

Evaluation of the thermal performance of PDMS composite serpentine combined with a synthesized green nanofluid

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ABSTRACT

As electronic components advance, managing areas of high heat density creates significant thermal management challenges. Polydimethylsiloxane (PDMS) has emerged as an attractive material for cooling systems due to its adaptability, low cost and ease of molding into complex channel geometries. However, its intrinsically low thermal conductivity remains a primary limitation. Concurrently, nanofluids (NFs) have shown promise in multiplying a fluid's heat transfer capacity, yet their commercial application is frequently hindered by high production costs and stability issues such as particle agglomeration. This study investigates a novel, sustainable approach to surface cooling by evaluating composite PDMS heat exchangers paired with a highly stable, green-synthesized nanofluid. A water-based iron oxide NF (0.05 wt%) was successfully synthesized utilizing an aqueous extract of the alga *Chlorella vulgaris* as a biological reducing agent. To overcome the thermal insulating properties of the base polymer, composite serpentine featuring 5 mm square channels were fabricated by integrating 30 wt% recycled graphite microparticles (PDMS@Graphite) and 30 wt% commercial aluminum nanoparticles (PDMS@Al) into the pure PDMS matrix. The thermal performance of these millimeter-scale cooling systems was experimentally evaluated against pure PDMS serpentine using both the green NF and distilled water. The fluids were pumped at flow rates of 5, 10, and 15 ml/min over a 65 mm by 65 mm stainless-steel sheet heated by a 6W direct-current power supply, with the real-time surface heat distribution continuously monitored via an infrared thermal camera. Experimental data revealed that increasing the fluid flow rate systematically reduced both the average and maximum surface temperatures across all configurations due to enhanced convective heat transfer. Among the heat exchanger materials tested, the PDMS@Graphite composite exhibited the highest overall thermal efficiency. When operating with pure water at 15

ml/min, this composite achieved an average surface temperature reduction of up to 12% and maintained maximum temperatures at least 7.5 °C below those recorded for pure PDMS, providing the most homogeneous heat distribution. The green iron oxide NF successfully minimized temperature gradients and promoted exceptional thermal uniformity, particularly within the pure PDMS serpentine. However, within the highly conductive composite serpentines, the NF did not have better cooling performance when compared to pure water, likely due to the inherently lower specific heat of the iron oxide nanoparticles. Ultimately, integrating recycled graphite into PDMS presents an effective, scalable solution for advanced thermal management.

1. Introduction

The cooling of surfaces has been one of the major challenges of our time, especially with the advancement of microchips which, although they have a reasonably low global power, their small dimensions end up creating areas of high heat density where heat removal becomes a challenge. In this sense, new technologies regarding both equipment and fluids have been developed to improve heat removal in order to increase the efficiency and useful life of this equipment (Li et al., 2024).

Nanofluids (NFs) are one of the significant scientific prospects of recent years since they allow for the improvement of thermal properties, especially thermal conductivity, without resulting in the deterioration of other properties such as thermal viscosity. Although their application has already been explored in several studies, commercial-level application is not yet a reality due to various factors such as cost, difficulty in predicting properties, and especially low stability, as they tend to agglomerate and sediment. One of the alternatives that has been gaining prominence is the green synthesis of metallic NFs, which has already been studied on a large scale in applications specifically aimed at biomedicine, but which has seen few applied studies regarding thermal fluid (Cardoso et al., 2025).

PDMS is an elastomer known for being transparent, versatile, and of easy fabrication. Although it is a material of low thermal conductivity, due to its ease of molding which permits the fabrication of the most diverse geometries, the ease of creating channels that have a larger contact area with the surface to be heated has drawn attention in recent works. In search of improving its thermal properties, one of the most known and utilized practices is the application of micro and nanoparticles that create composites which multiply the material's capacity to conduct heat severalfold (Cardoso et al., 2026; Shishkin, 2023).

In this work, the water-based NF with iron oxide synthesized through green synthesis with the alga *Chlorella vulgaris* is used at a concentration of 0.05%, produced according to the protocol of (Nobrega et al., 2024). Distilled water and the nanofluid are tested in coils of three different

materials: pure PDMS, PDMS with recyclable graphite particles (30%), and PDMS with commercial aluminium particles (30%).

2. Methodology

2.1 Nanofluids

2.1.1 Preparation of the *Chlorella vulgaris* Aqueous Extract

To prepare the biological reducing agent, 7.5 g of *Chlorella vulgaris* algal powder was added to 100 mL of distilled water. The resulting aqueous mixture was heated to 55 °C and maintained under continuous magnetic stirring for a duration of 24 hours. Following the stirring period, the solution was centrifuged at 6000 rpm for 20 minutes. The supernatant yielded from the centrifugation process was carefully filtered through Whatman No.1 filter paper. The final filtered aqueous extract was stored at 4 °C for subsequent use in the synthesis procedures.

2.1.2 Green Synthesis and Isolation of Iron Oxide Nanoparticles

The biosynthesis of the metallic nanoparticles was initiated by introducing 4 mL of the previously prepared *Chlorella vulgaris* aqueous extract into a 100 mL solution of 0.2 M iron chloride. This reaction mixture was incubated at 60 °C and allowed to react for 20 minutes, facilitating the primary reduction of the iron chloride via the natural reducing agents present within the algal extract. Subsequently, the pH of the mixture was adjusted to a range of 10 to 11 using a sodium hydroxide (NaOH) solution. The successful formation of iron oxide nanoparticles was empirically monitored through a visual colorimetric shift; within 30 minutes, the solution transitioned to a dark brown color, indicating active nanoparticle production. To isolate the newly synthesized nanoparticles, the dark brown solution was centrifuged at 6000 rpm for 20 minutes at room temperature. The supernatant was entirely discarded, and the precipitated nanoparticle pellet was resuspended in distilled water. To ensure the complete removal of unreacted precursors and secondary reaction by-products, this washing and resuspension procedure was repeated twice, thereby thoroughly cleansing the nanoparticle surfaces.

2.1.3 Nanofluid Formulation and Concentration Standardization

To formulate a highly stable colloidal suspension, the purified nanoparticles suspended in distilled water were subjected to ultrasonication for 20 minutes to enhance dispersion and mitigate

agglomeration. To precisely quantify the weight concentration of the resulting nanofluid, a 5 g sample was extracted and placed into a glass beaker of a predetermined mass. This beaker was then transferred to an oven and dried at 60 °C. Once completely desiccated, the beaker was re-weighed using a high-precision analytical scale to calculate the exact mass of the solid nanoparticles. Utilizing this baseline weight concentration, the appropriate volume of distilled water was calculated and added to the bulk nanofluid to achieve the exact target weight concentrations of 0.05 wt% required for experimental testing.

2.2 Serpentine fabrication

The fabrication of the heat exchangers, or serpentines, began with the design and 3D printing of polylactic acid (PLA) moulds. These moulds contained an exact inverted replica of the intended test section. For the serpentines made of pure polydimethylsiloxane (PDMS), the base elastomer and its corresponding curing agent were mixed in a 10:1 ratio. This mixture was stirred for approximately five minutes to ensure uniformity. The solution was then placed in a vacuum degasser to eliminate any entrapped air bubbles. Subsequently, the degassed mixture was poured into the PLA moulds, ensuring uniform filling, and was cured in an oven at 40°C. After the curing cycle, the solid serpentines were manually extracted from the moulds using a spatula and mechanical pressure. To enhance the thermal performance of the base polymer, two distinct types of particulate fillers were utilized to create the composite heat exchangers: commercial aluminium nanoparticles and recycled graphite particles. The commercial aluminium nanoparticles featured an average size of 38 nm and a high purity degree of 99.995%. Conversely, the recycled graphite was sourced from industrial machining process waste. A 30 mass% concentration was standardized for both the aluminium and graphite composites. The protocol for manufacturing these composite serpentines followed a similar process to the pure PDMS, with necessary modifications to properly integrate the dispersed phase. Initially, the desired 30 mass% of either aluminium nanoparticles or graphite microparticles was added directly to the pure PDMS base matrix and manually stirred for five minutes to achieve uniform dispersion. Following this step, the curing agent was added to the particle-infused PDMS mixture. The resulting composite blend was vacuum degassed to remove air bubbles, poured into the PLA moulds, and placed in an oven for 48 hours. Once fully cured, the composite serpentines were demoulded and finished utilizing the identical procedures applied to the pure PDMS heat exchangers.

3.3 Experimental Set-up

To conduct the experiments, the setup presented in Figure. 1 comprised PDMS serpentine with 5mm square channels, an AISI304 stainless steel sheet of 65mm x 65mm x 20 μ m, having as a heat source an Axio Met® AX-3020L 20VDC 20A DC power supply, clamped by acrylic plates with a 10mm centred hole in the lower part which was the target of the Onca MWIR-InSb-320 thermal camera and a syringe pump NE-4000 Two Channel Syringe Pump Multi-Phaser™, being similar to that used by (Nobrega et al., 2024). All tests were performed with a heating power of 6W and flow rates of 5, 10, and 15 ml/min. Before the experiment, the syringe pump was calibrated to ensure the flow rates were correct. A hole of 12 mm in diameter was made in the acrylic at the centre of the serpentine in order to observe the temperature map of the fluid and of the material of the coil, leaving the stainless sheet visible to the camera. The region recorded by the camera was painted with a black paint with an emissivity of 0.95.

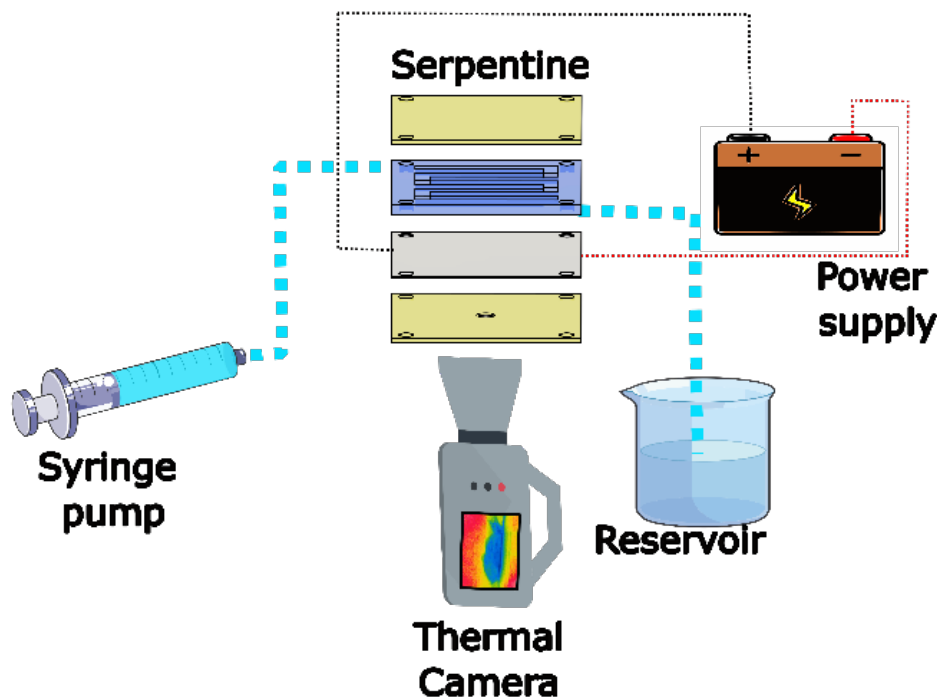


Figure. 1 Setup of the experimental system where the fluid pumped by the syringe pump passes through the serpentine which cools the surface heated by the energy source while the images are captured by the thermal camera.

3. Results and Discussion

The first clear influence that is observed in the results in Table. 1 is that of the flow rate which, as expected, decreased the surface temperatures as the flow rate increases. Regarding the material of

the coils, the PDMS composites had a fundamental action in the decrease of thermal conductivity in all flow rates, with an average temperature decrease of up to 12% with water at 15 ml/min for the PDMS@Graphite composite which obtained the best results. Regarding the maximum temperatures, with water, the difference from pure PDMS to the graphite composite was always above 7.5 °C. The results of the serpentine of the graphite composite are the most uniform, i.e., with lower variation between the maximum and minimum temperatures, followed by the Al composite. The NF also contributed to the temperature stability in all tests but was not able to lower the maximum and average temperatures in the composite coils, although in pure PDMS, the NF had great influence, contributing to the decrease of the maximum and average temperatures, in addition to rendering the system with more homogeneous temperatures.

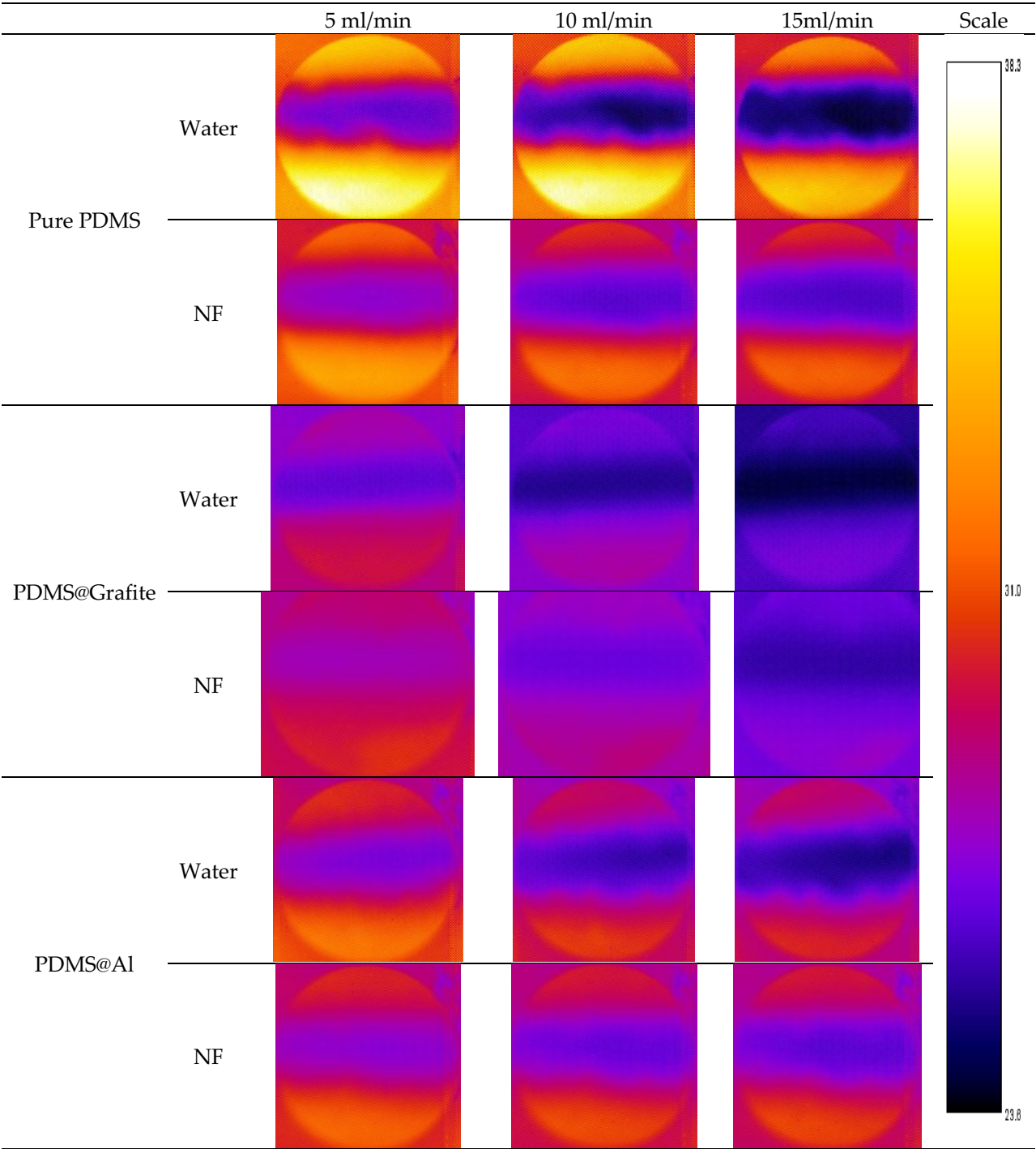
Table. 1 Results of the temperatures measured by the thermal camera with the different fluids and with the different materials of the serpentines

Material	Fluid	5ml/min			10ml/min			15ml/min		
		Ave	Max	Min	Ave	Max	Min	Ave	Max	Min
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
Pure PDMS	Water	31.95	38.34	26.01	29.91	36.14	23.94	29.19	35.42	23.47
	NF	30.16	33.93	26.86	28.94	32.37	25.37	28.59	31.91	25.55
PDMS@graphite	Water	28.11	30.37	25.91	26.53	28.50	24.56	25.55	27.47	23.64
	NF	28.88	30.76	27.38	27.23	28.81	25.95	26.40	27.89	25.15
PDMS@Al	Water	29.12	32.50	26.20	27.89	31.07	24.97	27.41	30.50	24.35
	NF	29.20	32.09	26.80	28.69	31.41	26.17	28.42	31.13	25.82

The images reported in Table 2 demonstrate, in relation to the material of the serpentine channels, that the configuration with the PDMS@graphite serpentine presented the overall results of lower temperature as well as the most homogeneous heat distribution, whilst the pure PDMS serpentine demonstrated the greatest contrasts, with the pure PDMS region presenting the highest identified temperatures whilst the region through which the heat passes presented the lowest temperatures, demonstrating a clear limitation in heat transfer along the observed section for this material. Another important factor to be observed is that, invariably, as the flow rate was increased, the mean temperature and also the fluid temperature decreased. Such a phenomenon is due in part to the increase in the relative velocity of the fluid in relation to the serpentine, which ultimately increases the convection effect, as well as to the actual renewal of the fluid inside the serpentine, since the fluid inlet temperature is lower than the mean temperature of the system. When the table

is analysed in relation to the fluid type, it is observed that the fluid channel has minimum temperatures always lower for water than for the NF, whilst in the tests with NF the temperature gradient is always lower and there are less significant variations between the flow rates of 10 and 15 ml/min when compared to what occurred with water. The lower temperature gradient of the NFs occurs due to the improvement in thermal conductivity, which allows a greater passage of heat and, consequently, a homogenisation of the temperature profile. In relation to the higher mean temperatures observed, this is possibly due to the fact that nanofluids with iron oxide particles usually have a lower specific heat (Sekhar & Sharma, 2015), which results in a temperature increase with a lower quantity of heat, which in turn is absorbed more rapidly due to the better conductivity. Although the thermal conductivity has increased, the nanofluid does not significantly increase the maximum measured temperatures and, especially in the case of poor conductors such as water, a significant decrease in the maximum observed temperature is observed.

Table. 2 Thermal imaging comparison of Pure-PDMS, PDMS@Grafite, and PDMS@Al using Water and NF at flow rates of 5, 10, and 15 ml/min



4. Conclusions

The experimental evaluation of pure and composite PDMS serpentine operating with pure water and a green-synthesized iron oxide nanofluid yielded the following primary conclusions:

- **Impact of Flow Rate:** Increasing the fluid flow rate systematically decreased both the average and maximum surface temperatures across all tests. This improvement is attributed to the increased relative velocity of the fluid, which enhances convective heat transfer, and the faster renewal of the cooler fluid entering the serpentine.
- **Performance of Composite Materials:** The addition of particulate fillers to the PDMS matrix significantly improved thermal conductivity and heat dissipation while the PDMS@graphite composite proved to be the most efficient material tested. When operating with water at 15 ml/min, it achieved an average temperature reduction of up to 12% and maintained maximum temperatures at least 7.5 °C below those of pure PDMS. It also displayed the most uniform heat distribution with the lowest variation between maximum and minimum temperatures.
- **Limitations of Pure PDMS:** The pure PDMS serpentine exhibited the highest thermal contrasts and the most significant heat transfer limitations, showing high temperatures in the solid region and low temperatures in the fluid channel.
- **Efficacy of the NF:** The 0.05% iron oxide nanofluid successfully reduced temperature gradients and promoted greater thermal stability and uniformity in all tests. This homogenizing effect is caused by the enhanced thermal conductivity of the fluid, which allows for better heat passage.
- **Fluid-Material Interactions:** While the NF significantly lowered maximum and average temperatures when used in the pure PDMS serpentine, it was not effective at reducing these temperatures in the composite serpentine compared to pure water. Water consistently produced lower minimum temperatures than the NF across the tests.
- **Specific Heat Considerations:** The higher average temperatures occasionally observed with the NF are likely due to the lower specific heat of the iron oxide NPs. This property implies that the fluid's temperature increases with a smaller amount of absorbed heat, even though that heat is absorbed more rapidly due to higher conductivity.

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