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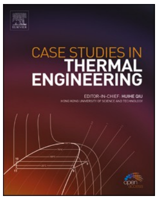

# Experimental study of an innovative elastomer-based heat exchanger

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## ARTICLE INFO

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## ABSTRACT

This work aims to present the development stages of a serpentine heat exchanger, composed uniquely of a thin layer of a silicon-based organic elastomeric polymer, polydimethylsiloxane (PDMS). The novelty of this heat exchanger is that it allows the flowing liquid to wet the surface to be cooled directly, an innovation in relation to traditional exchangers, generally made up of tubes coupled to the heating surfaces. In order to evaluate its thermal performance, experimental flow tests compared two PDMS serpentines with a hydraulic diameter of around 5.0 mm with a traditional tubular copper serpentine. The heat exchanger made of PDMS was coupled to a steel plate that simulated the rear side of a photovoltaic thermal solar panel (PVT). In addition, different geometries were tested. Although PDMS is considered a material of low thermal conductivity, the experimental results showed a greater cooling capacity when compared to the traditional heat exchanger reducing the surface's temperature by an average of 17%. Though the experimental results presented here were obtained for a specific case, the innovation can be used for thermal control of central process units (CPUs), smartphones, tablets, video games, and other mechanical and electronic devices with high cooling requirements.

**Nomenclature**

| | |
|---|---|
| $D_h$ | hydraulic diameter, (mm) |
| $h$ | internal height, (mm) |
| $L$ | channel length, (mm) |
| $Q$ | Volumetric flow rate, (ml/min) |
| $I$ | irradiance, (W/m$^2$) |

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| | |
|---|---|
| $T$ | temperature, (°C) |
| $w$ | internal width, (mm) |
| $t$ | time, (s) |

## 1. Introduction

The constant increase in energy demand caused by population growth and technological advancements is limited by the planet's resources. The most well-known example is fossil fuels, which face relevant finitude issues and environmental and geoeconomic problems related to their extraction and use. Among the alternatives researched and applied in recent decades, progress has been made with geothermal, biomass, wind, and solar energy. The most widely used way to convert solar radiation into electrical energy is using photovoltaic solar panels, which have the advantage of being easy to install and operate since they do not require a primary engine [1]. However, despite converting radiation energy into electrical energy, solar panels paradoxically face the issue that the same radiation, essential to their functioning, increases the panel's temperature, which may reduce its effectiveness. In addition to this issue, excessive temperature decreases the panel's useful life [2].

To address the abovementioned problems, solutions that use passive and active cooling methods have been studied, such as heat pipes, liquid immersion, spraying water, phase-changing materials [3] and changes in fluid circulation settings [4]. Serpentine pipes have been extensively used due to their ease of operation and control. They are usually made of circular section tubes that seek to cover as much of the cooling area as possible. However, traditional serpentine pipes have limitations, such as the geometry followed by the fluid and the contact area between the cooling fluid and the panel; since the tube is usually circular, the contact with the panel requires the use of thermal masses, as in the work of [5], or the use of a thick copper tape soldered to the pipe and two-sided thermally conductive tape to assemble it on the rear surface of the panel, as recently reported by Ref. [6].

In the present work it is proposed the manufacturing a serpentine pipe made of easily mouldable and transparent material. The ease of moldability allows for greater flexibility in the channel's geometry, significantly increasing the contact area between the fluid and the panel. Therefore, we used the silicone Sylgard® 184, an elastomer with good mechanical properties compared to other acrylate-based resins and frequently used in microfluidics and biomedical applications [7–9] and even to fabricate cells for thermal properties analysis [10]. Moreover, it is transparent and easy to manufacture, allowing for the construction of serpentine pipes that can be compared to traditional cooper serpentine, also analyzed in the current work. Additionally, because it has strong adhesion, it can be directly attached to the cooling area without needing other elements such as screws, nuts or glues.

If the transparency of the material is not a design requirement, an opaque or translucid silicon-based organic elastomeric polymer can be used, or nanoparticles can be added to the PDMS to improve the thermal properties, specifically the thermal conductivity of the composite [11–14].

Thus, innovatively, the serpentine heat exchanger made of PDMS allows the liquid to circulate in contact with the surface to be cooled since the liquid flows between the leaked PDMS channel and the heated surface.

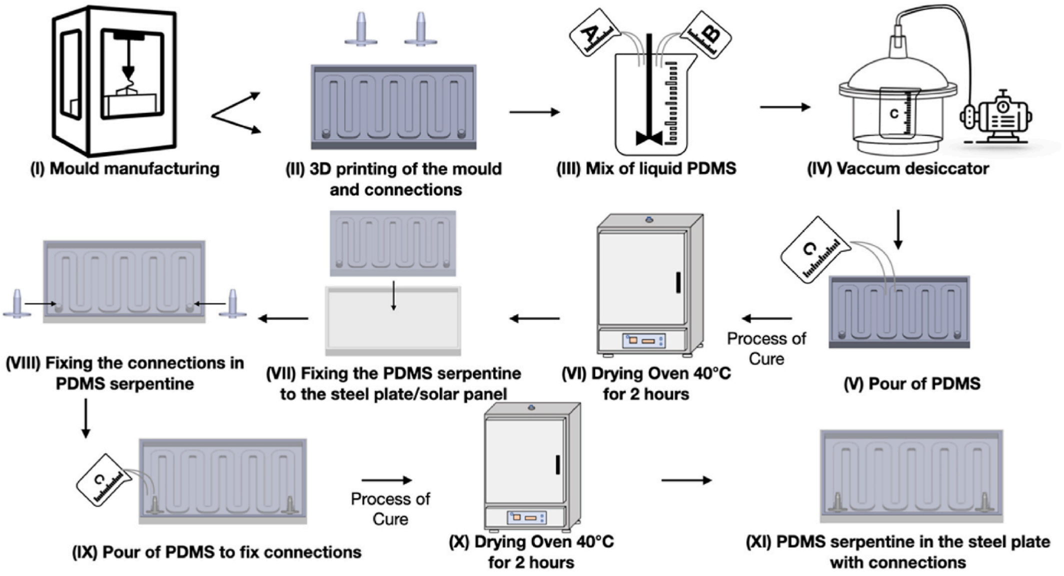


**Fig. 1.** Schematic representation of the method for obtaining the PDMS serpentine heat exchanger.

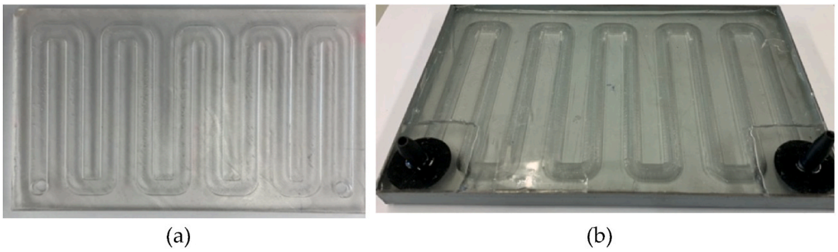


**Fig. 2.** Photos from the PDMS serpentine. (a) PDMS serpentine. (b) PDMS serpentine with connectors coupled at the steel plate.

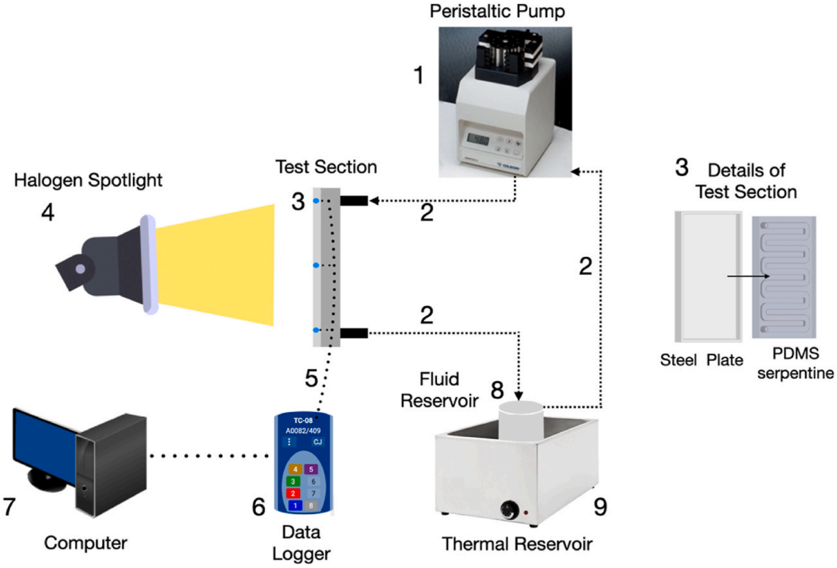


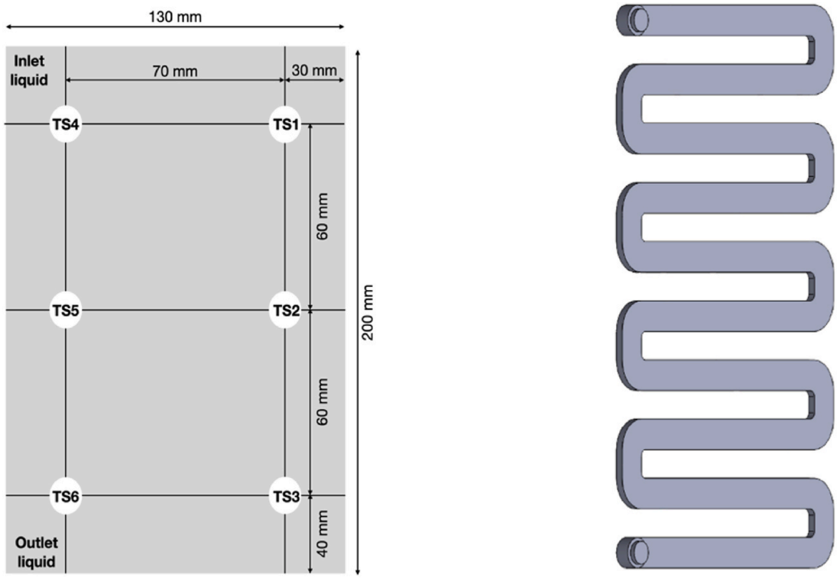
**Fig. 3.** Schematic diagram of the experimental apparatus.

## 2. Materials and methods

### 2.1. *Method for obtaining the PDMS serpentine*

Fig. 1 shows a schematic representation of the method for obtaining the PDMS serpentine heat exchanger. Fig. 1 (I) shows the mold manufacturing process using 3D printing. Fig. 1 (II) presents the printed mold and connections using polylactic acid (PLA) used in the current study. However, other techniques for the mold fabrication can be used, such as metal molding (casting, injection or others), polymethylmethacrylate (PMMA) laser cutting, acrylonitrile butadiene styrene (ABS), or other suitable materials. Fig. 1 (III) shows the PDMS resin preparation. The solution consists of a mixture of elastomer prepolymer, component A, and a commercial curing agent, component B, in which PDMS Sylgard® 184 was used in a proportion of 10:1, in that order, forming component C. The two components must be mixed for 10 min by agitation, which can be manual or mechanical. In the current work, the process was done manually with the help of a clean spatula. The mixture must be degassed in a vacuum desiccator for 10–20 min until no bubbles are visually observed, as represented in Fig. 1 (IV). Then, the silicon-based organic elastomeric polymer solution (component C) is poured over the mold, as shown in Fig. 1 (V), only by gravity. Fig. 1 (VI) shows the process for curing the PDMS using an oven for 2 h at 40 °C. Another possibility is curing at room temperature for 48 h or other suitable temperature/time combinations. The use of an oven at 40 °C is due to the thermal resistance of the polylactic acid mold used. Other materials, such as an aluminum machined mold, can allow oven-curing at higher temperatures, decreasing the silicon-based organic polymer curing time.

Fig. 1 (VII) shows the fixing process of the serpentine heat exchanger to a steel plate (electroplated), which simulates the rear side of a PVT panel. The steel plate consists of a rectangular plate with 200 × 130 × 2 mm. In addition, it contains a flap on the sides of 10 mm in height. After the curing process, the polylactic acid mold was removed with a spatula. In order to fix the serpentine to the steel plate, a thin film of the PDMS itself was used in a proportion of 10:1. Fig. 1 (VIII) shows the junction of two connections, also made of polylactic acid, positioned at the inlet and outlet of the serpentine, serving as fittings for the hoses that pass the liquid flow. The fittings are just suggestions for coupling the serpentine to the flow hoses or pipes, and other configurations can be considered. In order to fix the connections on the serpentine, the PDMS resin is also poured into the set, as shown in Fig. 1 (IX). The same procedure shown in step III was used for this step, as seen in Fig. 1 (III). For the curing process of the system, the oven is used at 40 °C for 2 h, as shown in Fig. 1 (X). Fig. 1 (XI) finally shows the serpentine fixed to the plate with the two connections.



(a) (b)

**Fig. 4.** (a) Location of the six thermocouples on the rear side of the steel plate; (b) Serpentine scheme showing the inlet and outlet of the liquid.

**Table 1**
Experimental uncertainties in the current study.

| Variable | Uncertainty range |
|---|---|
| Parameters of serpentines, $L$, $h$, $w$, $D_h$ | ±0.01 mm |
| Temperature, $T$ | ±0.27 °C |
| Flow rate, $\dot{m}$ | ±0.035 ml/min |
| Irradiance | ±9.61 W/m$^2$ |

Fig. 2 shows photos from the PDMS serpentine (Fig. 2a) and the PLA connectors (Fig. 2 b) coupled to the steel plate (which simulates the PVT panel's rear side).

### 2.2. *Experimental setup for evaluating the heat exchange performance*

Experimental tests were carried out under forced flow in the experimental setup shown in Fig. 3. The system is comprised of a peristaltic pump (1) and pipes to pump the fluid in a single-phase regime (2); the test section, formed by joining the steel plate and the PDMS serpentine (3); an artificial light source, which simulates the solar irradiation (4); thermocouples (5); a data acquisition system (6); a computer (7) and containers for storing and controlling the inlet fluid temperature (8 and 9).

Before starting the experimental tests, the steel plate with the PDMS heat exchanger was placed perpendicular to the artificial light source of 150 W *Dedolight DLHM4-300*. The heat source was fixed at 250 mm from the steel plate. On the rear side of the steel plate, six Type-T thermocouples were used to measure the wall temperature as a function of the time and fluid flow. The position of the six Type-T thermocouples on the rear side of the steel plate is shown in Fig. 4.

A thermocouple located at the inlet of the serpentine measured the inlet fluid temperature, and another one (located on the opposite side) measured the outlet fluid temperature. All temperature measurements were acquired by a data acquisition system (*TC-08 Thermocouple Data Logger, Pico®Technology*). After that, the serpentine channel was filled with the working fluid through the peristaltic pump *New Era NE-9000*, pumped from the reservoir (*Vesta Perfecta Water Bath*) at a controlled temperature. The working fluid used was DI-Water for all tests performed in the current work. Then, the artificial light source was turned on. When the average temperature based on the six thermocouples at the steel plate's rear side reached 40 °C, the peristaltic pump was activated, and the drains began. Flow rates between 25 and 250 ml/min were used. When the system reached the steady-state regime, the tests were finished. Table 1 shows the uncertainty values in the current study. In order to obtain the experimental uncertainties of thermocouples, the method described by Ref. [15] was used. For the peristaltic pump and power source, it was considered the uncertainties provided by the manufacturers. The uncertainty of the measuring instrument was used to measure the serpentines' length, width, diameter and height. The irradiance was measured at a distance of 250 mm from the artificial light source using an *SPN1-A765* pyranometer.

**Table 2**
The main characteristics of the serpentines.

| Shape | PDMS Serpentine | | Copper Serpentine |
|---|---|---|---|
| | rectangular (narrow, Fig. 5a) | rectangular (wide, Fig. 5b) | Circular (Fig. 5c) |
| Channel length, L, (mm) | 1027.65 | 1027.65 | 960.5 |
| Internal width, w, (mm) | 10.0 | 15.0 | – |
| Internal height, h, (mm) | 3.0 | 2.75 | – |
| Hydraulic diameter, $D_h$, (mm) | 4.62 | 4.65 | 5.0 |

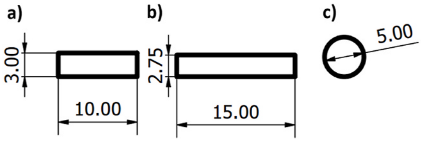


**Fig. 5.** Cross section of PDMS Serpentines. a) narrow; b) wide; and c) circular (copper serpentine). *all dimensions in mm.

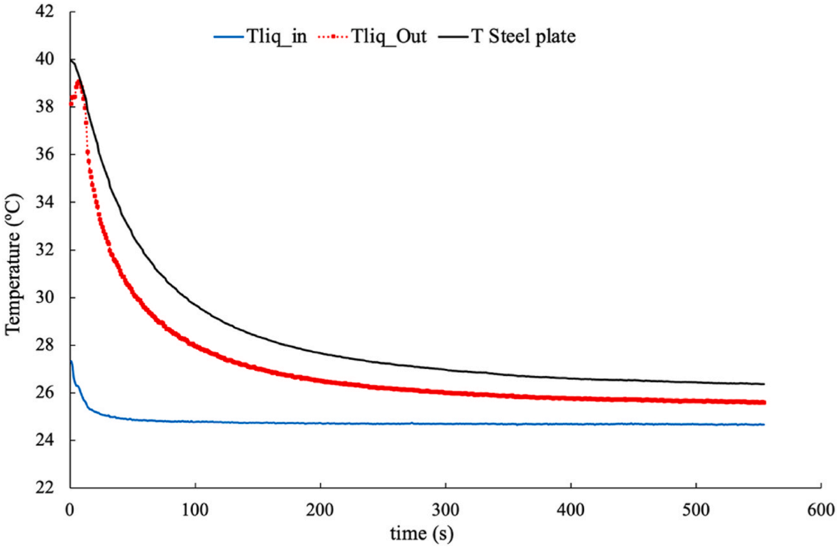


**Fig. 6.** Surface temperature behavior for a PDMS serpentine with a narrow rectangular channel and a 150 ml/min flow rate.

## 3. Results and discussion

Two PDMS serpentines with different rectangular flow channels were considered for the analysis. A copper serpentine with a circular section was used for comparison due to the challenge of obtaining a traditional heat exchanger with a rectangular geometry that prioritizes the contact area with the surface to be cooled and with the closest possible hydraulic diameter. Table 2 and Fig. 5 present the main characteristics of the heat exchangers used in the current study.

Fig. 6 shows the temperature data for a narrow rectangular channel with a 150 ml/min flow rate. It is worth mentioning that the 'T Steel plate' corresponds to the average temperature of the six thermocouples inserted on the rear side of the steel plate; 'T liq_In' is the inlet fluid temperature, and 'T liq_Out' is the outlet fluid temperature.

During the test, the inlet fluid temperature was maintained at around 24.5 °C, and the ambient temperature was 25.5 °C. One may observe that the steady-state regime is established after 400s of the liquid flowing, with both working fluid and steel plate temperatures stabilizing. At the end of the test, the outlet temperature of DI-water was 25.6 °C and the steel plate around 27 °C, demonstrating the effectiveness of the proposed PDMS serpentine.

The steel plate's temperature decreases during the DI water flow for all experimental tests, as shown in Fig. 7. One may observe the effect of the PDMS serpentine geometry configuration on the steel plate cooling. The columns in Fig. 7 represent the two cross-section serpentines analyzed in the current work, one wide (orange color) and the other narrow (blue color). The wide serpentine has a width of 15.0 mm and 2.75 mm in height, while the narrow serpentine has a width of 10.0 mm and 3.0 mm in height. A wider geometry provides a high contact area between the working fluid and the heated surface, increasing the heat transfer and significantly reducing the surface temperature.

With a hydraulic diameter of 5 mm (close to the hydraulic diameter of the PDMS serpentine), one traditional copper serpentine

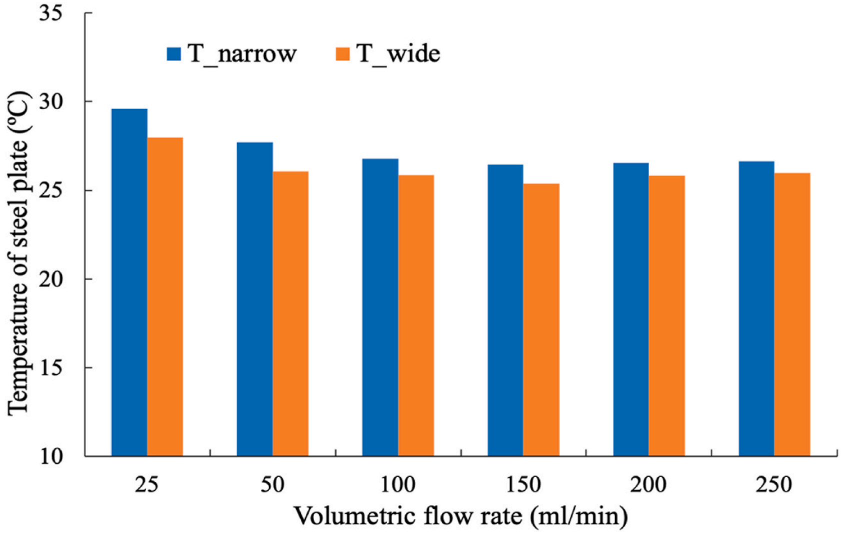


**Fig. 7.** PDMS serpentine geometry effect on the steel plate cooling as a function of DI water volumetric flow rate.

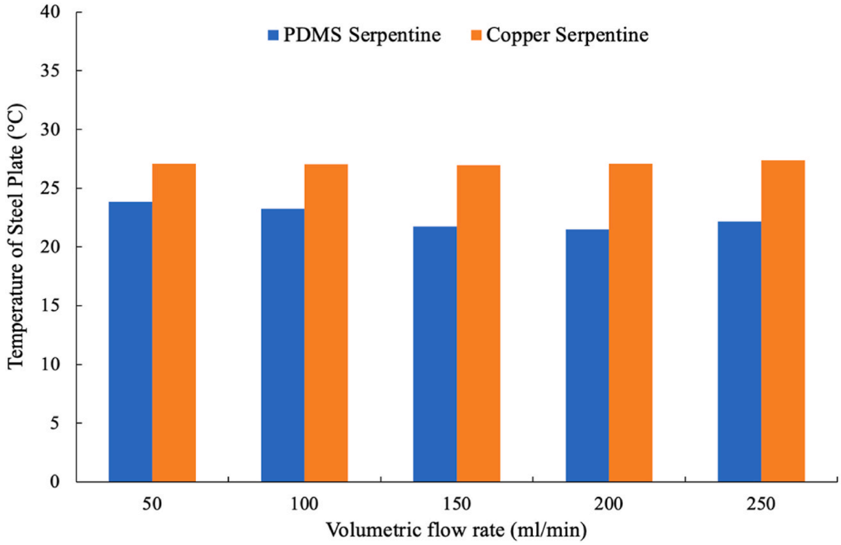


**Fig. 8.** Cooling capacity comparison between a copper circular serpentine and the PDMS rectangular serpentine.

with a circular cross-section was tested for comparison. The same procedure described in section 2.2 was assumed for these tests.

As observed in Fig. 8, regardless of the flow rate, the surface temperature using the traditional copper serpentine was always higher than that of the PDMS serpentine proposed in the current work (an average of 17% higher).

Therefore, the PDMS serpentine presents superior performance for all flow rates, and the performance difference between the two serpentines increases as the flow rate increases. The traditional serpentine has a low contact area between the cooling fluid and the rear surface panel, which can explain why the flow rate does not affect the surface temperature. Previous works have demonstrated various methods of maintaining the serpentine in contact with the panel to be cooled, such as the welding process [16], hinges [17], or conductive bonding [18], showing not only the difficulty in terms of contact area but also in maintaining the assembly. Although the copper thermal conductivity (398 W/m·K) is exceptionally high compared to the pure cured PDMS at room temperature (0.2 W/m·K), the cylindrical tubular geometry of the copper serpentine provides a small liquid-surface contact area leading to low thermal performance. On the other hand, the proposed PDMS heat exchanger significantly increases the heat exchange area due to the direct contact of the working fluid with the heated surface, consequently improving the thermal performance.

The promising results can be further enhanced in order to maximize heat transfer, particularly in addressing high heat density issues commonly observed in modern chips and microprocessors. In this regard, utilizing nanofluids and hybrid nanofluids can be highly advantageous. These advanced fluid systems have already exhibited exceptional performance in various heat exchanger applications, notably in the context of heat pipes [16,19,20].

Therefore, to improve the thermal performance of traditional serpentines (made of copper, similar to the one analyzed in the current work), the number of channels may be increased, which requires more material to manufacture, consequently increasing the overall costs. In contrast, the PDMS serpentine requires a low material amount to be manufactured, another advantage of the proposed serpentine.

## 4. Conclusions

Serpentines are indispensable for the thermal management of a series of devices, controlling the temperature of materials. However, as analyzed in this work, traditional serpentines offer challenges concerning their complete contact with the surface to be cooled. For this reason, in the current work, an elastomer was used to produce an innovative serpentine that allows the working fluid to flow through the heat exchanger in direct contact with the heated surface. In order to evaluate the heat transfer performance, an experimental setup was designed in which a heated steel plate simulated a photovoltaic solar panel (an artificial light source was used to simulate solar irradiation).

The traditional serpentine was compared with the proposed PDMS serpentine, and the results showed a significant improvement in the heat transfer performance with the proposed one. The proposed PDMS serpentine performs better than the traditional one (17% on average) and allows the manufacturing of serpentines with different geometries and sizes, expanding its potential applications. Additionally, the fluid flow phenomena can be visualized due to the material transparency.

For future work, the serpentine can be manufactured with different geometries and sizes; also, different PDMS composites can be used to enhance the serpentine's thermal properties. In addition, other thermofluids and new manufacturing methods can be explored to improve the overall system performance.

## Credit author statement

R.R. Souza, F. M. Sá Barbosa, R. Lima: Conceptualization, Methodology. R.R. Souza, F. M. Sá Barbosa, G. Nobrega: Validation, Data curation. R.R. Souza, R. Lima, E. M. Cardoso: Writing-Original draft preparation. R.R. Souza, F. M. Sá Barbosa, G. Nobrega, E. M. Cardoso, J. C. F. Teixeira, A. S. Moita, R. Lima: Writing - Review & Editing. A. S. Moita, R. Lima: Supervision. A. S. Moita, R. Lima, J. C. F. Teixeira, E. M. Cardoso: Resources, Funding acquisition.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Reinaldo Rodrigues de Souza has patent ELASTOMER COMPOSITE SERPENTINE FOR A HEAT EXCHANGER, METHOD FOR OBTAINING AND USES THEREOF pending to N/Ref.: P1245.3 PP and N.° do Pedido: 118128.

## Data availability

No data was used for the research described in the article.

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