

# Enhancing the Efficiency of Parabolic Trough Solar Collector Using Mini-Channel Flat Aluminium Tubes

Ebtehal Chasseb Jbary<sup>1</sup>, Alaa R. Al-Badri<sup>1</sup>

<sup>1</sup> Mechanical Engineering Department, Wasit University

Corresponding Author Email: [Std2022203.E.Chasseb@uowasit.edu.iq](mailto:Std2022203.E.Chasseb@uowasit.edu.iq)

Received Feb. 23, 2025

Revised Jul.19, 2025

Accepted. Aug.17, 2025

Online Jun.1, 2026

## ABSTRACT

This research aims to use mini-channel flat aluminum tubes with parallel flow in parabolic trough solar collectors. A parabolic trough solar collector was designed, manufactured, and tested for the present study. The length of the solar collector was 0.65 m, the collector aperture width was 0.5 m, the radius of the parabola was 0.25 m, and the rim angle was 90 degrees. In the experimental part, experiments were conducted at flow rates ranging from 0.1 to 0.8 liters per minute through three distinct heating stages to evaluate heat transfer efficiency. The results indicated that the largest amount of heat added to the water was in the case when it passed through the copper tube; the reason for this is the high thermal conductivity of the copper material, and also because of the large amount of solar radiation reflected by the reflective surface towards the copper tube. In addition, the two stages in which the water passes through the mini-channel tubes contribute to adding a good amount of heat, helped by their precise design that increases the heat exchange area between the channels walls and the water. The maximum efficiency achieved by the solar collector was 82% at a flow rate of 0.5 l/min at an angle of 135° towards the southeast in Al-Kut city. Pressure drop analyses revealed a linear relationship with flow rate. This innovative approach highlights the potential for improved solar energy utilization and represents a major breakthrough in the performance of solar thermal systems.

**Keywords:** Solar collector; Parabolic trough; Solar energy; Mini-channel tube; Parallel flow tubes

## 1. Introduction

Solar energy represents a viable alternative energy source that has the potential to significantly mitigate the effects of energy crises and climate change associated with fossil fuel dependence [1]. This clean energy option can help tackle global energy issues by directly conserving and indirectly replacing traditional energy. Direct energy conservation can be achieved through continuous enhancements in energy conversion efficiency and solar thermal management, fueled by technological progress. In a society that relies on and demands energy, the quest for affordable and sustainable energy solutions has become a crucial issue for both the community and researchers. The ambition for sustainability and self-reliance enhances the potential of renewable energy options. Solar energy is the most plentiful of the different renewable energy sources available. Nonetheless, it is vital to improve the design of solar collectors that transform radiant solar energy into thermal energy. With the evident promise of solar energy, the solar thermal sector, particularly systems utilizing evacuated tube technology, has seen impressive expansion in recent years [2]. The solar collector in this study adopts a parabolic trough configuration. A Parabolic Reflector is a concave, mirrored surface designed as a parabola, which efficiently focuses incoming solar energy onto a receiver tube. These reflectors are typically constructed from highly reflective materials, such as polished aluminum or silvered glass, to optimize sunlight concentration. The Receiver Tube (Absorber Tube) is located along the focal line of the parabolic reflector, capturing the concentrated solar energy. Typically constructed from metal, it is coated with a selective material to improve solar absorption and reduce thermal radiation losses. More advanced models may encase the tube in a glass

envelope to form a vacuum, which significantly decreases convective heat losses. The Heat Transfer Fluid (HTF) flows through the receiver tube, capturing and moving the absorbed thermal energy. Typical HTFs consist of synthetic oils, molten salts, or pressurized water, which convey the heat to a heat exchanger or a power generation system.

A support framework is necessary to uphold the exact alignment of the parabolic reflector and the receiver tube. This structure is designed to endure environmental forces like wind and temperature changes while maintaining the system's optical precision. The tracking mechanism guarantees that the reflector consistently directs sunlight onto the receiver tube as the sun traverses the sky. This is accomplished through a single-axis tracking system that adjusts the reflector's position throughout the day for optimal solar alignment.

In operation, the parabolic reflector directs sunlight onto the receiver tube, where the heat transfer fluid absorbs the thermal energy. This energy is then utilized for various purposes, including generating steam for electricity, providing industrial heat, or heating water. Several limitations must be considered, such as the constrained research on mini-channel flow tubes, and optimization within horizontal evaporatively cooled mini-channel parallel flow tube solar collectors [3]. These solar collectors function as passive solar systems, which do not require any external power or electricity, making them straightforward and maintenance-free. Moreover, they can operate without a differential controller and have attractive applications in food processing, drying, water heating, and space heating [4]. It can be concluded that research encounters obstacles related to heat dissipation from the absorber plate, tube functionalities, and vacuuming techniques. In addition, research on the theoretical and experimental examination of evaporative-cooled parallel flow tube solar collectors is scarce [3]. To overcome the limitations associated with vacuuming methods typically used in flat-plate collectors and to leverage gravity as a cost-effective cooling solution, compact, space-saving parallel flow mini-tube collectors have been created to operate as axial flow tube solar collectors [5]. Human solar energy conversion efficiency remains a challenge. There is a pressing need to make this process more efficient, and researchers worldwide are optimistic that the latest innovations can significantly increase technical and economic feasibility [6].

Not only does the solar collector operate at a higher solar energy conversion temperature, but land use underpins the necessity for higher efficiency. Investments in solar energy are said to skyrocket in the future [7]. However, sustaining an 8-12% solar market growth won't be easy unless two objectives are met: enhancing collector performance and reducing costs. The design of the solar collector also needs to be changed to improve the overall performance of the traditional solar collector, including developing newly designed collaterals and modifying light absorbers. Improving the heat transfer rate is challenging and limited for inefficient thermal collectors, which is typical in traditional collector technology. However, it is achievable through better heat transfer [8]. Various research studies employ such solar collectors. In addition, depending on volume, macro- and micro-channels can be spurted, etched, or molded into many types of substrates to construct heat exchangers [9]. It has been proven that using mini-channel parallel flow tubes to increase the heat transfer coefficient in the temperature range of 150-200°C would be a promising approach. As the system operates, water circulates through the mini-channel tubes, facilitating a heat exchange process between the heated walls of the tubes and the moving water [10]. The solar energy absorbed raises the temperature of the water within the tubes. Under ideal conditions, this configuration can generate enough thermal energy to bring the water temperature to its boiling point. Mini-channel heat exchangers, often called micro-channel heat exchangers, are increasingly utilized across various fields, such as automotive, air conditioning, and cooling for electronics. Their small footprint and improved functionality make them favored over traditional round-tube plate-fin heat exchangers. These devices effectively gather and release heat from their environment, making them well-suited for thermal management. Although the application of mini-channel heat exchangers in solar thermal systems has been limited, their adoption is gradually increasing. Incorporating these exchangers into solar collectors is motivated by their capacity to enhance the heat transfer area between the walls of the tubes and the working fluid, significantly improving thermal performance [11]. Manufacturing mini-channel tubes typically utilizes a metallurgical process known as extrusion. This process involves heating a metal to a high temperature until it becomes malleable, then pushing it through a die to create a specific shape with a consistent cross-section. This method allows for the development of precise and uniform designs. Aluminum mini-channel tubes, which are frequently used in these applications, are usually shaped in rectangular profiles with rounded corners and feature internal rectangular or circular openings termed "channels." These channels play a crucial role in enhancing heat transfer efficiency by increasing the surface area available for heat exchange. By integrating mini-channel tubes into solar collectors, these systems attain improved efficiency and more compact configurations, making them especially appropriate for low to medium-temperature uses. As this technology gains traction, it promises

to transform the effectiveness of solar thermal systems by merging high thermal efficiency with precise manufacturing and adaptability to specific thermal and structural needs.

## 2. Literature review

Several studies were conducted during the last exploration of solar collectors, particularly those utilizing mini-channel parallel flow tubes, which have garnered significant attention over the decades. This reflects an evolution of technology aimed at enhancing the efficiency of solar thermal systems. This literature review aims to synthesize key contributions from various studies that have shaped our understanding of this area.

Fast forward to 2008, and Sookdeos [12] an experimental investigation provided empirical insights into the thermo-fluid behavior within flat-plate solar collectors. This study is notable for filling a significant gap in experimental data regarding flow characteristics and wall temperature development within collector tubes. The pioneering measurements of flow fields within flat-plate collectors contribute to a more nuanced understanding of how radiant heating affects flow structures, setting a precedent for future research.

G. R. I. G. et al. [13] built on this foundation by validating a lumped parameter model that predicts the performance of solar water collectors, particularly in the Mediterranean region. Introducing a heat transfer enhancement technique involving partial porous media demonstrates a practical application of theoretical concepts, showcasing how modifications can substantially increase efficiency without necessitating complex redesigns. In 2010 [14] the article described a three-dimensional numerical simulation of the coupled heat transfer properties in the receiver tube of a parabolic trough solar collector using the Monte Carlo Ray-Trace Method (MCRT) along with FLUENT software. The simulation corroborated the physical model with experimental data, demonstrating an average relative error of 2%. It was examined the impacts of direct normal irradiance, Reynolds number, and emissivity on heat transfer properties were examined, indicating that minimizing radiation loss is essential for enhancing collector efficiency. The research highlights the importance of optimizing absorber characteristics to improve solar energy absorption. Bello-Ochende et al. [15] offered a numerical analysis of heat transfer, fluid friction, and thermodynamic efficiency in a parabolic trough receiver equipped with perforated plate inserts. It investigated a range of geometric parameters, such as the plates' orientation, spacing, and diameter, while testing Reynolds numbers between  $1.9 \times 10^4$  and  $3.2 \times 10^5$ . The findings indicate that incorporating perforated plates improves heat transfer performance, increasing the Nusselt number by up to 138.2%, although it also considerably increases fluid friction. The study determines that the ideal Reynolds number for reducing entropy generation rates is  $6.40 \times 10^4$ . In 2014, B. Yahaya Muhammad and N. Mariah Adam [16] provided a comprehensive review of flat-plate solar collectors, discussing their applications in solar thermal power generation and other uses such as water pumping and distillation. Their analysis highlights the comparative inefficiencies of flat-plate collectors against more advanced designs while emphasizing their suitability for low-temperature applications, thus situating flat-plate technology within a broader context of solar energy utilization. Beginning with foundational work, Z. Wen's [17] paper delved into the design of solar collectors, emphasizing the role of back-absorbing parallel plate polymer absorbers and optimal flow control within these systems. This early research laid the groundwork for understanding the heat transfer fluids essential for concentrating solar power systems, highlighting the importance of innovative designs in maximizing energy extraction. Qiu et al. [18] the study introduced an integrated optical-thermal model for a parabolic trough solar collector (PTC) using supercritical CO<sub>2</sub> as the heat transfer fluid (HTF) under varying solar flux conditions. It examines the flow and heat transfer behaviors of supercritical CO<sub>2</sub>, showing collector efficiencies for Rankine and Brayton cycles. The research highlights the significance of comprehending heat transfer mechanisms for the design and functionality of PTC systems, which enhances performance and dependability. Findings suggested the model is trustworthy, with numerical outcomes closely matching experimental results. Ebrahim Ghasemi and Akbar Ranjbar [19] were studied to explore the thermal efficiency of a solar parabolic trough collector that is enhanced by adding porous rings within the absorber tube. It was observed that reducing the inner diameter of the porous rings leads to an increase in the Nusselt number, thus enhancing the heat transfer rate. The research also analyzes how changing the spacing between the porous rings affects the heat transfer coefficient and the thermal performance factor. The findings show a strong correlation between the numerical model and the experimental results, validating the theoretical model for practical engineering uses. Naji et al. [3] focus toward mini-channel technology, analyzing the performance of modified solar collector plates equipped with mini-channels. It underscored the advantages of small-scale channels in enhancing heat transfer rates, marking a significant advancement in solar collector design to improve energy efficiency. The authors effectively illustrate how the integration of mini-channels can optimize thermal

processes, thereby contributing to the ongoing discourse on innovative solar collector designs. The research by Kuharat and Anwar Bég [20] further explored the integration of Nano fluids within solar collectors, emphasizing their potential to enhance thermal efficiencies through improved heat transfer mechanisms. Their findings indicate that the engineering of thermally stable Nano fluids can address operational challenges. However, the complexities of modeling heat transfer in such systems remain a critical area for future exploration. Similarly, it discussed volumetric absorption solar thermal platforms, highlighting the limitations of traditional surface absorption methods and advocating for designs that utilize nanoparticles to enhance thermal efficiencies. The work reflected an ongoing trend towards integrating advanced materials and nanotechnology in solar collector design, aiming to mitigate thermal resistance and improve energy conversion rates. Shi and Lin [21] validated and refined computational models for photovoltaic/thermal (PV/T) collectors. Enhanced thermal models elucidate the interplay between various control parameters, offering insights that could inform the design of more efficient hybrid systems that leverage thermal and electrical energy from solar sources. Sobhansarbandi et al. [22] introduced a groundbreaking design for Evacuated Tube Solar Collectors (ETCs) that utilizes "dry-drawable" Carbon Nanotube (CNT) sheet coatings combined with Phase Change Materials (PCMs) to improve solar energy capture and thermal storage for solar water heating systems. The CNT sheets offer excellent thermal conductivity and diffusivity, overcoming the drawbacks of PCMs, which are known for their low heat transfer rates. This synergy allowed for adequate heat storage, ensuring a reliable hot water supply even in overcast weather or nighttime. The research underscored the potential for enhanced performance and efficiency in solar water heating technologies. When Supriya [23] proposed new design of mini-channel receivers for compound parabolic collectors (CPC) enhances efficiency by optimizing fluid flow. The optimized mini-channel design increases thermal gain by 23% while minimizing pressure drop, with outlet fluid temperatures ranging from 82 to 155 °C at flow rates of 1.5–4 l/h. This innovative approach reduces heat loss, ultimately improving the overall efficiency of solar thermal systems, making it a significant advancement in solar collector technology. Finally, He et al. [10] presented a contemporary analysis of stainless-steel flat-plate solar collectors, emphasizing their commercial viability in meeting global thermal energy demands. Their investigation into design parameters and efficiency improvements underscores the importance of ongoing research in optimizing solar thermal technologies to meet the growing energy needs sustainably.

The present study aims to enhance the thermal efficiency of the solar collector using a mini-channel parallel flow tube.

The dimensions of the tubes were (60 mm in tube width, 3 mm in tube height, 1mm in wall thickness, and 6 mm in Channel width), as shown in Fig.3 represents the tubes in the first manufacturing stage and the addition of the end caps.

### 3. Theoretical analysis

In this section, the design of the solar collector is formulated using mathematical equations, and the pressure drop is determined accordingly.

#### 3.1. The solar collector designs

The relationship between the aperture width and the focal length can be represented as a function of the rim angle in Eq. (1):

$$\frac{W_a}{F} = \left(\frac{-4}{\tan\psi}\right) + \left(\sqrt{\frac{16}{\tan^2\psi} + 16}\right) \quad (1)$$

The arc length of the parabolic curved surface (S) can be expressed and calculated using Eq. (2):

$$S = \left(\frac{H_p}{2}\right)\left\{\sec\left(\frac{\psi}{2}\right)\tan\left(\frac{\psi}{2}\right) + \ln\left[\sec\left(\frac{\psi}{2}\right) + \tan\left(\frac{\psi}{2}\right)\right]\right\} \quad (2)$$

Where:  $H_p$  = latus rectum (m),  $H_p = 4 \times F$

The distance between the rim of the reflector and the focal centre is referred to as the radius of the parabola as shown in Eq. (3):

$$r = \frac{2F}{(1 + \cos\psi)} \quad (3)$$

The diameter of the receiver is determined using Eq. (4):

$$D = 2r\sin\theta \quad (4)$$

The concentration ratio (C) characterizes the performance of the concentrating solar collector. It is the ratio of the collector's aperture area to the receiver's area.

$$C_a = (W_a \cdot L) / (\pi \cdot D \cdot L) = W_a / (\pi \cdot D) \quad (5)$$

The useful heat production (Qu) of the collector can be determined by applying the energy balance equation to the fluid surface as shown in Eq. (6):

$$Qu = \dot{m} \cdot C_p \cdot \Delta t \quad (6)$$

Where:  $\Delta t = (T_o - T_i)$

The solar energy input (Qin) is calculated using the solar direct beam irradiation (I) and the collector aperture (Aa), as below:

$$Q_{in} = A_a \cdot I \quad (7)$$

Where  $A_a =$  aperture area ( $m^2$ ),  $A_a = W_a \times L$ .

The thermal efficiency of a parabolic trough collector is defined as the ratio of the useful energy generated over a given time period to the beam radiation incident on the collector aperture during the same period. This efficiency can be calculated using the following equation:

$$\eta = Qu / (A_a \cdot I) \quad (8)$$

Where:  $\eta =$  thermal efficiency. See Fig.1

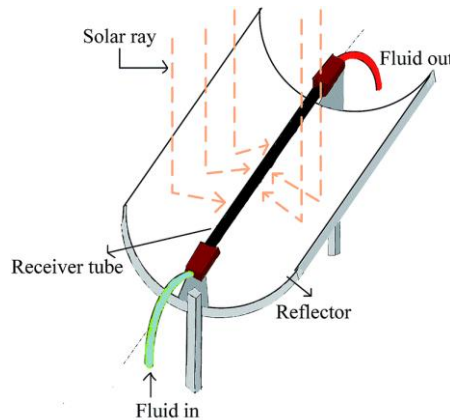


Figure 1. The Parabolic Trough Solar Collector.

The dimensions of the solar collector are shown in Table 1.

Table 1. The Dimensions of the Solar Collector

| Description                          | Dimensions (m) |
|--------------------------------------|----------------|
| Width aperture PTC                   | 0.5            |
| Length of parabola                   | 0.573          |
| Parabola focal distance              | 0.125          |
| The radius of the parabola           | 0.25           |
| Theoretical diameter of the receptor | 0.012          |
| PTC length                           | 0.65           |

Proof of the existence of a focal point is presented in the annex. An appropriate analytic representation of a parabola is:

$$Y = \frac{X^2}{4F} \quad (9)$$

Where Y = height of the parabola (m), X = horizontal distance from the vertex (m), then the parabolic arc is drawn as shown in Fig. 2.

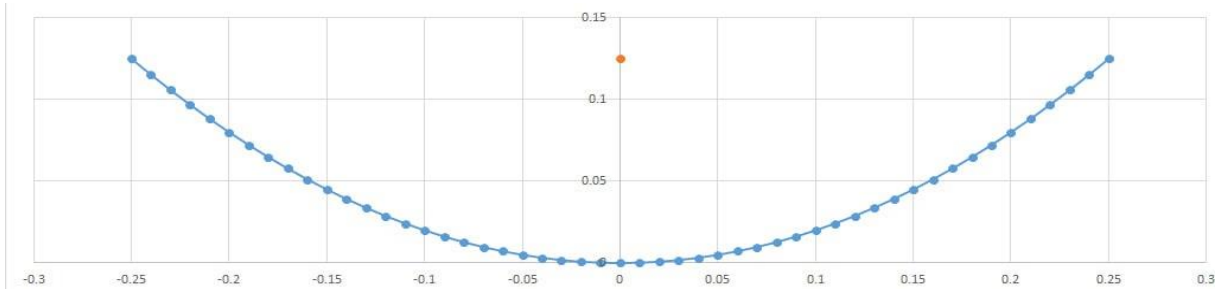


Figure 2.The Parabola Drawn.



Figure 3.The Cross-Section of Aluminium Mini-Channel.

Table 2.The Dimensions of The Aluminium Mini Channel Tubes.

| Description    | Dimensions (mm) |
|----------------|-----------------|
| Tube width     | 60              |
| Tube height    | 3               |
| Channel width  | 6               |
| Wall thickness | 1               |

To find the pressure drops, the following equations were used:

The hydraulic diameter is defined as the ratio of the cross-sectional area of the flow to the wetted perimeter and given by Eq. (10):

$$Dh = \frac{4A_{free}}{P_w} \tag{10}$$

Reynolds number is the ratio of inertial forces to viscous forces, it is calculated to determine the type of flow. Reynolds numbers were calculated based on the mean hydraulic diameter by Eq. (11):

$$Re_{Dh} = \frac{\dot{m}Dh}{A_{free}\mu} \tag{11}$$

The Darcy friction factor formulae are equations that allow the calculation of the Darcy friction factor, a dimensionless quantity used to describe friction losses in pipe flow and channel flow. Darcy friction factor for laminar flow is given by Eq. (12):

$$f = \frac{64}{Re_{Dh}} \tag{12}$$

Where f: Darcy friction factor.

The mean flow velocity of the working fluid calculated from Eq. (13):

$$v_{mean} = \frac{Re_{Dh}\mu}{\rho Dh} \quad (13)$$

The most popular formula used to calculate the pressure drop based on experiments was derived by the French Engineer Henri Darcy (1803-1858) and the German Professor Julius Weisbach (1806-1871) in about 1845. This formula is therefore known as the Darcy - Weisbach formula and is given by Eq. (14):

$$\Delta P = f \times \left(\frac{L_{tube}}{D_h}\right) \left(\frac{\rho(v_{mean})^2}{2}\right) \quad (14)$$

### 3.2. Experimental setup

Rectangular aluminium mini-channel tubes with rounded ends were used. The tubes were positioned with the end caps on the surface of the solar collector. These tubes help to improve the reflectivity of the surface with a bondable material to improve the radiation on the copper tube. Adding fiberglass insulation reduced our heat loss. The tubes are meant to improve sunlight capture; they also provide heat transfer as water flows through them. The water then increases the temperature progressively and clearly can guarantee energy usage for thermal energy systems and steam generation. The water flows through mini-channel tubes in two steps, first through 5 tubes which distribute across the 50 channels, and then 4 tubes across 40 channels, so the water has sufficient time to have an effective heat exchange before entering the copper tube.



Figure 4. Aluminium Mini-Channel Tubes.



Figure 5. Single Aluminium Flat Tube.



Figure 6. The Solar Collector Tubes.



Figure 7. The Solar Collector Tubes with Adhesive Material.






Figure 8. The Solar Collector with Fiberglass Insulation.

### 3.3. The measurement equipment

The measurement equipment used in this study is illustrated in Table 3.

Table 3. The measurement equipment.

| No. | The equipment                | Description  | The figure   |
|-----|------------------------------|--|--|
| a   | NI USB-6009 data acquisition | A Data Acquisition (DAQ) unit is a multifunctional measurement device that can be used in research, education and industry to acquire physical parameters to monitor and control them. It offers 8 analog (configurable 8 single-ended or 4 differential) inputs with a maximum sampling rate of 48 KS/s and a 14-bit resolution. In addition, the unit also provides 2 12-bit analog outputs, 12 digital I/O lines and a 32-bit counter for measuring frequency. The DAQ connects via USB and comes with a plug-and-play feature, able to use applications such as LabVIEW and DAQ Express making it the perfect tool for real-time signal generation and data acquisition. |  <p>Figure 9. NI USB-6009 Data Acquisition</p>    |
| b   | TES 1333 Solar Power Meter   | The TES 1333 Solar Power Meter (see Fig.10) is a portable solar radiation meter used to measure solar radiation, W/m <sup>2</sup> . It's frequently used in environmental research, solar panel installations, and energy efficiency projects to determine sunlight exposure and assess solar energy systems that require such data. The Solar Power Meter has many features including data hold for easy recording, memory function to keep the data and switching modes to indicate the values are in power or percentage values. Access and usability are key for assessing solar energy availability and for proper mounting of solar panels.                            |  <p>Figure 10. TES 1333 Solar Power Meter.</p>  |
| c   | TM-902C Digital Thermometer  | The TM-902C Digital Thermometer provides solid temperature readings both in Centigrade and Fahrenheit from -50°C to 1300°C with the Type K thermocouple sensor. It has a very clear digital readout with a simple ON/OFF button. This thermometer is used in laboratories, industries, and do-it-yourself (DIY) projects precisely and exactly where it measures extreme temperatures, whether in an oven, furnace, or refrigeration system. It provides portability and ease of operation for professionals and enthusiasts alike.  |  <p>Figure 11. TM-902C Digital Thermometer.</p> |

- d     The TYP 2500 Diaphragm Booster Pump     The TYP 2500 Diaphragm Booster Pump is a descent choice for water filtration systems like reverse osmosis (RO) systems. It is a 24V DC booster pump with a capacity of 50 gallons per day, a maximum pressure of 80 PSI, and a bypass pressure limit of  $\leq 125$  PSI. The TYP 2500 Diaphragm Booster Pump increases flow and filtration rate for residential, commercial, and industrial RO systems and is designed for energy-efficient water treatment with astounding durability.



Figure 12.The TYP 2500 Diaphragm Booster Pump.

- e     Rotameter     A rotameter (shown in Fig. 13) is a flow meter that measures the flow rate of a liquid or gas in a closed system. A rotameter uses a tapered vertical tube that allows a float to rise or fall with the flow rate, indicating the flow rate on a scale. Usually, there is a manually operated valve to adjust the flow. Rotameters are popular lab equipment, but they can also be found in industrial processes, medical equipment, and water and wastewater treatment because of their ease of use and precision.



Figure 13.Rotameter.

- f     Thermistors     Thermometers made of semiconductor materials, like thermistors, shown in Fig.14, operate with respect to temperature based on their resistivity change as the charge carrier mobility changes with temperature. For precise temperature measurement, the Steinhart–Hart equation is typically used. This Facilitates modeling of the non-linear resistance versus temperature relationship that thermistors exhibit.



Figure 14. Thermistors.

#### 4. Results and discussion

The experiments were conducted at flow rates of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.8 L/min across three heating stages. During stage 1, water flows through 50 channels. In stage 2, it flows through 40 channels. At stage 3, the water passes through the copper tube.

##### 4.1. Useful energy for the heating stages

Fig. 15 represents the amount of heat absorbed by the solar collector during the three heating stages at 12:00 pm at an angle of  $135^\circ$  towards the southeast. The largest  $Q_u$  gained by the solar collector during the different flow rates is during the third stage, in which the water passes through the copper tube. This is due to the high thermal conductivity of the copper material and the large amount of solar radiation reflected by the reflective surface towards the copper tube. The first and second stages add a good amount of heat acquired when the water passes through them, as the first stage outperforms the second because the water passes through 5 tubes in the first stage, where it is distributed over 50 channels. In the second stage, the water passes through 4 tubes distributed over 40 channels. The heat added by the copper tube is within the range of 54.5-76.2%, while the percentage of heat added by mini-channel aluminium tubes is within the range of 23.7-45.5%.

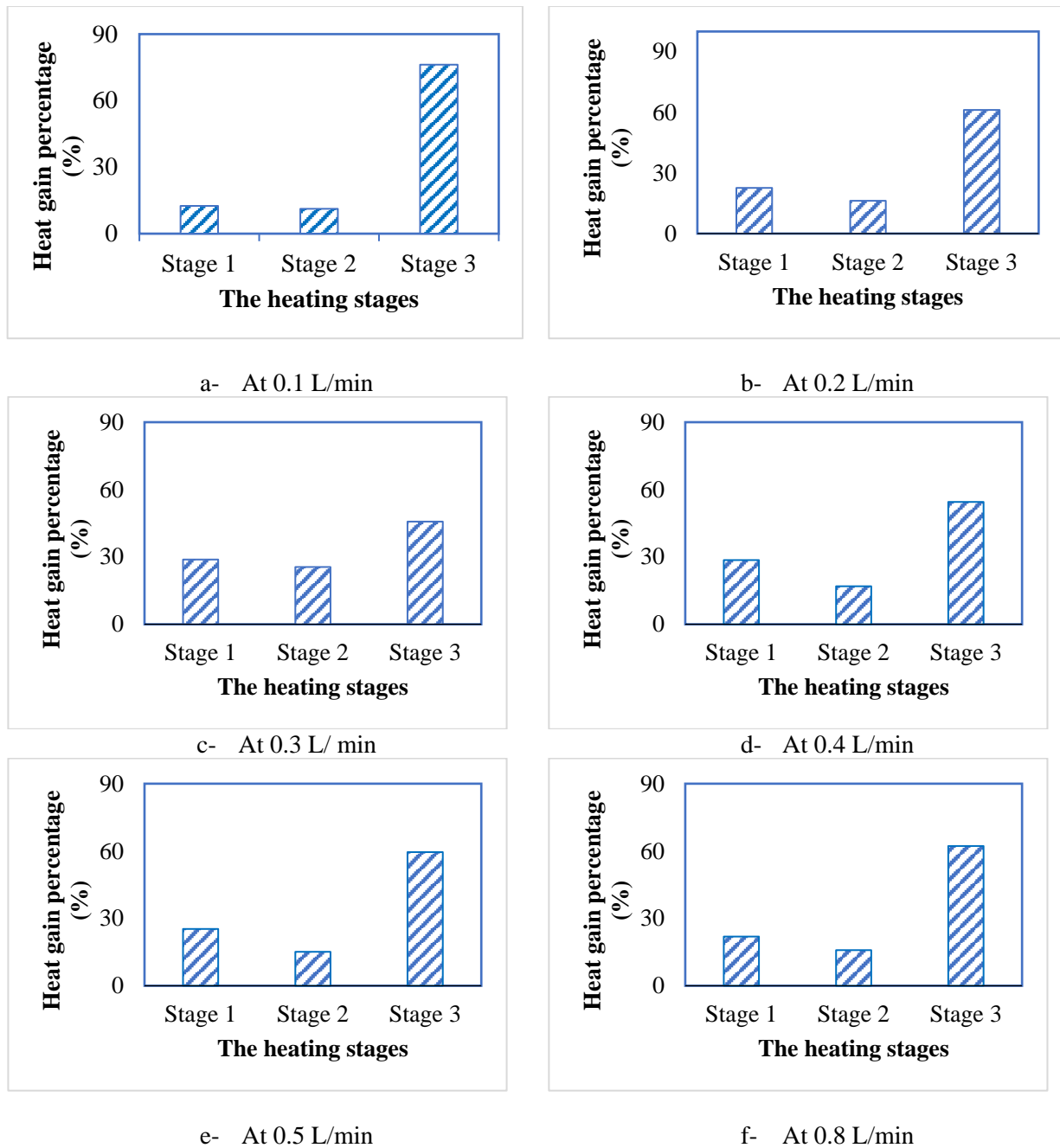


Figure 15. Heat Gain Percentage During The Heating Stages.

#### 4.2. Efficiency with time

Fig. 16 shows how efficiency ( $\eta$ ) changes over time for flow rates ranging from 0.1 to 0.8 L/min at the 135° angle heading southeast. The experimental results for the three-stage solar collector oriented at 135° toward the southeast showed that thermal efficiency is significantly influenced by the fluid flow rate and the time of operation during the day. The highest thermal efficiency of 0.82 was recorded at 12:00 PM with a flow rate of 0.5 L/min, which is attributed to the optimal balance between the fluid residence time inside the tubes and the available solar radiation. Flow rates of 0.4 and 0.3 L/min also achieved high efficiencies of 0.80 and 0.74, respectively, while efficiencies at lower flow rates (0.1 and 0.2 L/min) ranged between 0.71 and 0.74, due to slower fluid movement and increased thermal losses. Conversely, a slight decrease in efficiency to 0.79 was observed at the high flow rate of 0.8 L/min, attributed to the reduced fluid residence time inside the collector, limiting the amount of heat absorbed. These findings highlight the importance of adjusting the flow rate in accordance with solar radiation intensity and operating conditions to achieve optimal thermal performance of the collector.

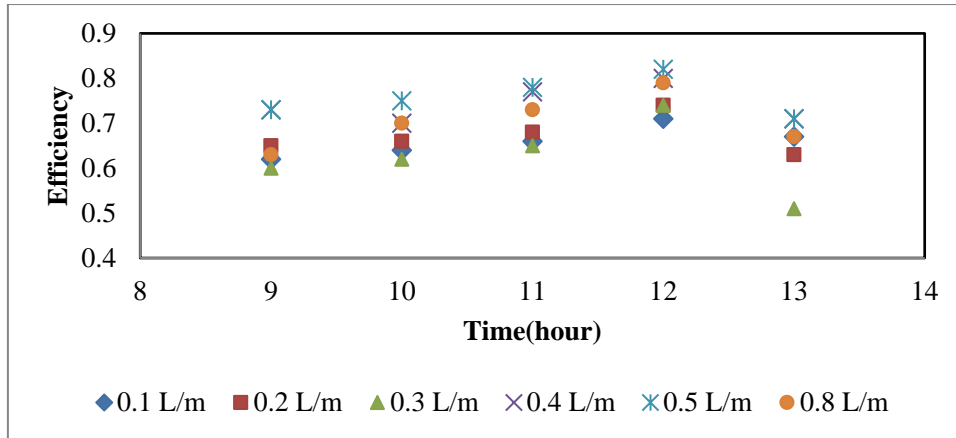


Figure 16. Efficiency with Time.

#### 4.3. Solar tracking angle with time

Fig. 17 represents the solar tracking angle in Kut at latitude of  $32^\circ$  over time during November, oriented at  $125^\circ$  towards the southeast. The collector was manually directed to the sun for the maximum heat energy obtained. This was ensured for each experiment by observing the amount of reflected sun rays on the absorber tube surface in addition to the measured outlet temperature. The collector's highest efficiency was achieved during working hours at 12:00 PM.

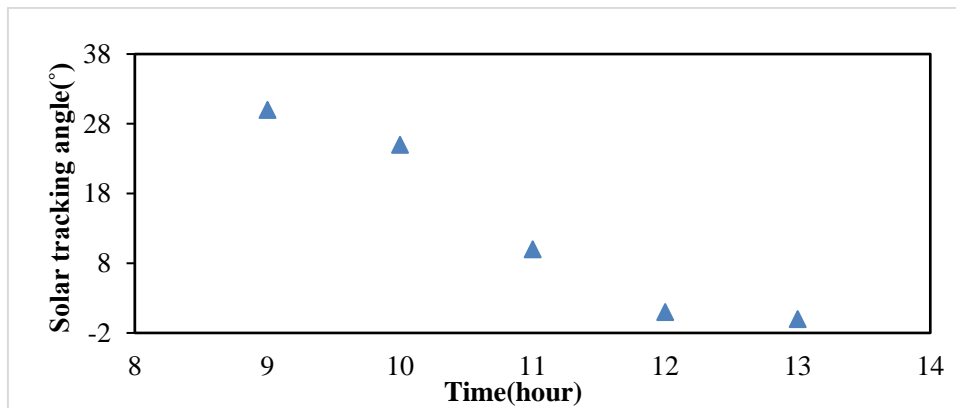


Figure 17. The Solar Tracking Angel.

#### 4.4. Pressure drop

Fig.18 discusses the pressure drop behavior ( $\Delta P$ ) across different stages in a fluid transport system. Pressure drops increase progressively across stages, with higher flow rates resulting in significantly greater drops, especially in Stage 3, which exhibits the highest pressure drop due to its narrow design.

Resistance increases as fluid transitions from wider channels to narrower tubes, leading to higher pressure drops due to friction and turbulence. An exponential relationship exists between flow rate and pressure drop, particularly noticeable at high flow rates like 0.8 L/min. Larger hydraulic diameters ( $D_h$ ) generally reduce pressure drops by increasing the cross-sectional area and lowering fluid velocity for a fixed flow rate, aligning with fluid dynamics principles. The Darcy-Weisbach equation highlights that pressure drop is directly related to the square of the velocity and friction factor while being inversely related to the hydraulic diameter.

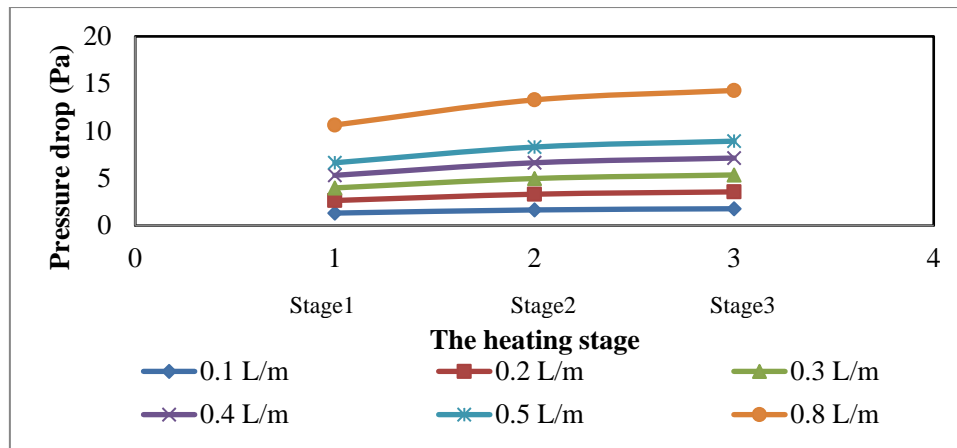


Figure 18. Pressure Drop with Stages

Fig.19. pressure drop as a function of flow rate. The relationship between flow rate and pressure drop ( $\Delta P$ ) appears linear within the range examined, indicating a direct proportionality. This linear trend suggests a transition phase between laminar and turbulent flow regimes, where the interplay between velocity and resistance follows predictable scaling laws. In fluid systems experiencing transitional flow (from laminar to early turbulence), the pressure drop increases nearly proportionally with the velocity of the fluid. This relationship reflects the evolving role of frictional resistance as flow patterns shift. As velocity increases, frictional losses in turbulent flows are proportional to the square of the velocity. This relationship explains the observed behavior in the system. At higher flow rates, turbulence intensifies, increasing frictional interactions. This heightened turbulence is reflected in the steeper slope of the pressure drop curve at greater velocities, underscoring the significant impact of turbulence on resistance. When the flow rate increases, the pressure drop increases due to the resistance, friction, and velocity. The pressure drop in the aluminium tubes was within the range 51.9-67.96%, while the pressure drop in the copper tube was within the range 32-48.1%.

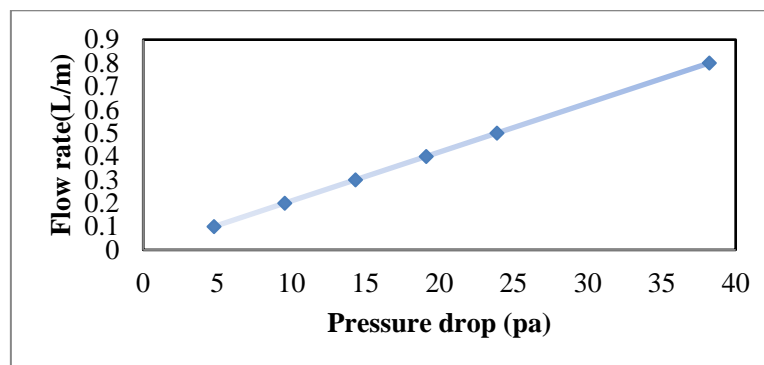


Figure 19. Pressure Drop with Flow Rate

## 5. Conclusion

- 1- Integrating mini-channel parallel flow tubes into a parabolic trough solar collector significantly enhances the system's thermal efficiency.
  - 2- The highest efficiency achieved by the solar collector was at a flow rate of 0.5 L/m at an angle of  $125^\circ$  towards the southeast.
  - 3- The heat added by the copper tube is within the range of 54.5-76.2%, while the percentage of heat added by mini-channel aluminum tubes is within the range of 23.7-45.5%.
  - 4- The pressure drop in the aluminum tubes was within the range of 51.9-67.96%, while the pressure drop in the copper tube was within the range of 32-48.1%.
  - 5- The solar tracking angle in Kut city was within the range of  $0-30^\circ$ .
- This study underscores the potential of mini-channel technology to enhance the performance of solar collectors, making them more efficient and compact.

## Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

## Funding Information

No funding was received from any financial organization to conduct this research.

## Author Contributions

All authors proposed the research problem. Author Ebtehal Chasseb Jbary collected recent articles and organized them in simple shapes. Authors Ebtehal Chasseb Jbary and Alaa R. Al-Badri1 verified the recommendation in the proposed work. Authors Ebtehal Chasseb Jbary and Alaa R. Al-Badri1 designed and proposed the work. Authors Ebtehal Chasseb Jbary and Alaa R. Al-Badri1 discussed the proposed design. All the authors discussed the results and the final version of this paper.

## Notation list

| Abbreviations | Meaning   |
|---------------|---|
| HTF           | Heat Transfer Fluid                                       |
| PTC           | Parabolic Trough Collector                                |
| DAQ           | Data Acquisition  |
| $A_a$         | Aperture Area ( $m^2$ )                                   |
| $A_{free}$    | The Free Flow Area Mini Channel Tube ( $m^2$ )            |
| $D_h$         | $D_h$ : is the hydraulic diameter (m)                     |
| $C_a$         | Concentration Ratio                                       |
| $C_p$         | Specific Heat Capacity of Water ( $J/kg \cdot ^\circ C$ ) |
| F             | Focal Length (m)  |
| f             | Darcy Friction Factor                                     |
| $H_p$         | Latus Rectum (m)  |
| I             | Direct Solar Radiation ( $W/m^2$ )                        |
| L             | Length of the Collector (m)                               |
| $L_{tube}$    | The Length Of The Mini Channel Tube (m)                   |
| $\dot{m}$     | Water Flow Rate (kg/s)                                    |
| $P_w$         | The Wetted Perimeter (m)                                  |
| $\Delta P$    | The Pressure Drop (Pa)                                    |
| $Q'$          | Useful Energy (W)   |
| $Re_{D_h}$    | Reynolds Number of The Working Fluid.                     |
| r             | Radius of the Parabola (m)                                |
| S             | Arc Length of Parabola Curved Surface (m)                 |
| $T_i$         | Inlet Temperature ( $^\circ C$ )                          |
| $T_o$         | Outlet Temperature ( $^\circ C$ )                         |
| $v_{mean}$    | The Mean Flow Velocity of The Working (m/s)               |
| $W_a$         | Width of the Aperture (m)                                 |
| X             | Horizontal Distance from The Vertex (m)                   |
| Y             | Height of The Parabola (m)                                |
| $\Psi$        | Rim Angle ( $^\circ$ )                                    |
| $\Theta$      | Sun Beam Angle ( $^\circ$ )                               |
| $\Delta t$    | The Difference of the Temperature ( $^\circ C$ )          |
| $\eta$        | Thermal Efficiency of the System                          |
| $\rho$        | The Density Of The Working Fluid ( $kg \cdot m^{-3}$ )    |
| $\mu$         | Dynamic Viscosity of The Working Fluid (Pa.s)             |

## References

- [1] S. Kalogirou, "Parabolic trough collector system for low temperature steam generation: Design and performance characteristics," *Appl Energy*, vol. 55, no. 1, pp. 1–19, 1996, doi: 10.1016/S0306-2619(96)00008-6.
- [2] S. A. Kalogirou, "Solar thermal collectors and applications," *Appl Math Lett*, vol. 18, no. 30, pp. 287–292, Mar. 2005, doi: 10.1016/j.aml.2004.09.006.
- [3] Z. H. Naji, M. Fowzi, M. Ali, and A. Ameer, "Heat Transfer Analysis of Modified Solar Collector Plate with Mini-Channel," *Journal of University of Babylon for Engineering Sciences*, vol. 26, no. 7, pp. 314–330, 2018, doi: 10.1615/heattransres.2016012266.
- [4] Y. Tian and C. Y. Zhao, "A review of solar collectors and thermal energy storage in solar thermal applications," *Appl Energy*, vol. 104, no. 6, pp. 538–553, 2013, doi: 10.1016/j.apenergy.2012.11.051.
- [5] B. Raudhah Binti Ab Majid and P. Darul Ridzuan, "Design and Development of an Innovative Flat Plate Solar Collector," Universiti Teknologi Petronas, Tronoh, 2010.
- [6] I. Ziemelis, L. Kancevica, Z. Jesko, and H. Putans, "Calculation of Energy Produced by Solar Collectors," in *ENGINEERING FOR RURAL DEVELOPMENT Jelgava*, May 2009, pp. 28–29.
- [7] K. Somalwar, "A Review of Solar Collectors in Solar Thermal Applications," *International Journal of Innovations in Engineering and Science*, vol. 441, no. 10, pp. 2456–3463, 2017, [Online]. Available: [www.ijies.net](http://www.ijies.net)
- [8] A. M. De Oliveira Siqueira, P. E. N. Gomes, L. Torrezani, E. O. Lucas, and G. M. Da Cruz Pereira, "Heat transfer analysis and modeling of a parabolic trough solar collector: An analysis," in *Energy Procedia*, Elsevier Ltd, 2014, pp. 401–410. doi: 10.1016/j.egypro.2014.10.193.
- [9] E. M. Ismail, S. J. Flayh, M. Saeedmohammed, and K. S. Mohammed, "Heat Exchanger Design and Optimization for Industrial Applications," *Nanotechnol Percept*, vol. 20, no. S3, pp. 211–229, 2024, doi: 10.62441/nano-ntp.v20is3.18.
- [10] Y. He *et al.*, "Thermal performance and experimental analysis of stainless steel flat plate solar collector with full-flow channels," *Heliyon*, vol. 10, no. 7, p. e28255, Apr. 2024, doi: 10.1016/j.heliyon.2024.e28255.
- [11] M. Saeed Mohammed, S. Fahad Dakel, A. Kadhim Alshara, and A. Mohsin Alsayah, "Numerical and experimental study of heat transfer in shell-and U-tube heat exchanger with baffles," *Chinese Journal of Geotechnical Engineering*, vol. 44, no. 5, pp. 11–26, Jan. 2022, doi: 10.11779/CJGE202205.2.
- [12] Steven. Sookdeo, "Experimental investigation of the thermofluid behaviour within a flat-plate solar collector," Concordia University, Montreal, Quebec, 2009.
- [13] G. Iordanou et al, "Flat-Plate Solar Collectors for Water Heating with Improved Heat Transfer for Application in Climatic," Durham University, 2009.
- [14] Z. D. Cheng, Y. L. He, J. Xiao, Y. B. Tao, and R. J. Xu, "Three-dimensional numerical study of heat transfer characteristics in the receiver tube of parabolic trough solar collector," *International Communications in Heat and Mass Transfer*, vol. 37, no. 7, pp. 782–787, Aug. 2010, doi: 10.1016/j.icheatmasstransfer.2010.05.002.
- [15] T. Bello-Ochende, J. P. Meyer, and A. Mwesigye, "Thermodynamic performance of a parabolic trough receiver with centrally placed perforated plate inserts.," in *International Conference on Applied Energy ICAE*, Pretoria, South Africa, Jul. 2013, pp. 1–11.
- [16] B. Yahaya Muhammad and N. Mariah Adam, "Flat plate solar collectors and applications: a review," *SCIENCES & TECHNOLOGY*, vol. 22, no. 2, pp. 365–385, 2014, doi: <https://api.core.ac.uk/oai/oai:psasir.upm.edu.my:40616>.
- [17] Z. Wen, "Research and Development in Novel Alternative Renewable Energy Technology," Bournemouth University, 2015.
- [18] Y. Qiu, M. J. Li, Y. L. He, and W. Q. Tao, "Thermal performance analysis of a parabolic trough solar collector using supercritical CO<sub>2</sub> as heat transfer fluid under non-uniform solar flux," *Appl Therm Eng*, vol. 115, no. 4, pp. 1255–1265, 2017, doi: 10.1016/j.applthermaleng.2016.09.044.
- [19] S. Ebrahim Ghasemi and A. Akbar Ranjbar, "Numerical thermal study on effect of porous rings on performance of solar parabolic trough collector," *Appl Therm Eng*, vol. 118, no. 2017, pp. 807–816, 2017, doi: 10.1016/j.applthermaleng.2017.03.021.

- [20] S. Kuharat and O. Anwar Bég, “Computational Fluid Dynamics Simulation of a Nanofluid-Based Annular Solar Collector with Different Metallic Nano-Particles,” *Heat and Mass Transfer Research Journal*, vol. 3, no. 1, pp. 20–42, 2019, [Online]. Available: <http://cansrg.com/journals/hmtrj/>
- [21] J. Shi and C. Lin, “Computational Simulation and Analysis of Major Control Parameters of Time-Dependent PV/T Collectors,” *J. Solar Energy Engineering*, vol. 143, no. 5, pp. 11–14, 2019, doi: 10.1115/IMECE2019-12184.
- [22] S. Sobhansarbandi, P. M. Martinez, A. Papadimitratos, A. Zakhidov, and F. Hassanipour, “Evacuated tube solar collector with multifunctional absorber layers,” *Solar Energy*, vol. 146, pp. 342–350, 2017, doi: 10.1016/j.solener.2017.02.038.
- [23] S. S. More, A. A. Sagade, G. Ravindranath, S. More, and S. More, “Innovative mini-channel design for a compound parabolic solar thermal collector serving intermediate temperature applications,” *Energy*, vol. 283, p. 129044, 2023, doi: 10.1016/j.energy.2023.129044.