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Enhancing thermal efficiency of a parabolic trough collector through geometric modification of absorber tubes: a performance analysis

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ABSTRACT

The study aims to investigate the impact of geometric modifications to absorber tubes on the thermal efficiency of a parabolic trough collector (PTC). Three absorber tubes with different cross-sectional areas were manufactured and tested, and the behavior of thermal efficiency was analyzed at different flow rates. The tests were conducted on sunny days, using water as working fluid. The results show that the thermal efficiency of the absorber tube is higher than that of the PTC, with an average value of 35.84% compared to 25.10% for the PTC. Increasing the cross-sectional area of the absorber tubes led to a reduction in fluid velocity, longer heat exchange time, and improved thermal efficiency. Despite reducing the concentration factor, the largest absorber tube (27 mm) showed the best thermal efficiency behaviour. Additionally, an increase in the volumetric flow of the fluid led to higher thermal efficiency values and absorption for each absorber tube. The study also compared characteristic curves for different volumetric flow rates and found that the largest absorber tube achieved the highest thermal efficiency for agricultural applications. These findings can be applied in designing and manufacturing absorber tubes for PTCs, leading to increased energy conversion efficiency and reduced energy costs.

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KEYWORDS
Parabolic trough collector; Solar energy; Absorber tube

Abbreviations

PTCs: Parabolic Trough Collectors;
eqt: equation of time;
IDE: Integrated Development Environment;
LEDs: Light Emitting Diodes;
LDRs: Light Dependent Resistors;
PTC: Parabolic Trough Colletor;
Alt: Altitude;
PWM: Pulse Width Modulation

1. Introduction

A parabolic trough collector is a solar thermal collector used to collect and concentrate sunlight to generate heat or electricity. It consists of a long, parabolic-shaped reflector that focuses sunlight onto a linear absorber that runs along the reflector's focal line (Samimi Akhijahani et al. 2023). The absorbed sunlight is then used to heat a fluid, such as oil or water, which is then circulated through a heat exchanger to transfer the heat to a working fluid or to a heat storage system. The collected heat can then be used for various applications, such as heating water for domestic or industrial purposes, or it can be converted into electricity using a thermal-to-electrical power conversion system. Parabolic trough collectors are highly efficient at converting sunlight into heat, making them a popular choice for large-scale renewable energy systems (Al-Rashed, Alnaqi, and Alsarraf 2021).

Recent advances in parabolic trough collector technology have focused on increasing efficiency and reducing the cost of the systems. Some of these advances include improved reflector materials with higher reflectivity and durability, such as glass-coated aluminum or silver, which has increased the efficiency of parabolic trough collectors by reflecting more sunlight onto the absorber (Khan et al. 2021). Better absorber materials with high thermal conductivity and durability, such as copper or aluminum, have improved the absorber's efficiency in converting sunlight into heat (Qin, Kim, and Lee 2019). Increased concentration ratios of more advanced optics and tracking systems have increased parabolic trough collectors' concentration ratios, allowing for higher temperatures and higher conversion efficiencies. Advanced tracking systems, such as dual axis tracking systems, have improved the systems' accuracy and reliability in tracking the sun, leading to increased energy production (Mashhadian, Heyhat, and Mahian 2021). Advances in materials science and manufacturing processes have reduced the cost of materials and the cost of manufacturing parabolic trough collectors, making them more affordable for large-scale deployment (Carmo Zidan, Maia, and Safaei 2022). These advances have led to a significant increase in the efficiency and cost-effectiveness of parabolic trough collectors, making them a competitive choice for renewable energy systems (Alnaqi, Alsarraf, and Al-Rashed 2021).

Using nanofluids in parabolic trough collectors is a relatively new and promising area of research. Nanofluids are suspensions of nanoparticles in a fluid, and they have unique thermal properties that can enhance the performance of parabolic trough collectors (Hamada et al. 2023). The high thermal conductivity of nanofluids can enhance the heat transfer process in parabolic trough collectors, resulting in higher efficiency and increased energy production (Bellos, Tzivanidis, and Said 2020). Nanofluids have been shown to have improved stability compared to

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traditional heat transfer fluids, reducing the risk of contamination and degradation over time(Al-Oran, A'saf, and Lezsovits 2022). Using nanoparticles with high absorption properties can enhance the absorption of sunlight in the collector, leading to higher efficiency and energy production (Martínez-Merino, Alcántara, et al. 2022). The enhanced heat transfer improved stability, and increased absorption can significantly increase the overall efficiency of parabolic trough collectors using nanofluids (Sadegh Hosseini and Dehaj 2021). While these advances are promising, further research is needed to fully understand nanofluids' potential benefits and limitations of parabolic trough collectors and develop practical and cost-effective methods for incorporating them into commercial systems (Mohammed, Vuthaluru, and Liu 2021). Nevertheless, the use of nanofluids in parabolic trough collectors holds great promise for improving the efficiency and competitiveness of these systems in the renewable energy market (Vahedi et al. 2022).

While using nanofluids in parabolic trough collectors is a promising area of research, several gaps need to be addressed to fully understand and realise their potential (Martínez-Merino, Estellé, et al. 2022). While much is known about the thermal properties of nanofluids, there is still much to learn about how these fluids behave in real-world applications, such as parabolic trough collectors. Further research is needed to understand how nanofluids interact with different materials and systems and how they behave over time (Farooq et al. 2022). The concentration of nanoparticles in a nanofluid can significantly impact its thermal properties. Further research is needed to determine the optimal concentration of nanoparticles for use in parabolic trough collectors, as well as to understand how this concentration affects the performance of the systems (Ahbabi Saray and Heyhat 2022). While using nanofluids in parabolic trough collectors significantly improve their performance, it is important to ensure that the technology is scalable and cost-effective for large-scale deployment (Mohammed, Vuthaluru, and Liu 2021). Further research is needed to determine the feasibility and cost-effectiveness of incorporating nanofluids into commercial systems and develop practical and cost-effective methods for their production and use (Alqarni et al. 2021). Nanoparticles in nanofluids raise concerns about their environmental impact, including the potential for toxicity and the long-term fate of the nanoparticles in the environment. Further research is needed to fully understand the environmental impact of nanofluids, as well as to develop methods for ensuring their safe and sustainable use. Addressing these research gaps will be crucial to fully realise the potential of nanofluids in parabolic trough collectors and ensure their safe and effective use in renewable energy systems (Alkathiri et al. 2022). Improving the thermal efficiency of a Parabolic Trough Collector (PTC) can have significant practical applications and benefits. PTCs are used in concentrated solar power (CSP) systems to generate electricity by converting solar radiation into heat, which is then used to power a turbine. By improving the efficiency of PTCs, more heat can be collected, which translates to more electricity generation. This, in turn, can lead to increased adoption of CSP systems as a renewable energy source, helping to reduce greenhouse gas emissions and mitigate climate change. Additionally, improved PTCs could have applications in other areas, such as heating and cooling systems or industrial processes requiring high-temperature heat. Overall, investing in research to improve PTC efficiency has the potential to contribute to a more sustainable and cleaner future.

While using nanofluids in parabolic solar trough collectors (PTCs) offers several advantages, several challenges must be addressed (Heyhat et al. 2020). Nanoparticles in nanofluids can settle over time, leading to particle accumulation in certain parts of the PTC system. This can lead to reduced efficiency and clogging of the system, which can affect the overall performance of the collector (Khan, Yan, and Ali 2022). Although nanofluids have a higher thermal conductivity than traditional heat transfer fluids, their higher viscosity and density can increase pumping power requirements, which can offset some of the benefits of their improved thermal performance. The cost of producing and using nanofluids can be higher than that of traditional heat transfer fluids, which can make their use less economically viable in some cases(Abbasian Arani and Memarzadeh 2021). Nanoparticles in nanofluids raise safety concerns related to their potential toxicity and environmental impact.

Further research is needed to assess the potential risks associated with using these materials in PTC systems (Hachicha et al. 2020). The stability of nanofluids can be affected by changes in temperature and pressure, which can cause the nanoparticles to agglomerate or settle. This can reduce the system's thermal performance and increase the risk of clogging. Overall, the challenges associated with using nanofluids in PTC systems highlight the need for further research and development to optimise these systems' performance and reliability (Pazarlıoğlu et al. 2023).

2. Materials and methods

To carry out the tests in this work, an attempt was made to improve the thermal efficiency of a small-sized Parabolic Trough Collector (PTC), utilising geometric alteration of the absorber tube. The PTC reflector parabola was built with a mirrored stainless steel plate with dimensions 1 mm x 689 mm x 1000 mm. To receive the absorber tube, two steel profiles were welded at the lateral ends, with holes on opposite sides with a diameter of 12.7 mm at the focal length of the parabola. The focal length (f) of the PTC is 150 mm, which is measured from the base of the parabolic reflector. The opening area (Aa) is 0.6 m⊃2 (0.6 m x 1.0 m). In the centre of mass of the concentrator, at a distance of 64.17 mm from the base of the parabola, a rotation axis was installed to allow the collector system's rotation with greater efficiency. At the axis limit, a gear is installed, which will be coupled with the actuator gear. For a focal length of 0.15 m, the relationship of x and y coordinates is represented by Equation $y = x^2/0.6$.

The minimum diameter for the absorber tube to intercept all the radiation reflected in the parabola is related to the edge angle. The smallest possible value for complete interception is for a 90° edge angle. The value obtained for the minimum diameter is 2.8 mm. This does not consider constructive errors in the parabola, which means that not all solar rays are reflected the focus line but to nearby regions. The larger the diameter of the tube, the greater the possibility of intercepting these rays diverted by constructive errors. However, in addition to the concentration rate, the acceptance angle (2θs) is also influenced by a change in the diameter of the absorber tube.

3 copper absorber tubes of different diameters were manufactured in the inner part of the parabola. Two tubes with a diameter of 15 mm and a length of 190 mm were welded to the

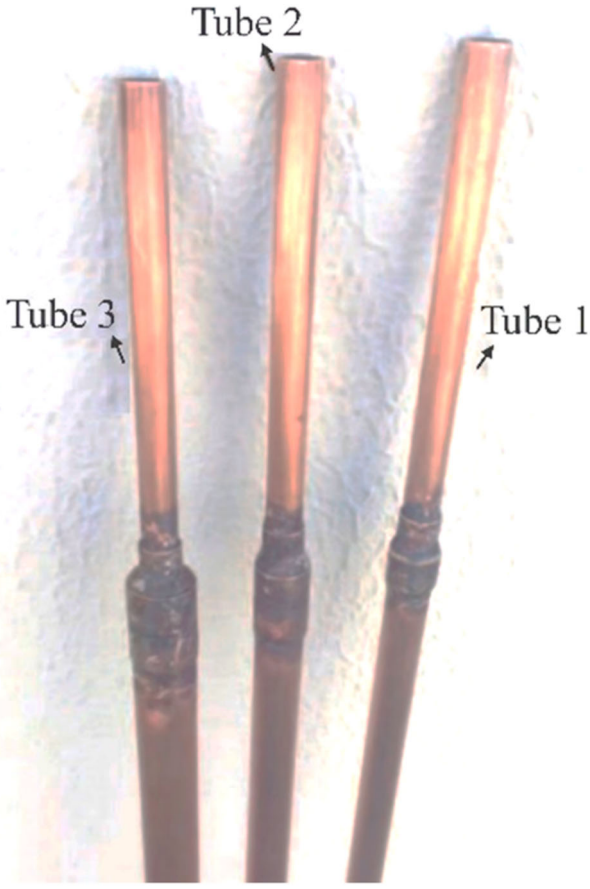


Figure 1. Absorber tubes.

ends of tubes with a diameter of 19.25 mm (3/4 in) and a length of 890 mm (Pipe 1), 22.25 mm (7/8 in) and a length of 862 mm (Tube 2) and 27 mm and length 850 mm (Tube 3), as shown in Figure 1.

As shown, the cross-sectional area was expanded only on the area inside the parabola. The area expansion and reduction were made using a solderable copper expander and joint, as shown in Figure 2. The solder was made with Oxy-Acethylene.



Figure 2. Expander and union.

After the tubes were welded, they were sanded to deposit a non-selective coating. The coating was matte black spray paint resistant to high temperatures (up to 600 °C).

The half acceptance angle (θs) for each manufactured absorber tube was 1.82° for Tube 1, 2.12° for Tube 2, and 2.67° for Tube 3. While for the tube of diameter 12, 7 mm or 1/2 inch (Tube 0) was 1.21°. Table 1 shows the constructive aspects of the reflecting parabola, and Table 2 shows aspects related to the absorber tube.

The functional absorption area is the area of copper piping inside the parabola that will receive the radiation reflected by the specular reflectors. This area is calculated taking into account the unions and expanders present in the tubes, which will receive the radiation, in addition to two nylon bushings, 10 mm wide each, which are located internally to the parabola and which support a glass surrounding surface.

The tubes were covered by a concentric borosilicate glass tube with an outer diameter of 37 mm, a thickness of 1.7 mm, and a length of 984 mm, supported by two nylon bushings at each end. Due to the oven's high temperature, silicone with resistance to high temperatures was used so that the seal was not compromised, as shown in Figure 3.

To calculate the optical efficiency of the system, reflectivity, absorptivity and transmissivity values of the materials used in the project were considered.

According to Table 3, the intercept factor value is calculated by the product of six factors. The reflector's reflectivity for this project's calculations was considered outside the intercept factor and with a value of 0.93. The effects of shading of the heat collection element, tracking error, the geometric accuracy of mirrors, and dirt on the heat collection element were considered influencers of the intercept factor.

The effect values of the angle of incidence (k(θ)) and the final geometric losses ($\xi(\theta)$) were taken as the unit, as they are dependent on the angle of incidence (θ), which has a value of 0° in

Table 1. Reflector Characteristics.

Description	Specification
Material	Mirrored stainless steel
Length (mm)	1100
Width (mm)	650
Focal distance (mm)	160
Aperture area (m^2)	0.70
Edge angle (φ_r)	90°
Reflectivity (ρ)	0.92
Minimum absolute diameter (mm)	2.70
Maximum concentration rate (C_{max})	67.31

Table 2. Characteristics of Absorber Tubes.

Description	Tube 0	Tube 1	Tube 2	Tube 3
Absorber material	Copper	Copper	Copper	Copper
Thermal conductivity (W/m.K)	402	402	402	402
Coating	Black paint	Black paint	Black paint	Black paint
Coating absorptivity (α)	0.8	0.8	0.8	0.8
Outer diameter (mm)	12.600	19.040	22.325	27.000
Thickness (mm)	1	1	1	1
Effective length (mm)	975	975	975	975
Effective absorption area (m^2)	0.039	0.059	0.068	0.086
Internal surface area (m^2)	0.0363	0.053	0.062	0.080
Concentration rate (C)	15.05	9.89	8.71	6.95
Acceptance half-angle (θ_s)	1.20°	1.81°	2.13°	2.68°

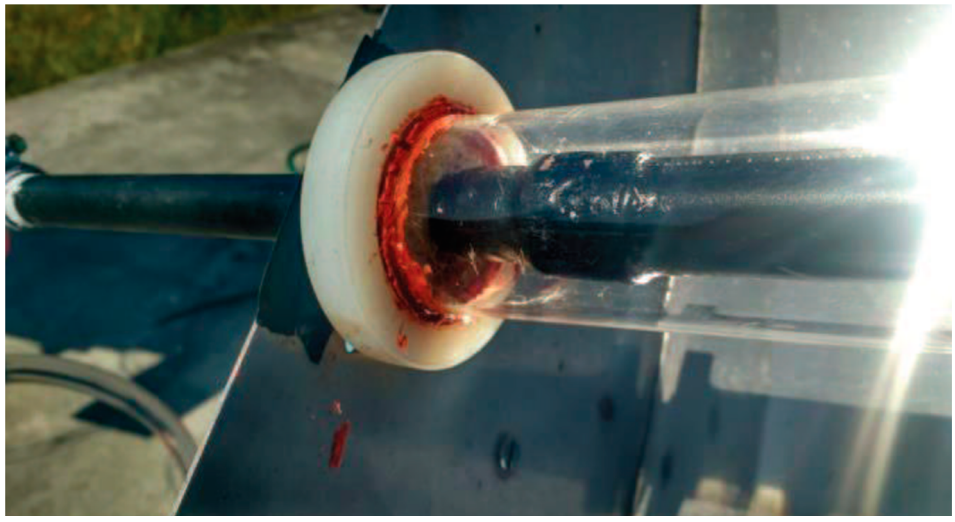


Figure 3. Glass-covered tube.

Table 3. Factors affecting the efficiency of the solar collector.

Optical Properties	Index	Value
Shading of the heat collection element	$f_{int,l}$	0.964
Tracking error	$f_{int,2}$	0.984
Geometric precision of the collector mirrors	$f_{int,3}$	0.970
Reflectivity of the clean mirror surface	$f_{int,4}$	0.940
Dirt on the heat collection element	$f_{int,S}$	0.970
Miscellaneous factors	$f_{int,e}$	0.975

Table 4. Values for optical efficiency determination.

Description	Values
Copper absorptivity (α)	0.91
Polished stainless-steel reflectivity (ρ)	0.92
Glass transmissivity (t)	0.91
Interception factor (f_{int})	0.93
Incidence angle effect (k(θ)	1.00
Geometric losses ($\xi\theta$)	1.00
Optical efficiency (η_0)	0.71

this project. Thus, based on the materials' properties, the optical efficiency is shown in Table 4.

Two Omega K-type thermocouples were used to measure the inlet and outlet temperatures of the fluid. They were connected to an RDXL12SD model datalogger from the same manufacturer to record temperature data during the experimental testing period. The manifold's copper piping inlet and outlet were insulated with black expanded polyurethane thermal foam. The system is shown in Figure 4.

The automatic east–west tracking was carried out by a NEMA 23 - 200 kgf.cm^3. A stepper motor with a reduction box, Figure 5 (a) and (b) an AKDMP16-4.2A model driver from Neoyama. An Arduino Uno, Figure 6(a) and (b), was used to drive the motor and two LDR sensors with a shading device to detect the brightest side, arranged as in Figure 6.

Manual north–south tracking was performed by periodically adjusting the PTC inclination with daily frequency by monitoring the solar declination angle (δ).

The angle adjustment is made utilising a hexagonal screw, which is tightened when the collector reaches the required inclination angle, jammed in a support base of the PTC, as shown in Figure 7. The angle of inclination is calculated from of the



Figure 4. Photographic view of the installed system.

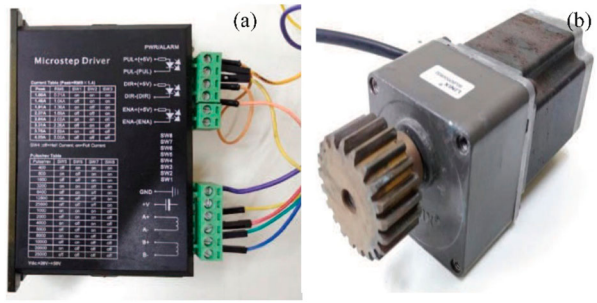


Figure 5. Actuation Devices: (a) driver; (b) Motor.

solar declination angle (δ) and the local latitude (ϕ), according to Equation $\beta = \delta$ - ϕ.

3. Experimental setup and procedure

An experiment was carried out to improve the thermal efficiency of a Parabolic Trough Collector (PTC). The PTC's absorber

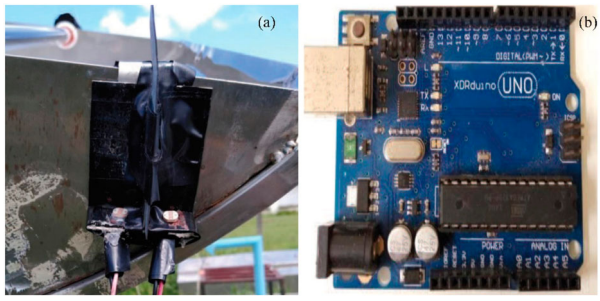


Figure 6. (a) Disposition of LDRs, (b) Arduino UNO.

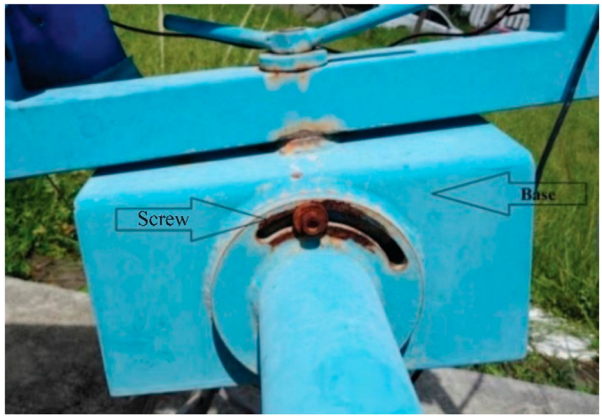


Figure 7. Tilt adjustment device.

tube was altered geometrically to enhance efficiency. The reflector parabola of the PTC was built using a mirrored stainless steel plate with dimensions 1 mm x 689 mm x 1000 mm, and two steel profiles were welded at the lateral ends to receive the absorber tube. Three copper absorber tubes of different diameters were manufactured, and the cross-sectional area was expanded only on the area inside the parabola using a solderable copper expander and joint. After welding, the tubes were sanded to deposit a non-selective coating of matte black spray paint resistant to high temperatures. The tubes were covered by a concentric borosilicate glass tube, and the inlet and outlet temperatures of the fluid were measured using two Omega K-type thermocouples connected to a datalogger. The automatic east–west tracking was carried out to increase the collector's efficiency. The optical efficiency of the system was calculated using the reflectivity, absorptivity, and transmissivity values of the materials used in the project.

The control volume defined for the system covers the absorber tube, as shown in Figure 8 by the dashed rectangular area. From it, it is possible to carry out the energy balance of the absorber system, in which the total energy absorbed by the fluid takes into account the variations in enthalpy, kinetic energy, and potential energy between the input (e) and output (s) of the control volume.

From the mass conservation, Equation 1, and the first law of thermodynamics, Equation 2, the energy balance was developed to allow the calculation of the total amount of energy absorbed by the fluid and, subsequently, the thermal efficiency analysis of the collector.

$$\frac{\partial}{\partial t}\int_{VC}\rho \cdot d\forall + \int_{SC}\rho \cdot \vec{V} \cdot d\vec{A} = 0 \tag{1}$$

$$\dot{Q} - \dot{W} = \int_{SC}\left(h + \frac{V^2}{2} + gz\right)\rho \cdot \vec{V} \cdot d\vec{A} \tag{2}$$

The considerations were of permanent and one-dimensional flow, uniform properties at the inlet and outlet, and areas perpendicular to the velocity and without carrying out or consuming work. Thus, Equation 3 can be represented for each two-minute interval of data storage.

$$\dot{Q} = \dot{m}\left[c_{pm}(T_s - T_e) + \left(\frac{V_s^2 - V_e^2}{2}\right) + g(z_s - z_e)\right] \tag{3}$$

The direct solar radiation data were obtained by a pyrheliometer installed as shown in Figure 9. The data are measured every two seconds, being recorded by an average value every two minutes, the same time as the temperature data.

The first tests were conducted to compare the efficiency of the Parabolic Trough Collector with the manufactured tubes concerning the result obtained with a 12.7 mm diameter tube of the initial PTC project. A 64 mL/min constant flow was used in an open circuit, manually controlled by a ball valve installed after the PTC. A continuous pipe pressure was obtained by using a water reservoir for exclusive use, with water volume controlled by a float.

The mean flow velocity values were approximately 11.86 mm/s (Tube 0), 4.67 mm/s (Tube 1), 3.32 mm/s (Tube 2), and 2.01 mm/s (Tube 3).

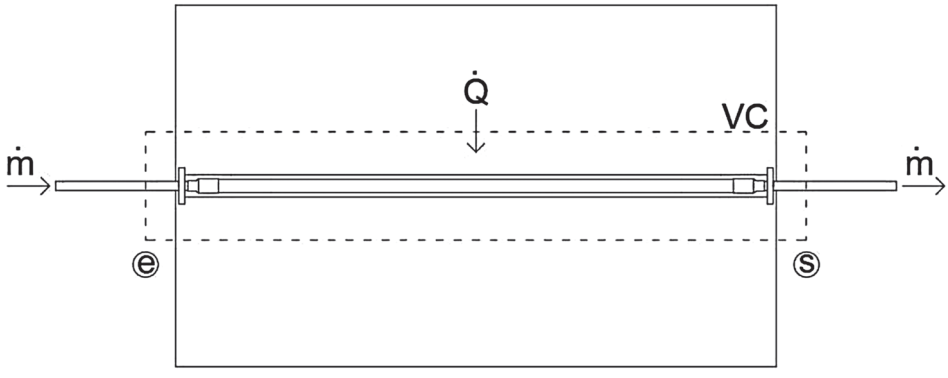


Figure 8. Determination of the control volume.



Figure 9. Pyrheliometer installed.

The manufactured tubes were imposed at different flow rates in the following tests to analyze the thermal efficiency behaviour. The flow rates analyzed were 50, 75, and 100 mL/min. For Tube 1, the average velocities were approximately 3.65 mm/s (50 mL/min), 5.47 mm/s (75 mL/min), and 7.3 mm/s (100 mL/min). For Tube 2, the velocities were 2.59 mm/s (50 mL/min), 3.89 mm/s (75 mL/min), and 5.19 mm/s (100 mL/min). For Tube 3, the speeds were 1.57 mm/s (50 mL/min), 2.35 mm/s (75 mL/min), and 3.14 mm/s (100 mL/min). The average for each data storage interval was calculated from the inlet and outlet temperatures obtained. Constant heat flux in W/m⊃2, Equation 4, was considered, incident on the pipe, for each 2-minute interval, where P is the internal perimeter, L is the useful absorption length, and Tm,ent is the average temperature of the fluid at the entrance to the control volume. This causes a linear behaviour of the temperature variation along the tube. The average temperature is obtained from Equation 5, where x is half the length L.

$$q'' = \frac{Q}{(P.L)} \tag{4}$$

$$T_m(x) = T_{m.ent} + \frac{q'P}{\dot{m}c_p}x \tag{5}$$

In this study, type K thermocouples are used to measure the temperature of the fluid at the inlet and outlet of the absorber tubes and the temperature of the PTC. The uncertainties associated with these measurements were determined by the manufacturer and were found to be ±0.5°C. Additionally, we used a digital flowmeter to measure the flow rate of the fluid, and the uncertainty associated with this instrument was ±1 mL/min.

4. Result and discussions

The experimental results were performed with water as an open circuit working fluid, comparing the thermal performance of the tubes manufactured with the tube performance of the initial design of 12.7 mm in external diameter at a flow of 64 mL/min and comparing the behaviour of thermal efficiency for the tubes manufactured at the flow rates of 50, 75 and 100 mL/min. The tests were conducted from August to December 2022 on sunny days between 10:00 and 17:00 h.

Multiple measurements were performed under similar conditions to ensure the repeatability of measurements in this study. For example, the experiments were conducted at the same time of day to control for changes in solar radiation intensity, and the flow rate of the fluid was kept constant for each measurement. Additionally, statistical analysis was used to evaluate the results' variability and identify any outliers or anomalous data points. Specifically, each experiment was repeated three times under similar conditions, and the average of the three measurements was used as the final result. This approach helps reduce the impact of random or systematic errors that may occur during the experiment and ensures that the results are reliable and repeatable. Moreover, the standard deviation was calculated for each set of measurements, and the values were reported in the results section to provide information on the level of variability observed in the data. This statistical analysis allowed for a more robust evaluation of the experimental results and helped to ensure the repeatability of the measurements.

The results and discussion section presents experimental results comparing the thermal performance of absorber tubes of different diameters (12.7 mm, 19.25 mm, and 22.25 mm) used in a solar thermal collector with water as an open circuit working fluid. The tests were conducted on sunny days between 10:00 and 17:00, with 50 mL/min flow rates, 75 mL/min, and 100 mL/min. The section presents the temperature differences between the input and output of the absorber tube and the direct solar radiation data. The temperature difference values are higher for larger diameter tubes. The behaviour of thermal efficiency throughout the day shows that efficiency values are lower during higher insolation due to increased thermal losses from the absorber tube to the environment. The average thermal efficiency values are 25.10% and 35.84% for the PTC and absorber tube, respectively.

4.1. Cross-sectional area increases in flow rate of 64 mL/min

4.1.1. 12.7 mm tube

The results of the temperature difference between PTC input and output and direct solar radiation data are shown in Figure 10. The most significant temperature difference of 31°C was obtained between 12:30 and 13:30, during which time the highest radiation values were observed. The mean value of direct solar radiation during the test period was 783.08 W/m2. The number of Reynolds, at the midpoint at the entrance and exit, varied around 208, characterising a laminar flow. The behaviour of thermal efficiency throughout the day is presented by the Figure 11, in which the efficiency values of the PTC in blue and the tube are represented absorber in purple. The values were represented by a sixth-order polynomial trend curve to perceive the day in which the highest and lowest efficiency values were obtained. It is possible to notice that thermal efficiency has lower values in times of higher insolation. This is due to the increase in thermal losses at these times because the absorber tube reaches higher surface temperature values, thus increasing the heat exchange with the environment. The average values of thermal efficiency for the PTC are 25.10% and 35.84% for the

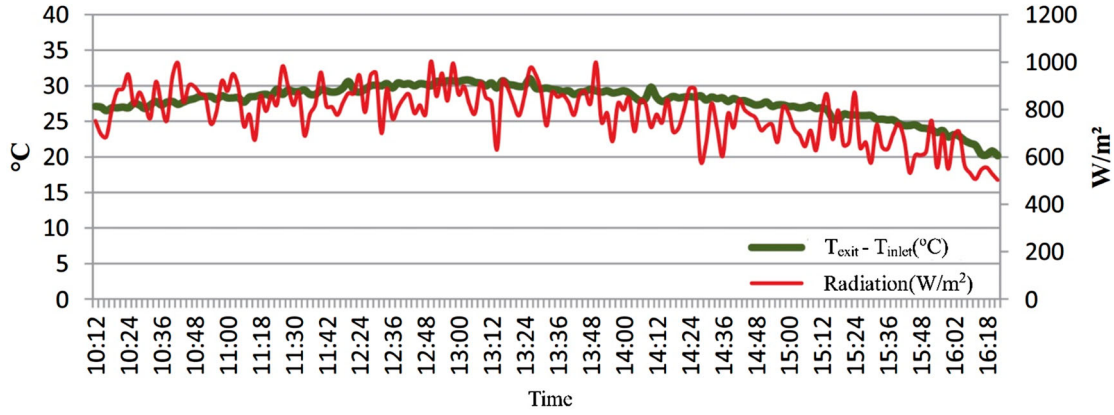


Figure 10. Difference of temperatures and direct solar radiation data (Tube 0).

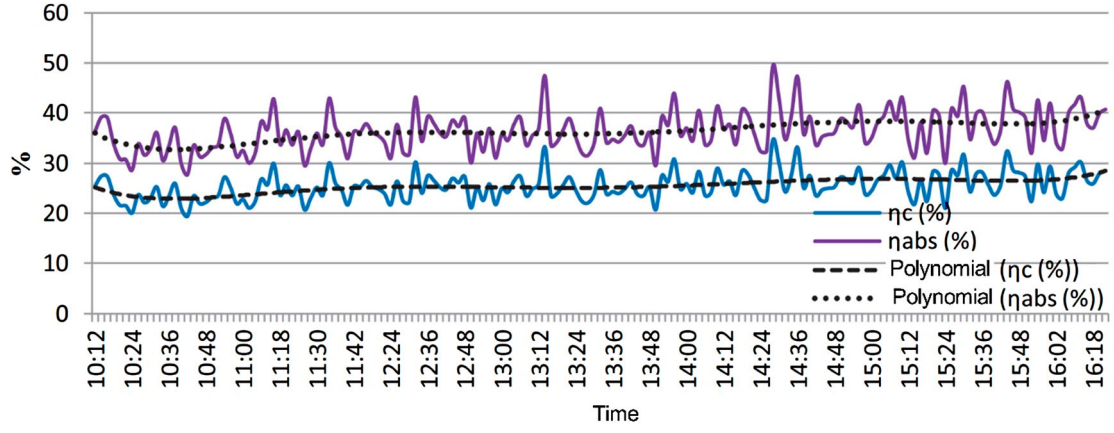


Figure 11. Thermal efficiency throughout the day (Tube 0).

absorber tube. The behaviours of the two efficiency curves are precisely the same, but the efficiency curve of the absorber tube has a greater amplitude. This is because the values of energy incident in the absorber tube (S) are around 70% of the values of $G_{dir,n.}$ From Figure 11, it is possible to perceive a variation in efficiency concerning the direct solar radiation incident and, Figure 12 was developed, in which the efficiency values for the PTC and the tube of 12.7 mm in diameter are represented by two linear trend lines: $y = -0.0208x + 41.708$ for PTC and $y = -0.0297x + 59.546$ for the 12.7 mm tube.

4.1.2. 19.25 mm tube

The results of a temperature difference between PTC input and output and direct solar radiation data are shown in Figure 13. Higher values of the difference between the inlet and outlet temperatures of the absorber can be observed concerning the 12.7 mm diameter tube during practically the entire test period, reaching a difference of up to 36.3 °C between 11:00 and 11:30. The mean value of direct solar radiation was 824.37 W/m2. The number of Reynolds, at the midpoint between the entrance and the output varied around 142, characterising a laminar flow.

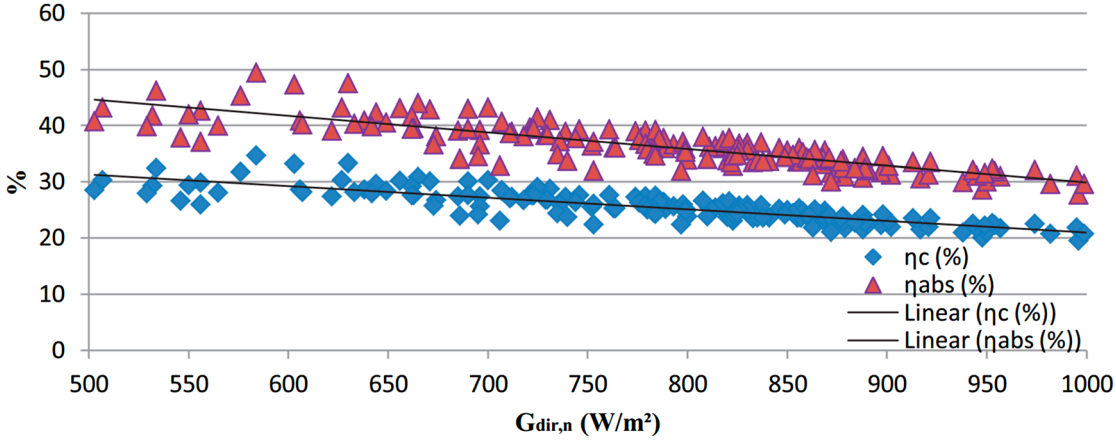


Figure 12. Thermal efficiency concerning direct solar radiation (Tube 0).

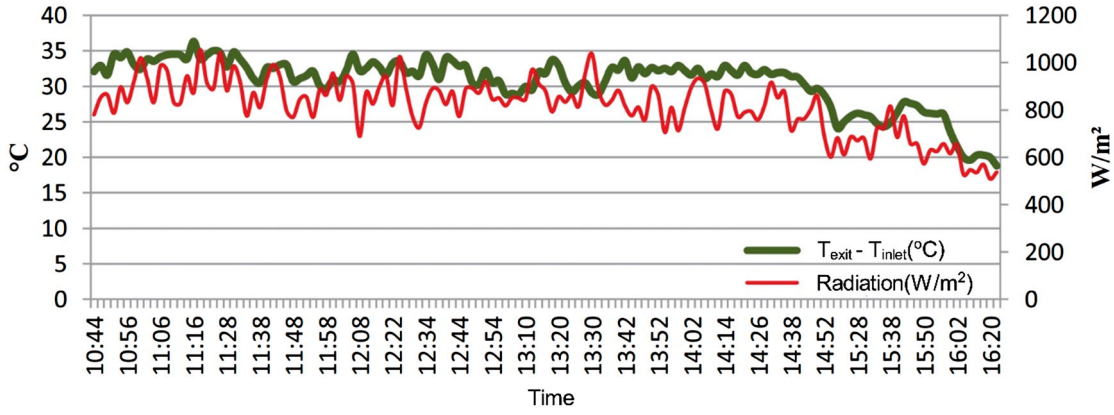


Figure 13. Difference in temperatures and direct solar radiation data (Tube 1).

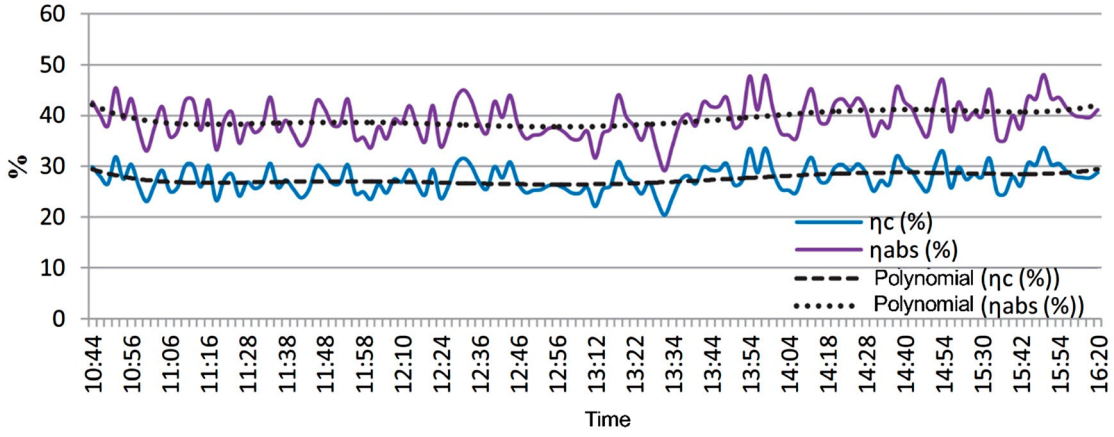


Figure 14. Thermal efficiency throughout the day (Tube 1).

The behaviour of thermal efficiency throughout the day is presented by the Figure 14. During the period from 11:00–13:30, the efficiency values reached the lowest mean values, represented by the polynomial trend curves. It can be seen that the thermal efficiency values of the PTC and the tube of 19.25 mm had higher values throughout the day compared to the results using the 12.7 mm tube. However, the value of direct medium solar radiation is more increased. The average values of thermal efficiency for the PTC are 27.31% and 39.00% for the absorber tube.

To know the relationship between thermal efficiency and direct solar radiation incident, not the collector and in the absorber tube, Figure 15 was developed, in which the efficiency is represented by a linear trend $y = -0.0158x + 40.588$ for the PTC and $y = -0.0226x + 57.948$ for the absorber tube.

4.1.3. 22.25 mm tube

The results of the temperature difference between PTC input and output and direct solar radiation data are shown in Figure

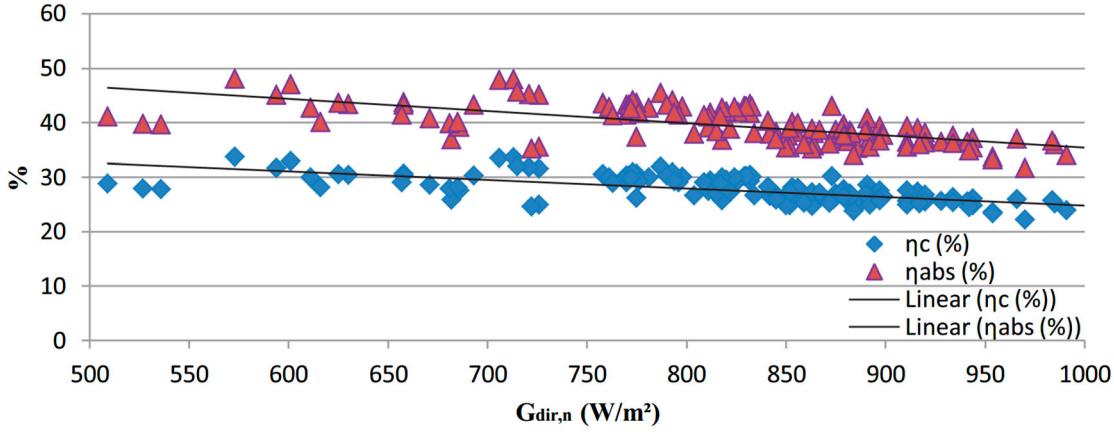


Figure 15. Thermal efficiency concerning direct solar radiation (Tube 1).

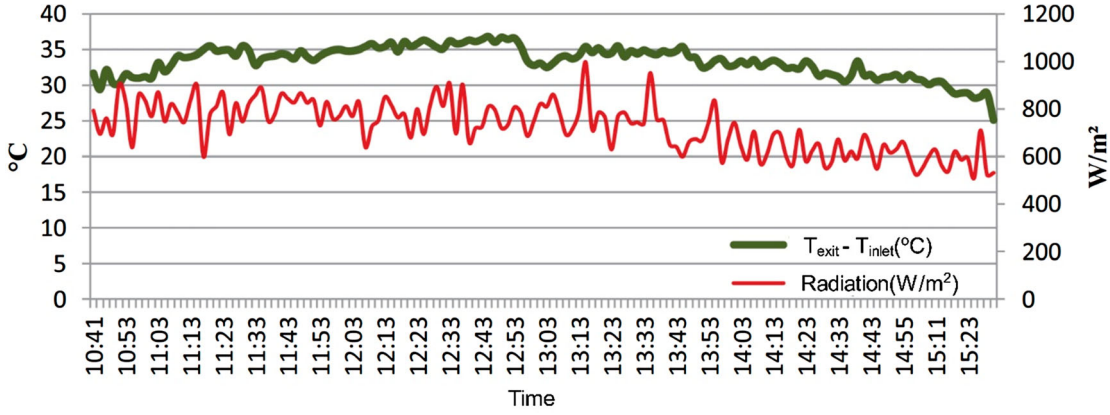


Figure 16. Difference in temperatures and direct solar radiation data (Tube 2).

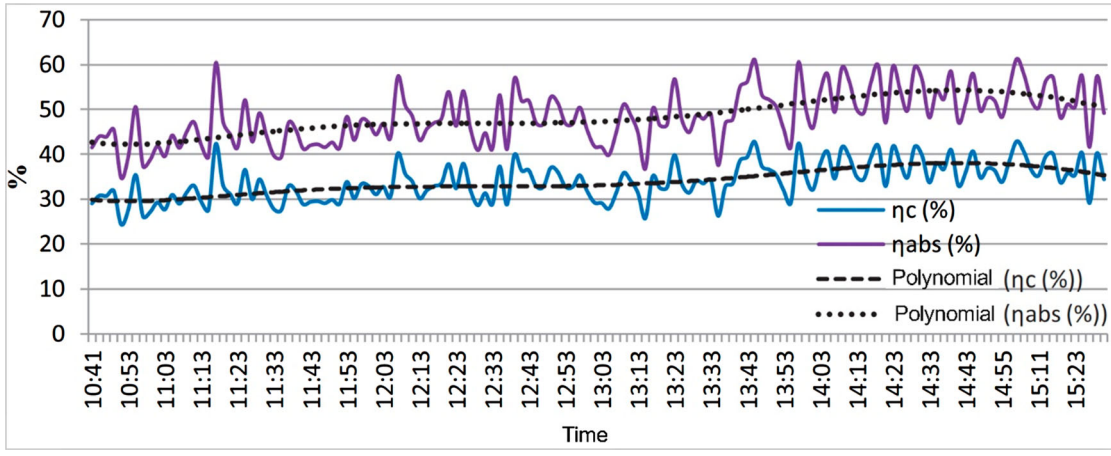


Figure 17. Thermal efficiency throughout the day (Tube 2).

16. Higher values of temperature variation can be observed concerning tubes of 12.7 mm and 19.25 mm, reaching values of up to 36.8 °C between 12:00 and 12:50, even with a lower mean direct solar radiation value, 725.65 W/^{m2}. The number of Reynolds, at the midpoint between the entrance and the output, varied around 124, characterising a laminar flow. (Figure 17)

The observed behaviour of the thermal efficiencies of the PTC and the absorber tube can be attributed to several scientific causes. Firstly, the increase in the useful area of absorption due to the geometric modification of the absorber tubes plays a significant role in increasing the thermal efficiency. As the cross-sectional area of the absorber tubes increases, the useful energy absorbed by the fluid increases, resulting in smaller thermal losses. This leads to an increase in the thermal efficiency of the PTC and the absorption of the absorber tubes. Secondly, an expansion in the area inside the collector allows for a reduction in fluid velocity, leading to a longer heat exchange time between the inner wall and the fluid. This reduction in fluid velocity increases the thermal efficiency of the absorber tube, as it allows for a more efficient transfer of heat from the absorber tube to the fluid. Thirdly, the volumetric flow rate of the fluid also plays a significant role in increasing the thermal efficiency of the PTC and the absorber tube. As the volumetric flow rate of the fluid increases, there is an increase in the thermal efficiency of the PTC and the absorption of the absorber tube. This is because an increase in the volumetric flow rate increases the convective heat transfer coefficient, which allows for a more efficient transfer of heat from the absorber tube to the fluid. Finally, the relationship between thermal efficiencies and direct solar radiation to the incident in PTC and absorber tube can be explained by the fact that as the direct incident solar radiation increases, the temperature difference between the absorber tube and the fluid also increases, leading to an increase in the convective heat transfer coefficient and, consequently, an increase in the thermal efficiency of the absorber tube. This relationship is represented by the linear trend $y = -0.0367x + 60.569$ for PTC efficiency and $y = -0.0524x + 86.474$ for absorber tube efficiency, as observed in Figure 18.

4.1.4. 27 mm tube

The results of the temperature difference between PTC input and output and direct solar radiation data are shown in Figure 19. More significant differences can be observed between the inlet and outlet temperatures compared to the 12.7 mm, 19.25 mm, and 22.25 mm tubes, reaching the highest values between 11:30 and 13:50 up to 38.6 °C. The mean value of direct solar radiation was 814.19 W/m2. The number of Reynolds, at the midpoint between the entrance and the output, varied around 98, characterising a laminar flow. (Figure 20)

The behaviour of the thermal efficiencies of the PTC and the absorber tube can be attributed to several scientific causes. One possible explanation for the higher efficiencies observed in the

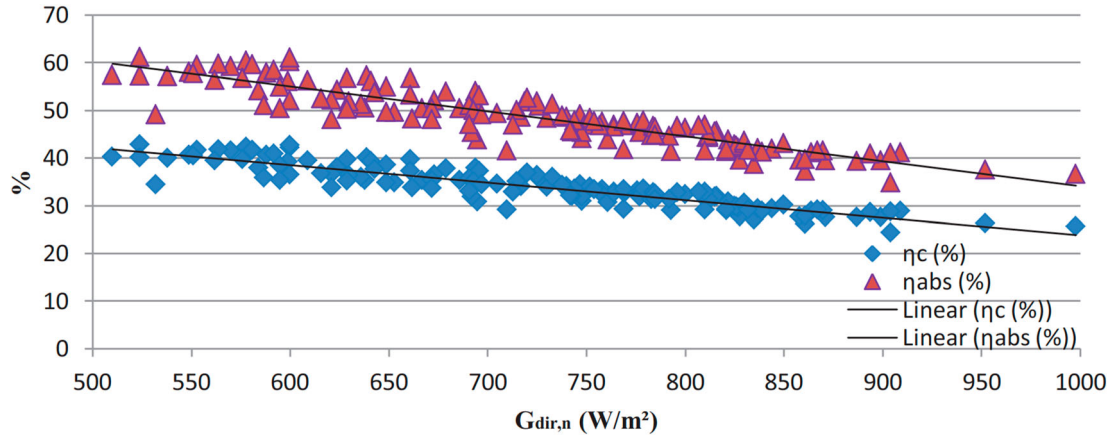


Figure 18. Thermal efficiency concerning direct solar radiation (Tube 2).

PTC and absorber tube is the design of the tubes. Using larger diameter tubes, such as the 22.25 mm tube, allows for greater heat transfer between the fluid and the tube walls, resulting in higher thermal efficiencies. Another factor influencing thermal efficiency is the direct solar radiation incident level on the collector. When the solar radiation is low, the collector's efficiency may be reduced due to lower heat transfer rates.

Conversely, during periods of higher solar radiation, the collector can achieve higher thermal efficiencies as more energy is absorbed and transferred to the fluid. The relationship between solar radiation and thermal efficiency can also explain the linear trends observed in Figure 21. The negative slope of the linear trends suggests that as the solar radiation increases, the thermal efficiency of the collector decreases. This can be attributed to the fact that as the solar radiation increases, the temperature of the absorber tube also increases, which can result in higher heat losses due to convection and radiation. The thermal efficiency of a solar collector is influenced by several factors, including the design of the collector, the level of solar radiation, and the system's operating conditions. Understanding these factors can

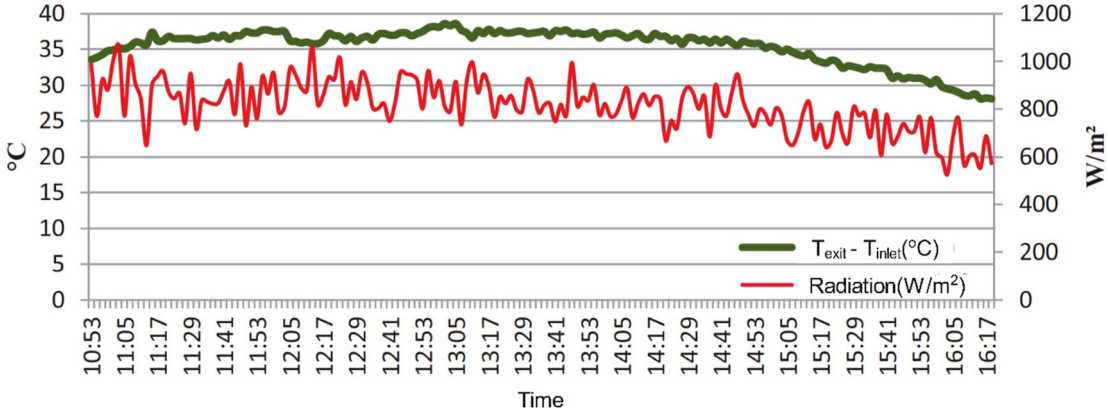


Figure 19. Difference in temperatures and direct solar radiation data (Tube 3).

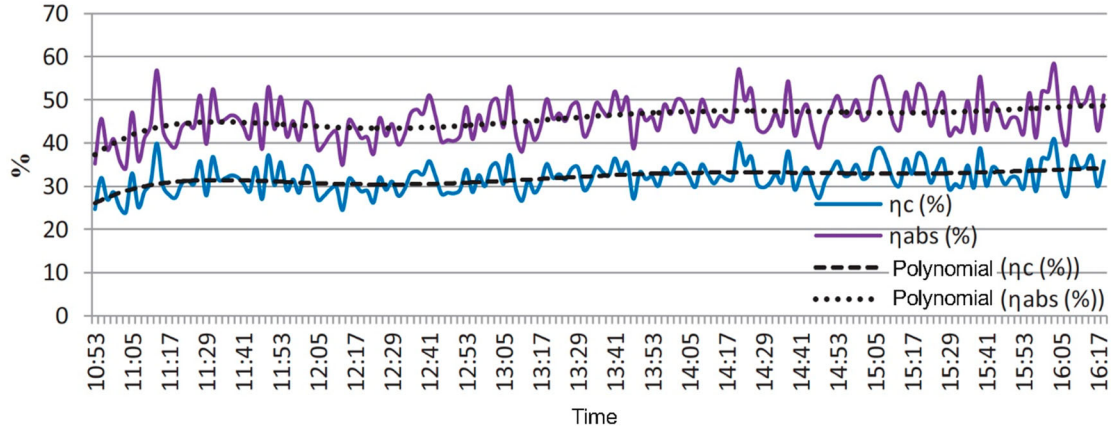


Figure 20. Thermal efficiency throughout the day (Tube 3).

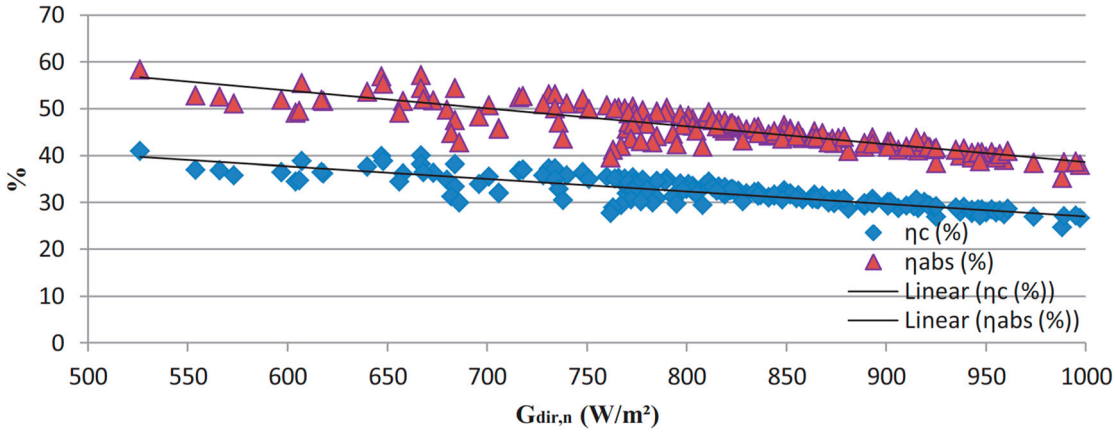


Figure 21. Thermal efficiency in relation to direct solar radiation (Tube 3).

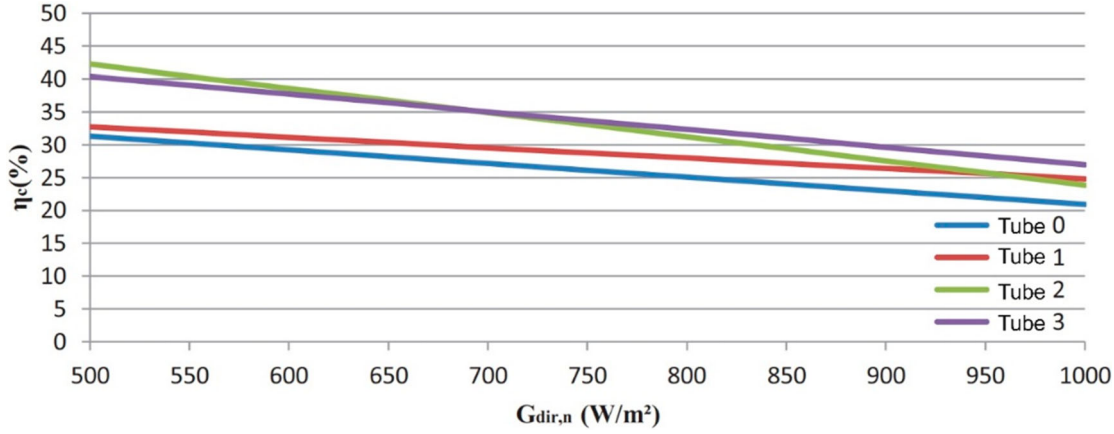


Figure 22. PTC thermal efficiency with different absorbing tubes.

help to optimise the design and operation of solar collectors for improved energy efficiency.

4.1.5. Comparative results in the flow of 64 mL/min

To compare the thermal efficiency of PTC with different absorbing tubes, the behaviour of efficiency concerning direct solar radiation incidents from trend lines was analyzed. Thus, Figure 22 was developed with the trend lines of the four tubes analyzed.

The results show that the larger the area of the internal cross-section to the parabola, the higher the thermal efficiency value of the solar collector. In periods of intense sun, in which solar radiation varies and there are 700–950 W/m2, usually, with some peaks at 1000 W/m^2, higher efficiency values for the tube of 27 mm in external diameter are perceived. Concerning the efficiencies of the absorbing tubes, Figure 23 was developed for comparison. The results show similar values for the

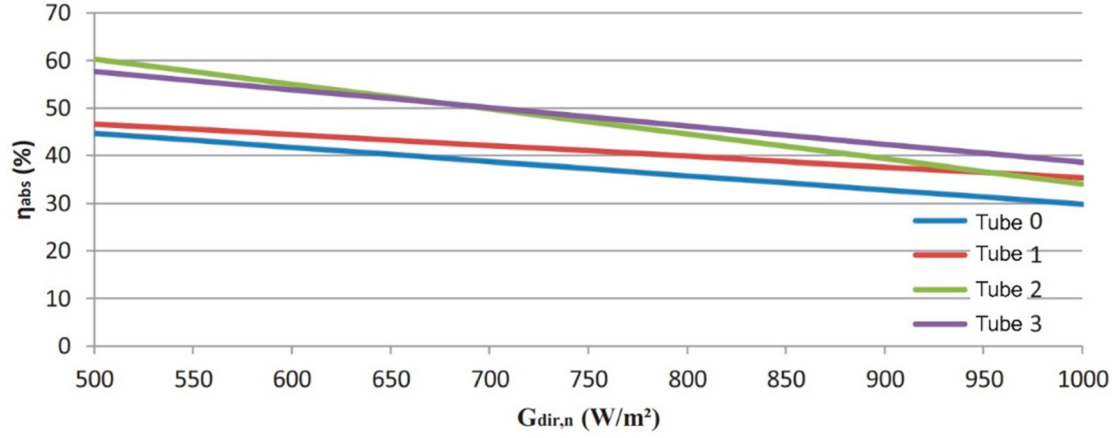


Figure 23. Thermal absorption efficiency of absorbing tubes.

22.25 mm and 27 mm tubes, but the latter performs better at higher radiation values.

To better understand the thermal losses of a solar thermal collector, it is crucial to consider both optical losses and geometrical changes of the absorbing tubes. The optical efficiency, denoted by the symbol η_0, measures the fraction of solar radiation that the collector absorbs. It is an important factor in determining the system's overall thermal efficiency, as it directly affects the amount of energy that can be converted into useful heat. In this study, the optical efficiency was independent of the geometric changes made to the absorbing tubes and reached a value of 0.70. This means that the collector effectively absorbed only 70% of the direct solar radiation, while the remaining 30% was lost due to optical losses. Figure 24 compares the losses observed for the tested tubes concerning direct solar radiation. It shows that the losses for the different tubes vary considerably, with Tube 2 presenting the lowest thermal losses, followed by Tube 3 and then Tube 1. This is consistent with the findings discussed earlier, which suggested that increasing the flow rate of the circulating fluid can lead to a reduction in thermal losses and an increase in useful heat.

It is observed that, even with a higher value of the external surface area for heat exchange with the environment, the values of thermal losses are lower for the tubes with greater cross-section. This is due to an increase in the useful heat absorbed by the fluid with the increase of the surface area of internal exchange, as can be observed in Figure 25.

The steeper slope of thermal loss lines concerning the useful energy lines explains the decrease in thermal efficiency in higher incident radiations. PTCs with high concentration rates result in a large and high flow of non-uniform heat in the outer wall of the absorbing tube, thus leading to high temperatures and circumferential temperature gradients in the absorbing tube. High temperatures of the absorber tube cause performance losses through the degradation of the heat transfer fluid at high temperatures, the significant increase in heat loss, thermal deformation, loss of thermal efficiency and life of the absorber tube.

As the results show, expanding the cross-sectional area on the inside to the parabola increases thermal efficiency values. For an average direct solar radiation of 800 W/m^2 the increases in the efficiency of PTC and absorber tube were, respectively, 11.49% and 11.41% for Tube 1, 24.50% and 24.50% for Tube 2 and 27.92% and 29.16% for Tube 3 concerning Tube 0. Pipes with larger diameters are also less susceptible to optical losses caused by construction errors of the solar collector. The results showed that the inclination error and misalignment of the absorber tube cause smaller reductions in thermal efficiency in the case of absorbing tubes and larger cross-sectional areas. The ratio of increase of useful absorption area, considering the area of the expanders and the area of the tube that does not receive

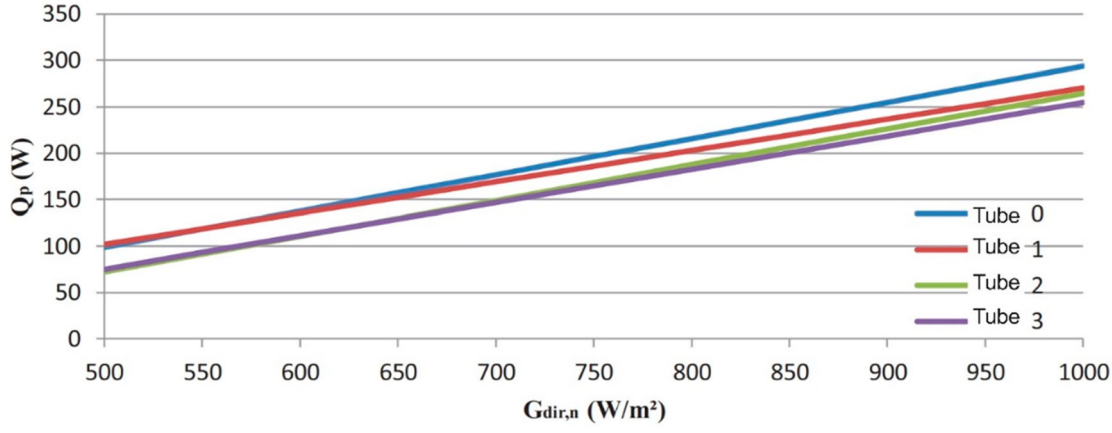


Figure 24. Losses of thermal energy from the absorber tubes.

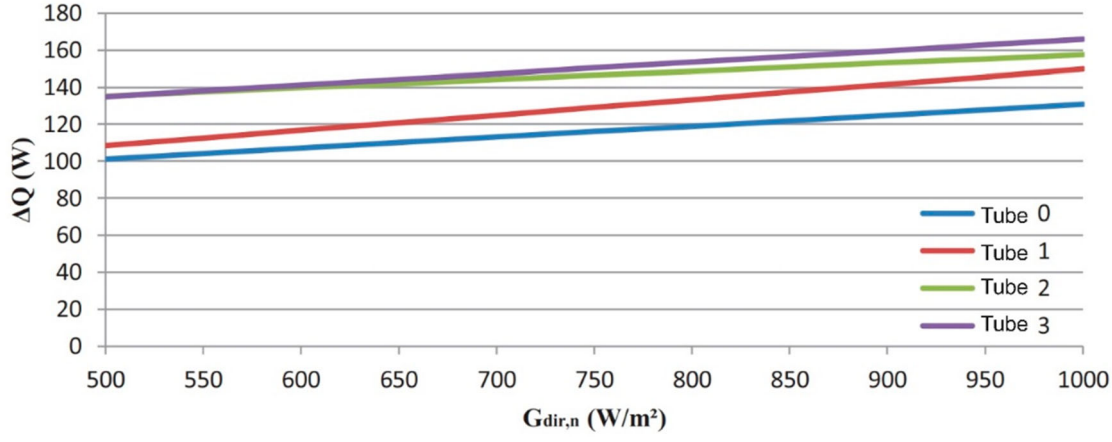


Figure 25. Useful energy transferred to the fluid with different absorbing tubes.

radiation because it is covered by the nylon bushings that support the glass, concerning the 12.7 mm tube, are 50.53%, 74.63% and 119.57% for the tubes of 19.25 mm, 22.25 mm, and 27 mm, respectively. An expansion in the area inside the collector reduces fluid speed, allowing for a longer heat exchange time between the inner wall and the fluid. Compared to the internal flow velocity of the diameter pipe 12.7 mm (0.01186 m/s) at a flow rate of 64 mL/min, these reductions are 60.61%, 72.00%, and 83.06% for the tubes of 19.25 mm, 22.25 mm, and 27 mm, respectively.

4.2. Flow rates of 50, 75 and 100 mL/min

The mass flow increase of circulating fluid is one of the primary methods for optimising the performance of a solar thermal collector. Increasing the mass flow rate of the circulating fluid in a solar thermal collector can improve its performance in several ways. Firstly, increasing the mass flow rate increases the rate of heat transfer between the absorber and the fluid, which means that more heat can be extracted from the collector per unit time. This results in higher thermal efficiency of the collector, defined as the ratio of useful heat output to the incident solar radiation. Secondly, increasing the mass flow rate can also reduce the thermal losses of the collector. When the fluid flows at a higher rate, it spends less time in the collector, which means there is less time for the fluid to lose heat to the environment through convection and conduction. This reduces the overall heat loss from the collector and improves its overall performance. Lastly, increasing the mass flow rate of the circulating fluid can also reduce the risk of overheating the collector. When the fluid flows more quickly, it absorbs heat more quickly. It carries it away from the collector, which means that the temperature of the collector is less likely to exceed the maximum safe operating temperature. This reduces the risk of damage to the collector and can improve its lifespan. In summary, increasing the mass flow rate of the circulating fluid is an effective method for optimising the performance of a solar thermal collector, as it improves heat transfer, reduces thermal losses, and reduces the risk of overheating.

4.2.1. 19.25 mm tube

The results presented in Figures 26 and 27 demonstrate the positive effect of increasing the mass flow on the PTC and absorber tube's thermal efficiency. Specifically, doubling the flow rate from 50 mL/min to 100 mL/min results in an increase of 10.98% in the PTC efficiency and 10.82% in the absorber tube efficiency, based on an average direct solar radiation of 800 W/m⊃2. These findings highlight the importance of optimising the flow rate to achieve the highest thermal efficiency and minimise energy losses.

It is also important to note that the Reynolds numbers, which are a dimensionless parameter used to characterise the flow regime, were found to increase with the mass flow rate. At the

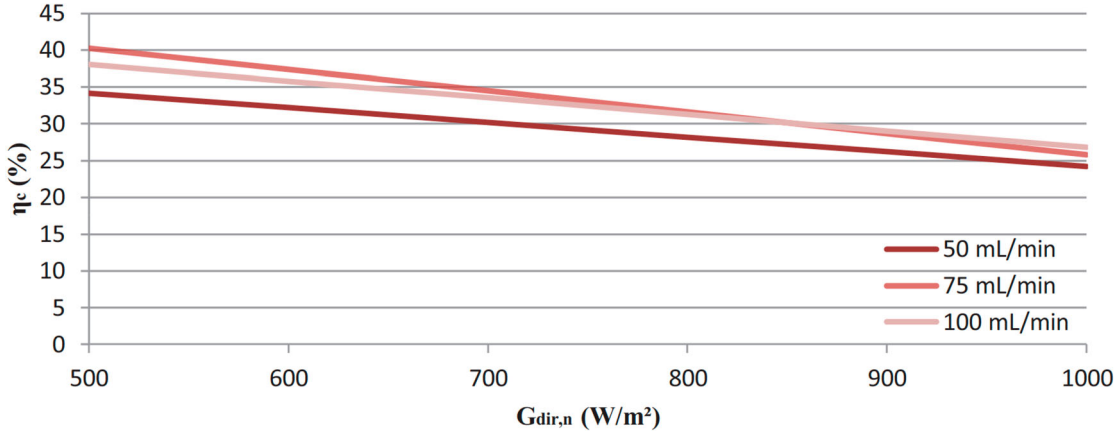


Figure 26. PTC thermal efficiency at different flow rates (Tube 1).

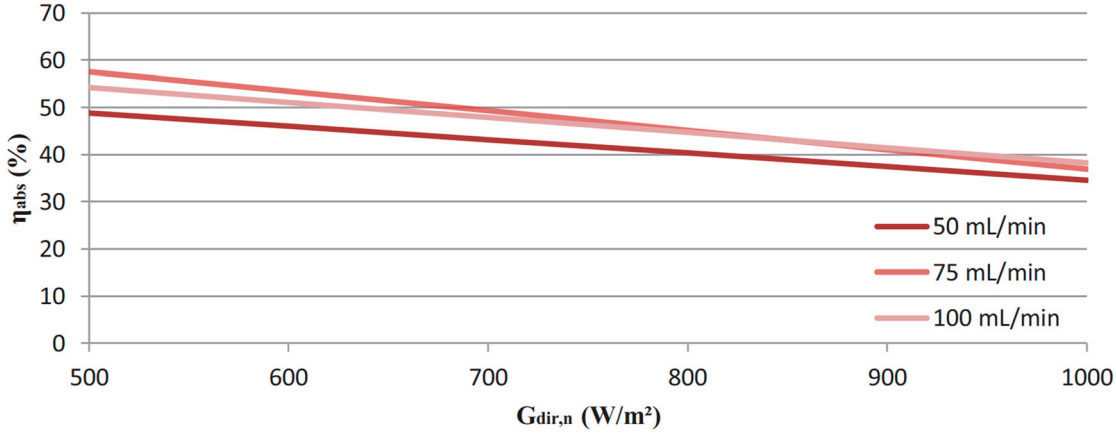


Figure 27. Thermal absorption efficiency at different flow rates (Tube 1).

midpoint between the inlet and outlet, the Reynolds numbers for flow rates of 50, 75, and 100 mL/min were approximately 116, 172, and 225, respectively. This indicates that the flow regime progresses from laminar to transitional to turbulent as the flow rate increases, which can also impact the heat transfer performance of the system.

Increasing fluid flow in a solar thermal collector is one of the primary methods for optimising its performance. Figure 28 shows that thermal losses are reduced as fluid flow increases due to the increase in internal heat transfer. This is supported by Figure 29, demonstrating that the internal heat transfer coefficient also increases with fluid flow. Therefore, increasing the mass flow rate of the circulating fluid can reduce thermal losses and improve the collector's thermal efficiency. Figure 30 shows the characteristic curve of Tube 1, which represents the losses and thermal efficiency values for each difference between the mean temperature of the fluid and the ambient temperature, which can be obtained by varying the flow rate. Overall, increasing the mass flow rate is an effective method for optimising the performance of a solar thermal collector by reducing thermal losses and increasing thermal efficiency.

4.2.2. 22.25 mm tube

The mass flow increase significantly impacts the thermal efficiency of the PTC and absorber tubes, as shown in Figures 31 and 32. The observed increases in efficiency are primarily due to the reduction in thermal losses as the fluid flow increases. This phenomenon can be attributed to increased internal heat transfer, as seen in previous experiments. The experiments demonstrate that the thermal efficiency of the PTC and absorber tube increase by 18.26% and 18.36%, respectively, when the volumetric flow is doubled from 50 mL/min to 100 mL/min, respectively, with an average direct solar radiation of 800 W/m⊃2. The Reynolds numbers, which represent the flow regime of the fluid, at the midpoint between the inlet and outlet, increase with the flow rate. The Reynolds numbers for flow rates of 50, 75, and 100 mL/min ranged around 103, 146, and 193, respectively. The results indicate that increasing the mass flow rate of the circulating fluid is an effective method for improving the thermal efficiency of solar thermal collectors.

Thermal losses and useful heat are important parameters for assessing the performance of a solar thermal collector. Figures 33 and 34 show that the thermal losses decrease and the useful heat increases as the mass flow rate increases. This is because the increase in mass flow rate leads to an increase in internal heat transfer, reducing thermal losses and increasing the useful heat. Figure 35 is the characteristic curve of Tube 2, which shows the losses and thermal efficiency values for each difference between the mean temperature of the fluid and the ambient temperature obtained by varying the flow rate. This curve can be used to optimise the performance of the solar thermal collector by

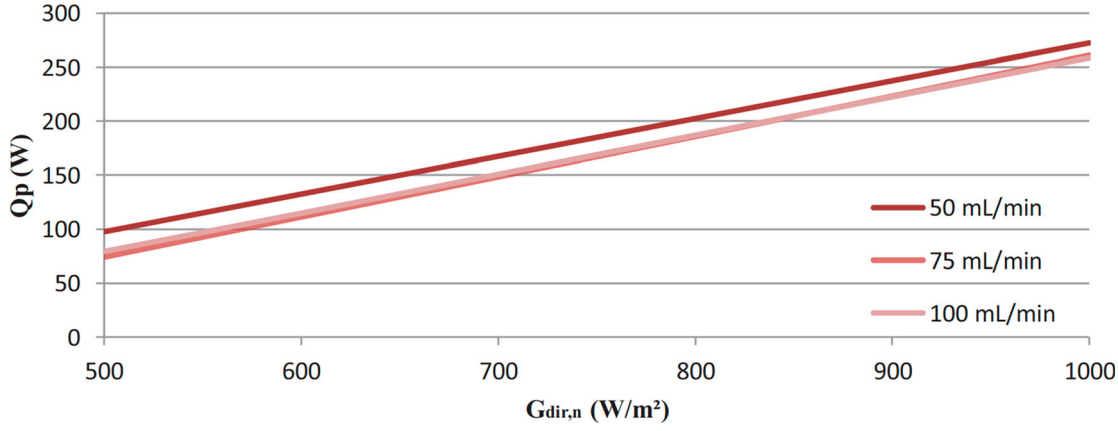


Figure 28. Thermal energy losses at different flows (Tube 1).

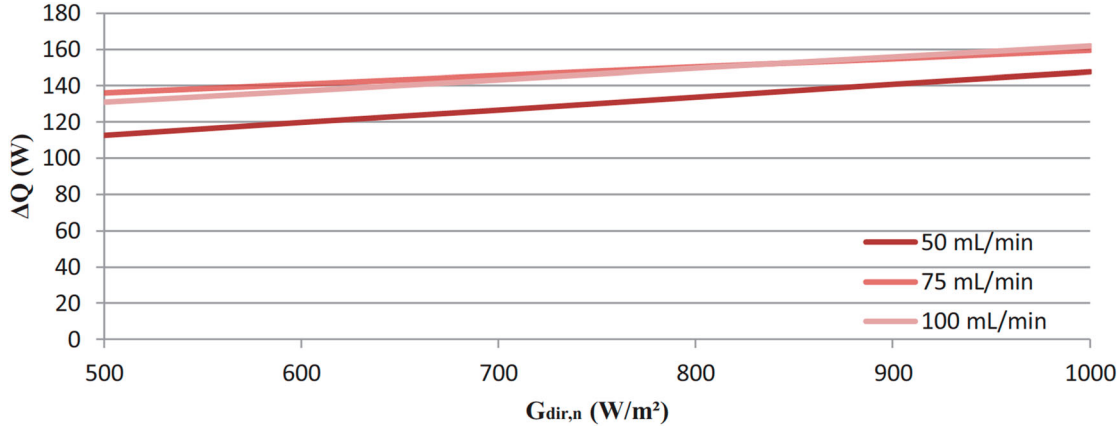


Figure 29. Useful energy transferred to the fluid at different flows (Tube 1).

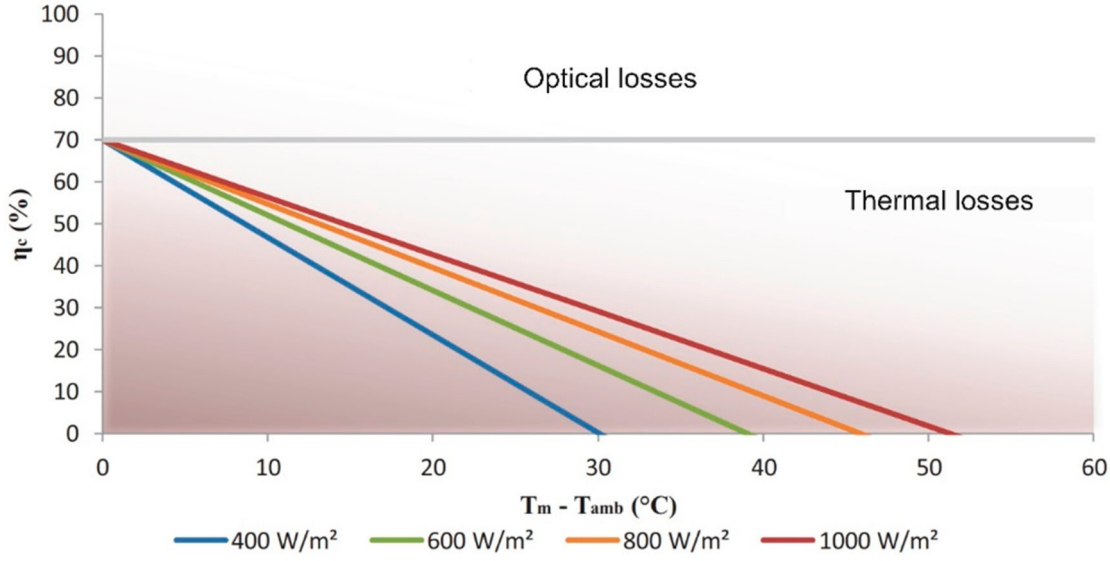


Figure 30. Characteristic curve of Tube 1.

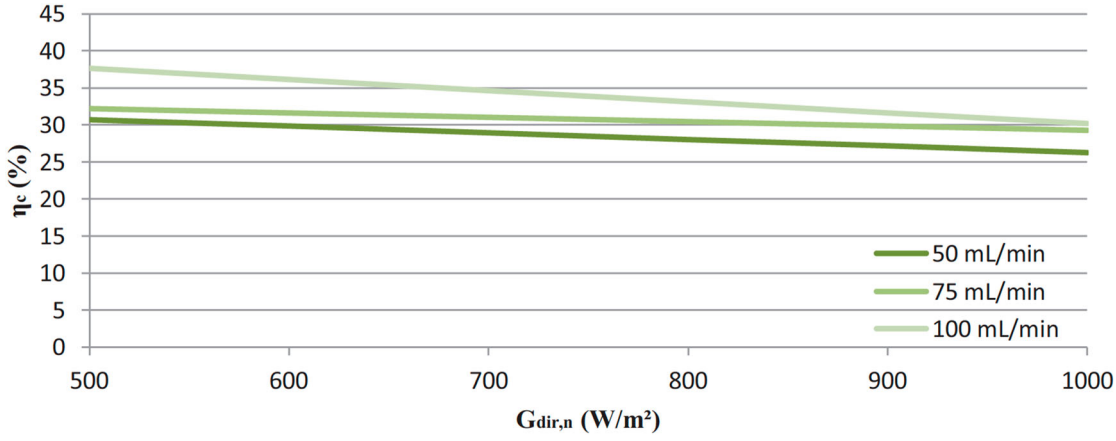


Figure 31. PTC thermal efficiency at different flow rates (Tube 2).

selecting the appropriate flow rate to achieve the desired thermal efficiency and useful heat. Overall, these results highlight the importance of mass flow rate in maximising the performance of a solar thermal collector.

4.2.3. 27 mm tube

The results for the volumetric flows of 75 and 100 mL/min obtained very similar values. However, the 100 mL/min flow achieved the best efficiency values, as shown in Figures 36 and 37. Increasing the volumetric flow by 50 mL /min to 100 mL/min leads to an increase of 8.37% and 8.27% in the collector and absorber tube efficiency, respectively, at an average direct solar radiation of 800 W/m⊃2. At the midpoint between inlet and outlet, the Reynolds numbers, respectively, for flow rates of 50, 75, and 100 mL/min, ranged around 80, 117, and 155.

The results presented in Figures 38 and 39 suggest that increasing the flow rate can reduce thermal losses and increase useful heat in a solar thermal collector. This is because higher flow rates result in more efficient internal heat transfer, which reduces the absorber tube's surface temperature and minimises energy lost to the environment. In other words, by increasing the flow rate of the circulating fluid, the collector can operate more efficiently, capturing more of the available solar energy and minimising heat losses.

Figure 40 shows the characteristic curve of Tube 3, which is based on the thermal efficiency values obtained in the experiment. By comparing the characteristic curves of Tubes 1, 2, and 3, it is possible to see that Tube 3 achieved higher average fluid temperature values, indicating that increasing the flow rate can significantly impact the overall performance of the solar thermal collector.

4.2.4. Comparative results of thermal efficiency in direct solar radiation of 800 W/m⊃2

The characteristic curves in direct solar radiation of 800 W/m⊃2 of the three tubes analyzed were plotted in Figure 41. The results show close values of thermal efficiency between Tubes 1 and 2. It is possible to perceive lower values of thermal losses for Tube 3, achieving higher efficiency values concerning Tubes 1 and 2.

The results indicate that Tube 3 is more suitable for achieving the desired outlet temperature of 60 °C for disinfestation purposes in agricultural areas while maintaining high thermal

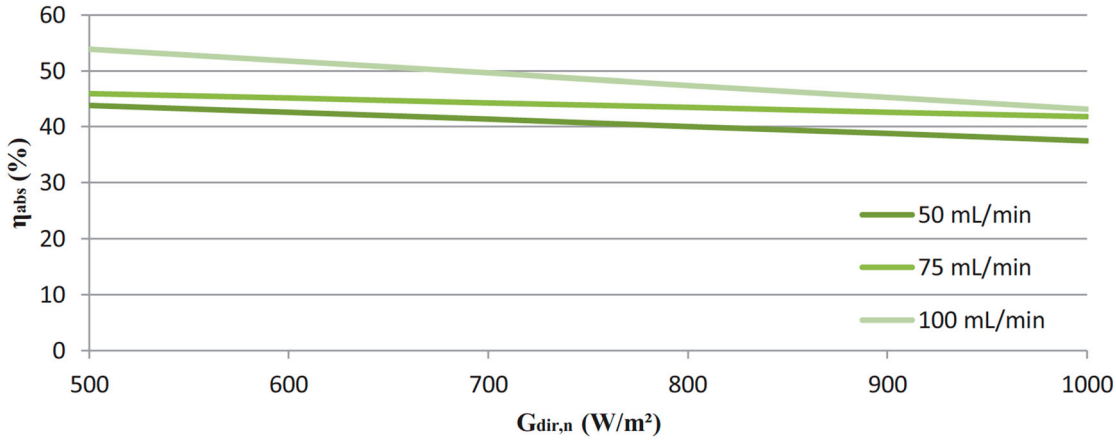


Figure 32. Thermal absorption efficiency at different flow rates (Tube 2).

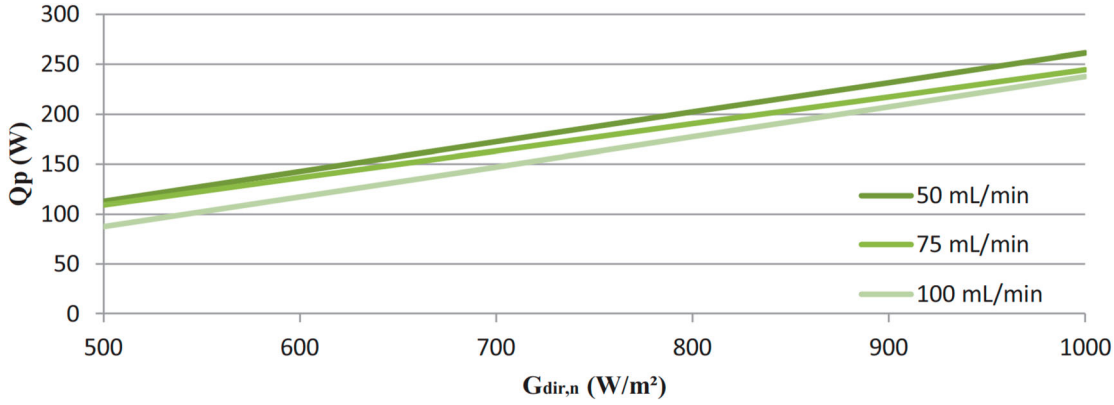


Figure 33. Thermal energy losses at different flows (Tube 2).

efficiency. Compared to Tube 1, both Tube 2 and Tube 3 showed improvements in thermal efficiency when the inlet and ambient temperatures were kept at 30 °C and the outlet temperature was raised to 60 °C. However, Tube 3 showed a significantly higher improvement of 9.57% in thermal efficiency compared to Tube 1, whereas Tube 2 showed a relatively smaller improvement of 0.87%. This suggests that Tube 3 can handle higher flow rates than Tube 1 and Tube 2 while still maintaining high thermal efficiency, making it a better choice for achieving the desired outlet temperature.

4.2.5. Results for the 27 mm tube at different volumetric flows

The results presented in Figure 42 suggest that direct solar radiation directly affects the temperature of the circulating fluid in the PTC, as the higher the solar radiation, the higher the fluid temperature. This is because solar radiation provides the energy needed to heat the fluid. The results also show that the increase in the fluid's volumetric flow rate directly affects the temperature difference between the inlet and outlet of the PTC, as shown in Figure 43. This is because a higher flow rate

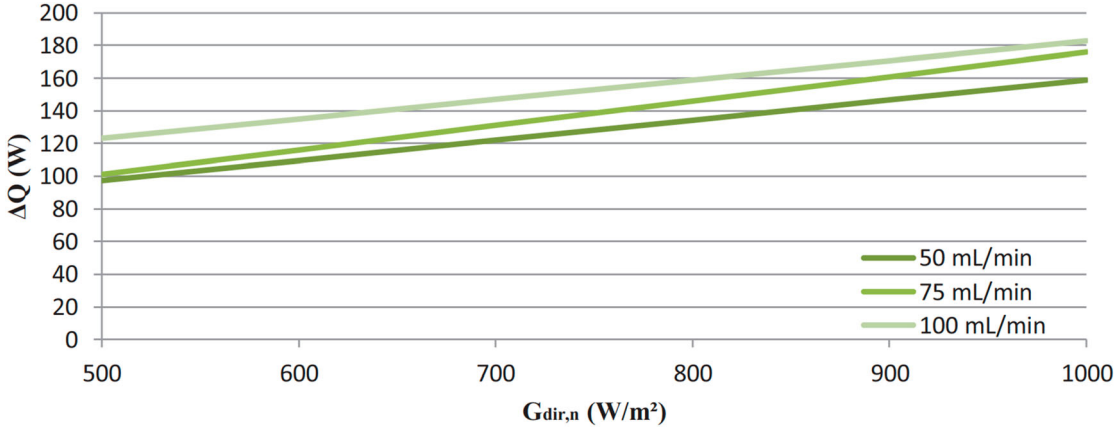


Figure 34. Useful energy transferred to the fluid at different flows (Tube 2).

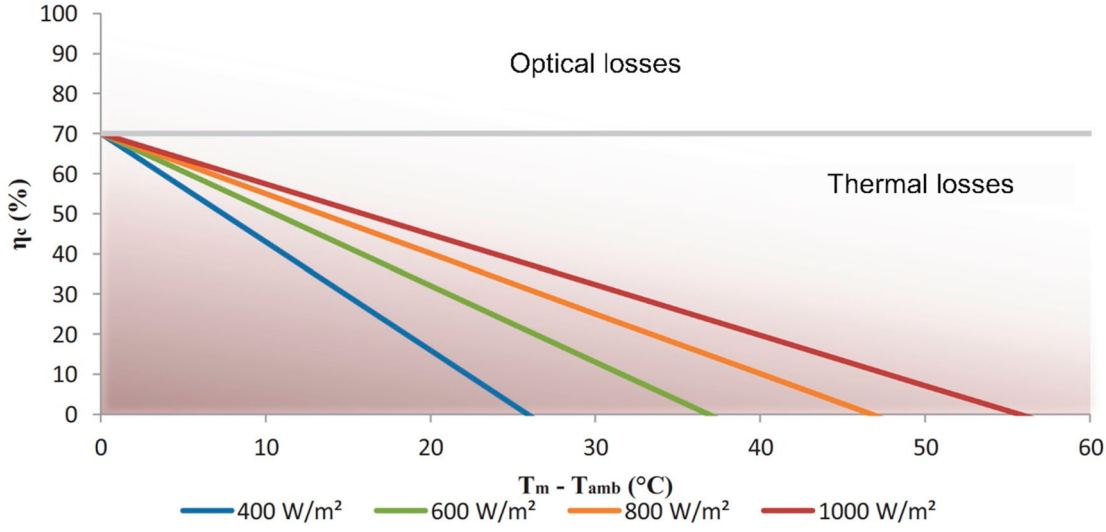


Figure 35. Characteristic curve of Tube 2.

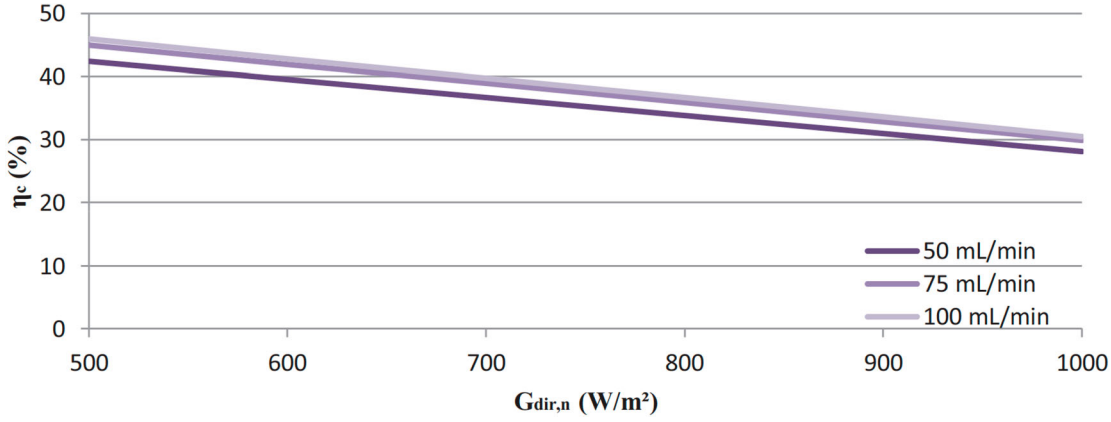


Figure 36. PTC thermal efficiency at different flow rates (Tube 3).

allows for more efficient internal heat transfer, resulting in a higher temperature difference between the inlet and outlet of the PTC. However, it is important to note that there is a trade-off between flow rate and outlet temperature, as increasing the flow rate can decrease the outlet temperature. This highlights the importance of analyzing the intended circulation fluid's working temperature to determine the project's best volumetric flow rate.

Based on the data collected during the experiment, the average direct solar radiation values for the three days analyzed were 839.54 W/m⊃2 at a flow rate of 50 mL/min, 844.25 W/m⊃2 at a flow rate of 75 mL/min, and 888.64 W/m⊃2 at a flow rate

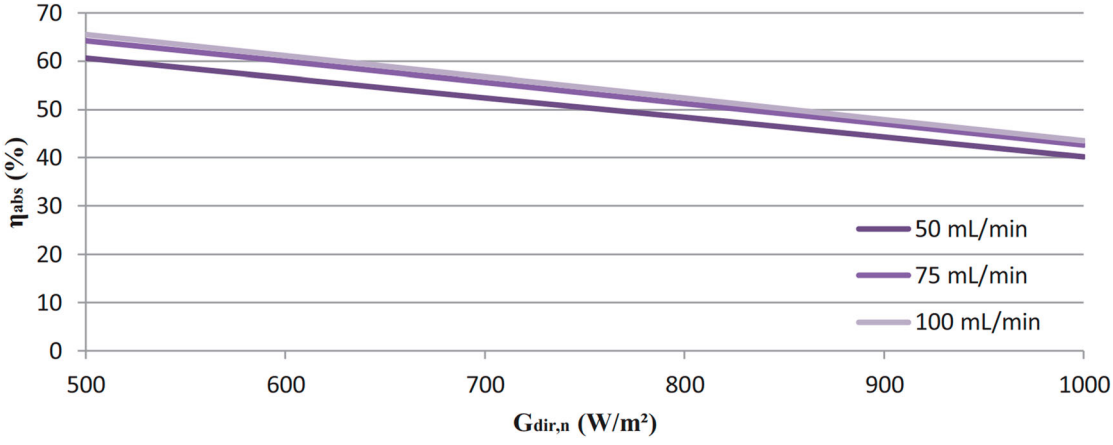


Figure 37. Thermal absorption efficiency at different flow rates (Tube 3).

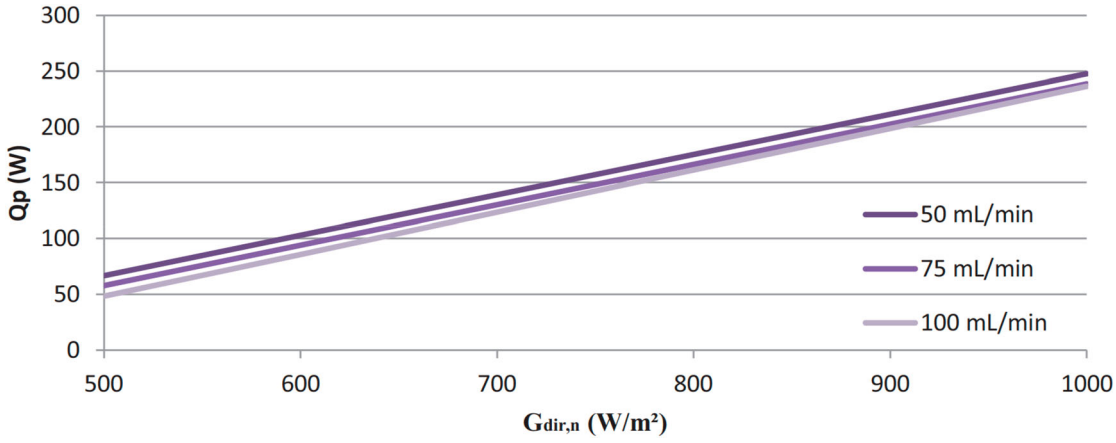


Figure 38. Thermal energy losses at different flows (Tube 3).

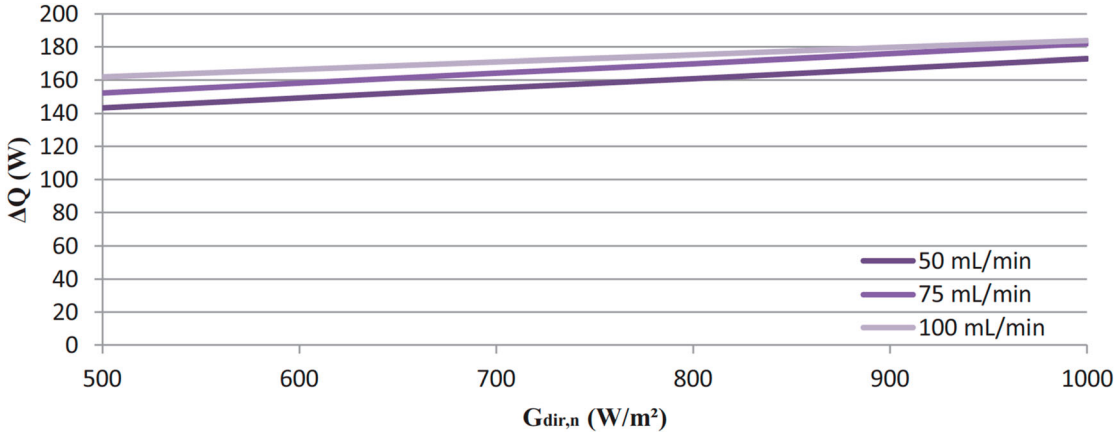


Figure 39. Useful energy transferred to the fluid at different flows (Tube 3).

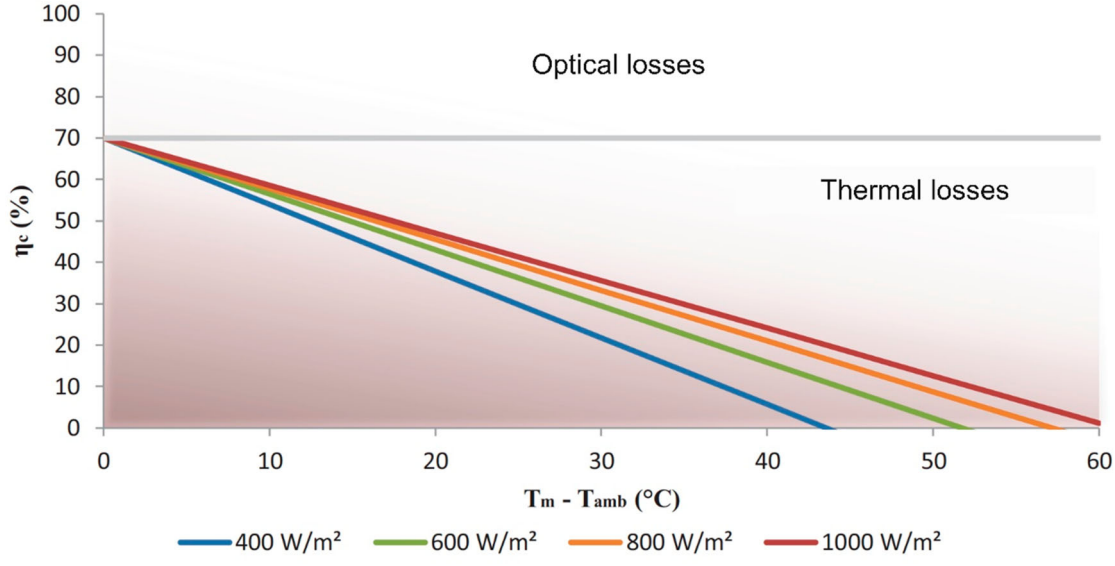


Figure 40. Characteristic curve of Tube 3.

of 100 mL/min. The results in Figure 43 shows that increasing the volumetric flow rate leads to lower temperature differences between the inlet and outlet of the PTC, although the reduction percentage is lower than the percentage increase in mass flow. However, increasing the flow rate results in higher thermal efficiency values. It is important to note that the temperature values at the fluid entry point in the PTC were 42.9 °C ± 5%, while the room temperature values were approximately 31 °C ± 4%. These

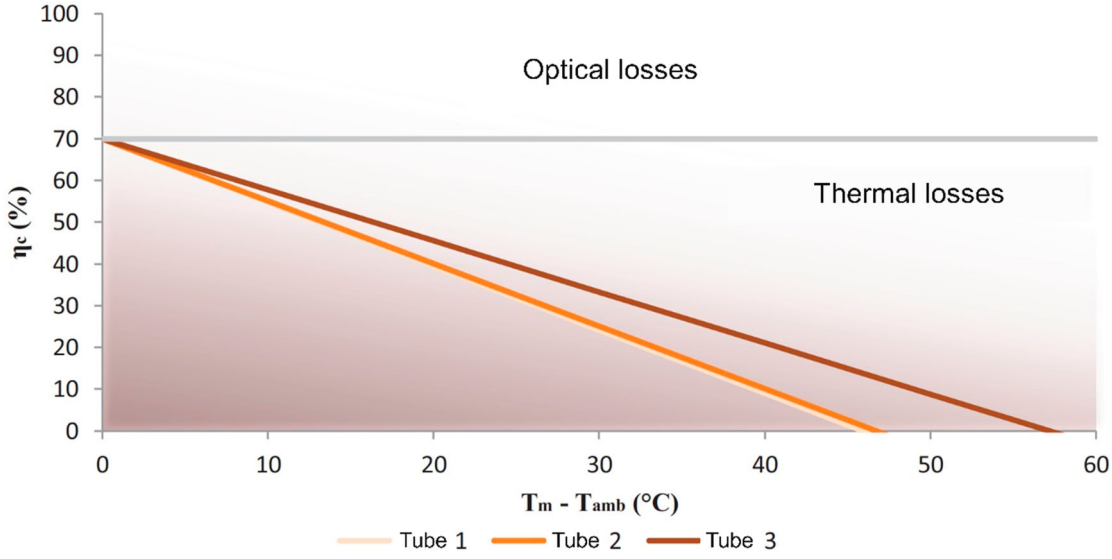


Figure 41. Characteristic curves for direct solar radiation of 800 W/m⊃2.

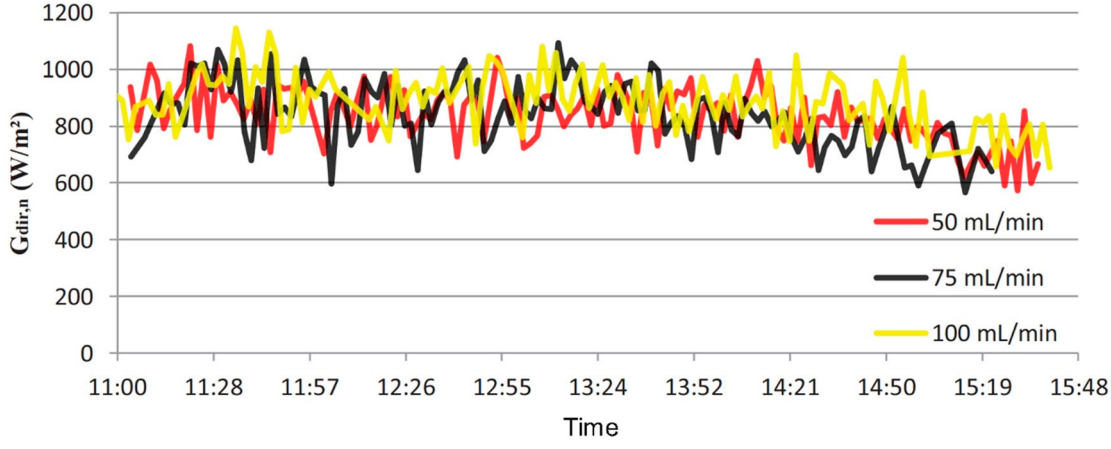


Figure 42. Direct solar radiation data for test days with Tube 3.

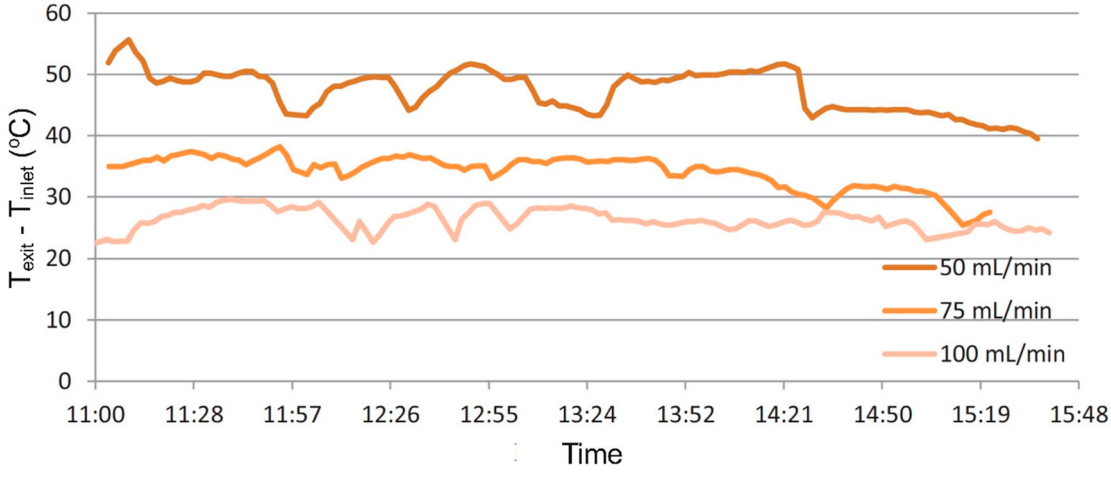


Figure 43. Temperature difference between inlet and outlet for Tube 3.

values indicate that the PTC could effectively capture solar radiation and transfer the heat to the circulating fluid. However, the working temperature of the intended circulation fluid must be considered to determine the optimal volumetric flow rate for the project.

The experimental results indicate that a 100 mL/min flow rate can achieve an average outlet temperature of 71.2 °C in the PTC, which is suitable for applications such as seed storage water thermotherapy and irrigation water disinfestation in crops. The temperature of 60 °C is effective in eliminating pathogens from the water, and the PTC can easily achieve this temperature. Therefore, using PTCs in agriculture can help reduce the use of chemical pesticides, which can negatively impact the environment and human health. Moreover, PTCs are sustainable and cost-effective solutions for providing thermal energy in a clean and renewable way, making them an attractive option for agricultural applications.

The results show that the 19.25 and 22.25 mm diameter tubes have higher efficiency values throughout the day than the 12.7 mm tube, despite having a higher mean direct solar radiation value. Additionally, the thermal efficiency values of the absorber tubes are higher than those of the PTC. The relationship between thermal efficiency and direct solar radiation incident is also presented. The section concludes that the absorber tube diameter significantly impacts thermal efficiency and that larger diameter tubes result in higher efficiency values.

In summary, further research could focus on optimising absorber tube geometry to improve the thermal efficiency of PTCs for specific applications. This could include investigating the impact of different materials or coatings on the absorber tubes and exploring alternative tracking systems and heat transfer fluids. Additionally, more studies could be conducted to evaluate the economic feasibility and scalability of PTCs for widespread adoption in various industries. Such research could help advance sustainable energy practices and promote the use of solar energy as a viable alternative to traditional energy sources.

5. Conclusions

This work aimed to analyze the influence of the geometric modification of the absorber tubes on the thermal efficiency of the PTC. Three absorber tubes of different cross-sectional areas expanded in the focal region of the reflector parabola of a small solar collector were manufactured. The PTC of this project has automatic east–west tracking and manual north–south tilt adjustment; the latter is based on the solar declination angle and local latitude. The tracking system was developed with an Arduino UNO and a NEMA 23 - 200 kgf.cm/^{3}. A stepper motor with a reduction box, uses two LDRs to detect the brightest side of the PTC.

The ratio of increase in the useful area of absorption, considering the area of the expanders and the area of the tube that does not receive radiation because it is covered by the nylon bushings that support the glass, concerning the 12.7 mm tube (Tube 0) of the initial project, are 50.53%, 74.63% and 119.57% for tubes of 19.25 mm (Tube 1), 22.25 mm (Tube 2) and 27 mm (Tube 3), respectively.

Expanding the area inside the collector reduces fluid velocity and increases the heat exchange time between the inner wall and the fluid. At a flow rate of 64 mL/min, the reductions in internal flow velocity compared to the 12.7 mm diameter tube are 60.61%, 72.00%, and 83.06% for tubes of 19.25, 22.25, and 27 mm, respectively.

The results show an increase in the thermal efficiency of the PTC and the absorption of the absorber tubes with a larger cross-sectional area. The increases, respectively, were 11.49% and 11.41% for Tube 1, 24.50% and 24.50% for Tube 2, and 27.92% and 29.16% for Tube 3 concerning Tube 0, at a flow rate of 64 mL/min, considering an average direct solar radiation of 800 W/m⊃2. The useful energy absorbed by the fluid increased as the cross-sectional area increased. Consequently, the thermal losses presented by the absorber tubes were smaller. The 27 mm absorber tube showed the best thermal efficiency behaviour as a function of the incidence of solar radiation, despite reducing the concentration factor by 54.46% concerning the 12.7 mm tube.

The manufactured tubes were submitted to experimental tests at flow rates of 50, 75, and 100 mL/min. The results show that the increase in the volumetric flow of the flowing fluid allows the increase of the thermal efficiency values of the PTC and absorption for each analyzed absorber tube. The additions, respectively, were 10.98% and 10.82% for Tube 1, 18.26% and 18.36% for Tube 2, and 8.37% and 8.27% for Tube 3, with a 100% increase in volume flow from 50 mL/min to 100 mL/min, considering an average direct solar radiation of 800 W/m⊃2.

The characteristic curves of Tubes 1, 2, and 3 were traced from the temperature and thermal efficiency values obtained through each volumetric flow analyzed. For agricultural applications in seed thermotherapy and irrigation water disinfestation, which require an outlet fluid temperature of 60 °C to eliminate pathogens, considering both fluid inlet and ambient temperatures of 30 °C, increases in thermal efficiency of 0.87% for Tube 2 and 9.57% for Tube 3 concerning Tube 1 for the 800 W/m⊃2 curve.

Comparing the three flows analyzed for Tube 3, the outlet temperature values for the flow of 100 mL/min vary around 71.2 °C, which can be applied to eliminate phytopathogens, with the possibility of applying a volumetric flow larger to reach an average temperature of 60 °C, which will allow a greater amount of heated fluid.

This study examined the impact of modifying the geometry of absorber tubes on the thermal efficiency of a parabolic trough collector (PTC). The results showed that increasing the cross-sectional area of the tubes led to an increase in the absorption of useful energy and a reduction in thermal losses, resulting in improved thermal efficiency of the PTC. Specifically, the 27 mm absorber tube showed the best thermal efficiency behaviour, despite reducing the concentration factor. Additionally, increasing the volumetric flow of the fluid led to increased thermal efficiency values and absorption for each absorber tube. These findings have significant implications for agricultural applications such as seed thermotherapy and irrigation water disinfestation, where an outlet fluid temperature of 60°C is required to eliminate pathogens. Overall, this research highlights the potential of geometrical modifications to enhance the efficiency and effectiveness of solar collectors and improve sustainable energy practices.

Some potential sources of error in this study could include variations in solar radiation, ambient temperature, and wind speed, which could all affect the performance of the PTC. In addition, the accuracy of the measuring instruments used, such as the thermocouples and LDRs, could also contribute to measurement uncertainties. It is also possible that the results could be affected by other factors not considered in the study, such as changes in the fluid properties over time or the potential for fouling in the absorber tubes. To address these limitations and potential sources of error, future research could consider using more precise measuring instruments, conducting experiments over a longer period of time to capture variations in environmental factors, and analyzing the effects of other factors on the performance of the PTC. Additionally, it would be beneficial to conduct a sensitivity analysis to determine the effect of each parameter on the performance of the PTC.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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