Performance Evaluation of Energy Collection Using Various Solar Flat Plate Collectors

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DOI: https://dx.doi.org/10.47772/IJRISS.2025.9010328

Received: 15 January 2025; Accepted: 20 January 2025; Published: 21 February 2025

ABSTRACT

Solar radiation, emitted by the sun and collected using solar collectors, can be converted into sound thermal energy. One of the most efficient energies harvesting methods is using solar Flat Plate Collectors (FPCs). These collectors' function by heating water from atmospheric temperature, which can be used for domestic and industrial applications. This study evaluates the performance of different types of FPCs, including color variations (black vs. white collectors), material (copper vs. polypropylene collectors), and glazing (double vs. single glazing collectors), using the Energy Solar Trainer. The experiments were conducted over three days under clear sky conditions, with ambient temperatures ranging from 20°C to 36.2°C. Data were collected from 9:00 a.m. to 5:00 p.m., with a fixed solar radiation intensity of 722 W/m² and a flow rate of 2 L/min. The results indicate that black collectors outperform white collectors, copper collectors are more efficient than polypropylene collectors, and double-glazing collectors have higher efficiency than single glazing collectors. Overall, double-glazing collectors demonstrated the highest efficiency among the tested FPCs. These findings provide valuable insights into optimizing solar energy collection for enhanced thermal performance in various applications.

Keywords: Keywords: Flat Plate Collector (FPC), Efficiency.

INTRODUCTION

Solar energy is the energy that sustains life on Earth for all plants, animals, and people. It provides a compelling solution for society's future needs for clean and abundant energy sources. Energy has played a key role in bringing about our modern civilization. In contemporary society, energy demands are likely to increase for power generation for industrial and domestic usage.

Solar radiation is primarily transmitted to the Earth by an electromagnetic wave that strikes the Earth's surface every minute [1]. Solar radiation provides us with an enormous amount of energy. People who heat and dry have utilized solar radiation for centuries. Solar water heating is one of the most successful applications of solar energy. Solar collectors for hot water domestic applications are flat plate, evacuated tube, or concentrating collectors.

A flat plate collector (FPC) is a unique heat exchanger that transforms solar radiation into internal energy, which is transferred through a working liquid. FPC is a well-known solar collector in the market for water heating

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue I January 2025

applications. It's simple design, ease of operation, and required low maintenance make the FPC commonly found in domestic houses.

The principle involved in FPC is to gain as much radiation energy from the sun as possible through heat absorption. The energy collected is transferred through conduit tubes by working fluids (usually water) integrated with a heat absorber plate. Then, the warm water carries the heat to the hot water system or storage subsystem that can be used during low sun radiation [2].
In FPC, the ability to absorb more energy is the most critical factor in its thermal performance. The heat absorber plate serves as the central component of the flat plate collector [3]. When the absorber plate absorbs more heat from the sun, the outlet temperature (Tout) should have a higher value than the inlet temperature (Tin). Thus, the FPC's efficiency can be obtained from the temperature values. For domestic water heating, the FPC can heat the water to 100°C [4].

LITERATURE REVIEW

A literature review is a text of a scholarly paper that includes current knowledge, substantive findings, and theoretical and methodological contributions to a particular topic. The definition of each term of solar flat plate collector (FPC), including the components of FPC and absorber plate, was also included.

Flat Plate Solar Collector

Flat plate solar collectors are special heat exchangers that transfer heat energy from incident solar radiation to the working fluid [5]. Flat plate solar collectors are vital components in solar thermal systems, functioning as special heat exchangers that convert solar radiation into thermal energy. Recent advancements in flat plate collector (FPC) designs and materials have enhanced their performance, durability, and cost-effectiveness. [18] introduced mathematical modelling approaches for optimizing FPC configurations, providing insights into deformation and structural stability. The [20] and [19] highlighted innovative material integrations that improve thermal efficiency and adaptability across diverse climates. These advancements underscore the potential of cutting-edge designs and materials to maximize energy collection. For example, studies by [5] and [9] explored improved absorber plate coatings and glazing materials, emphasizing their role in enhancing thermal efficiency. More recently, [16] examined nanostructured coatings that enhance heat absorption while minimizing emissivity, ensuring better performance in diverse climatic conditions. [18] introduced mathematical modelling approaches for optimizing FPC configurations, providing insights into deformation and structural stability. These advancements have shifted the focus toward integrating innovative materials and configurations to maximize energy collection. There are three principal parts of a flat plate solar collector: absorber plate, which absorbs solar radiation and transfers it to the working fluid; transparent cover, which allows short wave radiation to pass and prevents them from exiting; and insulation, which resists back and rear side heat losses. The most important advantages of these types of collectors include low construction costs and minimal effect in pressure drops.

A flat plate collector is essential and straightforward, absorbing heat from the sun's radiation. Flat plate collectors, as [25] now developed, were known in the 1950s and also from the latest study, namely [24]. The crucial flat plate collector in Figure 1 consists of a few components, and their essential function is stated as follows:

1. Glazing cover – transparent covers, typically glass, put on the top of a flat plate collector.
2. Glazing frame – to hold the glazing material.
3. Tubing or fluids pipe – to facilitate the working fluid flow. Water is commonly used as the working fluid. Fluid enters at the inlet connection and exits at the outlet connection.
4. Absorber plate – to absorb incident solar radiation to gain heat. Then, it allows for the efficient heat transfer to a working fluid.
5. Insulator – To minimize heat lost from the bottom and sides of the casing.
6. Casing – A waterproof box surrounds the foregoing components and keeps them free from dust and moisture.

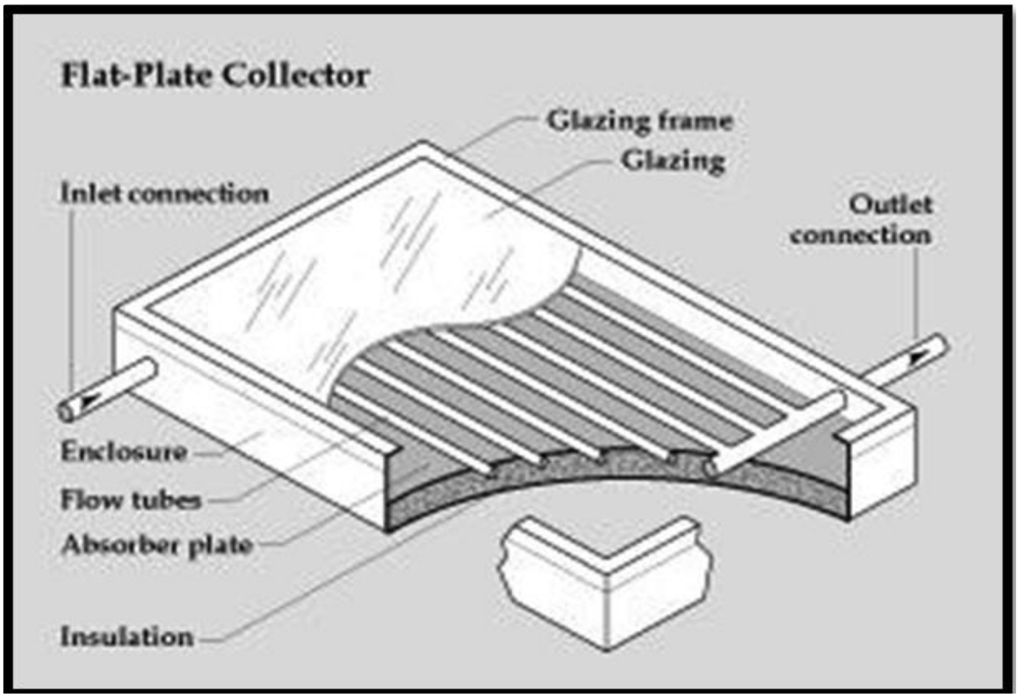

Fig. 1: Model of Flat Plate Collector

Glazing Material

Glazing is the top cover of a solar collector. It performs three primary functions: minimizing convective and radiant heat loss from the absorber, transmitting the incident solar radiation to the absorber plate with a minimum loss, and protecting it from the outside environment. Other essential characteristics of glazing materials are reflection, absorption, and transmission [8]. Reflection and absorption should be as low as possible to attain maximum efficiency, whilst transmission should be as high as possible [9]. Therefore, factors for consideration in selecting the glazing materials include strength of material, durability, no degradability when exposed to ultraviolet light (UV), and low costs. Usually, the common glazing materials used are glass and plastics.

Glass is the principal material used to glaze solar collectors [10][11]. Glass material has the highly desirable property of transmitting as much as 90% of the incoming short-wave radiation. In contrast, virtually none of the long-wave radiation emitted by the absorber plate can escape outwards by transmission [12]. Compared to glass, a plastic cover possesses high short- and long-wave transmittance and hence high performance. Generally, the main advantages of plastics are resistance to breakage, lightweight, and low cost. However, plastics have been reported to limit life span because of UV radiation, which reduces its transmissivity [13]. Also, plastics are transparent to long-wavelength radiation and are less effective in lowering radiated heat losses from the absorber plate. In addition, plastics cannot withstand high temperatures encountered in the collector, especially when idle [13].

Serpentine Configuration

The serpentine flow in Figure 2 below consists of one long, continuous flexible tube, so there is no problem with uniform flow rate. The working fluids flow continuously from the bottom to the top of the collector. This results in steady heat transfer from the heat absorber to the working fluid. Since the flow rate of the fluid through the serpentine tube is uniform, the heat collection process is also uniform. The size of this flexible tubing is an important consideration.

Thus, the serpentine configuration is used in this investigation due to uniform fluid flow, resulting in uniform heat transfer from the absorber plate to the working fluid. Furthermore, the serpentine configuration is more straightforward to construct than parallel, with many welding joints. The probability of leaking in parallel configuration is high compared to serpentine configuration. Copper tube is used because it has high thermal conductivity and is easy to fabricate [14].

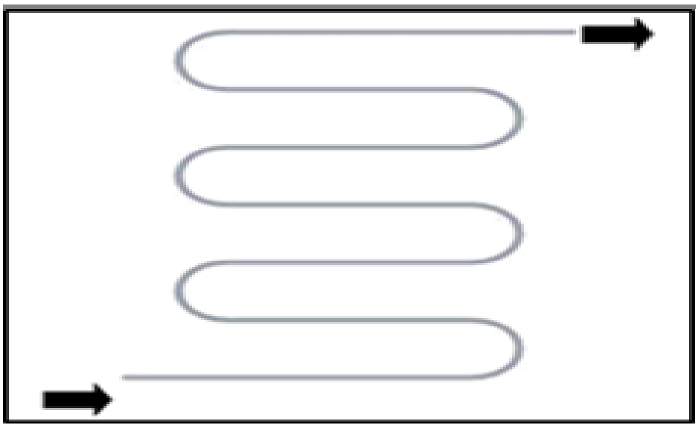

Fig. 2: Model of Serpentine Flow

Heat Absorber

The primary function of the heat absorber plate is to absorb as much as possible of the radiation reaching through the glazing and, at the same time, to lose as little as possible radiation reflecting upward to the atmosphere and downward through the back of the container later transfer the retained heat to the circulating working fluids.

In FPC, the heat absorber is usually made of mild steel. Its thermal conductivity, durability, and availability determine the material selection. A heat absorber plate is generally given a surface coating, mainly black, that increases the fraction of available solar radiation absorbed by the plate [15].

Working

Flat-plate collectors, developed by Hottel and Whillier in the 1950s, are the most common type. They consist of a dark flat-plate absorber, a transparent cover that reduces heat losses, a heat-transport fluid (air, antifreeze, or water) to remove heat from the absorber, and a heat-insulating backing. The absorber consists of a thin absorber sheet (of thermally stable polymers, aluminium, steel, or copper, to which a matte black or selective coating is applied) often backed by a grid or coil of fluid tubing placed in an insulated casing with a glass or polycarbonate cover [16].

In water heat panels, fluid is usually circulated through tubing to transfer heat from the absorber to an insulated water tank. This may be achieved directly or through a heat exchanger. Most air heat fabricators and some water heat manufacturers have a completely flooded absorber consisting of two sheets of metal between which the fluid passes. Because the heat exchange area is more significant, they may be marginally more efficient than traditional absorbers. Sunlight passes through the glazing and strikes the absorber plate, which heats up, changing solar energy into heat energy. The heat is transferred to liquid passing through pipes attached to the absorber plate. Absorber plates are commonly painted with "selective coatings," which absorb and retain heat better than ordinary black paint. Absorber plates are usually made of metal, typically copper or aluminium, because the metal is a good heat conductor

Seasonal and Geographical Variations

Seasonal and geographical factors, such as ambient temperature, solar radiation intensity, and weather conditions, significantly influence the performance of FPCs. Recent studies, such as those by the [20], highlight the need for managing seasonal and interannual variability to enhance renewable energy reliability. Similarly, the [19] provides insights into spatial and temporal solar resource variability, underscoring the importance of considering regional climatic differences in FPC design. Research by [7] demonstrated that the efficiency of FPCs varies considerably between summer and winter, with efficiency dropping in colder months due to increased heat losses. Additionally, [8] highlighted the need to consider regional differences in solar intensity when designing and deploying FPCs, particularly in areas with high cloud cover or significant diurnal temperature variations. The [20] further emphasizes managing seasonal and interannual variability to enhance the reliability of renewable energy systems. Incorporating an analysis of these factors ensures that the findings are applicable across diverse contexts, enhancing the practical utility of the research.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue I January 2025

Environmental Sustainability of Materials

A critical aspect of FPC design is the environmental sustainability of the materials used. Copper, widely recognized for its excellent thermal conductivity and corrosion resistance, is preferred for absorber plates and tubing. However, its high cost and environmental impact during extraction and processing necessitate exploring alternatives like polypropylene. Polypropylene offers lower cost and recyclability benefits but is limited by its lower thermal conductivity and susceptibility to UV degradation. Comparative studies, such as those by [10] and [11], underscore the importance of balancing material performance with environmental considerations. Recent studies, including [21] and [22], further highlight the life cycle environmental impacts of materials used in solar collectors, emphasizing the importance of integrating sustainable manufacturing practices and exploring eco-friendly alternatives. [21] highlights solar panel materials' life cycle environmental impact, stressing the need for sustainable manufacturing practices. Further research into bio-based polymers and advanced composites could provide sustainable solutions without compromising efficiency.

Long-term Performance Indicators

Understanding the long-term performance of FPC components, such as glazing and absorber materials, is crucial for ensuring reliability and cost-effectiveness over time. Studies by [13] and [14] examined the degradation rates of glazing materials exposed to prolonged UV radiation and temperature fluctuations. More recently, studies by the [19] and [18] explored advanced materials and coatings that improve resistance to environmental degradation, ensuring longer operational lifespans and enhanced efficiency under varying climatic conditions. They found that tempered glass with anti-reflective coatings is more durable than polycarbonate or acrylic covers. Similarly, absorber plates with advanced selective coatings demonstrate reduced efficiency loss over extended operational periods. The [19] studied spatial and temporal variability in solar resources, providing critical insights into optimizing materials for long-term performance. Incorporating these findings into FPC design can significantly enhance the system's lifespan and overall performance, making them more viable for domestic and industrial applications.

METHODOLOGY

There were appropriate methodology processes in the direction of achieving the objectives of this study. Several procedures have been selected to accomplish this study, as shown in the overview of the methodology process in Figure 3.

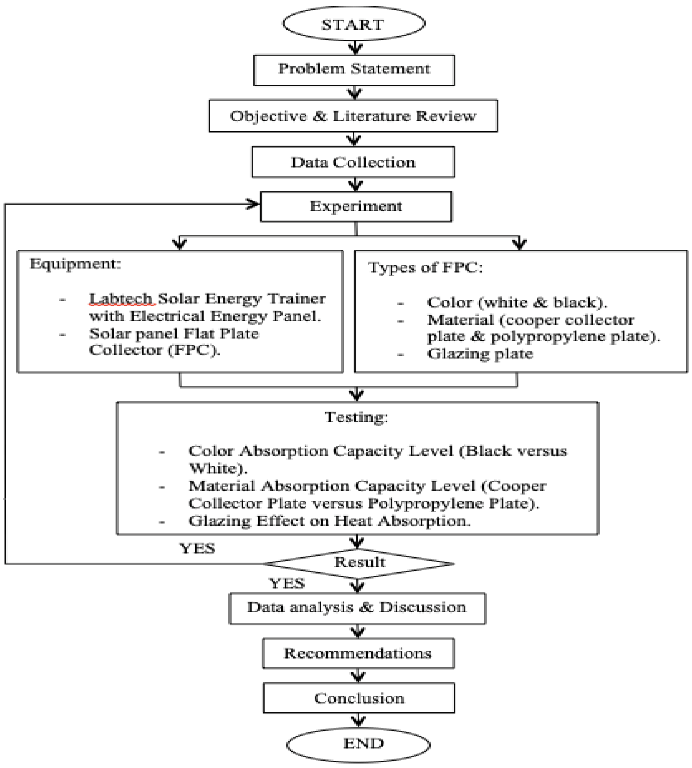

Fig. 3: Methodology Chart

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue I January 2025

Experimental

All Experiments will be conducted in three terms, which are colour absorption capacity level (black collector versus white collector), material absorption capacity level (cooper collector versus polypropylene collector), and glazing effect on heat absorption (single glazing collector versus double glazing collector).

The colour absorption capacity level experiment (black collector versus white collector) to understand the colour effect on absorption capacity level. Other than that, it is essential to know if there are any significant temperature differences between black and white collectors.

Next, the material absorption capacity level (copper collector versus polypropylene collector) experiment to understand the heat absorption effect in different materials and to know if there is any significant temperature difference between copper collector and polypropylene collector. Besides that, it is to see the heat transfer application by thermal conduction.

Lastly, the glazing effect on heat absorption (single glazing collector versus double-glazing collector) experiment was conducted to determine any significant temperature difference between collector panels with single and double-glazing covers. Temperatures for the collector plate and the glazing cover were taken to determine whether the temperature had increased.

The data will be collected on three different days for each collector, and for the data, the average values will be considered. The field experiments will commence at 9.00 a.m. and complete at 5.00 p.m. During the experimental period, the water tank (T1), the water temperature at the inlet (T2), and the water temperature at the outlet (T3) will be automatically tabulated by the Solar Energy Trainer every 15 minutes into the computer. For ambient temperature (T), the data will be taken every hour using 4 in 1 meter. After collecting all the data, the FPCs' efficiency will be calculated using Equations 3.4 and 3.5.

Instrumentation

Solar Energy Trainer comes complete with all standard components for solar energy systems. The trainer unit also can move quickly to an area with direct sunlight. Figure 4 shows the identification of the parts for the trainer.

Solar Energy Trainer was used for this experiment to compare the effect of different types of FPC (color, material, and glazing) on heat absorption and efficiency. It is coming complete with all standard components for solar energy systems. The unit has several types of FPC made of different materials and characteristics, which will be able to compare all those for absorbing the heat and light from the sun.

Solar Energy Trainer comes complete with a connection to the computer so that the data on water temperatures can be directly observed on the computer.

Fig. 4: Solar Energy Trainer

Flat Plat Collector Specifications

Table 1 shows the specifications of the FPC for this project. Materials for the fabrication process used in this experiment were used to collect the heat energy from the sun.

Table 1: Types of collector plates

Collector plate	Description	Picture
White coated collector plate	White collector plate is made from copper plated that painted with white color. It is completed with collector tube.	
Black coated collector plate	Black collector plate is made from copper plated that painted with black color. It is completed with collector tube. There are two black collectors for this experiment.	
Polypropylene tubes collector plate	Polypropylene tube collector plate is made from polypropylene sheet. It is completed with collector tube.	
Glazing	Glazing is mount on a wooden panel. It is used to isolate the heat energy in collector panel assembly during operation.	

Experiment Procedures

Solar Energy Trainer was placed between blocks G and H, and the FPC was put in the collector box. The angle of the collector box was adjusted to receive direct sunlight on the FPC. The thermometer sensor was placed in FPC's inlet and outlet. The 4 in 1 meter measured the ambient temperature. The Solar Energy Trainer was connected to the computer, and the control panel was turned ON. The water flow rate was fixed at 2Lm-1. After that, the flow animation was opened using the Solar Energy Trainer software on the computer to see the water flow. The temperatures of the water and chart can also be seen on the computer. Finally, the data logging from the Solar Energy Trainer was converted to Microsoft Excel.

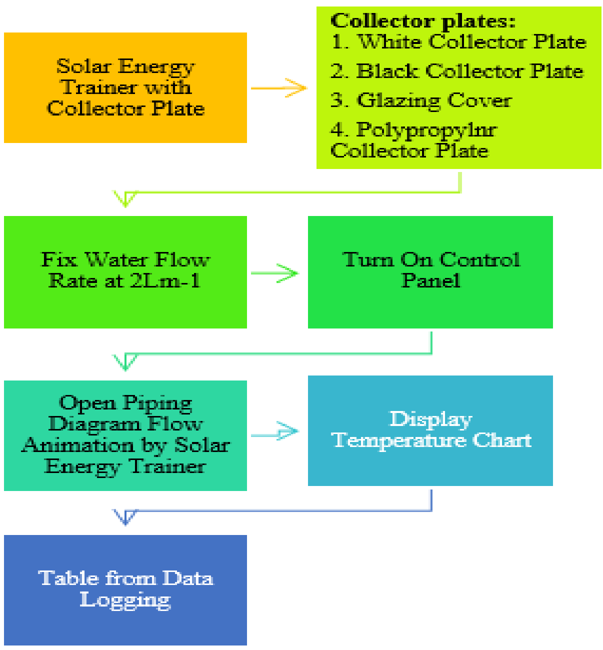

Fig. 5: The procedure flow

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue I January 2025

Calculation of Efficiency

The steady-state efficiency is calculated [17]. The source of heat in a solar collector is solar energy. The input power is usually the irradiation I that is received on the surface of the collector, absorbed and then transferred to the working fluid. An overall efficiency can be defined by dividing the net output by the input power. Such efficiency is generally considered instantaneous efficiency because it is a function of instantaneous operating conditions, including local climatic parameters like ambient temperature, wind speed, etc.

The experiment was conducted on three different days for each collector, and the average values were considered for the following calculations. The solar radiation intensity, I = 722 W/m2, in this experiment was referred to the study of [4]. This is because the experiment [4] was conducted in Malaysia with the same methodology as this experiment. His Fixed flow rate was also the same in this experiment, which is 2 Lm-1 (equivalent to 0.033 kgs-1). The efficiency of FPC was calculated by using Equations 1 and 2.

$Q_u = mC_p\,(T_{outlet} - T_{inlet})$ (Eq. 1)

Where,
Q_u: Useful heat gain (Watt)
m: Mass flow rate (kg/s)
C_p: Heat capacity at constant pressure 4.182 kJ/kg. K
T_{outlet}: Fluid outlet temperature (°C)
T_{inlet}: Fluid inlet temperature (°C)

Thus, the efficiency of the flat plate collector can be calculated by using;

$$f_1 = \frac{Q_u}{IA}$$

$$f_1 = \frac{Qu}{IA} \quad \text{(Eq. 2)}$$

Where,
Qu: Energy absorbed by the flat plate collector (W)
I: Energy gain from solar irradiation (W/m2/Hr.)
A: Collector absorber area (m2)

RESULTS AND DISCUSSIONS

Average Water Temperature at Outlet

Figure 6 shows the average water temperature at the outlet (T3) of FPC from colour (black collector versus white collector), material (cooper collector versus polypropylene collector), and glazing (single glazing collector versus double glazing collector).

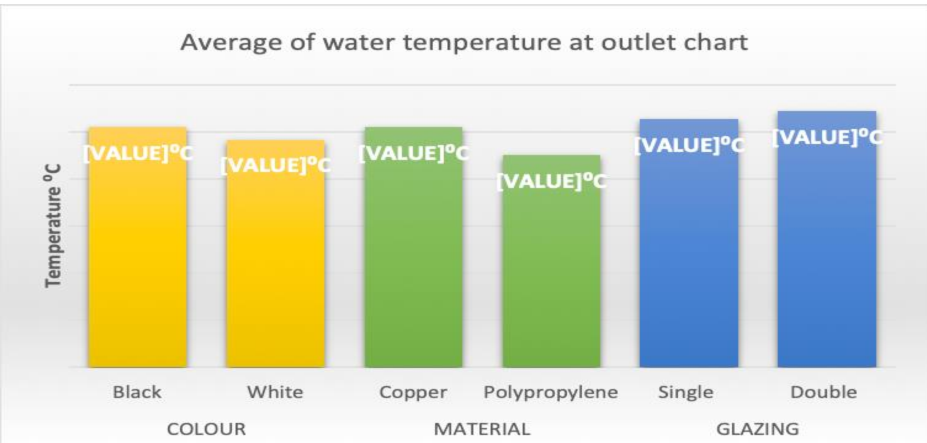

Fig. 6: Average water temperature at the outlet for the different FPC

For the colour absorption capacity level (black collector versus white collector) experiment, it was observed that (T3) for the black collector was higher than for a white collector. The (T3) black and white collectors were 51°C and 48.4°C respectively. This is because black collectors absorbed more heat compared to white collectors.

Next, FPC with copper and polypropylene tubes was tested. The material absorption capacity level (copper collector versus polypropylene collector) experiment showed that (T3) for copper collector was higher compared to polypropylene collector. Cooper collector is well known for its suitable heat absorption property; it has (T3) of 51.1°C compared to polypropylene collector with (T3) of 45°C. This is because copper is a material with suitable heat conductor properties. On the other hand, polypropylene is a material with poor heat conductor properties.

Lastly, for the glazing cover effect on heat absorption (single glazing collector versus double glazing collector) experiment, it shows that the double-glazing collector has higher (T3) with 54.5°C compared to single glazing collector with (T3) of 52.8°C. Glazing helps trap more solar energy's heat by increasing the number of covers.

The comparison of the different FPCs will assist in selecting which FPC will conduct heats with the highest (T3). To determine the (T3) different FPC, it is evident that the double-glazing collector was the highest (T3) at 54.5°C and that the polypropylene collector was the least (T3) at 45°C.

Average Efficiency

Figure 7 shows the average efficiency of FPC from colour (black collector versus white collector), material (cooper collector versus polypropylene collector), and glazing (single glazing collector versus double glazing collector).

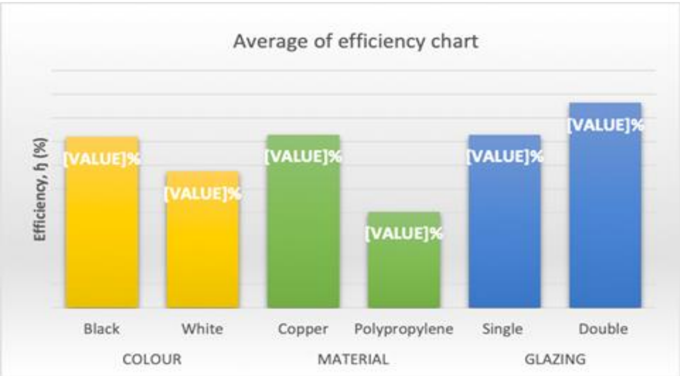

Fig. 7: Average of efficiencies for the different FPC

The black and white collectors of heat absorption were compared for the colour absorption capacity level (black collector versus white collector) experiment. It was found that the black collector heated up more than the white collector, with an efficiency of 14.4% for the black collector and 11.5% for the white collector. This is because when the FPC absorbs light, the light energy is transferred to heat energy. Since light is energy, the lighter that FPC absorbs, the more heat can be absorbed. Black collectors are known for better heat absorbance than white collectors, reflecting light.

The following experiment was material absorption capacity level (cooper collector versus polypropylene collector). For this experiment, FPC tubes made from copper and polypropylene were used to absorb energy from the sun. It was found that the copper collector absorbs more heat for the material experiment compared to the polypropylene collector. Cooper collector, known for having good heat absorbing and conducting properties, results in a significant increase in efficiency at 14.6% compared to polypropylene collectors, which have an efficiency of 8.1%.

Lastly, glazing covers were assembled on the collector panel in the glazing cover effect on heat absorption (single glazing collector versus double glazing collector) experiment. This experiment shows that a double-glazing collector has higher efficiency at 17.3% compared to a single glazing collector at 14.6%. The solar radiations pass through the glazing cover onto the FPC and help trap the solar energy's heat. With the increasing number of covers, heat loss from the FPC will decrease, and maximum efficiency will be obtained.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue I January 2025

The comparison of the different FPCs will assist in selecting which FPC will conduct heat with the highest efficiency. To determine the efficiency of the different FPCs, it is evident that the double-glazing cover collector had the highest efficiency at 17.3% and that the polypropylene collector was the least efficient at 8.1%. Examining the disparity between the two factors would indicate that a conclusively double-glazing collector would outperform a polypropylene collector in a SWH.

Applicability Across Diverse Contexts

The results highlight the importance of adapting FPC designs to local climatic and geographical conditions. For instance, black-coated copper collectors with double glazing showed the highest efficiency, particularly in high solar radiation regions. However, the efficiency gap between copper and polypropylene collectors narrows in areas with lower solar intensity, making polypropylene a cost-effective alternative. Additionally, seasonal variations in efficiency should be accounted for, as double-glazing systems may exhibit higher performance in colder climates by minimizing heat losses.

Environmental Considerations

The comparison between copper and polypropylene collectors highlights a trade-off between thermal performance and environmental impact. While copper collectors outperform in terms of efficiency, their ecological footprint is significantly higher due to the energy-intensive extraction and processing of copper. On the other hand, polypropylene collectors, despite their lower efficiency, offer advantages such as recyclability and reduced production costs. [22] emphasized solar technologies' role in supporting sustainable development, underscoring the importance of material choices. This underscores the need for a holistic approach to material selection, incorporating environmental sustainability alongside performance metrics.

Long-term Performance Insights

The analysis of long-term performance indicators, such as degradation rates of glazing and absorber materials, reveals that tempered glass and selectively coated absorbers maintain their efficiency better over time than their counterparts. This finding supports the recommendation to use high-quality materials despite their higher initial costs, as they offer better value and reduced maintenance needs over the system's lifespan.

CONCLUSION AND RECOMMENDATIONS

In conclusion, the energy collection of different FPCs has been compared. This experiment has fulfilled the objectives as shown as Table 2:

Table 2: Objective achievement

Objective	Achievement
1. To measure the efficient types of FPC intense of heat absorption for water temperature due to energy collection by using different colour, material and glazing. 2. To compare the water temperature at outlet, (T3) of colour, material and glazing of FPC. 3. To compare efficiency of colour, material and glazing of FPC on Solar Water Heater (SWH).	*Colour Collector* • The black collector absorbed more heats than white collector did. • Black collector has higher (T3) than white collector. • Efficiency of the black collector was highest than the white collector. *Material Collector* • The copper collector absorbed more heats than polypropylene collector did. • Copper collector has higher (T3) than polypropylene collector. • Efficiency of the copper collector was highest than the polypropylene collector. *Glazing Collector* • The double glazing collector has less heats loss from single glazing collector. • Double glazing collector has higher (T3) than single glazing collector. • Efficiency of the double glazing collector was highest than the single glazing collector.

Based on the results, there are several recommendations for this study:

1. Adapting black color, copper-based material, and double-glazing cover shall be the most efficient way to harvest solar energy for FPC.
2. It is recommended that the Solar Energy Trainer be put in an open area facing east to harvest more solar energy.
3. Since copper has high thermal conductivity and resistance to water corrosion, it is considered used in solar thermal applications as SWH.
4. Although the efficiency of polypropylene collector is the lowest, it is still suitable for swimming pool heating applications because it requires lower water temperatures.
5. Investing in solar energy systems to use the sun's energy for electricity or heat. The generation of electrical power may emit a certain amount of CO2. Solar energy systems can help reduce CO2 emissions mainly by being a clean and renewable energy source.

While this study provides valuable insights into the performance of different FPC configurations, several limitations warrant further investigation. First, the experiments were conducted under controlled conditions with fixed solar radiation intensity and flow rates, which may not fully capture real-world variations. Future studies should include field experiments across different climatic regions and seasons to validate the findings. Additionally, the environmental impact of FPC materials should be quantified using life cycle assessment (LCA) methodologies to provide a more comprehensive evaluation of their sustainability.

Future research should also focus on integrating advanced technologies, such as nanomaterials and phase-change materials, into FPC designs. These innovations can enhance thermal performance while reducing material usage and environmental impact. The [23] best practice guidelines also suggest employing economic and technical KPIs to optimize FPC designs and evaluate their feasibility. Moreover, exploring the financial feasibility of hybrid systems that combine FPCs with photovoltaic panels could provide a more versatile solution for energy generation and thermal applications.

ACKNOWLEDGMENT

This research was supported by University Tun Hussein Onn Malaysia and the Ministry of Education (MOE) through the Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTHM/03/35).

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