Experimental Study of a Solar Flat Plate Collector with Propylene Glycol as Heat Transfer Fluid in Pakistan's Climate

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Abstract

Solar energy can meet the increasing energy demands as it is a clean and renewable source of power. Pakistan has huge potential for solar energy. Especially in remote and rural areas where access to electricity is limited, solar energy can provide an affordable and reliable solution. In current research work, the experimental investigation using a flat plate solar water heating system has been conducted. The main goal of this investigation is to evaluate the behavior of a Flat Plate Solar Water Heating System (FPSWHS) with a 2.3 m^3 receiver surface area in South Punjab weather conditions in Pakistan and to estimate the heat energy produced by the receiver for domestic applications, which reduces electricity consumption and aids the country in carbon fuel energy conservation. The results showed that the average effectiveness of the solar thermal system is 41.2% and the system's highest water output temperature was observed at 44 °C. The findings of this study are particularly relevant within the context of Pakistan's climatic conditions, characterized by high solar irradiance and significant seasonal temperature fluctuations. The use of propylene glycol as a heat transfer fluid was found to perform efficiently under these conditions, showing stability and high thermal efficiency during peak summer months.

Keywords—renewable energy, solar thermal system, heat transmission, carbon fuel energy conservation

1 Introduction

The usage of fossil fuels in the domestic and commercial sectors has increased to an unsustainable level, contributing to the rapidly expanding energy demand. It is estimated that by 2025, oil consumption will rise to almost 120 million barrels per day [1]. Air pollution and, by extension, global warming, are both exacerbated by the widespread use of fossil fuels[2]. Utilizing renewable energy sources allows for more eco-friendly technology. Solar power is a clean, sustainable option for powering homes and businesses alike. Location, season, time of day, and weather all have a role in how much solar energy you soak up. Whether or not the sun is clear affects the characteristics of solar radiation that is transmitted through the atmosphere [3]. The scientific community has paid increased attention to solar thermal systems over the last several decades because of their potential to provide low-cost heating for homes and businesses [4, 5]. To harness the sun's rays, many methods have been created. Food preparation, metalworking, and even armament have all benefited from this energy source [6]. Still, in the current day, fossil fuels are the norm. People have started using solar energy as a replacement for fossil fuels due to concerns about the latter's depletion and harmful effects on the planet. Solar thermal systems may now be used to provide heat for a variety of reasons, including residential heated water production, zone heating, cooking (solar ovens), desalination, and drying and maturation in the industrial sector[7]. Solar technologies are applied on vast as well as minor levels. The first kind is ideal for producing home hot water, supplementary heating, and process heat in either residential areas or commercial and industrial settings. Technology in large-scale systems is often more complicated than that found in smaller systems, which are often sold in pre-configured bundles. These systems are often installed in domestic hot water stor-

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age tanks, making them ideal for single-family homes. In addition, large-scale systems need individualized preparation and sizing in light of the consumption pattern. While large-scale systems are more costly due to their greater technical level, the increased efficiency and CO2 reductions more than make up for the higher initial investment. This study aims to fill that gap by conducting a thorough literature search of scholarly publications and other relevant recent works on solar thermal collectors. Energy assessments, innovations, and various technologies (such as Photovoltaic/Thermal collectors), all connected to the fundamental components, are taken into account. Differences throughout the globe are also highlighted by discussing international standards and performance evaluations. This comparative evaluation helps researchers, engineers, and producers stay current on the latest findings in their respective fields.

To a significant degree, the sun is the source of all of the many kinds of energy that exist in the world as we know it. Photosynthetic processes were initially responsible for the production of oil, coal, natural gas, and wood. Subsequently, decaying plant matter was subjected to very high temperatures and pressures for an extended time, resulting in more complex chemical processes. It took a long time for these situations to improve. When compared to other types of energy, the fact that solar energy is pure and can be generated without causing any harm to the surrounding environment is by far the most significant benefit it possesses. In solar thermal applications, where it conveys thermal energy from the sun to the working fluid, and in PV (photovoltaic) applications, where it converts solar energy directly into electrical current, the solar collector is the one and only energy exchanger. Through a solar collector, the heat from the sun is delivered to the system's thermal fluid (air, water, or oil). The heat from the working fluid may either be utilized now to produce residential hot water and heating or saved for later use by using a thermal energy storage tank (at night or on cloudy days). Although photovoltaic (PV) modules are great at converting solar radiation into energy, they also generate a lot of waste heat, which may be put to good thermal use by connecting a PV board with recuperating tubes filled with carrier fluids. Concentrating collectors and non-concentrating collectors are the two main types of solar collectors [8-10]. The concentration ratios they employ imply. A sun-tracking concentrated solar collector uses concave reflecting surfaces to intercept and concentrate the solar irradiation on a much smaller receiving area to boost the heat flow and allow the thermodynamic cycle to operate at higher temperatures with greater Carnot efficiency. The absorbing area and the intercepting zone are the same in a non-concentrating collector [11-15].

As versatile pieces of equipment that have the potential to produce energy, building-integrated solar thermal (BIST) systems are becoming increasingly common. Conventional solar thermal collectors can't match their aesthetic appeal since they take into consideration the architectural characteristics of the structure, such as color, texture, and form. These systems take into consideration the generation of energy, the development of thermal insulation, and the aesthetics of a building, all at the same time, which makes them a flexible solution for a broad variety of construction applications. For seamless integration into existing buildings, solar thermal collectors must meet some conditions in addition to being technically and structurally efficient[16-18]. Aesthetic appeal, use of suitable colors and materials, proportionality to the rest of the building, continuity with its surroundings, and creative thinking are some of the requirements that need to be satisfied by the design [19-22].

The objective of experiments conducted in the current study is to demonstrate, with concrete data, that solar heating systems may significantly cut down on energy costs and fossil fuel usage. Due to their excellent durability and simple design, flat-plate solar collectors (FPSCs) are increasingly being adopted for use in residential settings. The following procedures would be taken as part of the inquiry into the compatibility of an FPSCS with Propylene Glycol as a heat transfer fluid: -

- i Characteristics of Flat-plate thermal collector
- ii Effect of collector temperatures
- iii Measuring thermal characteristic curves, establishing energy balance, and determining efficiencies.

2 Research Methodology

2.1 Mathematical Modelling

Experimentation on the Flat Plate Collector for Domestic Water Heating apparatus is performed at NFC-IET, Multan, Pakistan. The price of oil has become the benchmark for all other fuels; therefore, it stands to reason that energy costs will rise over the next several decades at a pace that is at least as fast as inflation. The rising number of people living in Pakistan has resulted in a higher need for both fossil fuels and modern conveniences like electricity. Most of Pakistan has its highest temperatures during the summer, so making use of this plentiful sunshine to generate eco-friendly electricity is a no-brainer. Solar energy may be

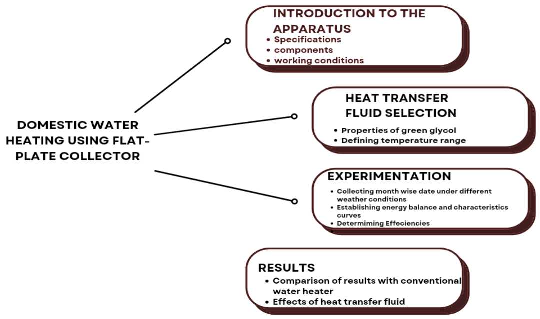

Fig. 1: Methodology of Research

utilized for both heating and cooling, helping to satisfy the needs of the growing population while reducing the environmental impact of the energy sector. Laundries, small-scale food companies, and subterranean water storage are all possible applications for hot water heated by the sun. Figure 1 represents the methodology of the proposed research work.

2.1.1 Heat loss calculation

Using Klein's generalized formula to calculate the top heat loss coefficient, which is:

$$U_{top} = \left(\frac{N_c}{\frac{C}{T_p}\left[\frac{T_p - T_a}{N_c - f}\right]^e} + \frac{1}{h_w}\right)^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{(\epsilon_p + 0.00591 N_c h_w)^{-1} + \frac{2N_c + f - 1 + 0.188\epsilon_p}{\epsilon_c} - N_c} \quad (1)$$

whereas,
U_{top} is the heat losses at the top of the collector, W/m^2K
N_c is the number of glass covers
T_a is the ambient temperature, K
T_p is the temperature of the plate, K
ϵ_p is the emissivity of the plate
h_w is the heat transfer coefficient of wind, W/m^2K
ϵ_c is the sensitivity of the glass cover

Heat losses from the back of the collector are:

$$U_{back} = \frac{k_{ins}}{Lins} \quad (2)$$

Whereas,
k_{ins} is the thermal conductivity of the insulation, W/mK
L_{ins} is Insulation Length, m

So, the total heat loss becomes:

$$U_T = U_{top} + U_{back} \quad (3)$$

2.1.2 Heat Removal factor

The collector heat removal factor FR is a measure of the reduction in the useful energy gain due to the deviation of the inlet fluid temperature from the plate temperature.

$$F_R = \frac{\dot{m}C_p}{A_C U_L}[1 - exp[\frac{-A_C U_L \acute{F}}{\dot{m}C_P}]] \quad (4)$$

Where, $\acute{F}$ becomes:

$$\acute{F} = \frac{\frac{1}{U_T}}{W[\frac{1}{U_T[D+(W-D)F]} + \frac{1}{C_B} + \frac{1}{\pi h_{fiD_i}}]} \quad (5)$$

Where,
C_B is the bond Conductance
D_i is the inside diameter of the tube
$\dot{m}$ is the collector flow rate
$h_{fi}$is the heat transfer coefficient between the pipe wall and the working fluid.

2.1.3 Absorbed Energy

Absorbed Energy on the surface of the plate can be written as:

$$Q_p = A + p\,sin(\tau\alpha) - Q_i \quad (6)$$

Whereas,
Q_p is the energy absorbed on the surface of the collector plate, W
A_p is the area of the collector plate, m^2
$\tau\alpha$ is transmittance-absorbance product
Q_i are the heat losses, W When plate temperature T_p and heat loss coefficient U_T are taken into account, then the absorbed solar energy on the plate surface can be calculated as:

$$Q_p = A_p[sin(\tau\alpha] - U_T(T_P - T_a)] \quad (7)$$

2.1.4 Convective Heat Transfer of the Fluid

Because there is solar energy that is incident on the absorber of the collector, part of that energy will be transferred to the fluid via convection as it travels up the collecting tube. This kind of energy is referred to as usable energy, and it may be formulated as follows:

$$Q_u = A_p F_R[Sin(\tau\alpha) - U_T(T_{f,in} - T_a)] \quad (8)$$

Finally, collector efficiency can be calculated as:

$$\eta_c ol = \frac{Q_p}{S_{in}A_p} = \frac{A_p[sin(\tau\alpha) - U_T(T_p - T_a)]}{S_{in}A_p} \quad (9)$$

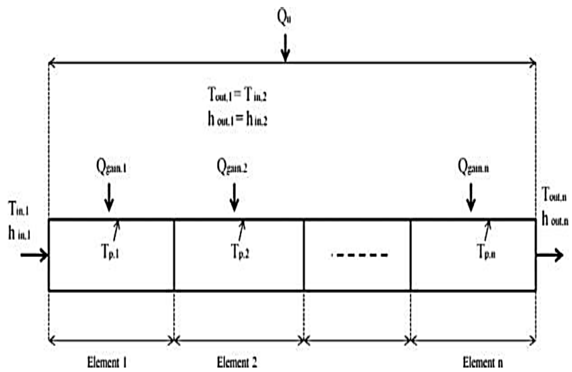

Fig. 2: Schematic diagram of collector's elements

3 Experimental Setup

The installation of the setup makes use of a piece of equipment from the 2E - ENERGY & ENVIRONMENT line of goods; specifically, an HL 313 Domestic Water Heating with Flat Plate Collector. This device will encourage researchers to put this interest into practice by providing them with a practical means of heating water using renewable energy. Figure 2 demonstrates the schematic diagram of the collector's elements.

Using components used in actual systems, HL 313 may illustrate the key features of solar thermal home water heating. A commercially available flat collector transforms the sun's rays into heat, which is then transmitted to a heat transfer fluid in the solar circuit. A heat exchanger transfers the warmth into the hot water network. The pumps in the hot water and solar circuits are managed by a solar controller. A combination of an expansion tank and a safety valve keeps the solar circuit safe. The proposed setup was made such that full preheating may be done in the lab. Flow in the solar circuit is recorded in addition to temperatures in the storage tank's outlet and the collector's inlet. The embedded data logger stores the readings. The solar circulation station shows the actual input and return temperatures. This solar controller has a built-in router for easy operation. The UI may be viewed from an unlimited number of devices, so long as they have access to the internet. There are a variety of permission tiers available, each with its own set of features. Endpoints running Windows can connect to a WLAN with an integrated router or a local area network to retrieve recorded measurement results. Sunlight or the HL 313.01 artificial light source (which is optional) should be used to power the device and ensure enough lighting. Figure 3 represents the experimental test setup.

Any solar thermal hot water system may be improved by choosing a fluid that is efficient and steady in transferring heat from the collector to the hot water heat exchanger. Under typical operating conditions, a glycol and inhibitor package can reduce corrosion risk and extend the life of the system. As a heat exchange medium, a solution of propylene glycol and water is utilized in the current research work. Liquid propylene glycol, commonly known as propanediol, is a stable, viscous hygroscopic liquid. It has no discernible hue, and its odor and taste are both faint and acidic. Many resins, dyes, and essential oils are soluble in propylene glycol, and it is also miscible with water and many organic solvents. Propylene glycol (PG) is used for a wide variety of applications such as a solvent in industry, as a chemical intermediate, in the production of cosmetics and medicines, and in the manufacture of food, as well as paints and coatings. The typical propylene glycol/water combination contains a glycol/water ratio of 50/50; however, this can be adjusted up or down depending on the potential for freezing. Since Ethylene Glycol is harmful, we have to utilize Propylene Glycol (PG) instead. The use of propylene glycol as a heat transfer fluid significantly influences the efficiency and reliability of solar flat plate collectors, particularly in Pakistan's climate, which experiences high solar irradiance, hot summers, and cooler winters. Propylene glycol's excellent thermal stability at elevated temperatures and its antifreeze properties during colder months contribute to consistent year-round performance. Our experimental results demonstrated that the collector maintained a high thermal efficiency, even during seasonal temperature fluctuations, due to the stable thermophysical properties of the fluid. The physical properties of PG are mentioned in Table 1.

TABLE 1: Physical properties of PG

Property	Value
Molecular Weight	76.1 g/mol
Empirical Formula	$C_2H_2O_2$
Appearance	Colorless Liquid
Freezing Point	-60C°
Boiling Point @ 760mm Hg	187C°
Flash Point-Closed Cup	107C°
Autoignition Temperature	371C°
Density @ 25C°	1.032 kg/L
Vapor Pressure @ 25C°	$<$ 0.1 mm Hg
Vapor Density (air = 1)	2.52
Solubility in Water @ 20C°	100%
Refractive Index @ 20C°	1.4329
Viscosity @ 20C°	56.0
Dielectric Constant @ 25C°	32.0
Heat of Vaporization @ 25C°	711 J/kg
Specific Heat @ 25C°	2.481 J/g C°

Direct hydrolysis of propylene oxide with water is

(a) Flat-plate Collector

(b) Artificial light source

Fig. 3: Experimental test setup

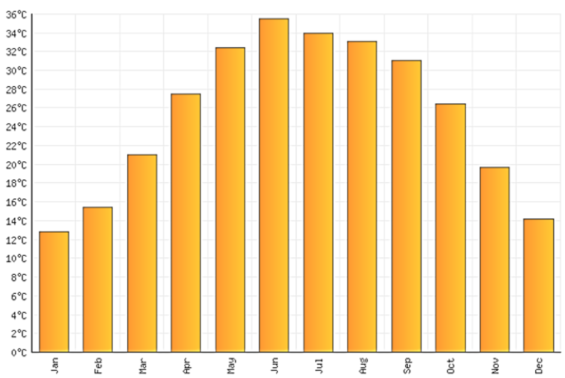

Fig. 4: Average Annual temperature of Multan [23]

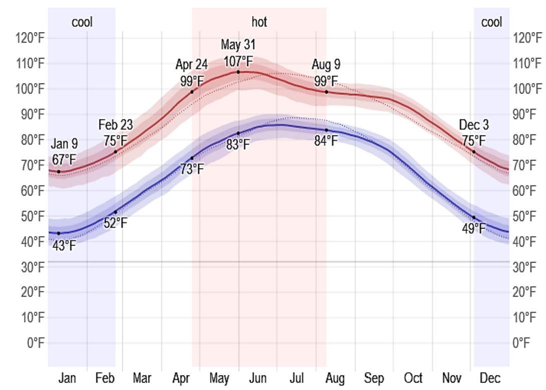

Fig. 5: Month-wise Temperatures [23]

a commercially viable method for producing propylene glycol. The monomer propylene is the starting point for both the chlorohydrin reaction and peroxidation (also called pro-pene, a three-carbon chain that contains one carbon-to-carbon double bond). Propylene oxide is formed as an intermediate in both procedures; this compound is subsequently hydrated to produce propylene glycol.

4 Climate Conditions

In Multan, rainfall is quite rare during the year, and weather conditions are extremely hot in the summer season. According to Koppen and Geiger, this area receives the BWh classification. The city of Multan has an annual temperature average of 25.6 degrees Celsius and an annual rainfall average of 175 millimeters. Figure 4 demonstrates the average annual temperature of Multan.

The hot season starts on April 24 and lasts until August 9, with an average daily high temperature that is greater than 99 degrees Fahrenheit. During this time, the humidity level is also higher than normal. The average high temperature in Multan for June is 106 degrees Fahrenheit, while the average low temperature is 85 degrees Fahrenheit. This makes June the hottest month of the year. During the colder season, which starts on December 3 and lasts until February 23, the average high temperature each day is lower than 75 degrees Fahrenheit. This season lasts from December 3 to February 23. The month of January in Multan has the year's coldest average temperatures, with lows of 44 degrees Fahrenheit and highs of 68 degrees Fahrenheit. The range of month-wise Temperatures is illustrated in Figure 5.

Extreme variations in day duration may be seen all year round in Multan. There will be 10 hours and 12 minutes of daylight on December 22nd, and 14 hours and 6 minutes of daylight on June 21st. This section gives an overview of the total daily incident shortwave solar radiation that strikes the Earth's surface across a large region after taking seasonal variations in day length, the Sun's position above the horizon, and air absorption into consideration. Shortwave radiation includes, for example, visible light and ultraviolet light. The average daily incident shortwave solar energy varies significantly seasonally. The sun is at its brightest from April 17 to July 18, with an average daily incident shortwave energy per square meter of more than 6.9 kWh. Multan has 7.6 kilowatt hours of average daily sunlight in May. During the year's darkest

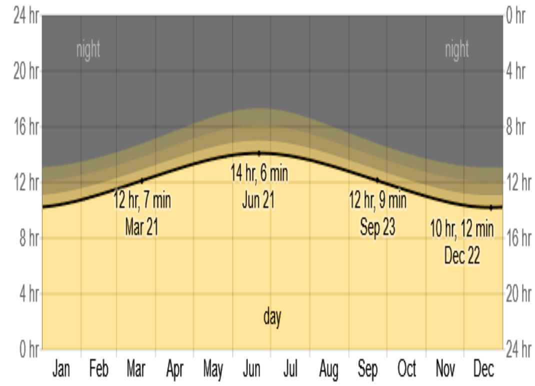

Fig. 6: Hours of daylight and twilight in Multan[23]

period, which lasts from November 9 to February 5, the average daily incident shortwave energy per square meter falls below 4.3 kWh. In Multan, December is the darkest month of the year with an average of only 3.5 kWh. Figure 6 shows the hours of daylight and twilight in Multan.

5 Results and Discussions

At the NFC IET Power Plant Lab in Multan, the experiments were carried out between the hours of sunrise and dusk from May 2023 to October 2023. A series of experiments have been carried out to establish the convergent validity. The purpose of the experiment is to determine whether or not the flat collector can successfully heat the contents of the storage tank. This allowed for the observation of the curves that were acquired from the experiment, as well as the thermal power of the collector temperatures at the various measurement sites. Either natural sunshine or an artificial light source may be used to carry out this experiment successfully. On days with very poor visibility, the use of an artificial light source is recommended. It is recommended that there be about 1.6 meters of space between the HL 313.01 artificial light source and the collector. Illuminance is around 430 watts per square meter when measured at this distance. The temperature of the water and the surrounding environment were both measured using temperature sensors, and the average temperature of the water was calculated by taking the average of the temperatures obtained at each point of measurement.

A measuring cup is used to determine the volume of water that has been released as part of the investigation. To avoid having the water storage tank get overfilled, the shut-off valve is used to manage how much cold fresh water is brought into the tank. Warm water may also be removed from residential storage tanks through an outlet located in the top portion of the tank. This guarantees the provision of hot water at the highest temperature that may be achieved. Because the layers of the storage tank's contents do not mix, there will be considerable temperature changes if it is possible to keep the contents of the tank are not allowed to mix. Reading the instructions provided by the controller's manufacturer allows us to get more acquainted with the controller's settings, which is the first step in the preparation process for the experiment. Throughout the experiment, the switch-on threshold for the pumps will be adjusted in various ways. The temperature differential that has been specified between the collector outlet and the storage tank is the one that determines the switch-on threshold. Additionally, the jump-start function of the controller is activated before the game begins. To carry out this experiment, the water storage tank was first filled until the level of water reached just below the top nozzle. The manual mode was selected for the controller. The acquisition of the measured values was preceded by the completion of the necessary preparations. Figure 7 illustrates the variation in fluid temperature at both the inlet and outlet of the solar collector throughout the day. As the sun rises and solar irradiance increases, the temperature of the heat transfer fluid begins to rise steadily. This increase continues until midday, when solar intensity is at its peak, resulting in the highest recorded temperatures at both the inlet and outlet. The outlet temperature remains consistently higher than the inlet, demonstrating effective heat absorption and transfer within the collector.

As the day progresses into the afternoon and evening, a decline in solar irradiance causes a corresponding drop in fluid temperatures. This reduction in temperature signals the onset of sunset and reduced thermal energy input. The observed temperature trends highlight the collector's responsiveness to solar availability and underscore the importance of sunlight intensity in maintaining efficient thermal performance.

Figure 8 demonstrates the correlation between the temperature of the heat transfer fluid and the temperature of the water in the storage tank. As the temperature of the fluid increases—particularly at the inlet of the collector—it facilitates more effective heat transfer to the storage tank. This results in a gradual rise in the water temperature over time. The maximum recorded water temperature in the tank reached 44°C, which coincides with periods of high inlet fluid temperatures. This behavior reflects the principle that higher inlet temperatures correspond to greater thermal energy being delivered to the tank, leading to increased storage temperatures. The efficiency of this thermal exchange is crucial for optimizing the system's

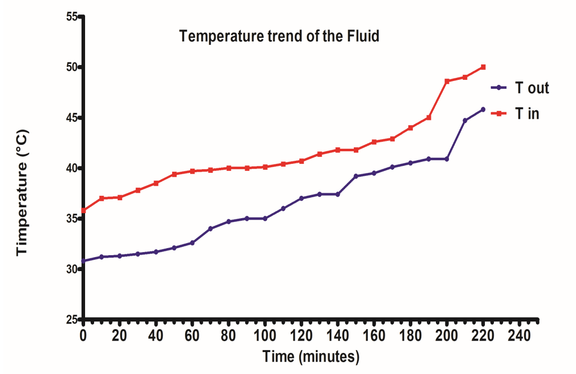

Fig. 7: Trends in fluid temperatures

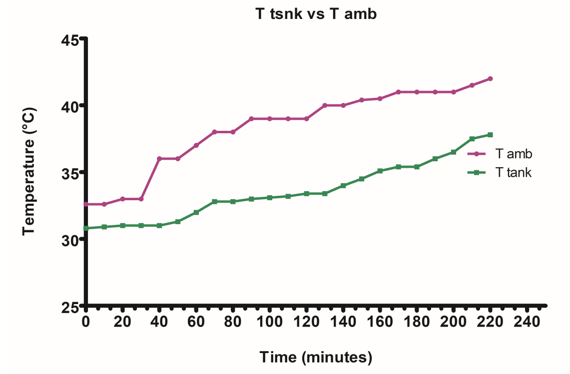

Fig. 9: Ambient Temperature Vs Storage Temperature

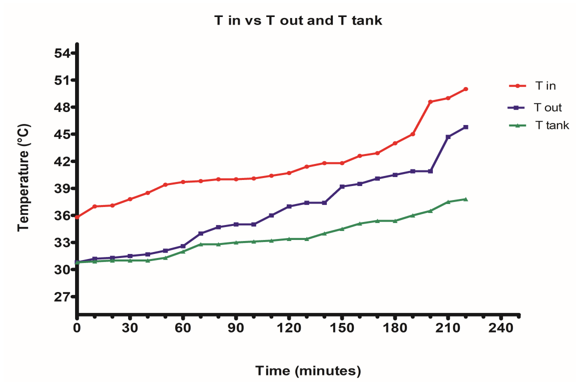

Fig. 8: The average temperature of fluid and tank

performance, as it directly impacts the availability of hot water for end-use applications. These results highlight the system's dependency on solar input and efficient heat transfer mechanisms to achieve optimal thermal storage outcomes.

Figure 9 illustrates the impact of ambient temperature on the heat transfer process and the corresponding rise in the storage tank water temperature. As ambient temperature increases, the temperature difference between the heat transfer fluid and the surrounding environment becomes smaller, resulting in reduced heat losses to the atmosphere. This allows more thermal energy to be retained and transferred efficiently from the solar collector to the storage tank. Consequently, higher ambient temperatures support enhanced thermal performance, leading to increased water temperatures within the tank. This trend confirms that favorable environmental conditions, specifically elevated ambient temperatures, contribute significantly to the overall heat retention and energy storage capacity of the system.

The incident power of the artificial light source and the thermal net power output of the collector are both monitored at a variety of collector temperatures to evaluate the efficiency of the collector at each temperature. When the flow rate is adjusted, the collector temperatures are found to vary even while the luminance remains the same. It is essential to carry out these measurements in circumstances of steady state if one wishes to steer clear of inaccuracies in the energy balance. This indicates that the system must be in a steady condition to record a measured value, and there must not be any further changes to the measured values that may be noticed. At this moment, all of the temperatures that are shown, together with the luminance and the current time, are being recorded. After another 2 minutes of recording, these values were once again gathered. As soon as there was no longer any fluctuation in temperature at the collector output, the actual measured values for the present flow rate were written down and recorded. After that, the shut-off valve was used to determine the subsequent figure for the flow rate. In this scenario, an increase of 10 Uh on each subsequent occasion is suitable. When calculating the waiting time for each measurement point, we have to take into consideration the amount of time that passed until the temperature at the collector outlet became steady. The measurement was carried out several times until the maximum possible flow rate was determined. Figure 10 indicates the mean efficiency of the collector.

The system achieved its highest efficiency of 59.4% in August, primarily due to elevated ambient temperatures and intense solar irradiance typical of summer months. The daily efficiency pattern indicates a noticeable dip during the early morning hours, which can be attributed to lower solar angles and reduced irradiance. As the day progresses, efficiency steadily increases, reaching its peak in the early afternoon when solar radiation is at its maximum. This trend highlights the system's strong dependency on solar energy availability, as higher irradiance levels sig-

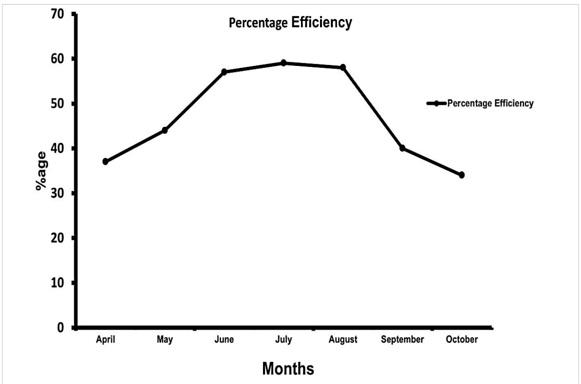

Fig. 10: Mean efficiency of FPSC

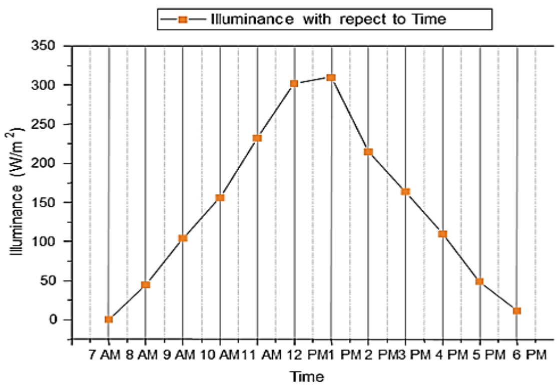

Fig. 11: luminance variation with respect to time

nificantly enhance performance. The combination of clear skies, longer daylight hours, and higher ambient temperatures during August contributed to optimal operating conditions, thereby maximizing energy conversion efficiency. Figure 11 shows the variation of luminance from morning to evening.

It was observed that luminance reaches its peak during periods of full sunlight and gradually declines as the day progresses toward dusk. This pattern directly impacts the performance of the solar thermal system. Specifically, a reduction in luminance corresponds to a decrease in the inlet temperature of the heat transfer fluid. This indicates that lower light intensity results in reduced solar energy absorption by the collector, thereby limiting the amount of heat transferred to the fluid. Consequently, diminished luminance leads to less efficient thermal exchange, emphasizing the system's reliance on high solar irradiance for optimal operation.

6 Conclusion

In current research work, the thermo-phonic driven flat plate solar water heating system (FPSWHS) was installed and evaluated for the climatic conditions of Southern Pakistan (Multan) to determine its performance. A series of experiments was carried out, and the results of these experiments, together with their average values, were analyzed and reported. The maximum recorded water temperature was up to 44C° at sunset, while the maximum instantaneous efficacy was up to 71.3% in the late afternoon. It was found that the average effectiveness was 41.2%, which is sufficient for making use of the proposed FPSWHS at the site. In order to improve the overall average thermal performance efficiency, it was noticed to use a combination of propylene and water. The average temperatures in the South Punjab region are maximum from May to August, which leads to an increase in the effectiveness of this solar thermal system. It has been demonstrated how effectively we can utilize the summer season to produce hot water, which can be stored using thermal storage systems for use during the winter months. This stored hot water can then be used as a reliable source of heat throughout the colder season. The successful implementation of solar flat plate collectors using propylene glycol as a heat transfer fluid can significantly contribute to the socio-economic development of cities in Pakistan. By providing a sustainable and efficient alternative to conventional heating systems, this research promotes the adoption of renewable energy, thereby reducing dependence on fossil fuels and lowering energy costs for households, businesses, and public institutions.

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