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Construction and Performance Analysis of a Flat Plate Solar Collector with Parallel Rectangular Tubes

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ABSTRACT

This study focuses on assessing how the circular and rectangular tube geometries of absorber tubes influence the performance of flat-plate solar collectors. To enhance the thermal performance of FPC, the traditional circular riser tubes have been replaced with rectangular riser tubes of FPC. Therefore, in present study, two FPCs with circular and rectangular riser tube were constructed and experiments were conducted in similar weather condition at the same time using water as heat transfer fluid and for same mass flow rate, experimental data was collected. The rectangular tube collector provided higher thermal performance than circular tube collector. The maximum efficiency recorded for the circular tube configuration was 55.98%, while the flat plate with rectangular tubes reached about 68.25%. The factor influencing the efficiency increase and thermal performance improvement between the two experimental setup is the higher heat transfer rate due to the increased contact surface area between the riser tube and the flat plate due to the use of parallel rectangular tubes instead of circular ones. In this study, two different FPCs incorporated with circular and rectangular riser tube configurations were both used for collection of inlet and outlet temperature data along with global solar radiation to calculate heat gain, efficiency and compare the results.

Keywords: Solar Energy, Flat Plate Solar Collector, Riser Tube Modification, Thermal Performance, Collector Efficiency

1. Introduction

Energy generation and use is the fundamental catalyst that propels our technological advancements, economic growth and social progress [1]. A nation's economic development is correlated with its energy and environmental conditions. Perhaps the only way to achieve sustainable economic growth is to employ fossil fuels wisely and efficiently, along with locally accessible natural resources like biomass, solar, wind, and hydro energy as the fossil fuel deposits are being depleted at a faster rate along with the lingering concerns for green house effects [2]. Solar energy is a versatile and adaptable energy source that can be used in a wide range of settings, from small-scale homes to large-scale farms. Its accessibility makes it a suitable solution for communities around the world, especially in areas with limited or no access to traditional power grids. By empowering individuals and communities to manage their own energy needs, solar energy paves the way for a sustainable future [3]. Subsequently, solar energy can be efficiently converted into heat energy by solar collectors, in which the absorber tube directly absorbs solar radiation and heat is transferred into the working fluid [4]. Solar energy systems, which capture the sun's energy to produce electricity, heat water, or provide space heating, often depend on solar collectors as a vital element. One of the most prevalent forms of solar collector is the FPC. FPCs are a type of solar collector that can be used for applications requiring moderate temperatures. They possess a simple and low maintenance design and can utilize both beam and diffuse solar radiation [5].

According to the findings of Sharafeldin et al. [6] the proper way to effectively use FPC is to modify some part of the FPC according to the need. Most of the research on FPC are conducted specifically on riser tube, absorber plate and absorber coating [7]. Taherian et al. [8] analyzed the dynamic simulation of a thermosyphon FPC and made a comparison between simulation results and experimental outcomes. While performing the experiment under two different weather conditions (partly cloudy and sunny), they found an average deviation of 6.3% for the outlet working fluid temperature (Sunny days) based on the simulation results, which was quite convincing. However, on partly cloudy days the deviation was much larger, as the flow of fluid through the riser tube was interrupted due to the absence of the thermosiphon effect along with reduced solar radiation. Saxena et al. [9] worked on the modification of conventional flat plate collectors to increase the efficiency and effectiveness of the collector. They used finned riser tubes instead of traditional ones in order to increase heat transfer rate. They also used some other modifications such as using corrugated absorbers, packed bed materials, and artificial roughness to enhance the performance of the collector. Islam et al. [4] performed research for the betterment of thermal efficiency of a flat plate collector by changing the geometric shape of the riser tube. They considered both circular shaped and rectangular shaped riser tubes in their simulation-based analysis. Their analysis indicated that for the rectangular shaped riser tubes, the heat exchange rate was 8.1% higher than that of the circular tube. The Observed efficiency for the rectangular one was 70.44%, and for the circular one, it was about 65.9%. Even though the FPC with rectangular riser tubes performed better in the context of efficiency and heat exchange rates; the pressure

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drop was introduced as a notable limitation for this type of FPCs. But Islam et al. [4] performed their computational analysis of rectangular tube flat plate solar collectors; which still lacks experimental validation. Clearly their simulation results provided a way to elevate the FPC technology towards a better thermal performance as well as increased efficiency. But their study did not incorporate any real-life weather conditions as well as variables for it to be considered a feasible advanced version of FPC.

Therefore, in this study, experimental research was conducted to evaluate the performance of a flat plate solar collector with rectangular riser tubes. The modified flat plate solar collector was successfully constructed and tested. The design modifications, particularly the use of rectangular tubes, were intended to improve the thermal performance and efficiency compared to traditional designs. The experimental testing of the constructed solar collector was done in order to evaluate its efficiency in terms of heat transfer and fluid temperature variation at different mass flow rates. This research assesses the impact of design modifications on overall system efficiency under similar operating circumstances.

2. Experimental setup and procedure

Two experimental setups were constructed – one with the conventional Flat Plate Collector with circular shaped parallel absorber tubes, and the other was with rectangular shaped absorber tubes. Performance of both of the FPCs were analyzed while keeping them in the same environmental conditions along with same mass flow rates.

2.1 General description of FPC

Flat plate solar collectors are a simple and clean energy technology that are incredibly beneficial for converting solar energy into usable thermal energy. Typically, FPCs are designed to be used for moderately heated water and space heating. Due to its electricity-free operation and lower energy costs, solar water heating is currently receiving a lot of attention. In order to heat the absorber plate and absorber tube, sunlight must first pass through the collector's glazing material and incident on the absorber plate. Glazing material not only creates greenhouse effects but also reduces heat loss by convection due to air passing over the absorber plate and riser tubes. Fig.1 shows the isometric drawing of the FPC, which consists of an absorber plate, riser tube arrangements and major dimensions.

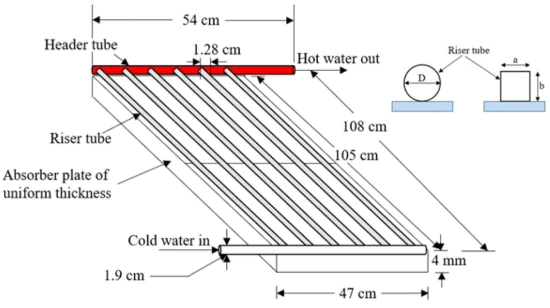

Fig.1 Isometric drawing of FPC's absorber plate with riser tube arrangement.

2.2 Description of the experimental setup

The flat plate collectors, water tanks, and pumps are the major components of the system. The whole assembly of the FPCs, the fluid carrying pipes and the reservoir tank are mounted on metallic stands. The collector box surrounds all components and protect them from dust. As it houses all of the other collector components, it is made of wood that is resistant to all weather conditions as well as sun radiation intensity. The geometric design and construction of the shell require specific attention in order to ensure high collector stability, tightness, and durability during installation. Water was used as the working fluid. A galvanized iron plate with the length of 109 cm and width of 51 cm was used as the absorber plate for each FPCs. In order to limit heat losses, cork sheet was used as insulation on the bottom and around the sides of the collector. The collector cover is made of 2.5 mm clear glass of 105 cm length and 47 cm width. The riser tubes and header tubes of both FPCs were constructed of copper. Due to difference in geometric properties, cross-sectional area of rectangular shaped riser tube and circular shaped riser tubes did not have any matching specifications. However, their perimeter was kept nearly the same – rectangular tube having a perimeter of 4.02 cm and circular tube having 5.08 cm. Table 1 showed the detailed specifications of both of the FPCs with dimensions.

Table 1 Detailed specification of rectangular riser tube FPC and circular riser tube FPC.

Specification	Dimension
Collector area	109 cm × 51 cm
Absorber plate area (with uniform thickness)	105 cm × 47 cm
Insulation area	105 cm × 47 cm
Glass cover area	105 cm × 47 cm
Riser tube	1.28 cm (Outside Diameter) Thickness = 0.5 mm Perimeter= 4.02 cm 1.905 cm × 1.905 cm(rectangular) Thickness = 0.5 mm Perimeter= 5.08 cm 108 cm (length)
Riser tube spacing	7 cm
Header tube	1.9 cm (Outside Diameter) Perimeter= 5.97 cm 1.27 cm × 1.27 cm (Rectangular) Perimeter= 7.62 cm 54 cm (length)

Even though the cross-sectional area of the rectangular shaped riser tube and circular shaped riser tubes are not same, their mass flow rate was kept constant during experimentation. As we the study is to increase the heat transfer rate by increasing contact surface area with flat place, the perimeter of both types of tubes were kept nearly the same. For circular riser tubes, the perimeter was 4.02 cm whereas for rectangular one, it was kept to 5.08 cm.

2.3 Working procedure

Two centrifugal pumps with a 0.5 HP rating were utilized to move fluid between the storage tank and the collector. The solar irradiance was measured using a pyranometer with an accuracy of ±4%. A water level controller ensured a continuous supply of water at a constant head to the FPC's inlet port, while the outlet was connected with a measuring jar to collect the water flowing through the collector. K-type thermocouples with a length of 60 ft and an accuracy of ±2.2°C were used to measure the inlet and outlet water temperatures. A 3-liter capacity flowmeter with ±5% accuracy was employed to measure the flow rate of water. The collector's performance characteristics were tested directly with a multimeter, which had an accuracy of 3%.

Fig.2 shows the experimental setup of FPC with conventional circular riser tubes (right) and FPC with rectangular riser tubes (left). To ensure consistent temperature conditions, the experiment was initiated with proper flushing of the collectors. During the observations, the mass flow rate was maintained constant at 0.01434 kg/s for 2nd November, 0.0156 kg/s for 3rd November, and 0.0143 kg/s for 4th November. The experiment was conducted from 12:25 PM to 2:00 PM for all three days.

Fig.2 Experimental setup of FPC with conventional circular riser tubes (right) and rectangular riser tubes (left).

2.4 Equations for performance parameters

For testing the FPC, the standard procedure is to operate the collector under steady-state conditions. These conditions ensure that the solar radiation and other conditions are essentially constant for long enough time to allow the outlet water temperature and the rate of the useful gain (Q_{gain}) to become steady. For calculating the steady state instantaneous efficiency of the collector, the instantaneous method is adopted.

The amount of heat gain can be calculated with –

Heat gain,

$$Q_{gain} = m.\, s.\, \Delta T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where,

$m =$ mass flow rate of water (kg/sec)
$s =$ specific heat of water (J/kg°C)
$\Delta T = T_o - T_i$
= outlet water temperature – inlet water temperature
= temperature rise (°C)

Mass flow rate must be kept constant for the heat gain to provide accurate results. However, mass flow rates differ slightly due to the changes in operating conditions – electricity input, frictional losses, and changes in pump efficiency. Again, with changes in weather conditions, water density might change as well, implicating the practical use of Eq. (1). These changes are ignored as both the rectangular as well as circular riser tube FPCs were facing the same operating conditions – mitigating the effects of variables, such as, slight change in mass flowrate.

The amount of solar incident energy can be calculated with-

$$Q_{in} = A_c.\, I$$

Where,

$A_c =$ area of the collector (m^2)
$I =$ incident global solar radiation (W/m^2)

The efficiency can be calculated with-
Collector efficiency,

$$\eta = \frac{\text{Qgain}}{\text{Qin}} \times 100\ (\%) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

2.5 Uncertainty analysis

For this study, various instruments were used for various purposes. For measuring global solar radiation, a pyranometer – Apogee instrument SP110 – was used. For measuring flowrate, inlet and outlet temperature of water as well as for logging the data automatically the devices used are flowmeter, K-type thermocouple, Jinko JK4000. However, each of the instruments comes with a certain error percentage or accuracy. These are crucial for the analysis of the experiment results. Table 2 shows the instruments, their output range as well as accuracy.

Table 2 Accuracy and rated output range of instruments for this study.

Name	Output range	Accuracy
Apogee SP-110	0 mV to 400 mV	± 4 %
K-type thermocouple	-200°C to 1260°C	+/- 2.2C
Flowmeter	–	±5%
Jinko JK4000	-200°C to 1800°C	±(read value ×0.2%+1)℃

3. Results and discussion

Based on the experimental data acquired on 2nd, 3rd and 4th of November, 2024 – global solar radiation, variation of outlet temperature, heat gain and efficiency were plotted against time of the day.

3.1 Variation of outlet temperature

Fig.3 showed the outlet temperature variation of rectangular tube FPC and circular tube FPC on 2nd November, 2024. On that day, global solar radiation level was measured to be within 500 W/m^2 to 650 W/m^2. The outlet temperature of rectangular tube configuration increased from 29.4°C at 11:05 AM to 34.1°C by 1:00 PM, while circular tubes peaked at 32.9°C. Despite a temperature difference ranging from 0.5°C to 1.5°C, it remains steady, indicating that the rectangular tube FPC maintained a slight thermal advantage.

Throughout the whole experimentation period of 2nd November, the output temperature of rectangular tube configuration was always higher than that of circular tube configuration. It is due to the increased contact surface area with the flat plate surface. Even though both of the FPCs have the same collector area, heat transfer from flat plate to absorber tube and then absorber tube to heat transfer fluid occurs. However, due to having larger contact surface area rectangular tubes gets more heat transferred to it from the collector. This difference in heat transfer rate directly affected the output temperature [10]. However, due to having greater heat transfer rate, rectangular tube FPC showed more changes in output temperature with the variation of solar radiation.

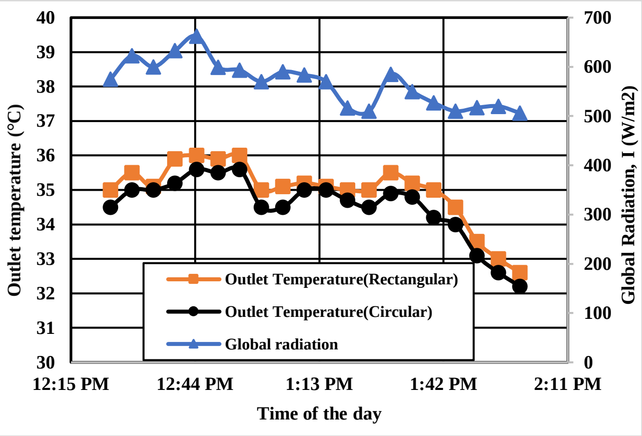

Fig.3 Outlet temperature variation of rectangular tube FPC and circular tube FPC on 2nd November, 2024.

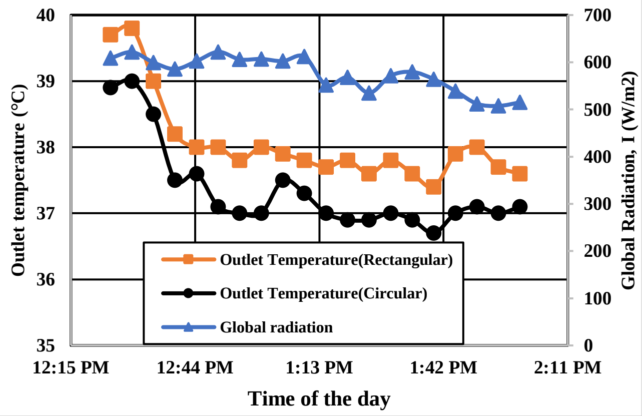

Fig.4 Outlet temperature variation of rectangular tube FPC and circular tube FPC on 3rd November, 2024.

Fig.4 showed the outlet temperature variation for both type of FPCs on 3rd November, 2024. It was observed that rectangular configuration showed higher output temperature than the circular one. Initially the temperature was observed to be higher which is the result of the FPCs being exposed to the sun without any water flow prior to the start of the experiment. Given enough time to become stable, the outlet temperatures became lower. Despite some irregular weather conditions, such as clouds, most of the time increasing solar radiation increased the outlet temperature for both of the FPCs. However, Rectangular tube FPC showed fast temperature rise as well as fast temperature decrease compared to the circular tube FPC. It was observed on 3rd November, 2024 that at 1:20 PM global solar radiation increased to 568 W/m^2 from previously measured 551.5 W/m^2. This resulted in increased inlet-outlet temperature difference of 2.4 °C to 2.6 °C for the rectangular tube FPC whereas for circular tube FPC it was 1.7 °C without any change.

Fig.5 shows the outlet temperature variation of rectangular tube FPC and conventional circular tube FPC on 4th November, 2024. The general trend of higher outlet temperature for rectangular FPC than the circular tube FPC were observed. Rectangular tube FPC also showed higher outlet temperature increase or decrease than the circular ones due to its higher heat transfer rate than the circular tube FPC.

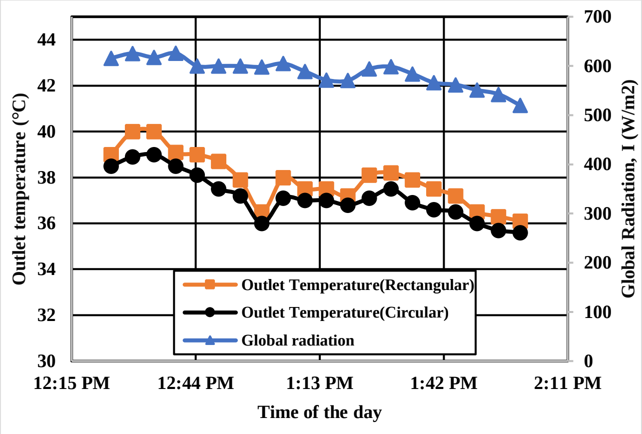

Fig.5 Outlet temperature variation of rectangular tube FPC and circular tube FPC on 4th November, 2024.

3.2 Thermal performance

Heat gain data further highlighted the superior performance of rectangular tubes. Across the observed days, FPCs with rectangular tubes consistently showed greater heat gains than those with circular tubes. This was particularly evident on 3rd November, where solar radiation levels fluctuated between 529 W/m² and 695 W/m², and rectangular tubes responded with significant increases in heat gain, reflecting their enhanced capacity to capture and use solar energy effectively.

Fig.6 showed the heat gain variation of rectangular tube FPC and circular tube FPC with respect to time of the day on 2nd November, 2024.

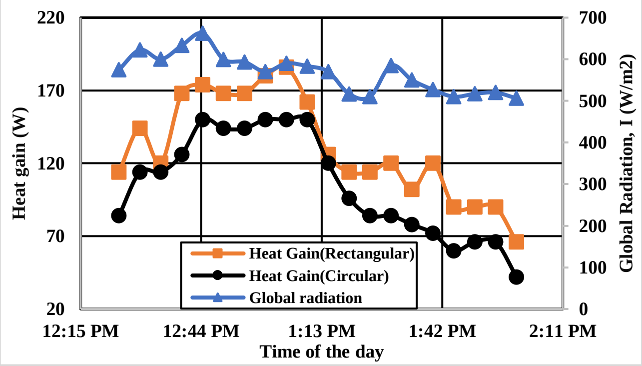

Fig.6 Heat gain variation of rectangular tube FPC and circular tube FPC with respect to time 2nd November, 2024.

Rectangular tubes often outperformed circular tubes in terms of heat gain by 10–15%. This may be due to their larger surface area, which provides better exposure to solar radiation and enhances heat transfer. Consequently, FPCs with rectangular tubes appear more efficient at converting solar energy into thermal output, particularly when the irradiance fluctuates.

Fig.7 showed the heat gain variation of rectangular tube FPC and circular tube FPC with respect to time of the day on 3rd November, 2024.

Fig.8 showed the heat gain variation of rectangular tube FPC and circular tube FPC with respect to time of the day on 2nd November, 2024.

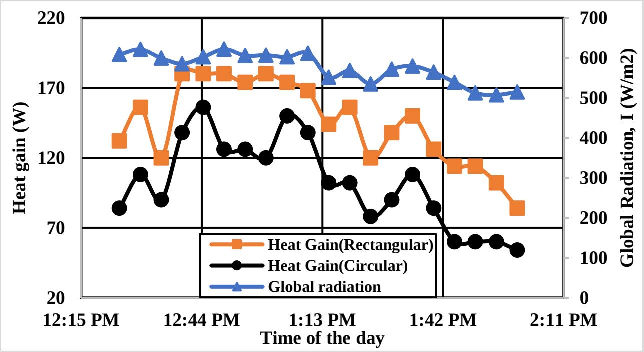

Fig.7 Heat gain variation of rectangular tube FPC and circular tube FPC with respect to time 3rd November 2024

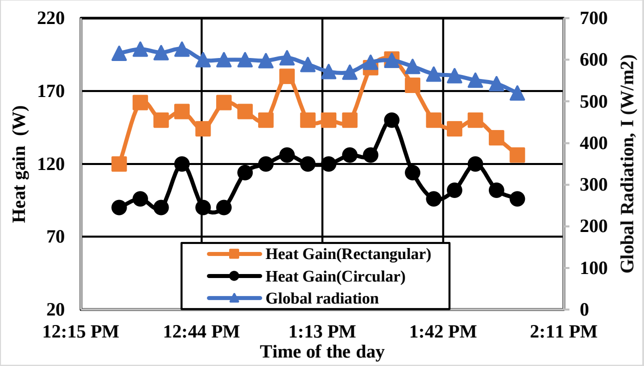

Fig.8 Heat gain variation of rectangular tube FPC and circular tube FPC with respect to time 4th November 2024

3.4 Efficiency analysis

The efficiency trends of the two tube geometries reveal additional distinctions. Even though tube types show increased efficiency as solar radiation intensifies, rectangular tube FPCs reach higher efficiency levels sooner in the day and under lower levels of radiation. For example, on November 4, by 11:30 AM, with solar radiation still below 600 W/m², the rectangular tube FPCs already displayed greater efficiency than their circular counterparts. This early advantage persists throughout the day, as rectangular tubes demonstrate greater stability in efficiency even there is fluctuations in solar radiation.

Fig.9 showed the efficiency of rectangular tube FPC and circular tube FPC with respect to global solar radiation and time of the day on 2nd November, 2024. The general trend were the same – rectangular tube FPC with higher efficiency than the circular ones. However, the changes in efficiency was more evident in the rectangular FPC, specially at 12:45 PM of the same day efficiency dropped from 49.2% to 42.5% due to the drop of solar radiation from 622.5 W/m^2 to 600 W/m^2 whereas the circular tube FPC showed 38.9% to 40.4%. It is due to the circular shaped having lower contact surface, i.e., heat transfer rate, when the solar radiation decreased, there were more residual thermal energy in the absorber plate of the circular tube FPC than the rectangular tube FPC due to having lower heat transfer rate. Even though this lower heat transfer rate lowers the performance of FPC, it can help providing a consistent output up to a certain time.

This variation might be due to the fluid flow characteristics shaped by each tube's geometry. Rectangular tubes, with their specific structure, could allow for a more stable transfer of heat, thereby minimizing thermal losses and enhancing energy collection, particularly under fluctuating conditions. Fig.10 showed the efficiency of rectangular tube FPC and circular tube FPC with respect to global solar radiation and time of the day on 3rd November, 2024. Fig.11 showed the efficiency of rectangular tube FPC and circular tube FPC with respect to global solar radiation and time of the day on 4th November, 2024.

Even though the global solar radiation was stable between 500 W/m^2 to 600 W/m^2 throughout the experimental period, there were some abrupt changes to the efficiency for both setups. It is due to the slight change in flow rate due to the pump proving inconsistent water flow. Other weather conditions like cloud, dust particles as well as human error of measurements forms some irregular data points such as circular tube FPC efficiency at 12:40 PM, rectangular tube FPC efficiency at 1:05 PM. In both cased the efficiency increased abruptly which needs to be filtered during analysis.

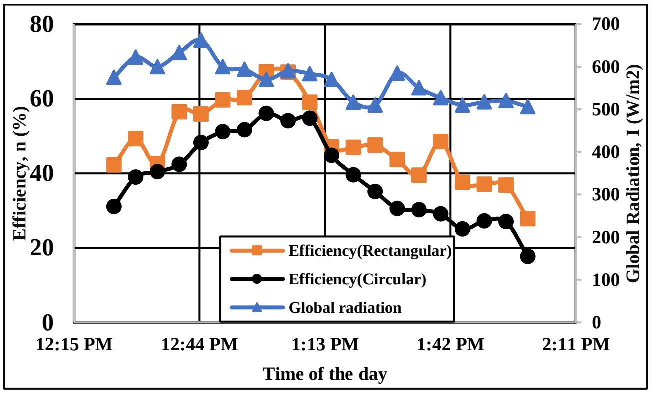

Fig.9 Efficiency of rectangular tube FPC and circular tube FPC with respect to global solar radiation and time of the day on 2nd November, 2024.

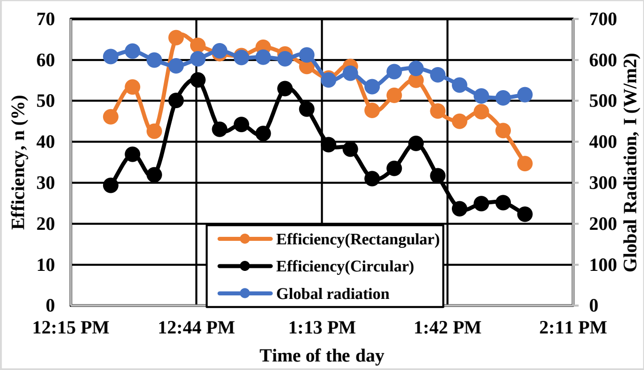

Fig.10 Efficiency of rectangular tube FPC and circular tube FPC with respect to global solar radiation and time of the day on 3rd November, 2024.

4. Conclusion

From the study it was observed that-

- The maximum efficiency recorded for the circular tube configuration was 55.98%, while the flat plate with rectangular tubes reached about 68.25%. It was also found that highest heat gain by the former was about 155 W whereas the latter provided about 192 W.
- From the plots it was also clear that outlet water temperature was always lower in case of FPC with circular riser tube. So, it can be concluded that FPCs with rectangular riser tubes outperformed those

with circular riser tubes in terms of heat gain, efficiency, and output temperatures.

- The perimeter of each of the tube configuration was kept nearly the same for normalizing the results as heat transfer rate from flat plate to working fluid increased due to the increased contact surface area between absorber tube and flat plate and tube perimeter as well shape was responsible for it.
- Rectangular tube FPC's higher surface area and flow characteristics contribute to improved heat absorption and retention, making them ideal for applications requiring dependable and efficient thermal performance.

These findings suggest several avenues for further investigation. Alternative tube forms and materials that might increase FPC efficiency, particularly in the presence of changing solar conditions, should be studied in future study. This study emphasizes the importance of tube design in solar collectors, as well as the possibility for developing solar technology for energy-efficient applications.

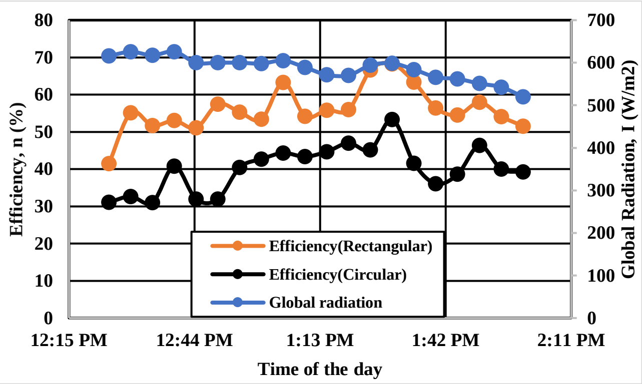

Fig.11 Efficiency of rectangular tube FPC and circular tube FPC with respect to global solar radiation and time of the day on 4th November, 2024

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NOMENCLATURE

FPC	: Flat plate collector
T_i	: Water inlet temperature, (°C)
T_o	: Water outlet temperature, (°C)
ΔT	: Outlet to inlet temperature difference, (°C)
Q_{gain}	: Heat gain from the collector, (W)
m	: Mass flow rate of water, (kg/sec)
s	: Specific heat of water, (J/kg°C)
A_c	: Area of the collector, (m^2)
I	: Incident global radiation, (W/m^2)
Q_{in}	: Total incident radiation energy, (W)
η	: Collector efficiency, (%)