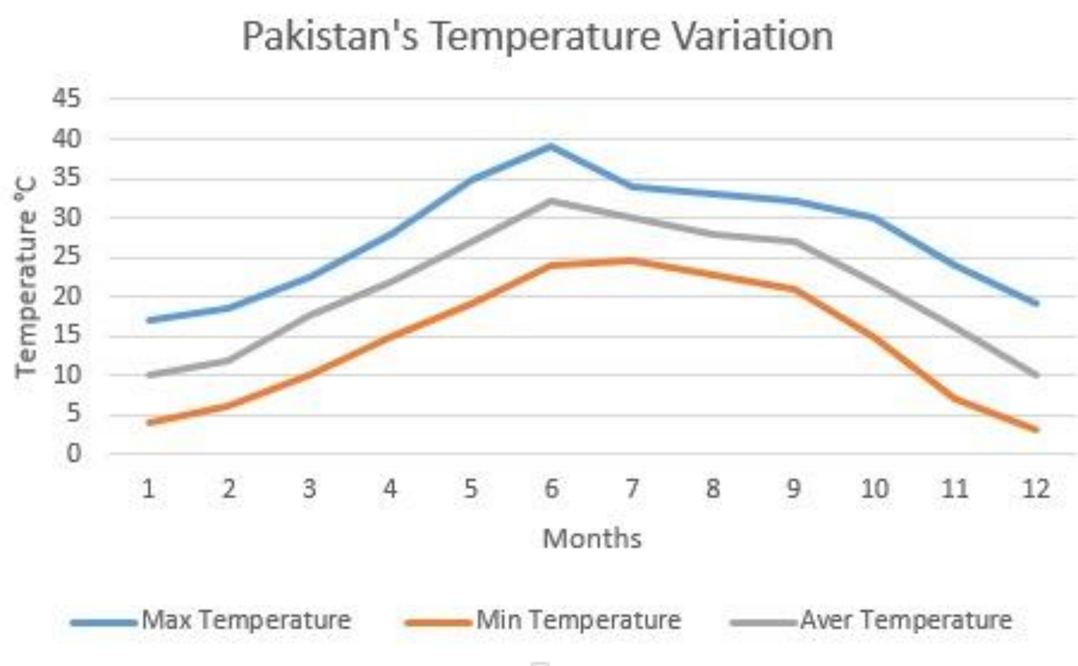

Figure 1.2 Temperature variation graph yearly for Islamabad weather conditions [15]

1.6. Motivation

Pakistan receives solar radiations in abundant due to its geographical location if correctly utilized. On industrial side Pakistan has many textile industries, because the production of cotton in Pakistan is in huge amount. Mostly in Pakistan textile industry consumes natural gas or electricity in abundant to produce steam in the boilers. Proper research study accomplishment is necessary at this sector for saving of natural gas and electricity. People are unaware of the solar thermal energy, which has a greater solar thermal potential at this area. Also, there is not enough research on the evacuated flat plate collector in the literature and its application for process heat in industry. Therefore, this research study has been started to reduce losses from flat pale collector by creating vacuum, increase efficiency, economic analysis, and to study its implementation in textile industry for process heat.

1.7. Thesis Outline

The detailed sections of this study are summarized below.

Chapter 2: This chapter will the summarize the work done in the literature on solar thermal technologies like ETC, FPC and evacuated flat plate collector. It will also summarize an outline of the evacuated flat collector and its applications used for process heat in textile industry. This study will help us to understand the potential of evacuated flat plate collector.

Chapter 3: This chapter will summarize a detail study of mathematical modeling of evacuated flat plate collector. Equations used for modeling are briefly discussed in this section. Design parameters for MATLAB programing to study sensitivity analysis and effect of evacuated flat plate collector has been discussed.

Chapter 4: This section sum up the results of code generated in MATLAB program, sensitivity analysis to study different parameters, model validation with experimental, model validation with reference study, thermal resistance network, and summarize the significance of evacuated flat plate collector.

Chapter 5: This chapter will summarize the overall current research study that why evacuated flat plate collector is better. It will include conclusion, recommendations, and future work to be carried out on this article.

Summary

This chapter explains the declining of fossil fuels energy day by day in Pakistan, also describes the effects of using fossil fuels that how it can be dangerous for human health and development of a country. This chapter explains in detail the climate change and its effect on human health and resources. The steps taken to reduce the climate change by different departments and awareness platforms. Solar energy potential and currently installed solar projects and its output in Pakistan. It also includes detail study of solar radiations in different areas of Pakistan and the process how to utilize this energy in a useful way. Energy demand, electricity deficit and capacity of solar energy in Pakistan. Also explains different alternatives for solar thermal energy and its performances and comparison in detail. Solar thermal energy usage in Pakistan for different process in industries and domestic. Overview of different solar thermal collector used in Pakistan for hot water system. This chapter describes Study objectives of this research and the steps to complete the required work. Climatic conditions of Islamabad also discussed in details and plotted graph are shown.

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Chapter 2

Literature Review

2.1. Outline

Solar thermal collectors are used to utilize solar thermal energy to heat water. There two types of thermal collector concentrating solar collectors and non-concentrating thermal collectors. In second type of collectors evacuated tube collectors and FP collectors are used, which are normally used hot water application system. EFP collectors can be made by creating vacuum inside the enclosure of the collector. By creating vacuum inside the plate flat collector, top losses through convection from absorber to collector glazing glass was reduced. These types of collectors are used for achieving higher thermal outputs and efficient for industrial process heat.

The author in his research article tests two experimental models of evacuated flat plate collector to investigate theoretical aspects as well as provide technical solutions. One model has a metal tray to the rear, while the second one has two sheets of glass. The author designed experimental models to increase the efficiency and heat gain by reducing the heat loss. While reducing the internal vacuum pressure from 0.5 Pa there is a significant drop in the heat loss. By evacuating the collector overall heat losses reduced from 7.43 to 3.65 W/m^2K and efficiency at $\Delta T = 60^oC$, $G = 1000\ W/m^2$ has increased from 36% to 56% [1].

The author developed a model of an evacuated flat plate solar thermal collector for industrial process heat supply and for cooling application. The author used a low-pressure krypton filling inside the collector, as well as an emissive selective absorber, and a high reflective aluminum foil between the collector's back side and absorber to reduce thermal losses and increase thermal efficiency. Instabilities in the evaporator caused by two-phase flow were successfully controlled, and system design was examined. The prototype was tested in an outdoor environment and showed very high efficiency more than 60 percent at 100°C temperature and 45 percent at 150°C temperature [2].

The author designed two experimental models of evacuated flat plate collectors, each having black chrome absorber plate with an area of 0.5 × 0.5 m and tested under a solar simulator. Inlet and outlet temperature was observed by RTD and glass temperature was measured with the help of thermocouples. He conducted indoor tests with and without fan to cool down the top glass cover. By evacuating the collector, total losses was reduced by 3.6 W/m^2K matches with prediction results, and aperture efficiency was increased from 0.31 to 0.61 at $T_M/G = 0.06m^2K/W$. He also indicated that the black painted absorber plate coating was less efficient than commercial plate coatings, which resulted in low efficiency in non-evacuated situations [3].

The author done a comprehensive literature review on latest developments of evacuated collectors, their types, structure, applications, and challenges. Efficiencies of numerous types of evacuated tube collectors have been recorded, as well as their performance using different working fluids. After investigation, the author concluded that evacuated collectors are the most efficient collectors at higher thermal outputs. By analyzing literature, the author found that evacuated collectors perform better with nanofluids as compared to the conventional working fluids like water and air [4].

The author in this paper investigated Evacuated flat plate collector performance and effectiveness and then compared the results with conventional, photovoltaic thermal, and photovoltaic panels. The author performed simulations and demonstrated experimental model of evacuated flat plate collector and validating his model compares the data with commercial EFP collector for investigation the possibility of efficiency improvement. Concentrating and non-concentrating Organic Rankine Cycle power plants was compared with PV and PVT option, and observed the results that PVT is the best option for both heat and power. The overall heat loss calculated was 3.65 W/m^2K higher because of absorber coating emissivity and should be reduces to 0.41 W/m^2K when high selective vacuum and coating are used. The author discovers that an EFP collector can produce 104 percent more heat than a typical FP collector and 73 percent more heat than ETC collectors after studying simulations. He concluded that an flat plate collector having vacuum may be a viable alternative to the concentrating type of collector for power production in an Organic Rankine Cycle based on the findings [5].

2.2. Solar Thermal Technologies

The use renewable energy resources gain a lot of interest in recent days for reducing the adverse environmental impacts due to global warming, climate change, use of conventional energy resources, for reducing the energy demand for the fossils fuel energy and preserve this energy for the coming decades. Solar energy due to its abundance is the most reliable alternative source than any other renewable resources. solar energy can be used for different applications like drying agricultural products, building heating, cooling of air, water heating, power generation and distillation of sea water. Solar collectors are used for this purpose to deliver energy from moderate to high temperature. In solar collector, solar radiations are absorbed through the plate and converted to heat energy, then the heat passes to the working fluid flowing via the collector tubes or ducts and exchanges heat with the secondary fluid in the heat exchanger. In Pakistan many varieties of solar thermal technologies have been introduced for domestic purposes, that has a large contribution in market shares, but at industrial and commercial side solar thermal heat has a smaller contribution in market share. For improving solar thermal heat technologies in industrial applications, International Energy Agency (IEA) authorized a program solar heating and cooling. About 90 solar thermal power plants are in operating conditions for process heat application creating 25 MW of thermal energy in the world [6].

FP and evacuated tube collectors are most common types of thermal collectors used for water heating purpose in the home and commercial sectors. A new solar thermal collector technology evacuated flat plate collector has been introduced in recent years that has less contribution in market share and little work done in literature. All these collectors have different cost, structure, and performance. Collector should be selected according to the application, so that overall system performance, energy output, energy savings, cost and payback period is optimized. Types of solar thermal non-concentrating collectors are explained below.

2.2.1. Evacuated Tube Collectors

An evacuated tube collector is made of evacuated glass tubes in circular form arranged in several parallel rows. Each glass tube is made up of two tubes: an inner tube and an outer tube. The outside tube is transparent, while the inner tube is covered with solar radiation-absorbing materials. Solar radiation transmits through the outer tubes, and is subsequently absorbed by the inner tubes. Both have a low level of reflection. When the inner tubes absorbed radiations, it becomes heated and to keep the heat inside the tubes vacuum is created between outer and inner tube to prevent heat transfer from inner tube to ambient. Evacuated tube collector has good thermal performance during cold weather conditions and can easily be installed and transported from one place to another. To create a vacuum both the tubes are fixed together, and the air is removed through the pump. Inside the glass, tubes contain copper tubes connected to the heat exchanger on one side for heating [4]. When the working fluid inside the tube gains heat it is converted to vapors and goes upward where it exchanges heat with water in the manifold. These types of collectors are used for lower temperature outputs. Evacuated tube collectors are the best option for water heating of household purposes and on smaller scale where temperature requirement is not higher. Evacuated tube collectors can achieve lower thermal outputs than the evacuated flat plate collectors. These types of collector are efficient in low irradiance. **Figure 2.1** and **Figure 2.2** Shows evacuated tube collector and application of evacuated tube collector respectively.

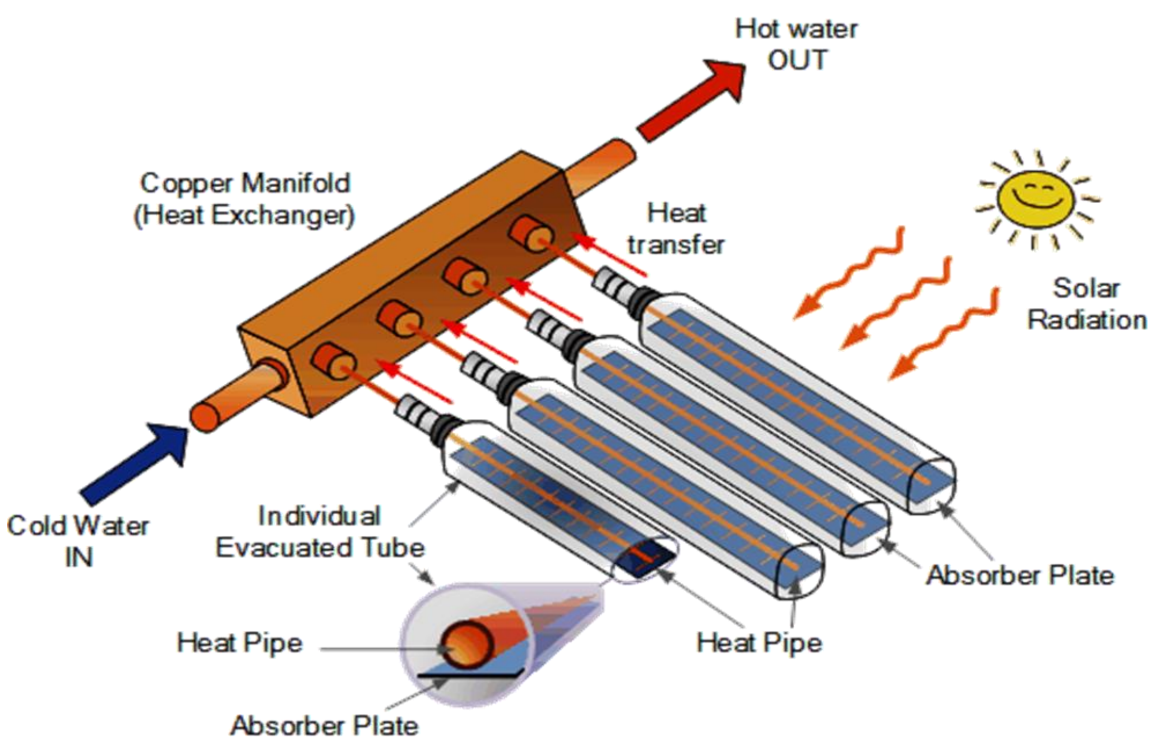

Figure 2.1 Evacuated tube collector model [7]

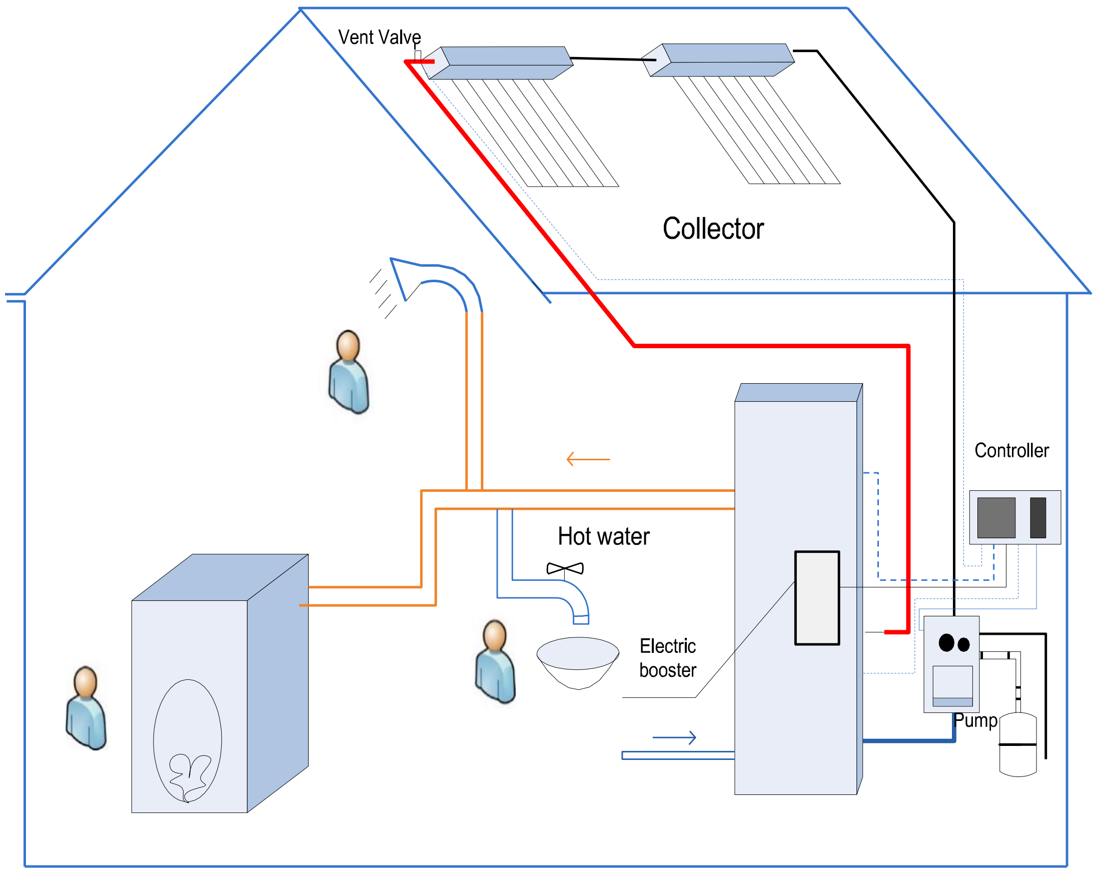

Figure 2.2 Evacuated tube collector application for domestic purposes [4]

2.2.2. Flat Plate Collector

The FPC is the simplest of the several types of solar thermal technologies, of low cost, and easily installed, therefore they are the most usable collectors globally. The performance of a FPC is extremely sensitive to changes in the collector's design characteristics. A simple FPC consists of a glazed glass fixed on the collector's upper surface, an absorber that absorbs radiations, tubes fixed on the absorber's bottom surface that contain fluid circulates in the collector tubes, and insulation fixed below the absorber to prevent heat transfer to the ambient. Between the glazing glass and the absorber Air is present. The glazing glass is used to minimize the reflected flux and radiation heat transfer to the environment. Working fluid flows via the tubes gains the energy absorbed by the plate, which rises the temperature of the working fluid used directly for application or exchanges heat with secondary medium in the heat exchanger and then returns to the collector [7].

Flat plate collectors are simple designed collectors which are used for achieving moderate temperature ranges. Both diffuse and beam radiations are utilized in this type of collector and do not require any sun tracking. Flat plate collectors are used for heating purposes with different working fluids like air, water, glycol etc. Collector having air is a working fluid needs air to be handled in large volume with low thermal capacity, which is a primary disadvantage of solar air collector. While collectors with working fluid water gains higher thermal outputs than the solar air collectors and achieves higher thermal efficiencies. On the other hand, collector with working fluid glycol or water glycol mixture can achieve higher temperature than the collector having water as a working fluid, because of the difference between the working fluids boiling points.

The author studied the energy and exergy evaluation of flat plate collectors in great depth. After some research, he discovered that utilizing back insulation with a thickness of 5 cm had no influence on the flat plate collector's exergy and energy efficiency. The author used water is a working fluid in heating pipe of the collector for gaining heat energy from absorber and then exchange this heat energy with another fluid through heat exchanger. The exergy analysis for this study assumed that the fluid input temperature would be the same as the ambient temperature and that the total heat loss coefficient from the collector would be constant [8]. **Figure 2.3** shows flat plate collector model from literature.

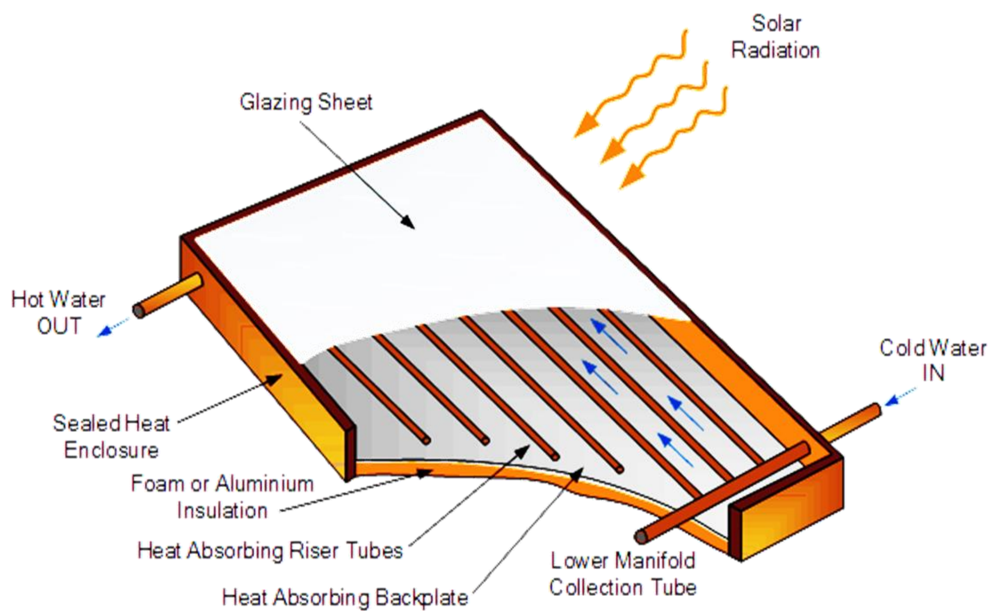

Figure 2.3 Flat plate collector experimental model [11]

The author discussed the flat plate solar collector and performed theoretical and experimental analysis to study the effect of parallel barriers on efficiency flat plate solar thermal collector. The author performed experimental analysis of the collector for different barriers location. He concluded that center line is best option for barrier location for gaining higher thermal efficiencies [9]. **Figure 2.**4 shows cross section view of flat plate collector and **Figure 2.5** shows block diagram of FPC system in a closed loop.

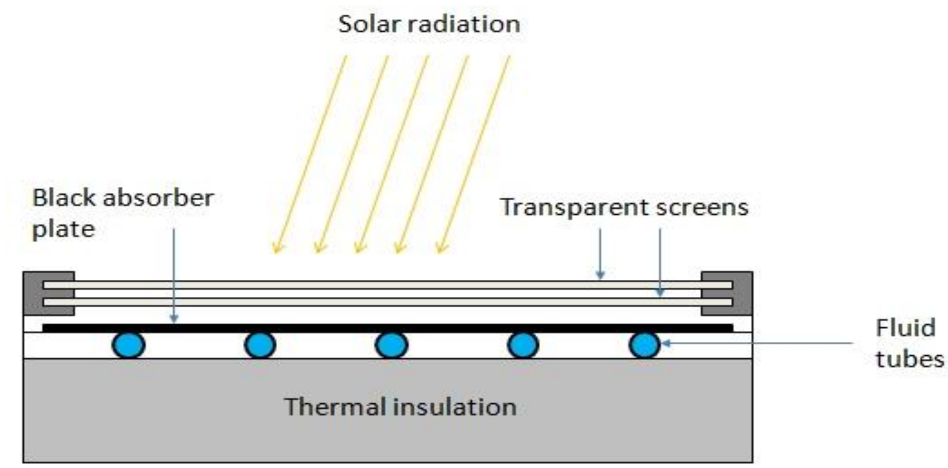

Figure 2.4 Flat plate collector cross-section view [12]

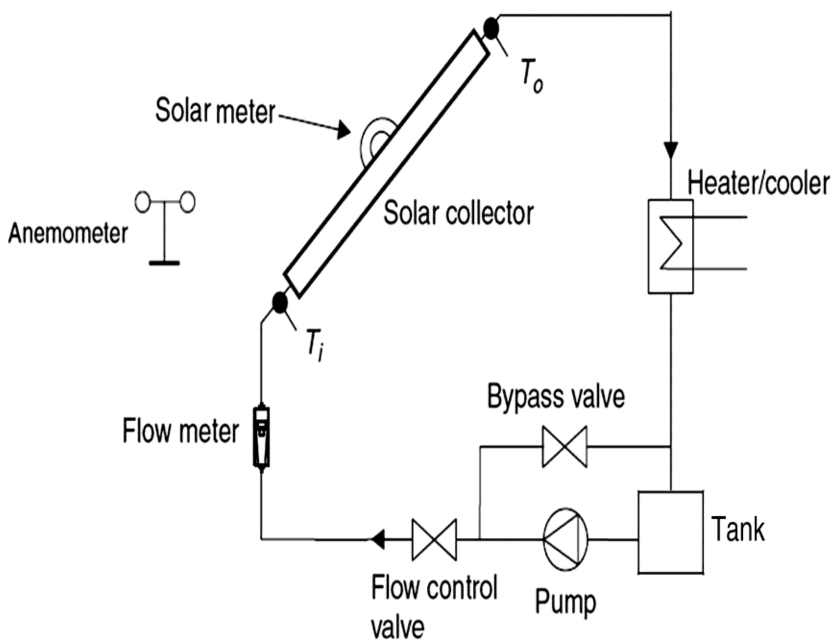

Figure 2.5 Schematic diagram of closed loop test system for flat plate collector [13**]**

2.2.3. Evacuated Flat Plate Collector

A novel solar thermal technique is the EFP collector having less contribution in the market shares. The advantage of this sort of collection system is that it is simple to construct, low cost and achieving higher thermal outputs due to its vacuum generated between the collector's absorber and the glass cover, which reduces convective heat losses from plate to the glazing glass. EFP collector comprises of a glass cover fixed at the top surface of the EFP, absorber plate gains solar energy and converts it to heat, and an array of fins attached between the collector's plate and the top glass cover to protect the cover from the vacuum-induced high air pressure load. Working fluid circulates inside the closed heating loop that absorbs heat from plate and transfer it to the secondary fluid in the heat exchanger. Due to evacuating the enclosure overall heat losses have been reduced from 7.43 to 3.65 W/m^2K [1]. EFP collectors can achieve higher thermal outputs and most suitable for hot water supply in industrial applications. As well as these types of collectors are also efficient in low irradiance. For evacuated flat plate collector tracking of sun is not important as a result of which it may be simply fitted into the building envelope and can also absorb diffuse radiations [10]. These collectors have the advantage of lower cost than other types of collectors, it can easily be handled and operates at higher temperatures, when losses are minimized. The lifetime of an evacuated flat plate collector is longer than that of a collector without vacuum, Because of vacuum in the enclosure condensation and humidity issues do not arise inside the collector shell. EFP collector can operate at higher temperatures in the range of 100 to 150 °C by using selective absorber having very small losses to the top and bottom of the collector casing [2].

For selection of solar collector absorber temperature is an important parameter. The point at which the absorber touches the edges of the stainless steel strip creates a thermal resistance to heat transfer from absorber to steel having a very little impact on collector efficiency, because of the low conductivity of the steel strip [3]. The evacuated enclosure creates a good insulation between the top and the back cover and also minimizes the absorbers heat loss, therefore EFP collector replaces conventional insulation [11]. Domestic hot water applications require temperature in the range of 50 to 70 °C, while in industries temperature requirement is higher. Solar thermal collector can also operate efficiently for the production of combined heat and power (CHP) [12]. **Figure 2.6** represents the cross-section view of evacuated flat plate solar thermal collector. **Figure 2.7** presents the prototype of evacuated flat plate collector.

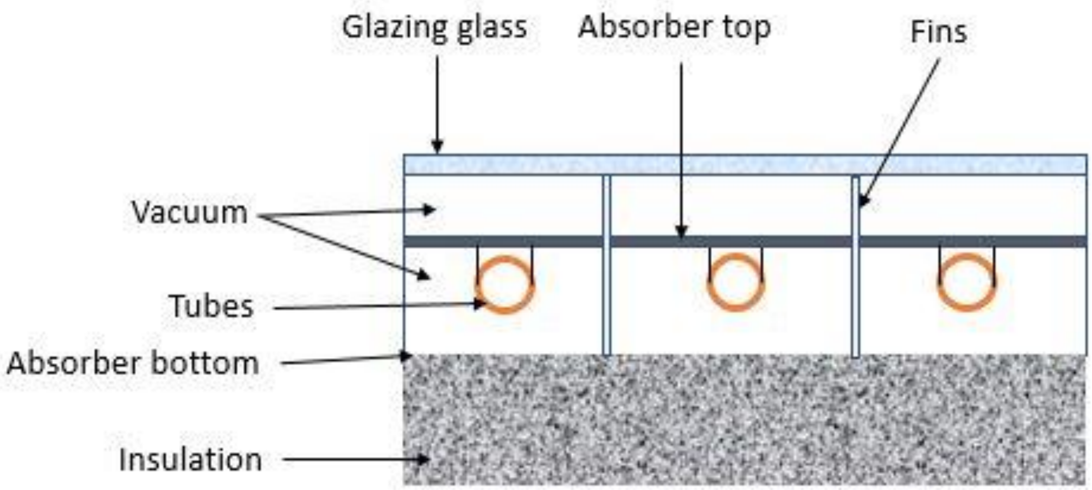

Figure 2.6 Cross-section view of Evacuated Flat Plate Collector

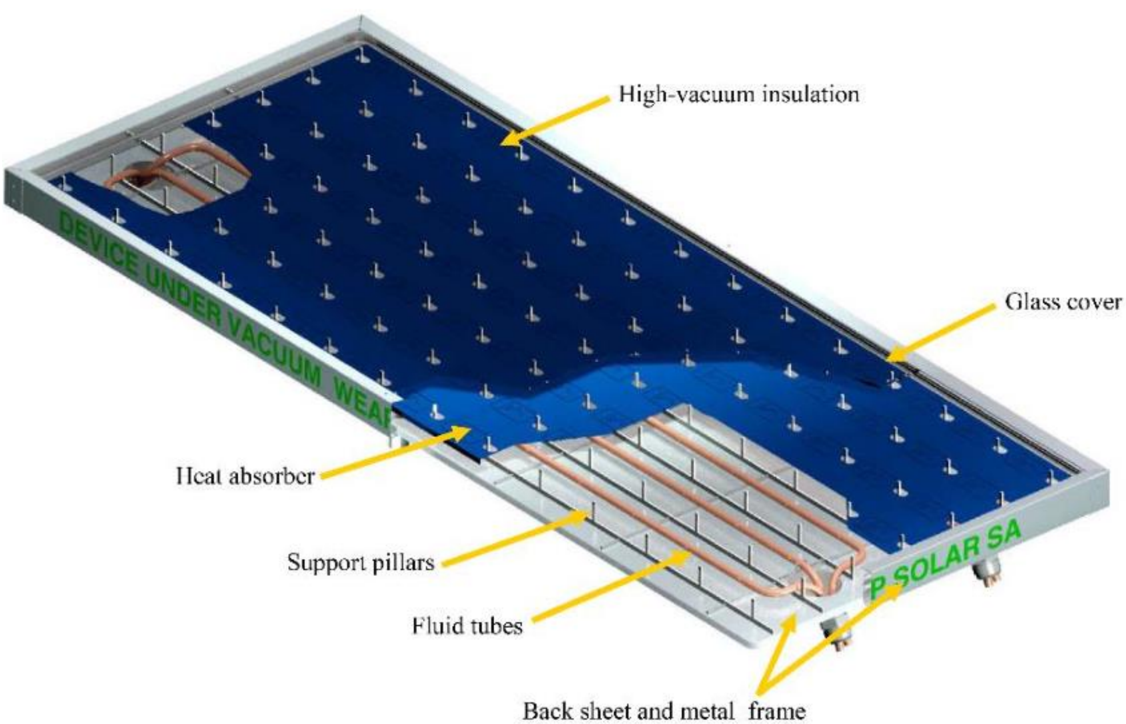

Figure 2.7 Prototype of EFP system for process steam production [8]

This research article discusses the EFP solar thermal collector type. The EFP collector has a 4 m^2 surface area and copper tubes having 0.010 m of diameter. Inside the collector's heating pipe, a water-glycol combination is employed as a working fluid. Vacuum is created by using vacuum pump. To find the features of design parameters that would yield satisfying results by studying the influence and sensitivity investigation of an EFP collector on solar radiations average basis. Solar radiations, weather data and monthly average collector characteristics of a specific month were used as input parameter data in MATLAB programming codes. MATLAB code has been written to experiment with different collector parameters and observe the outcomes. The program is developed in MATLAB and simulated under collector's design circumstances with an input climate data obtained from MHP equipment positioned at USPCAS-E, NUST Islamabad**,** Pakistan (33.64^o N, 72.99^o E). The study also comprises of parametric sensitivity investigation of the collector using MATLAB programming to better understand different settings and results. The results of this programming are then compared with a reference study of solar flat plate collector.

2.3. Textile Industry

In Pakistan textile industry has a greater impact on total exports, as cotton is produced in abundant amount in Pakistan. A larger portion of fossil fuels is consumed in Pakistan industrial sector. Textile industry process consumed abundant amount of energy in the form of electricity or natural gas. From year 1971 to 2004 total energy consumed in textile side has been increased from 47 Ej/year to 90 Ej/year in the world, which shows that energy consumption is almost doubled that will have a greater impact in energy crises[13]. In Pakistan we know the prices of natural gas are going to increase day by day and the demand is higher than the supplied. When abundant amount of gas is consumed in textile industry there is always load shedding for residential applications. Between 1980 and 2010 there is abundant increase in natural gas consumption from 50 tcf to 115 tcf according to Energy Information Administration (EIA) reports 2012, and this consumption will be increased from 115 tcf in 2010 to 186 tcf in 2040 by EIA 2013 data [14]. In industry there are a plenty of process like washing, heating, bleaching, drying, weaving, wet processing etc., use thermal technologies for process heat, which be feasible on both technical and economical side [15]. In cotton textile 95% of water is consumed raw material processing while 5% is used in cotton fabric production. For processing of 1 kg of cotton textile 100-150 liters of water will be consumed. In textile industry a unit which produces 20,000 lb/day fabric will consume 36,000 L of water per day [16]. **Figure 2.8** presents the schematic diagram of EFP collector for process steam production.

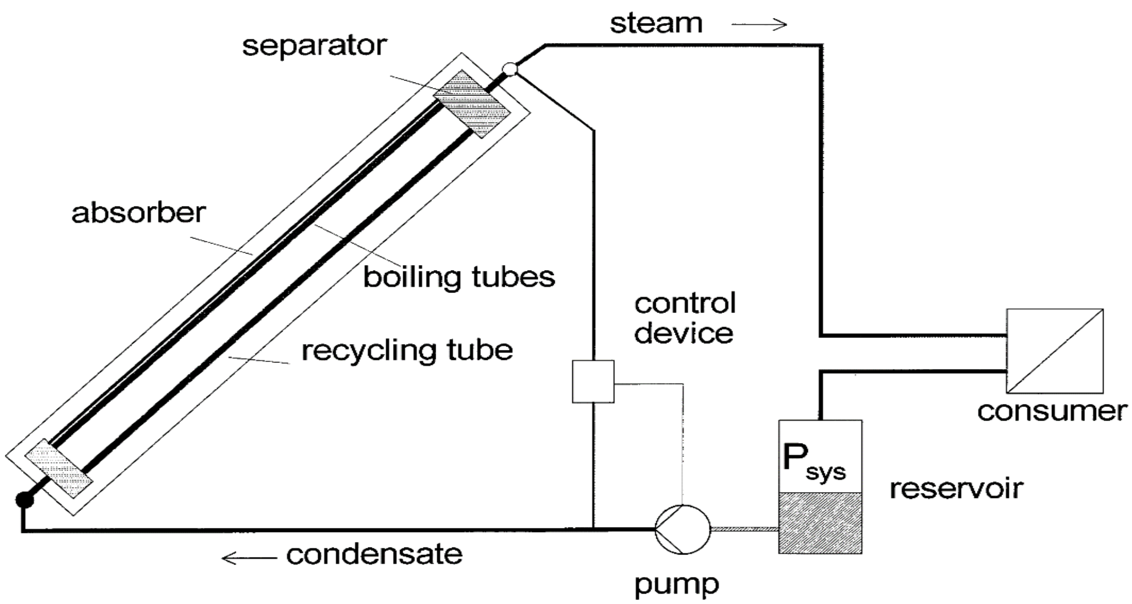

Figure 2.8 Schematic diagram of flat plate collector for process steam production [2]

Summary

Chapter 2 explains the detailed literature study of EFP collector and other solar thermal collectors. It explains briefly the work done on the EFP collector in the literature, their methods of work, process includes in the study and the outputs of their research work. Different alternatives used for shifting from fossil fuels towards the renewable energy. Solar thermal collector technologies are explained in detail with figures, configurations, and performances. Three main types of solar thermal collectors are explained in detail i.e. evacuated tube collector, flat plate collector and evacuated flat plate collector. Overview of collector experimental model and their different parameters are discussed. Weather data collection source for Islamabad and its accurate location. Hot water used in textile industry for different processes and how the collectors are useful to replace the fossil fuels with renewable energy.

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Chapter 3

Mathematical Modeling

3.1. System Description

For domestic hot water usage normally adopt non-concentrating thermal collectors like FPC and ETC. For medium temperature ranges in industries evacuated tube collectors are feasible. Higher temperatures ranges can be achieved through high efficiency collectors like EFP collector. EFP collector model has been discussed in this research article. The EFP collector has a 4 m^2 surface area and copper tubes having 0.010 m of diameter. Inside the collector's heating pipe, a water-glycol combination is employed as a working fluid. Vacuum is created by using vacuum pump. **Figure 3.1** shows the experimental model of evacuated flat plate collector installed at USPCAS-E, NUST.

Figure 3.1 Evacuated flat plate collector experimental model

To find the features of design parameters that would yield satisfying results by studying the influence and sensitivity investigation of an EFP collector on solar radiations average basis. The heating loop of the collector contains water-glycol mixture, which is pumped at a flow rate of $\dot{m}$, and having known specific heat capacity Cp. Such type of collectors can operate at higher thermal outputs and is efficient for industrial application. Even in low irradiance EFP collector work efficiently. For evacuated flat plate collector tracking of sun is not important as a result of which it may be simply fitted into the building envelope and can also absorb diffuse radiations [1]. Unlike simple flat plate collector, EFP collector has vacuum between absorber and top glass, which has negligible convective heat transfer losses in space between absorber plate and glazing glass cover. And moreover, it can achieve higher operational temperature. Using meteorological data from Islamabad, the main purpose is to determine the working fluid's exit temperature and the collector's usable energy gain. **Figure 3.2** represents pumping station, datalogger and controller integrated with collector. **Figure 3.3** represents experimental setup of the collector.

a) b) c)

Figure 3.2 a) Pumping station, b) Datalogger, c) Controller

Figure 3.3 Experimental setup of evacuated flat plate collector model

3.1.1. Assumptions

For simplification of solar collector modeling, following assumptions should be made [2].

1. Mass flow rate through collector tubes should be uniform.
2. One dimensional heat transfer system.
3. Heat transmission from the collector's edges is minimum.
4. Insulation and glass cover properties will be independent of temperature.
5. Losses from the collector front and rear are set to the same temperature.
6. Solar radiations and ambient temperature both are time dependent.
7. Dust on collector's surface are negligible.
8. The cover's heat flow is one-dimensional.
9. Negligible temperature drops through the cover.

Figure 3.4 illustrates the storage tank integrated with the collector system works as a heat exchanger.

Figure 3.4 Storage tank installed as a heat exchanger for hot water system

3.1.2. Thermal Resistance Network

Thermal resistance network diagram easily explains the temperature distribution along the flow direction, heat transfers through radiation and convection from different parts of the collector and overall losses of the collector as shown. "Tc" represents cover temperature, "Ta" represents ambient temperature, "Tp" absorber temperature and "Tb" represents bottom plate temperature. "hw" represents heat transfer through convection due to wind. Where "hr,c-a" illustrates heat transfer through radiation from glass cover to surrounding. "hr,p-c" stands for radiation from absorber to glazing, "Δx/k" stands for the conductive heat transfer from absorber to the wall of tube, "hfi" shows the heat transfer due to convection inside the copper tubes. "Ub" stands for the heat losses from the collector's bottom. Thermal resistance network helps in writing relations for the matrix used in the MATLAB programing code for simulation of the collector. **Figure 3.5** represents the thermal resistance network diagram for EFP.

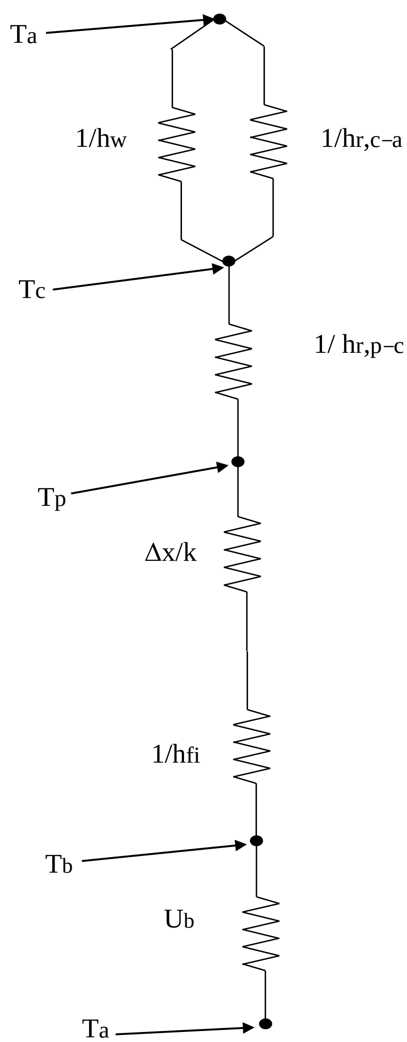

Figure 3.5 Thermal resistance network diagram for EFP collector

3.2. Methodology

For design parameters and its characteristics, the following method have been used.

3.2.1 Determination of Mathematical Modeling

Calculation of program codes were developed in MATLAB programmed by using equations from 1 to 18. Daily solar radiation on average basis and weather data of Islamabad has been used as input for calculation of different parameters in evacuated flat plate collector.

3.2.2 Optimization of Collector Parameters

To find the features of design parameters that would yield satisfying results by studying the influence and sensitivity investigation of an EFP collector on solar radiations average basis. Solar radiations, weather data and monthly average collector characteristics of a specific month were used as input parameter data in MATLAB programming codes. By varying some characteristics of collector like Tube spacing, mass flow rate, gap between absorber flat and glazing, collector area and length of collector tube in MATLAB codes to study its effects.

3.3. Numerical Modeling

Solar radiations, weather data and monthly average collector characteristics of a specific month were used as input parameter data in MATLAB programming codes. MATLAB code has been written to experiment with different collector parameters and observe the outcomes. The program developed in MATLAB is simulated with collector's design circumstances with an input climate data obtained from MHP equipment positioned at USPCAS-E, NUST Islamabad**,** Pakistan (33.64^{o} N, 72.99^{o} E). The study also comprises of parametric sensitivity analysis of the EFP using MATLAB programming to better understand several settings and results. The results of this programming are then compared with a reference model of a flat plate collector. For modeling the following analytical procedure was used for calculating different parameters of collector.

3.3.1 Losses Through Radiation from Absorber to Cover

The transfer of heat through electromagnetic waves is radiation, which requires no medium for heat transfer. Solar radiations that are transmitted through glazing glass heat up the absorber and little radiations are transmitted back to the glazing glass. Equation for heat transfer via radiation from absorber to glazing is expressed as [2].

$$h_{r,p-c} = \frac{\sigma\left(T_p^2 + T_c^2\right)\left(T_p + T_c\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \tag{1}$$

whereas,

$h_{r,p-c}$ = radiation heat transfer from absorber to cover

σ = Stefan Boltzmann constant

Tp = plate mean temperature

Tc = temperature of top glass cover

ε_p = emissivity of plate

ε_c = emissivity of glass cover

3.3.2 Losses Through Radiation from Cover to Ambient

Solar radiation when transmitted through glass cover, some of radiations are absorbed through glass cover which goes back to ambient through electromagnetic waves. The absorbed radiations are in very small amount and can be expressed through the following equation [2].

$$h_{r,c-a} = \varepsilon_c \sigma (T_c^2 + T_a^2)(T_c + (T_a) \tag{2}$$

Whereas,

$h_{r,c-a}$ = radiation heat transfer from glazing glass to the ambient

3.3.3 Total Top Losses

Overall top losses from collector top glazing glass and plate can be expressed through the following equation [2].

$$U_t = \left(\frac{1}{h_w + h_{r,c-a}} + \frac{1}{h_{r,p-c}}\right)^{-1} \tag{3}$$

h_w = heat transfer through convection from glazed cover due to wind

h_w = 2.8 + 3.3 × V

3.3.4 Losses from Absorber Top Plate to Absorber Bottom Plate

Solar radiations that are absorbed through absorber plate heats up the fluid(glycol) inside the tubes which fixed at the back side of the absorber. Some of the heat losses from absorber back side to the absorber's bottom through radiation, that heat is expressed through the following relation [3].

$$h_{r23} = \frac{\sigma(T_3 + T_2)(T_3^2 + T_2^2)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_p} - 1} \tag{4}$$

Whereas,

h_{r23} = radiation from absorber back to bottom

T_3 = absorber bottom plate temperature

T_2 = absorber temperature

ε_p = emissivity of plate

As the radiation occurs between the two surfaces having the same material, so emissivity for both will be the same.

3.3.5 Overall Losses

The sum of total top losses is the collector's total heat loss coefficient, bottom losses and losses from the edges of the collector. The following Relation represents overall heat loss coefficient of the collector [2].

$$U_L = U_t + U_b + U_e \tag{5}$$

Whereas,

$U_b =$ Bottom losses

$U_e =$ Edge losses

Bottom losses for Evacuated flat plate collector are usually in the range of 0.8 – 1 ($^{W}/_{m^2K}$) and edge coefficients are $U_e \approx 0.2$. From units we can see that rate of energy loss is proportional to the collector area and the temperature difference of the solar thermal system and the ambient air [4].

3.3.6 Heat Removal Factor of the Collector

The heat removal factor of a collector F_R is the ratio of the collector's real useful energy gain to the collector's actual energy gain, if the surface temperature of the whole collector is same as the inlet temperature of the fluid, and heat losses to the environment is minimum. Heat removal factor depends on the fluid inlet and outlet temperatures, ambient temperature, and collector area. The actual usable energy gain is calculated by multiplying the heat removal factor by the collector's maximum useful energy [5]. The collector heat removal factor is the function of the heat transfer fluid flow rate [6].
Relation for collector heat removal factor is expressed as [7].

$$F_R = \frac{\dot{m}C_p}{A_c U_L}[1 - \exp\left(\frac{-A_c U_L F'}{\dot{m}C_p}\right) \quad (6)$$

Whereas,

$\dot{m}$ = mass flow rate of collector

C_p = specific heat capacity of water glycol mixture

A_c = collector area

U_L = overall heat loss from collector

F' = collector efficiency factor

Collector efficiency factor (F') is the ratio of actual thermal energy of the collector to the thermal energy of an ideal collector, whose fluid temperature and absorber temperature is same. The collector efficiency factor describes the thermal quality of solar thermal collector. As the collector efficiency factor F' is strongly depends on distance between the tubes w and plate thickness δ, and strongly related with the material of the absorber plate and tubing[8]. It may be estimated by comparing the temperatures of the two pipes and assuming that the temperature gradient along the flow direction is insignificant [2]. The correlation of collector efficiency factor with tube spacing and plate thickness can be expresses from the following **Figure 3.6**.

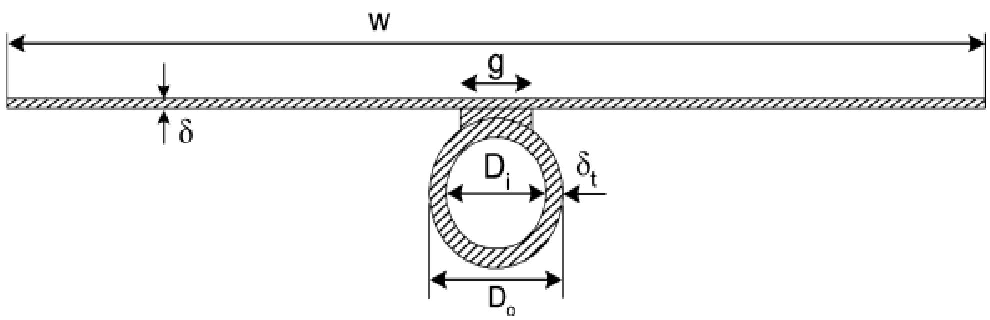

Figure 3.6 Nomenclature of tube and absorber [8]

Collector efficiency factor can be expressed from the following relation [7].

$$F' = \frac{1/U_L}{W\left[\frac{1}{U_L(D + (W-D)F)} + \frac{1}{\pi D h_{fi}}\right]} \tag{7}$$

Whereas,

W = spacing between the tubes

D = internal diameter of pipe

h_{fi} = convective heat transfer coefficient inside the tubes

F = standard fin efficiency

Standard fin efficiency(F) can be expressed through the following relation [7].

$$F = \frac{\tanh[\frac{m(W-D)}{2}]}{\frac{m(W-D)}{2}} \tag{8}$$

$$m = \sqrt{\frac{U_L}{K\delta}} \tag{9}$$

$U_L =$ collector's total heat transfer coefficient

$K\delta =$ the product plate thermal conductivity and its thickness

D = internal diameter of pipe

3.3.7 Heat Transfer Coefficient Inside the Tubes

When solar radiations absorbed by the plate, then theses radiation transfers from tube walls to the working fluid through convective heat transfer. For turbulent liquid flow inside the tubes (2300<Re = ρVDh/μ < 5 × 10^6 and 0.5 < Pr < 2000 relation for Nusselt number will be expressed as [2].

$$Nu = \frac{\left({}^{f}/_{8}\right)(Re-1000)Pr}{1.07 + 12.7\sqrt{\left(\frac{f}{8}\right)}\left(Pr^{2/3}-1\right)}\left(\frac{\mu}{\mu_w}\right)^n \tag{10}$$

n for cooling is 0.25 and for heating is 0.11. Darcy fraction f is given by

$$f = (0.79 \ln Re - 1.64)^{-2} \tag{11}$$

The thermal boundary condition is critical for laminar flow inside collector tubes. The Nusselt number for tube walls with constant temperature is 3.7, while the average Nusselt number for constant heat flux is 4.36 for fully developed thermal profiles. The thermal state in solar thermal collectors is completely reflected by constant resistance inside the tubes and the constant temperature surroundings. Thermal boundary conditions approach constant heat flux when the resistance between the flowing fluid and the surroundings is great, and constant temperature when the resistance is minor. Convective heat transfer coefficient within the tubes for laminar flow is represented by the following equations [2].

For laminar flow inside the tube, average Nusselt number is 4.36. And Nusselt number can be find from the **Figure 3.7**.

$$Re = \frac{4\dot{m}}{\pi D_i \mu} \tag{12}$$

Whereas,

$\dot{m} =$ mass flow rate per tube of collector

Di = internal diameter of tube

μ = dynamic viscosity of water glycol mixture (3.6×10^{-4})

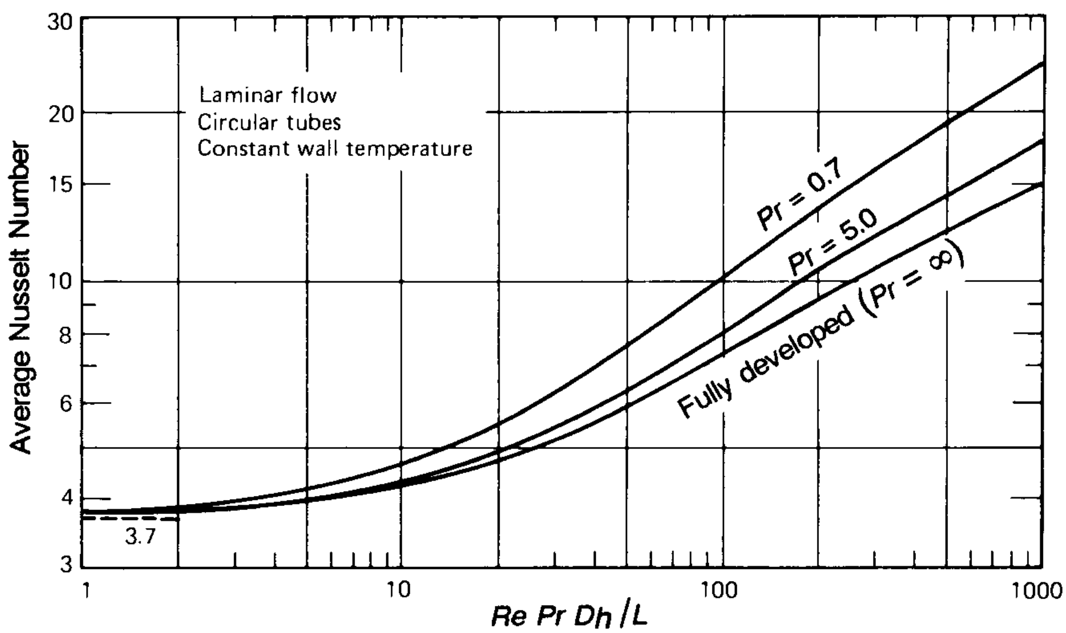

Figure 3.7 Average Nusselt number in tubes for various Prandtl numbers [2]

$$\frac{Re\,\mathrm{Pr}\,Dh}{L} \tag{13}$$

By calculating the above relation, we can easily find the Nusselt number against the Prandtl number from figure 3.1. Now final relation for the heat transfer through convection inside the tubes is given by.

$$h_{fi} = \frac{NuK}{D} \tag{14}$$

K = Thermal conductivity of water glycol mixture

Nu = Nusselt number for laminar flow

Fluid outlet temperature of collector can be expressed by the following relation.

$$T_{fout} = 2T_f - T_{fi} \tag{15}$$

3.3.8 Useful Energy of Collector

The engineering goal of solar collector system designing is to minimize the thermal losses from the collector, to arise the useful energy yield of thermal system and to prioritize the season for collector performance. The useful energy gain of an evacuated flat plate collector may be used to describe its performance (Qu). The difference between incident solar irradiance and thermal losses from the collector equals the solar radiation absorbed via the collection plate per unit area [7]. The relation for useful energy gain of evacuated flat plate collector is given as [2].

$$Q_u = F_R A_c\left[S_2 - U_L\left(T_{fi} - T_a\right)\right] \tag{16}$$

$$S2 = H \times \alpha_p \times \tau \tag{17}$$

Whereas,

Q_u = Useful energy gain of the collector

F_R = Collector heat removal factor

S_2 = Heat flux collected by the absorber plate from solar radiation

T_{fi} = Fluid inlet temperature

U_L = Overall losses of collector

α_p = Absorptivity of the plate

τ = Transmissivity

The heat removal factor is the effectiveness of the heat exchanger. And we know that we will get maximum useful energy output when the overall collector is at fluid inlet temperature. This energy balance equation is very useful for all type of flat plate collectors. When analyzing solar thermal collector system fluid inlet temperature must be known. When the solar thermal collector approaches to the inlet temperature of the fluid, then losses from plate to collector are very small and the fluid has an increasing temperature in the flow direction. By multiplying FR with the maximum useful energy output, it gives actual energy gain of the collector. By increasing fluid flow rate through the collector, temperature rise of the fluid in tubes decreases, and collector's heat removal factor increases. When the fluid flow rate becomes very high, the fluid temperature decreases towards zero, but the absorber temperature will always be high from fluid temperature.

3.3.9 Sensible Heat Requirement for Desired Temperature Rise of the Fluid

The usable energy necessary to increase the temperature of the working fluid to the appropriate temperature is referred to as this form of heat demand. When fluid flowing inside the copper tubes at a mass flow rate of $\dot{m}$, with temperature inlet T_{fi} to the desired temperature T_{fout}, then the useful energy required to gain this temperature can be find through the following relation [7].

$$Q_L = \dot{m}C_p\left(T_{fout} - T_{fi}\right) \quad (17)$$

Whereas,

$Q_L =$ Sensible heat requirement

$C_p =$ Specific heat capacity fluid

3.3.10. Efficiency of Collector

Efficiency of the collector is the ratio of solar energy collected by the fluid to the total incident solar energy in a specific time. Relation for collector efficiency is given as[9].

$$n_c = \frac{Q_u}{HA_c} = \frac{F_R[S_2 - U_L(T_{fi} - T_a)]}{H} \quad (18)$$

Summary

Chapter 3 describes the evacuated flat plate collector different parameters, process used inside the collector, different flow rates and the methodology. It explains the different parts of the collector, its sizes, and types. Different figures of the experimental model and their symmetric pictures are discussed in detail. Thermal resistance network diagram is shown and discussed the way of heat transfer through the collector with the help of this diagram. Solar radiations, weather data and monthly average collector characteristics of a specific month were used as input parameter data in MATLAB programming codes. The program written in MATLAB programing is simulated under collector's design circumstances with an input climate data obtained from MHP equipment positioned at USPCAS-E, NUST Islamabad**,** Pakistan (33.64^{o} N, 72.99^{o} E). Equations used in programing for radiations, convection, losses from the collector, efficiency, useful energy, and other parameters are discussed in detail.

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Chapter 4

Results and Discussion

4.1. Design Conditions for Simulation

The numerical equations mentioned in Chapter 3 of the current study were examined using MATLAB programming, which resulted in a program code for simulations to investigate the various parameters of the EFP collection system. Program code has been simulated with an input climatic conditions obtained from MHP equipment positioned at USPCAS-E, NUST, Islamabad. Design parameters of the collector are shown in the **Table 4.1** To study different parameters of the collector and its effect on useful energy and collector's fluid outlet temperature sensitivity analysis has been performed through MATLAB. EFP collector has been validated with reference model in the literature by considering design circumstances of the chosen reference model study.

Table 4.1 Collector specifications

Parameter	**value**
Collector Area	4 m^2
Fluid used	Water-glycol mixture 50/50 %
Emissivity of glazing glass	0.92
Emissivity of absorber's plate	0.95
glazing glass transmittivity	0.90
Absorber's plate absorptivity	0.95
Plate thickness	0.001 m
Insulation thickness	0.025 m
Absorber plate thermal conductivity	205 W/m*K
Vacuum pressure	-0.8 bar
Inner diameter of the tube	0.010 m

The significance of an EFP solar thermal collector has been examined by comparing the EFP collector simulation results with FP collector in the chosen reference study. Simulations performed for EFP collector are also validated with experimental results of the collector. Solar irradiance profiles for 15 June are illustrated in the **Table 4.2** and **Table 4.3** illustrates the solar irradiance profile for 10 February.

Table 4.2 Solar irradiance profile for 15 June

Hours (h)	**H (W/m^2)**	**T_{air} (ºC)**	**Wind speed (m/s)**	**S_2 (W/m^2)**
1	0	34.1	0.3	0
2	0	33.8	0.4	0
3	0	32.5	0.4	0
4	0	32.5	0.4	0
5	0	32.2	0.4	0
6	70	34.1	0.3	55.86
7	237	34.6	0.4	189.1
8	449	35.8	0.5	358.3
9	580	37.5	0.8	462.8
10	702	39	0.9	560.2
11	848	41	1.3	676.7
12	985	41.3	1.5	786
13	901	41.3	1.8	719
14	817	41	2	652
15	695	40.2	2.3	554.6
16	524	39.2	2.3	418.2
17	419	37.9	2.6	334.4
18	264	35.8	2.6	210.7
19	89	34.2	2	71.02
20	0	33.1	1.7	0
21	0	31.8	1.1	0
22	0	31.1	1.1	0
23	0	30.8	0.9	0
24	0	30.3	0.9	0

Figure 4.1 and **Figure 4.2** shows solar irradiance and ambient temperature trends for 15 June and 10 February respectively.

Table 4.3 Solar irradiance profile for 10 February

Hours (h)	H (W/m^2)	T_{air} (^oC)	Wind speed (m/s)	S_2 (W/m^2)
1	-4.98	15.93	5.81	-3.977
2	-4.33	16.08	5.1	-3.457
3	-5.05	15.03	5.02	-4.037
4	-5.56	14.52	4.087	-4.442
5	-5.88	13.85	3.54	-4.69
6	-9.59	10.55	0.328	-7.65
7	-0.37	10.22	2.69	-0.296
8	160.9	13.64	2.86	128.39
9	370.2	14.85	3.35	295.43
10	552.2	17.13	3.60	440.66
11	678.3	18.29	4.75	541.25
12	747.9	19.24	4.81	596.87
13	743.7	20.3	4.82	593.51
14	673.9	20.55	5.76	537.77
15	544.4	21.35	4.45	434.41
16	350.5	21.37	4.02	279.75
17	139.4	20.92	3.72	111.27
18	-4.10	18.73	3.88	-3.27
19	-7.95	17.09	2.31	-6.35
20	-5.92	16.98	3.22	-4.72
21	-6.89	16.54	1.84	-5.50
22	-6.48	17.19	2.18	-5.178
23	-8.80	16.89	1.79	-7.024
24	-5.99	16.58	2.58	-4.78

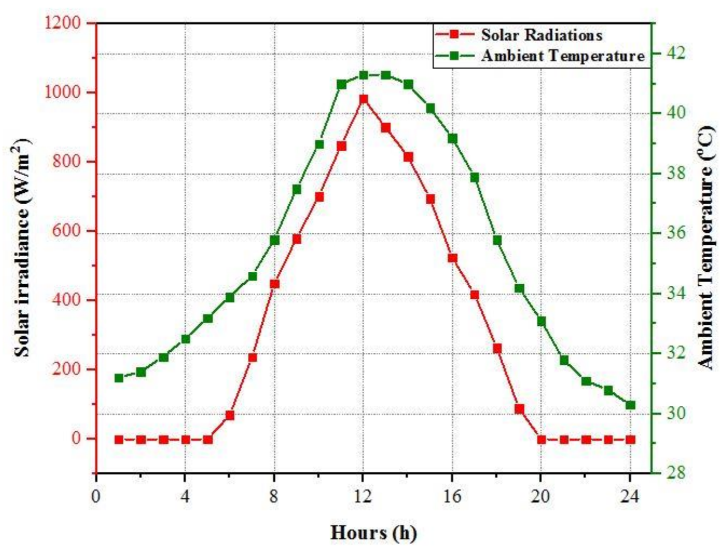

Figure 4.1 Solar irradiance and ambient temperature graph for 15 June

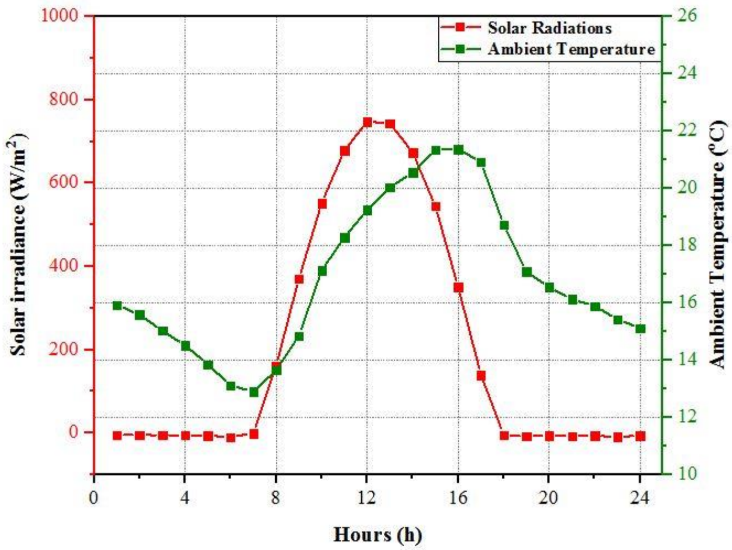

Figure 4.2 Solar irradiance and ambient temperature graph for 10 February

4.2. Temperature variation with respect to time

With design specifications of 4 m^2 area, the resulting program code is simulated for the months of February and June at mass flow rate of 0.0196 kg/s and examined the results for temperature of absorber plate, cover, fluid outlet temperature and ambient temperature. **Figure 4.3** shows that fluid outlet temperature will be maximum at 12 p-m. At that time

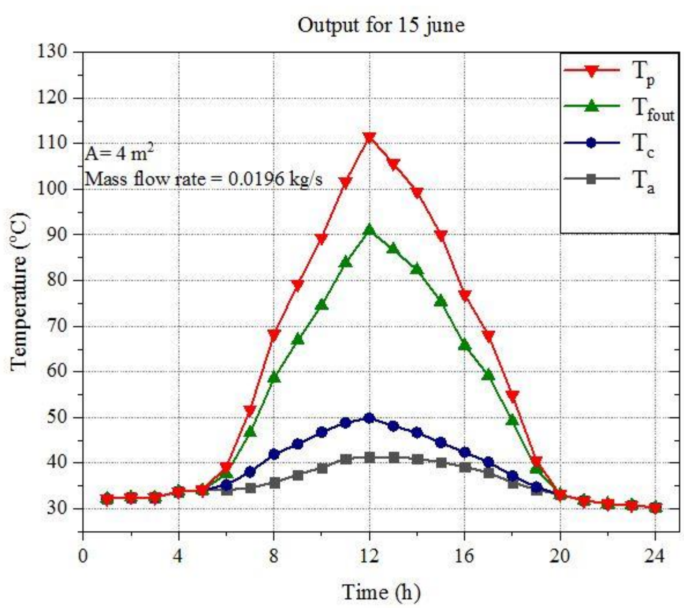

Figure 4.3 Variation of temperature with respect to time

absorber gains maximum radiations and converts it to heat, which arise the working fluid temperature inside the collector. EFP collector achieves higher temperature because of its vacuum between the plate and the glazing glass, which reduces the losses through convection from absorber plate to the glazing glass. Program code developed is simulated with input weather data of 10 February and plotted the results shown in the **Figure 4.4** **Figure 4.5** displays the results for storage tank outlet temperatures.

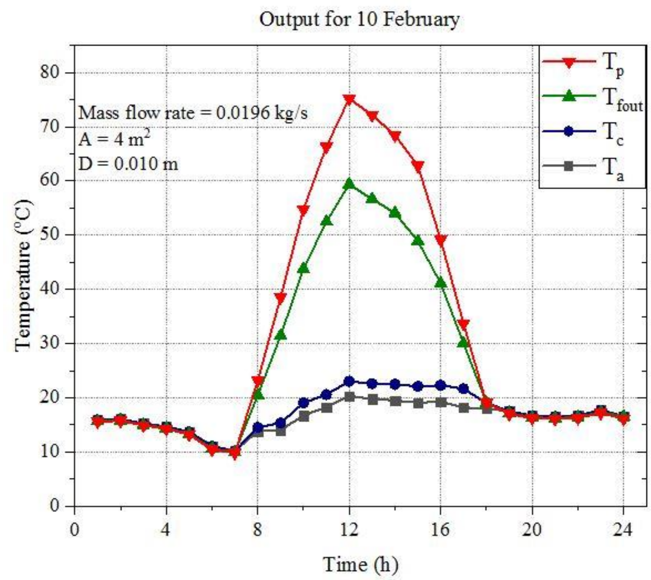

Figure 4.4 Variation of collector parameter temperatures with respect to time

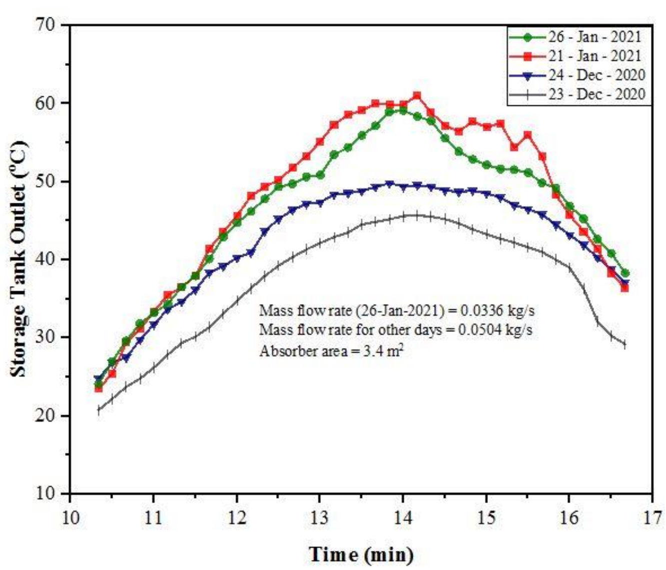

Figure 4.5 Sotage tank outlet temperature for given days

The cover temperature of EFP collector does not go higher due to the vacuum as it rises in FP collector, that drastically reduced convective losses from plate cover. It is observed that EFP achieves maximum of 59 °C fluid outlet temperature in the month of February. The results show that EFP collector also work properly in low solar irradiance.

4.3. Model Validation

Program code developed in MATLAB programing are simulated with design parameters of collector experimental model. Program code has been simulated with an input climatic conditions obtained from MHP equipment positioned at USPCAS-E, NUST, Islamabad. Simulated results are then validated with reference model study in the literature and validated with experimental results of evacuated flat plate collector model.

4.3.1 Validation with Reference Study

Using the design characteristics of the model in the literature, the collector model mentioned in chapter 3 is validated against the EFP collector model in the reference research [1]. **Figure 4.6** displays the impact of solar radiation on useful energy output for model validation. The author in this study compared the EFP collector experimental model

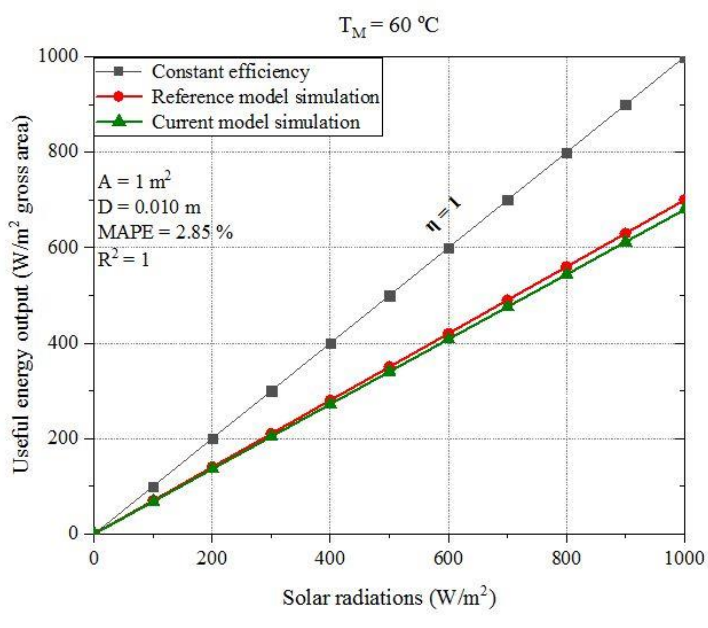

Figure 4.6 Solar radiation versus useful energy output of the collector

to Photovoltaic thermal and Photovoltaic panels in the reference model research. The current study EFP collector model simulation results are validated against the outputs of optimized EFP collector in the reference research. It demonstrates that the present study simulations agree with the reference research in the literature, which has a MAPE of 2.85 percent, the linear line indicates that the ideal collector has an efficiency of 1, R^2 indicates that the trends are linear. It can be seen as the solar radiations rises, the collector's useful heat energy increases as well. Results showed in **Figure 4.7** for maximum heat output per day on monthly basis are simulated against input parameters of the reference model at an area of 0.27 m^2 and fluid flow rate of 0.002 kg/s [1]. The current model conforms with the reference model, according to the results. It is observed that the collector has maximum heat output in the summer while having maximum irradiance.

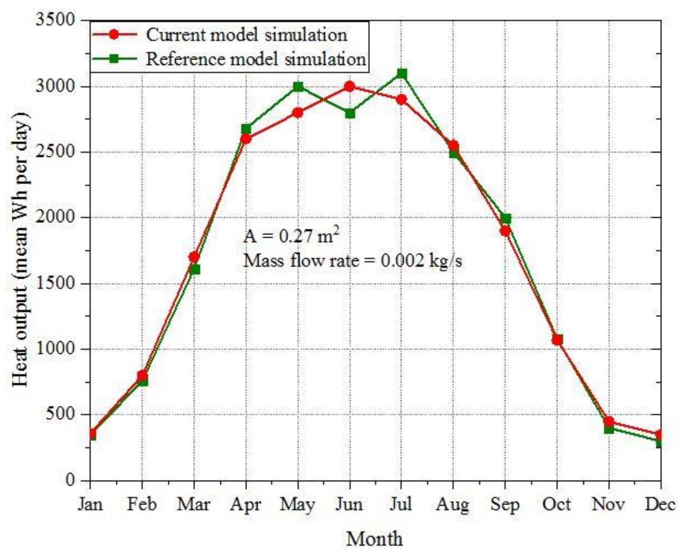

Figure 4.7 Average heat output per day versus corresponding months

For thermal efficiency, EFP collector model simulations are validated with the model in the reference study. The author compared non- evacuated collectors and EFP collectors in the presence and absence of PV modules in the reference model [2]. Simulations are run using the design circumstances and specifications of the model in the reference study, and the results are presented for fluid mass flow rate and collector's efficiency. **Figure 4.8** shows that the absolute percentage error is 8.56 percent and the R^2 is 0.71. According to the findings, the reference model in the literature agrees with the present model simulations.

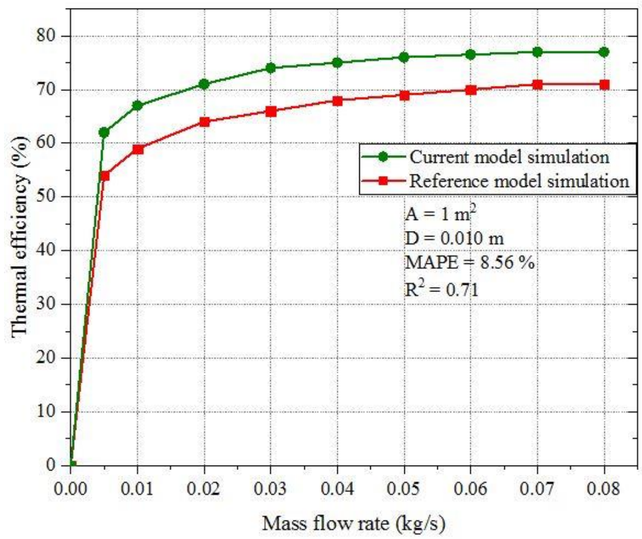

Figure 4.8 Effect of mass flow rate on the thermal efficiency of the collector

4.3.2 Validation with Experimental Results

Program code developed in MATLAB programing are simulated with design parameters of collector experimental model. Program code has been simulated with an input climatic conditions obtained from MHP equipment positioned at USPCAS-E, NUST, Islamabad. Evacuated flat plate collector was installed and vacuum is created by using vacuum pump maintained a pressure of −0.8 bar inside the collector. Storage tank with heat exchanger was integrated with the collector system and water-glycol mixture of 50/50 % was used inside the copper tubes of the collector. Experimental results were taken for different days through data logger. The simulation results developed through MATLAB was then validated with experimental results and plotted the graphs through origin. **Figure 4.9** shows the results fluid outlet temperature for 23 December 2020, it is observed that both the trends are concurrent having route mean square error of 1.5849 and percentage error on average basis is 2.619. Collector model achieved 56.7 °C of fluid outlet temperature from simulations, while 55.5 °C was achieved by experimental results. It is observed from the trends that simulations results are valid for EFPC collector system. On the same day experimental results for absorber temperature was taken through data logger and checked the validation by comparing it with simulation results for absorber temperature.

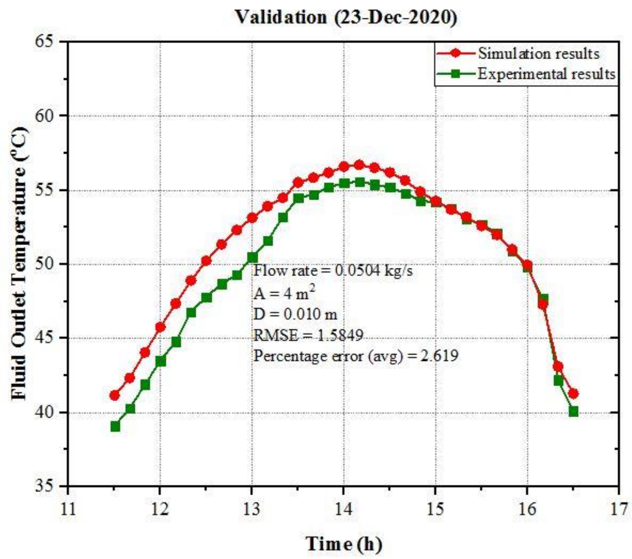

Figure 4.9 Model validation for fluid outlet temperature versus time

Figure 4.10 shows the results for absorber temperature by achieving a maximum 60 °C of temperature for simulation and that of 56.5 °C for experimental results. It can observe that simulation for absorber temperature is valid, while having RMSE of 2.58 and percentage error of 4.184.

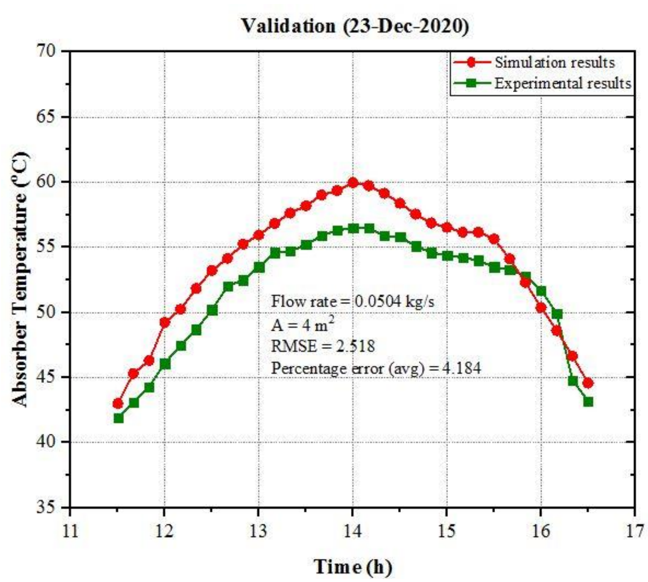

Figure 4.10 Model validation for absorber temperature versus time

Figure 4.11 shows the validation results for fluid outlet temperature on 24 December 2020. The simulation results from the same day was validated against the experimental results and plotted the graph, which present that route mean square error of 1.5587 and percentage

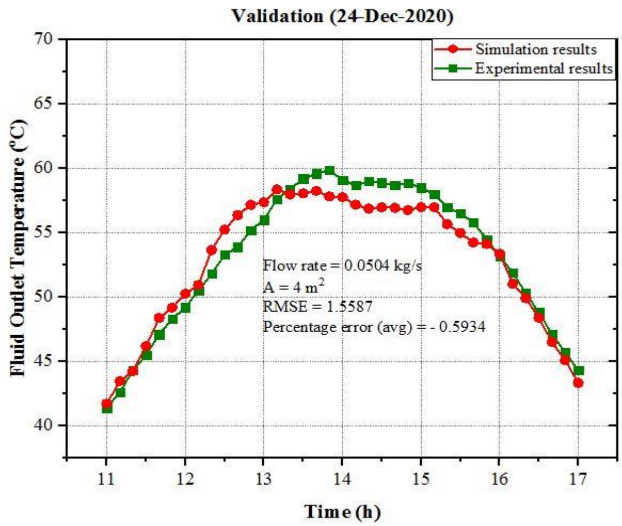

Figure 4.11 Model validation for fluid outlet temperature versus time

error of −0.584. Results for Absorber temperature was also validated with experimental results for the same day in the **Figure 4.12**, while having RMSE of 1.5213 and percentage error of 1.9914. Both the graphs reveal that simulations performed for EFP collector are valid against the experimental results taken through data logger integrated with the collector system.

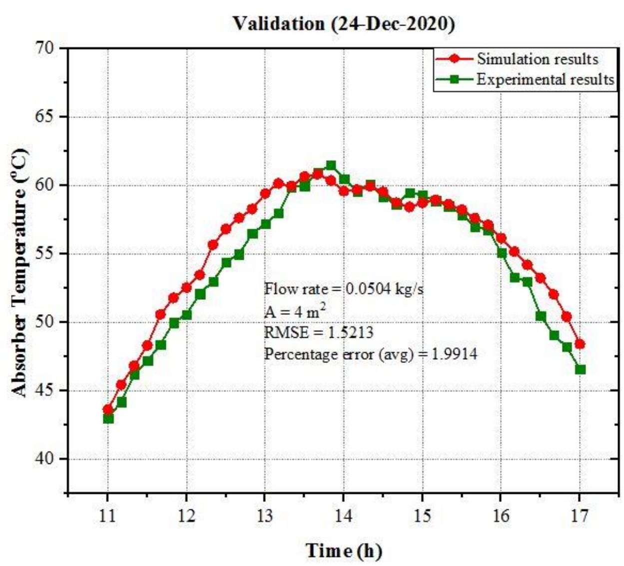

Figure 4.12 Model validation for absorber temperature versus time

Results taken for 21 January 2021 were also validated with simulation results for fluid outlet temperature of the collector. **Figure 4.13** shows RMSE of 2.717 and percentage error of 4.144, while achieving maximum peaks of 71 °C and 68.2 °C for simulations and experimental results respectively. The errors reveal that simulations performed for the evacuated flat plate collector system are valid. **Table 4.4** shows the RMSE and percentage errors taken from experimental validation of evacuated flat plate collector.

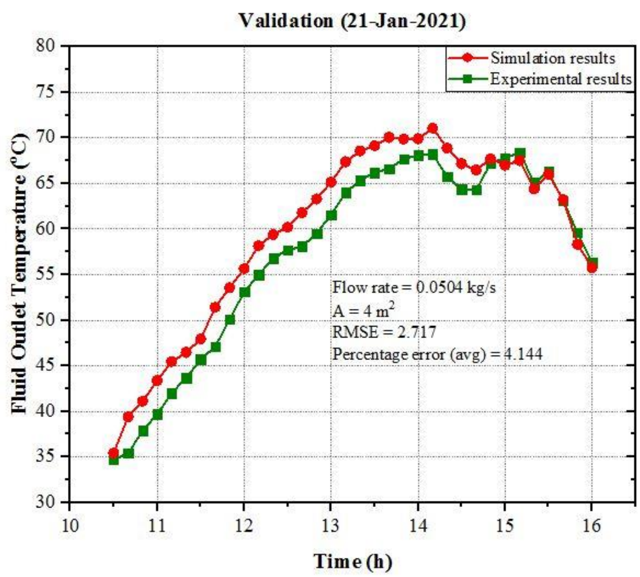

Figure 4.13 Model validation for fluid outlet temperature versus time

Table 1.4 Collector model validation with experimental results

Parameter	Date	RMSE	Percentage error (avg)
Fluid outlet temperature	Dec-23-2020	1.5849	2.619
Absorber temperature	Dec-23-2020	2.518	4.184
Fluid outlet temperature	Dec-24-2020	1.5587	- 0.5934
Absorber temperature	Dec-24-2020	1.5213	1.9914
Fluid outlet temperature	Jan-21-2021	2.717	4.144

4.4. Sensitivity Analysis

Sensitivity analysis of collector model was performed by varying design conditions and parameters of the collector to study its effect on collector efficiency, useful energy gain, and fluid outlet temperature. Simulations are performed by varying mass flow rates, collector area, solar radiations, and inlet temperature of fluid, then results are plotted to observe its effect on useful energy and fluid outlet temperature. Mass flow rate, collector area, and type of working fluid are important parameters for obtaining satisfactory required results.

4.4.1 Effect of Collector Area on Useful Energy Gain of the Collector

Surface area of the collector is considered as very important parameter of the collector. Collector having larger absorber area has the capacity to absorb solar radiations in abundant amount as compared to the collector having smaller absorber area. The influence of area on the collector's usable energy gain is seen in **Figure 4.14**, that shows maximum useful energy output of the EFP collector for larger areas while absorbing solar fraction in larger amount. By increasing absorber area of the collector receives larger amount of solar fractions [3]. When solar fraction on the absorber increases it increases useful energy output of the collector [1].

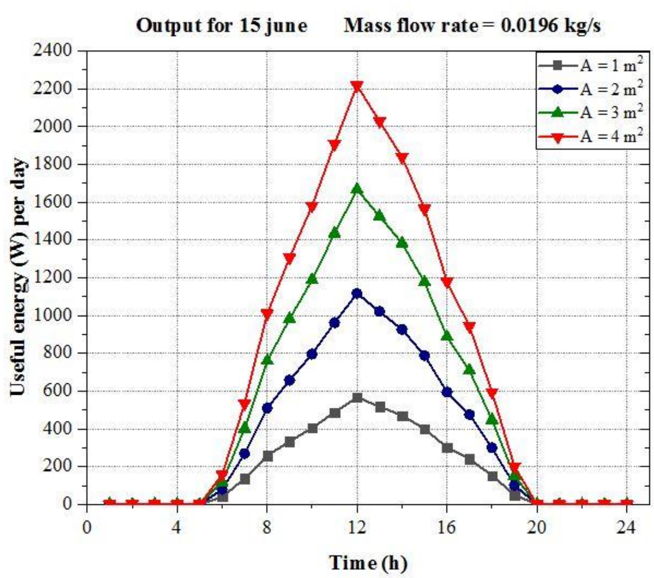

Figure 4.14 Effect of collector area on useful energy gain of the collector

4.4.2 Effect of Collector Area on Fluid Outlet Temperature

Figure 4.15 displays the variation in fluid outlet temperature with respect to the collector area for 24 hours. By increasing the collector area absorber surface exposed to the solar radiation will be increased and hence it will absorb radiations in abundance, which in turn raises the heat gain of the water-glycol mixture in the heating pipe results in a temperature rise of the fluid. Simulations are carried out at a flow rate of 0.0196 kg/s, the diameter of tube 0.010 m, and the area is the variable parameter varying from 1 to 4 m^2 and plots the results. It is that maximum fluid outlet temperature will be achieved when the collector area is greater.

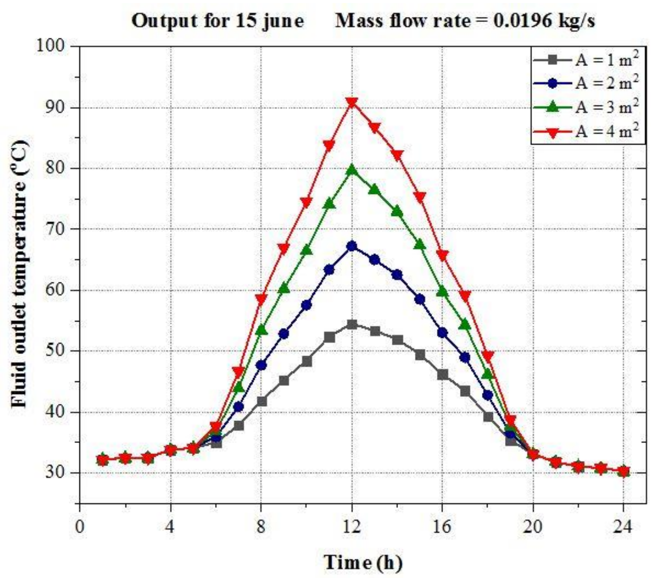

Figure 4.15 Effect of collector area on fluid outlet temperature at different hour

4.4.3 Effect of Mass Flow Rate on Absorber and Fluid Outlet Temperature

At a given time, **Figure 4.16** depicts the influence of flow rate of the working fluid inside heating tubes on absorber plate temperature and temperature of the working fluid at outlet. Absorber plate temperature and working fluid temperature at outlet of the collector are higher at minimum flow rate and decreases when the working fluid flow rate increases. The reason for the temperature curve's decline is because when the mass flow rate of the fluid increases, working fluid has less time to heat up inside the collector's heating loop. The mass flow rate of the collector is a critical parameter for attaining desired outputs.

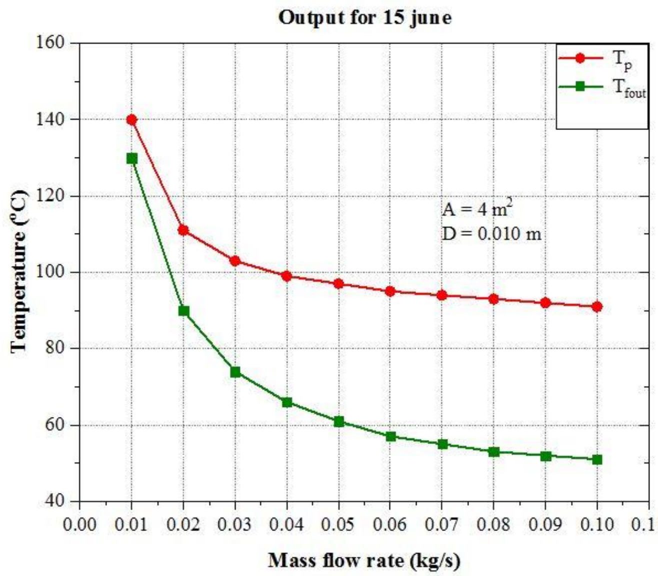

Figure 4.16 Effect of mass flow rate on absorber plate and fluid outlet temperature

4.5. Significance of Evacuated Flat Plate Collector

The relevance of the EFP collector is determined, when compared to the outputs of flat plate (FP) collector. MATLAB simulations are run using the same design circumstances and input settings as the reference study's FP collector model [4]. In **Figure 4.17** the variation of absorber plate temperature with respect to the fluid inlet temperature is shown.

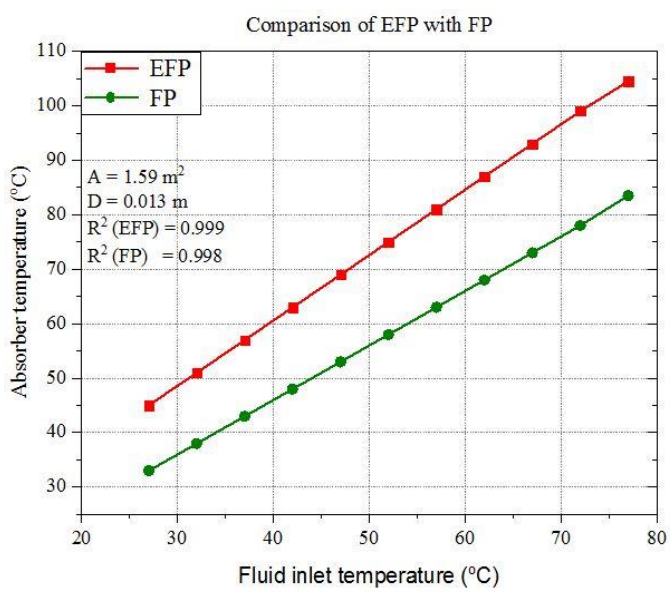

Figure 4.17 Effect of fluid inlet temperature on absorber plate temperature

In the reference study, the author had done mathematical modeling and sensitivity analysis for the potential of flat plate collectors. He also performed different simulations to study the effect of fluid flow rate and inlet temperature of the fluid on absorber plate temperature. The results were shown using the designing conditions of reference model generated in a MATLAB program for EFP collector. An increase in working fluid inlet temperature tends to increase in absorber plate temperature as result there is an increase in system overall efficiency. Due to the vacuum inside the collector's enclosure, the EFP collector's absorber temperature rises higher than the FP thermal collector's, which minimizes convective losses from the collector's plate to the glass that in turn rises the absorber temperature higher. It can be observed that about 20 ºC of absorber temperature is increased by using evacuated enclosure.

Effect of mass flow rate on absorber plate temperature is illustrated in **Figure 4.18**, increasing the fluid mass flow rate lowers the plate temperature. When the temperature gradient between the absorber plate and the environment starts to decrease it, in turn, decreases the system's overall heat loss coefficient, as a result, the collector's thermal efficiency improves. By evacuating the collector's enclosure minimizes the losses due to convection between the plate and glazing glass, which in turn rises the absorber plate temperature of an EFPC higher than FP collector under the same design parameters. The

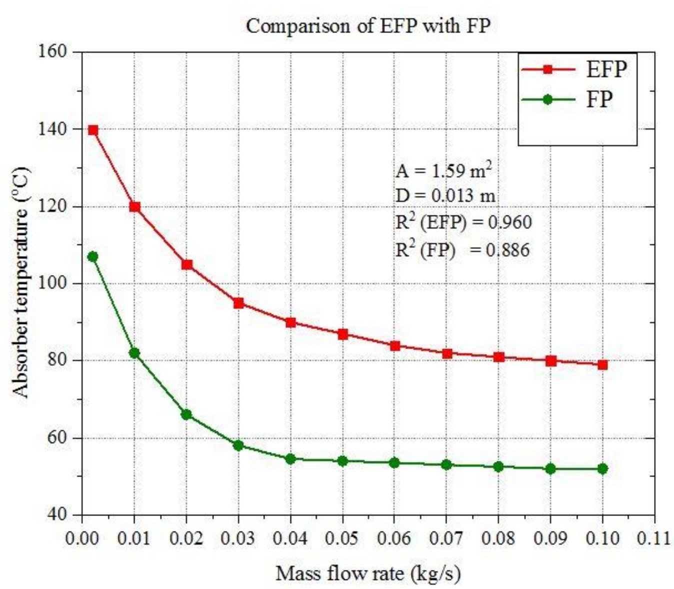

Figure 4.18 Effect of mass flow rate on absorber plate temperature

results show that EFP collector is the best option for obtaining Fluids with a wider temperature range.

Figure 4.19 depicts the fluid outlet temperature over time for EFP and FP solar thermal collectors under the identical design parameters of the FP collector in the reference research. Due to vacuum heat losses through convection from absorber plate to the glazing glass was reduced that rises the absorber plate temperature more than the simple flat plate collector. The extra heat gain of the absorber plate due to evacuated enclosure heats the working fluid to a large extant receives higher thermal outputs, useful energy and collector efficiency as compared to the FP collector without vacuum. Temperature of the glass cover in evacuated flat plate collector do not goes higher because of the evacuated enclosure. From comparison results it is observed that Evacuate flat plate collector can achieve 9 ºC higher fluid outlet temperature than simple flat plate collector, and there is an increase in collector's thermal efficiency up to 7 %.

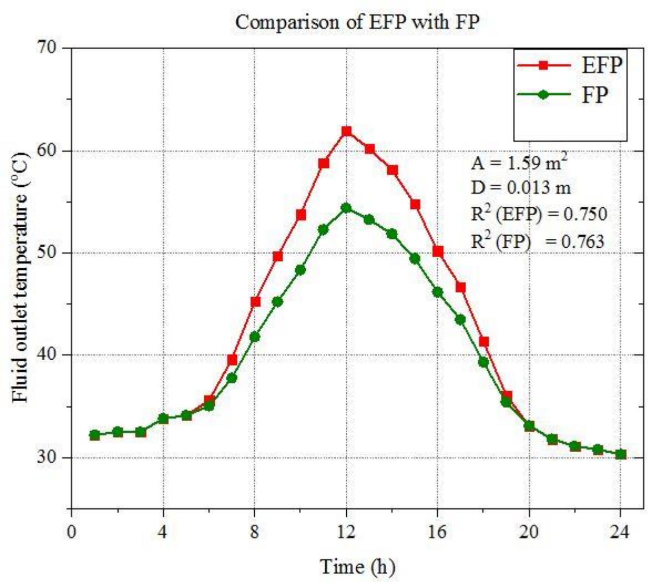

Figure 4.19 Fluid outlet temperature versus time for comparison

4.6. Economic Analysis of EFPC System for Industrial Process Heat

Utilizing heat energy with EFC is one of the most efficient techniques. The heated water may be utilized for a variety of purposes, including domestic and industrial applications. In textile industry there is plenty of processes like washing, heating, bleaching, dying, weaving, wet processing uses hot water and steam generated with boilers. In the textile industry, feed water tank is used to feed the boiler at a temperature of 90°C, and the input of water to feed water tank is at ambient conditions.

In textile industry, a unit that produces 20,000 lb/day fabric will consume 36,000 L of water per day [5]. **Figure 4.20** illustrates the fluid outlet temperature and temperature of water at storage tank top of the collector model for extreme summer and winter days. The following calculations are performed to integrate the EFPC collector system for pumping water to feed water tank at an average temperature of 83°C and 52°C for natural gas saving and reduction of GHG emissions.

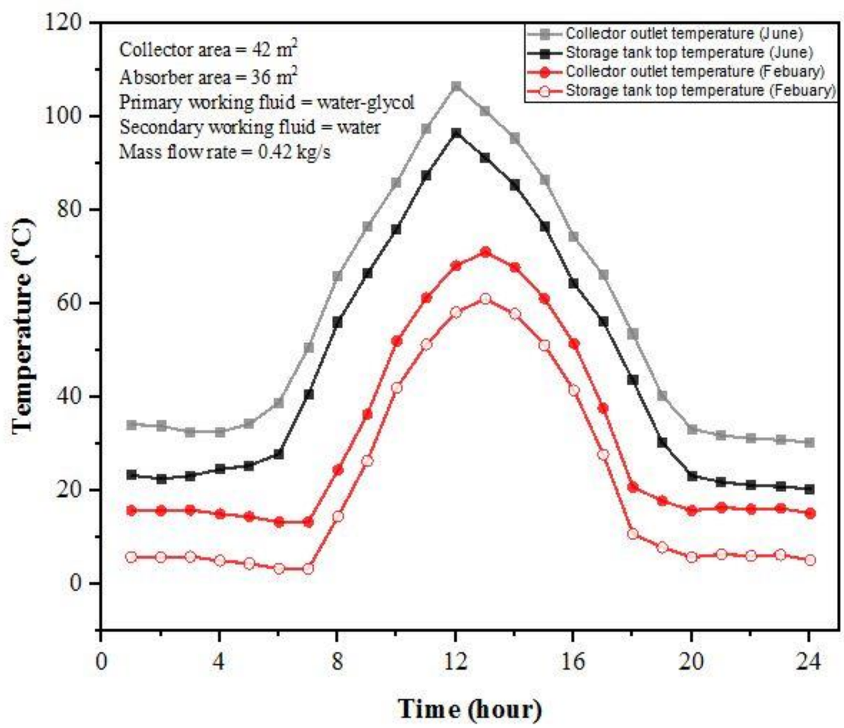

Figure 4.20 Collector outlet and storage tank top temperatures for 24 hours

Economic analysis is performed based on the data collected from a textile industry located at Faisalabad, Pakistan. **Table 4.5** illustrates the specifications of the textile industry for process heat. Based on the previous calculations, total number of collectors and mass flow rate of the working fluid is selected according to the required temperature and mass flow rate for process heat in textile industry.

Table 4.5 Specifications of textile industry for process heat

Parameter	**Value**
Boiler type	Fire tube boiler
Fuel used	Natural gas
Capacity of boiler	5 ton/h
Inlet temperature of boiler	90°C
Boiler efficiency	0.85
Water consumption in textile industry per day	36 ton
Total water consumption from 9am to 4 pm	10.5 ton
Temperature of steam at outlet	156 - 162°C
Feed water tank inlet temperature (summer)	30°C
Feed water tank inlet temperature (winter)	20°C
Feed water tank outlet temperature	90°C
Pressure	6 bar

Following are the specifications for EFPC collector. **Table 4.6** illustrates the design conditions and parameters of the collector model to be designed for achieving the required temperature and mass flow rate for process heat in textile industry.

Table 4.6 Design specifications of the collector model for process heat

Parameter	**Value**
Total number of collectors	21
Total area of the collectors	42 m^2
Total absorber area	36 m^2
Working fluid	water-glycol mixture
Mass flow rate	0.42 kg/s
Storage tank outlet temperature average (summer)	83°C
Storage tank outlet temperature average (winter)	52°C
Time duration	9 am to 4 pm

The inlet temperature of water at the feed water tank in summer is 30°C and 20°C in winter, feed water tank temperature rises to 90°C by using natural gas and then supplied to the boiler for steam generation. For saving the natural gas used to raise the temperature from 20°C (winter) and 30°C (summer) to 90°C, an EFPC will be integrated into this system to supply water to feed water tank at an average temperature of 83°C in summer and 52°C in winter for sunshine hours (9 am to 4 pm). **Table 4.7** illustrates the final results for natural gas consumption to rise the temperature of water for summer and winter. **Table 4.8** illustrates cost of natural gas savings and capital cost of the collector model.

Table 4.7 Calculation results for natural gas consumption to rise temperature of water

Parameter	Value
Energy required to rise 1°C temperature of 1 ton of water	4.18 MJ
Energy in 1m^3 of natural gas in MMBTU	0.0408 MMBTU
Energy in 1m^3 of natural gas in joules	43.06 MJ
Total energy in 1m^3 of natural gas for respected boiler	36.6 MJ
Natural gas required for 1 ton of water to rise 1°C temperature	0.114 m^3
Natural gas required for 1°C rise of 10.5 ton of water	1.197 m^3
Natural gas required in summer for 53°C temperature rise	63.441 m^3
Natural gas required in winter for 32°C temperature rise	38.30 m^3

Table 4.8 Cost of natural gas savings and capital cost of collector model

Parameter	Cost in US$
Cost of natural gas per m^3	0.31
Natural gas saving per day (summer)	19.66
Natural gas saving for 6 months (summer)	35.40
Natural gas saving per day (winter)	11.87
Natural gas saving for 6 months (winter)	2137.4
Total savings per year	5677
Cost per m^2 area of the collector	1001.5
Capital cost for 42m^2 area of the collector	42063

Relation used for finding payback period of the capital cost is given below [6].

$$\text{Payback period} = \frac{\textit{Capital cost of the solar thermal collector system}}{\textit{Natural gas saving per year}}$$

Payback period = 7.4 years

Figure 4.21 illustrates the payback period of the capital cost for the EFP collector system for textile industrial process heat.

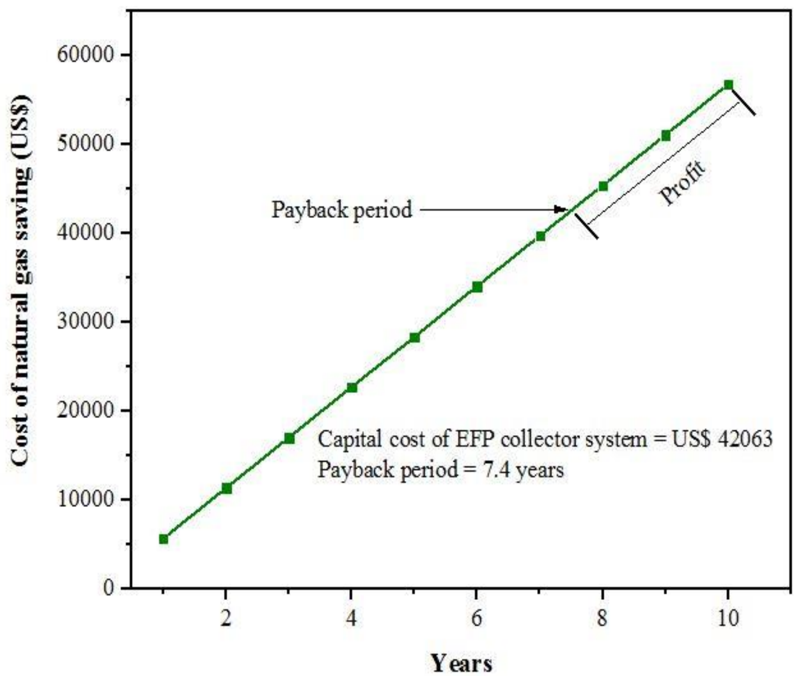

Figure 4.21 Payback period of the capital cost

In the literature economic feasibility of flat plate collector is carried out for manufacturing industries to reduce the use of fossil fuel and carbon emissions under several climatic conditions, performed sensitivity analysis of saving to investment, after analysis payback period of 12.78 years is observed for the capital cost of the system [7]. Economic analysis is carried out to investigate the profitability of evacuated tube collector for hot water supply in the meat industry. The author carried out analysis for the industry using electric boiler for water heating comes to the conclusion with a payback of 11 to 16 years, while performing analysis for the diesel boiler to replace it with evacuated tube collector, observed payback period of 10 years for the capital cost [8].

Summary

In chapter 4 design conditions of the collector for simulation are discussed in detail and parameters are shown in table. Solar irradiance profiles for the specific days are shown in the tables and plotted on graphs. Program codes generated in MATLAB are simulated against the weather data of Islamabad, Pakistan obtained from MHP equipment positioned at USPCAS-E, Islamabad. Simulated results are then validated with reference model study in the literature and validated with experimental results of evacuated flat plate collector model. The results taken from simulations are explained in detail with the help of figures. Sensitivity analysis are performed to examine the effect of different specifications of the collector and results taken are explained with figures. To study the significance of the collector, simulation results are compared with the flat plate collector without vacuum and plotted the results.

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Chapter 5

Conclusions and Recommendations

5.1. Conclusions

1-D model of EFPC is discussed in the current study based on the thermal energy balance, thermal losses of the collector, useful energy gain, heat removal factor and thermal efficiency of the collector. Inside the enclosure of the collector, a vacuum is created maintaining pressure of -0.8 bar for reduction of convective losses from absorber plate to the top glass cover. Program code is developed in MATLAB to investigate the parametric sensitivity analysis and model validation of EFPC using ambient conditions obtained from meteorological high precision equipment integrated at USPCAS-E, NUST, Islamabad, Pakistan (33.64^o N, 72.99^o E). The program code developed in MATLAB is simulated using the design conditions of the EFPC model and validated with experimental results for specific days. According to the findings, outlet temperature of the fluid reaches a high of 90 degree Celsius in June, 2.2 kW of useful energy. The outlet temperature of the fluid hits 60 degrees Celsius.

The influence of variable collector area, Mass flow rate, and spacing between the tubes on collector outputs was investigated by performing parametric sensitivity analysis of the EFPC through MATLAB. Sensitivity analysis reveals that increasing collector area will result in an increase in useful energy gain and working fluid outlet temperature, increasing the mass flow rate of the working fluid will decrease the outlet temperature of the working fluid. Smaller the tube spacing higher will be the useful the energy gain. It is concluded from parametric sensitivity analysis that collector area and mass flow rate are the important parameters in collector designing for achieving higher thermal outputs.

The total heat losses were lowered to 4.60 W/m^{2}K, according to the findings of the current study. Losses due to convection from absorber to the glazing glass has been decreased significantly. Due to the vacuum enclosure, the absorber temperature rises, maximizing the temperature of the working fluid by 9 ºC than FPC collector without vacuum and increasing the collector's efficiency by 7%. In February's results, it was also discovered that evacuated flat plate collectors operate well in low irradiance. According to the findings of this study, an EFPC collector is considered as the best solution for greater temperature working fluid ranges than any other thermal collector.

5.2. Future Recommendations

For improving and obtaining higher thermal outputs and useful energy gain of the collector, parameters such as vacuum pressure, absorber material, and copper tube spacing to be considered very important in further research area. Simulation as well as experimentation should be performed under different vacuum pressures to observe the fluid outlet temperature and collector's thermal efficiency. Absorber material is one of the important parameters to be considered in research area, selective absorber material should be checked for the collector that have the capacity to absorb maximum solar fractions. Also, sensitivity analysis of evacuated flat plate collector system should be performed for different tube spacing to study its effect on thermal outputs of the collector.

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APPENDIX-PUBLICATIONS

1. Zohaib Hassan, Mariam Mahmood, Adeel Waqas, Majid Ali, Naveed Ahmed *"Mathematical Modeling and Thermal Analysis of Evacuated Flat Plate Collector in Pakistan"*. International Conference on Emerging Power Technologies, April 2021 (ICEPT'21) (Published).

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Mathematical Modeling and Thermal Analysis of Evacuated Flat Plate Collector in Pakistan

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***Abstract*— Energy is a key parameter for a country's development. From recent decades Pakistan is facing energy crises due to the limitation of traditional energy resources. In Pakistan, natural gas, electricity, and coal are used for domestic hot water systems and industrial process heat. Due to climate change, traditional energy resources are declining, and energy demand is increasing. To support the developmental work, increasing population, and industries, Pakistan will need energy in an abundant amount to run the system on the proper track. To solve these problems, we just need to replace traditional energy resources with renewable energy. Solar thermal collectors are sources to complete the demand for hot water on small and large scales. This paper demonstrates an evacuated flat plate collector having an area of 4 m^2 and working fluid water-glycol mixture inside the tubes circulates with different mass flow rates of 0.01 to 0.1 kg/s with the help of a pump. The vacuum is created inside the collector with the help of a vacuum pump and pressure maintained less than 1 bar. Program is generated in MATLAB and simulated under design conditions of the collector with input weather data collected from meteorological high precision equipment installed at US-PCASE, NUST Islamabad, Pakistan having a latitude of 33.64° N and longitude of 72.99° E. By evacuating the enclosure convective losses from plate to cover are drastically reduced, which in turn decreases overall heat loss coefficient from 7.50 to 4.60 W/m^2K. absorber temperature is also increased due to reduction of convective losses, which in turn increases fluid outlet temperature by 7 to 9 °C and also increases the efficiency of the collector by 7 % as compared to non-evacuated flat plate collectors.**

results in the limitation of fossil energy. The generation of thermal energy is the breaking of chemical bonds in oil, natural gas, and coal, which emits carbon dioxide that causes greenhouse gas emissions [3].

Pakistan is an agricultural country that contributes a larger portion of the economy from the agricultural sector. Climate change affects weather conditions and has a direct impact on agriculture production, cropland area, trade, and variability of the prices [4]. Word health organization (WHO) 2010 survey reveals about 16,000 deaths reports due to climate change [5]. In Pakistan, 44% of natural gas is consumed for electricity generation [2]. Contribution of about 60% in the total exports of the country covers by industrial sector, which has a greater impact on economic growth. The consequences of climate change and greenhouse gas emissions force us to replace the energy from traditional energy resources like fossil fuels with the energy taken from renewable energy resources like solar thermal energy.

Energy demand in Pakistan increases every year by 9% and it should be increased up to 8-fold by 2030 and 20-fold by 2050 [6]. Only 0.3% of the energy needs are covered through renewable resources in Pakistan, which shows a very small contribution to energy. On the renewable side, solar has the greater potential to cover all the energy issues.

Pakistan receives solar radiations in abundance, which needs correctly utilization for many applications. Because of