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Numerical Investigation of Double-Layered Sinusoidal Microchannel Heat Sinks: The Role of Porous Fins in Thermal Enhancement

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Abstract

Efficient thermal management is essential in microelectronics to prevent overheating and maintain performance. This study investigates a double-layered sinusoidal microchannel heat sink with porous fins (PMHS), using water as the coolant, to enhance microscale heat transfer. Through computational fluid dynamics (CFD) simulations, the effects of porosity (ε = 0.66) and inlet velocity (0.2469–0.9665 m/s) on thermal and fluid dynamics are analyzed. The microchannel has specific dimensions and is subjected to a heat flux of 100 W/cm². Steady-state, incompressible, and laminar flow conditions are assumed, and porous fins are modeled with the Darcy-Forchheimer-Brinkman equation, accounting for permeability and drag effects. Results show a 1.5-fold increase in the heat transfer coefficient in porous zones compared to non-porous designs. Additionally, pressure drops are reduced with increasing porosity and maintain linear behavior with varying inlet velocities. The thermal resistance is also lowered, indicating improved heat dissipation. Velocity and temperature contours demonstrate enhanced fluid-solid interactions in porous fins. A mesh independence test confirms 4 million elements provide accurate results efficiently. Simulation results match experimental data with a maximum error of 4.79%, validating the methodology. Overall, the PMHS design

significantly improves heat transfer while minimizing pressure loss and thermal resistance, outperforming traditional solid fin structures. This highlights the potential of porous media in optimizing thermal management in compact, high-performance systems. Future studies should examine different porosities and working fluids to further refine and expand the applicability of this innovative cooling approach.

Keywords
Double-Layered Microchannel Heat Sinks, Porous Fins, Heat Transfer Enhancement, Fluid Flow Analysis, Pressure Drop.

1. Introduction

Double-layered heat sinks with porous fins are gaining traction for managing heat in high-density electronics, where traditional forced air convection often fails. Heat sinks (MCHS), with numerous parallel microchannels, effectively dissipate heat from electronic components by circulating coolant such as water, ethylene glycol, or engine oil. Despite their effectiveness, these coolants have low thermal conductivity, necessitating improvements in their thermal properties to enhance heat transfer. Proposed by Tuckerman and Pease in 1981, this advanced cooling technique reduces coolant usage, minimizes size, and lowers costs, making MCHS a preferred choice for efficient thermal management in modern applications (Choi, 1995), (Tuckerman 1981) (Figure 1).

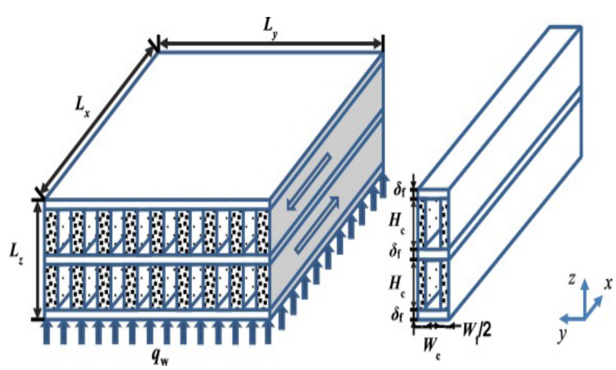


Figure 1. Microchannel heat sink (Tuckerman et al., 1981).

Heat sinks (MCHS) have been extensively studied for their potential to enhance thermal management in electronic devices. Qu and Mudawar investigated three-dimensional fluid flow and heat transfer in rectangular MCHS using water as the coolant. Their study found that the heat flux and Nusselt number varied around the channel's perimeter, with values decreasing to zero at the corners and increasing near the intake. They noted that the length of the developing area is influenced by the Reynolds number, with well-established flow becoming less significant at high Reynolds numbers (Re = 1400). To reduce the temperature at the heat sink's base near the channel exit, enhancing the thermal conductivity of the substrate is essential (Qu, 2002).

Kawano et al. (1995) analyzed a heat exchanger using water as a coolant in channels with cross-sections of 8 mm and 10 mm. Their experimental and numerical studies revealed minimal heat loss in silicon chips and found that the measured pressure loss closely matched analytical predictions for fully developed flow (Kawano, 1995).

Similarly, Wong and Ghazali (2007) conducted numerical simulations to investigate conjugate fluid flow in heat sinks (MCHS) for cooling microelectronics. The study utilized a channel with a hydraulic diameter of 86 mm, revealing notable temperature fluctuations in the solid region close to the heat source. The research determined that silicon outperforms copper and aluminum as a material for MCHS, thanks to its better heat transfer capabilities (Wong, 2007).

Vafai and Zhu (1999) proposed a two-stacked heat sink system to enhance cooling uniformity. In this configuration, the coolant moves in opposite directions through the top and bottom layers, which helps minimize the temperature gradient along the flow path, offering an advantage over single-layered MCHS designs. Yin and Bau (2002) hypothetically analyzed a heat sink made from silicon wafers using liquid nitrogen as the working fluid. They found that an optimal channel size minimizes heat resistance (Yin, 2002).

Enhancing the thermal performance of MCHS can also involve utilizing wavy channels, incorporating porous materials, or adding micro ribs (Patel, 2012). Missaggia and Walpole (2007) introduced a single-layer counter-flow heat sink design, featuring alternating water flow directions in adjacent channels to improve cooling performance. Vafai and Lu (1999) further expanded this concept by developing a double-layer counter-flow heat sink, achieving reduced thermal resistance and pressure drops compared to traditional designs.

This study aims to examine the impact of various morphological parameters of porous fins, such as permeability, inertial coefficients, and fin thickness, on the hydraulic and thermal performance of a heat sink. Through numerical simulations, the research investigates fluid flow and heat transfer behavior within the channel, with a particular emphasis on the effects of sinusoidal shapes and the incorporation of porous fins. Key objectives include determining the convective heat transfer coefficient across the heat sink, analyzing velocity profiles and contours at different Reynolds numbers, evaluating the temperature distribution and heat transfer performance of the double-layered sinusoidal heat sink, and assessing its overall cooling efficiency.

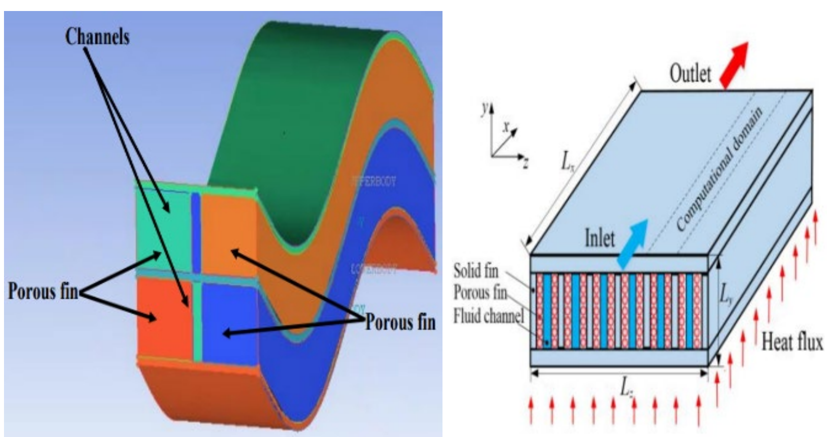
1.1 Objectives

- To investigate velocity profiles and contours with varying Reynold's number.
- To determine the temperature distribution and the heat transfer co-efficient of the double layered sinusoidal microchannel heat sink.
- To analyze the cooling performances of the double layered sinusoidal micro channel heat sink.

2. Methodology

The In this study, a Sinusoidal double layer heat sink with a sinusoidal porous fin is used. The experimental data from "Thermal Performance of Microchannel Heat Sink with Metallic Porous/Solid Compound Fin Design" by L. Gong et al (2018) were used for validation where a three-dimensional rectangular model of the heat sink with metallic porous/solid compound fin is used (Gong, 2018).

2.1 Geometry of Model



(a) (b)

Figure 2. (a) Sinusoidal double layer heat sink with sinusoidal porous fins, and (b) Overall view of porous/solid compound fin heat sink (Gong et al., 2018).

The geometrical dimensions of the double-layer sinusoidal heat sink with fin and rectangular porous/solid compound fin heat sink are listed in Figure 2. (Gong,2018)

2.2 Mesh Technique and Grid Independence

The study employed refined mesh and specific solver settings to ensure accurate numerical analysis of the heat sink. As shown in Figure 3, a finer mesh was applied to the thin channels for enhanced computational smoothness, while the mesh at the outlet and inlet regions was also detailed. The mesh consisted of 5,079,352 nodes and 5,167,900 quadrilateral elements, with a skewness of 0.1, an orthogonal quality of 1, and an aspect ratio of 13.60, indicating a high-quality mesh capable of capturing intricate fluid dynamics (Table 1).

Table 1. Geometrical dimensions

Parameter	Present Work	Reference work (Gong et al., 2018)
Length, Lx	20 mm	20 mm
Height, Ly	5.75 mm	3 mm
Width, Lz	6.167 mm	20 mm
Width of Channel	0.5 mm	0.5 mm
Height of Channel	2.5 mm	2.5 mm
Substrate Thickness, δ1	0.25 mm	0.25 mm
Substrate Thickness, δ2	0.25 mm	0.25 mm
Heat flux, qw	100 Wcm-2	100 Wcm-2
Porosity, ε	0.66	0.66

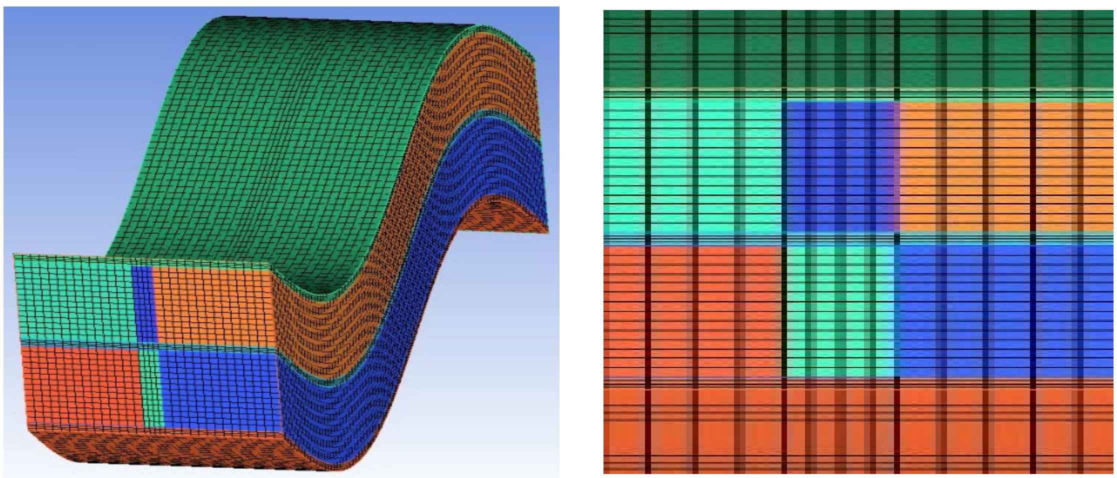


Figure 3. Mesh generation arrangement of Double-Layered Sinusoidal Microchannel Heatsinks with Porous Fins.

2.3 Governing Equations and Boundary Conditions

The study is based on several key assumptions to simplify the analysis:

i. The fluid flow and heat transfer are considered to be in a steady-state condition.
ii. The fluid is treated as single-phase, incompressible, and laminar.
iii. The thermal properties of both the fluid and the heat sink material are assumed to be temperature-independent.
iv. All surfaces of the heat sink exposed to the environment are insulated, except for the bottom plate, which is subjected to a constant heat flux to simulate heat generation from an electronic chip.
v. A uniform wall heat flux is applied.
vi. The fluid enters the channel with a uniform velocity.
vii. Radiation heat transfer is assumed to be negligible.

The study assumes steady-state, laminar, and incompressible flow with temperature-independent properties for the walls and coolant. Viscous dissipation, gravitational forces, and radiation are neglected. The porous walls are modeled as homogeneous, isotropic, and in thermal equilibrium with the coolant. Due to manufacturing complexities, minor inconsistencies in pore structures are possible. Flow through the porous media is also incompressible and laminar. A constant heat flux is applied to the heat sink's bottom surface. The Darcy-Forchheimer-Brinkman equation models the porous fins, simplifying the analysis while focusing on mass, momentum, and energy equations for system characterization. Thus, the governing equations for the system include the mass, momentum, and energy equations, as outlined below:

$$\nabla.\vec{V} = 0 \tag{1}$$

$$\rho\left(\vec{V}.\nabla\right)\vec{V} = -\nabla p + \mu\nabla^2\vec{V} - \left(\frac{\varepsilon\mu}{k_p} + \frac{\rho\varepsilon^2 C_F}{\sqrt{k_p}}\left|\vec{V}\right|\right)\vec{V} \tag{2}$$

$$\rho c_p\left(\varepsilon\vec{V}.\nabla T\right) = k_{eff}\nabla^2 T \tag{3}$$

Where k_{eff} is the effective thermal conductivity of porous ribs, calculated by,

$$k_{eff} = 2k_s + \frac{1}{\varepsilon/_{(2k_s+k_1)} + {}^{(1-\varepsilon)}/_{3k_s}} \tag{4}$$

where k_s is the thermal conductivity of solid-ribs.

The boundary conditions for the computational domain are specified as follows:

i. The channel inlet condition: at $x = 0$, $u = u_{f,}$, $v = w = 0$.

ii. For fluid, $T_f = T_{in} = 300K$ for the channel. For the porous fin, $u = v = w = 0$

iii. At the inlet $(x = 0)$: $u = u_m, T = T_m, w = v = 0$

iv. At the bottom $\left(y = L_y\right)$: $q = q_w$

v. At the outlet $(x = L_x)$: $\frac{\partial T_f}{\partial x} = 0, \frac{\partial u}{\partial x} = \frac{\partial v}{\partial y} = \frac{\partial w}{\partial z} = 0$

vi. At the two sides of the wall $(z = 0 \; and \; z = W)$: $\frac{\partial T_f}{\partial z} = 0$

vii. At the interface of fluid and porous: $q|_f = q|_p, w|_f = w|_p,\ \mu_f \frac{\partial v}{\partial z}\Big|_f = \frac{\mu_f}{\varepsilon}\frac{\partial v}{\partial z}\Big|_p$

viii. At the other outside walls: $-k\frac{\partial T_s}{\partial n} = 0$

3. Results and discussion

3.1 Mesh Technique and Grid Independence

The simulated data is initially validated against experimental data, using water as the working fluid. The validation study proceeds in two stages. Initially, pressure drop data is validated against Gong's results, with temperature contours also examined. Figure 4 compares the pressure drop data across various Reynolds numbers with Gong's findings and showing a high degree of consistency and a maximum error of just 4.79%. This small error confirms the accuracy of the numerical method (Table 2). The observed increase in pressure drop with the Reynolds number aligns with expectations for improved heat transfer. Overall, the numerical study is deemed valid, as the discrepancies are minimal and do not significantly impact the results. (Gong, 2018).

Table 2. Property table for Water (H2O) and copper solid material

Property	H_2O	Cu
Density, ρ	997 kg/m^3	8960 kg/m^3
Specific Heat, C_p	4179 J/kgK	385 J/kgK
Thermal Conductivity, k	0.613 W/mK	385 W/mK
Dynamic Viscosity, μ	0.000100003 Pa.s	0.00178 Pa.s

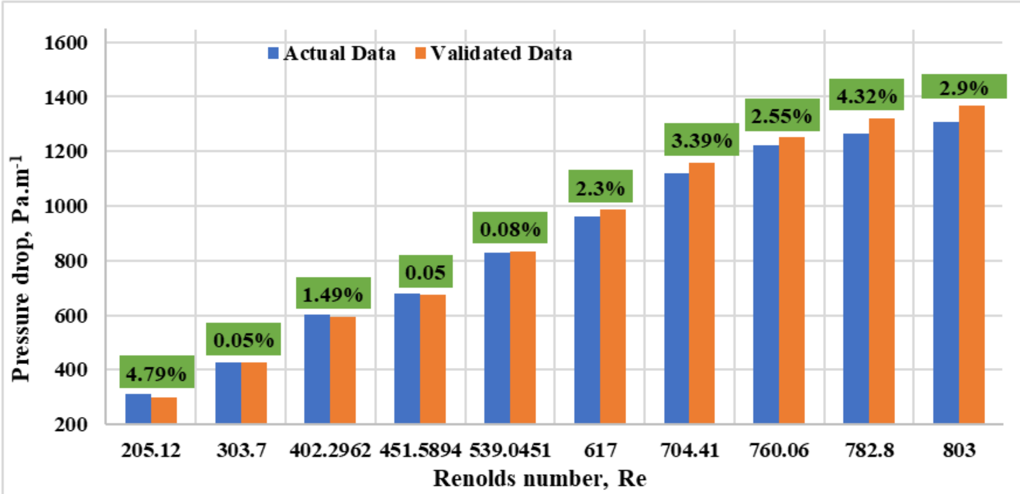


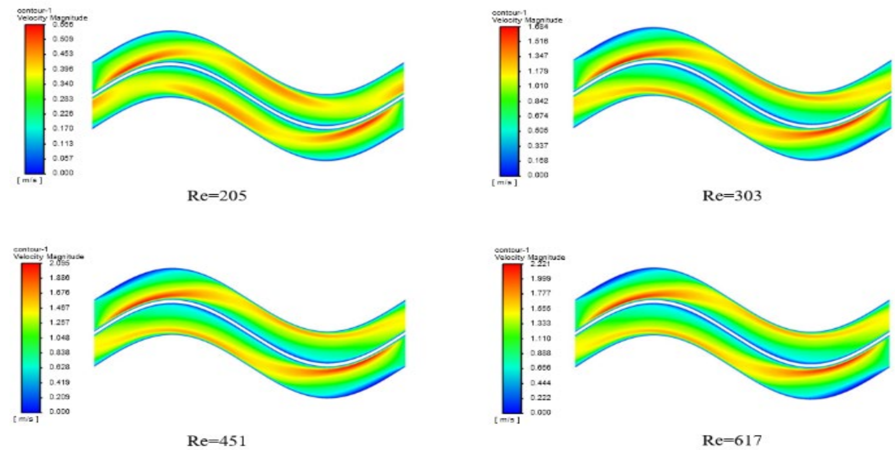
Figure 4. Validation study for the pressure drop.

3.2 Contours and Outcomes of the Parameters

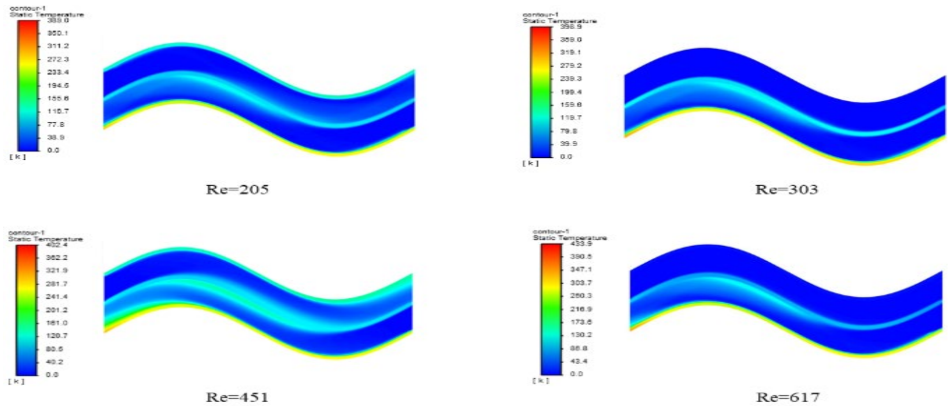
The analysis of a heat sink focuses on its heat transfer and hydrothermal characteristics, including the convective heat transfer coefficient, bottom surface temperature, and pressure drop, using water as the coolant. The system operates in a steady-state, laminar flow regime with Reynolds numbers ranging from 205 to 617. Figure 5 (a) illustrates the velocity contours within the double-layer sinusoidal heat sink with porous fins, showing that higher Reynolds numbers lead to increased local velocities and improved convective heat transfer. Figure 5 (b) depicts temperature contours at various Reynolds numbers for the same configuration, highlighting the temperature distribution variations under different flow conditions.

3.3 Comparison between Solid Fin and Porous

Figure 6(a) illustrates that the average coefficient of heat transfer rises nearly linearly with the Re for both porous and non-porous double-layer sinusoidal heat sinks. The porous consistently exhibits a higher heat transfer coefficient due to its increased surface area, which enhances convective heat transfer. The porous structure allows more fluid to flow through the fins, improving interaction with the coolant, whereas solid fins provide limited interaction and, thus, reduced heat transfer. As Re increases, the flow becomes more turbulent, further improving the coefficient of convective heat transfer. Figure 6(b) shows that thermal resistance decreases with increasing Re for both heat sinks. The porous heat sink demonstrates notably lower thermal resistance compared to the solid fin design, indicating more effective heat transfer. The greater surface area and improved fluid mixing in the porous structure contribute to better heat dissipation. However, higher porosity can lead to increased pressure drops due to higher flow resistance, which requires balancing heat transfer enhancement with pressure loss.



(a)



(b)

Figure 5. (a) Velocity contours of present work with a porous fin at various Reynolds numbers, and (b) Temperature contours of present work with a porous fin at various Reynolds numbers

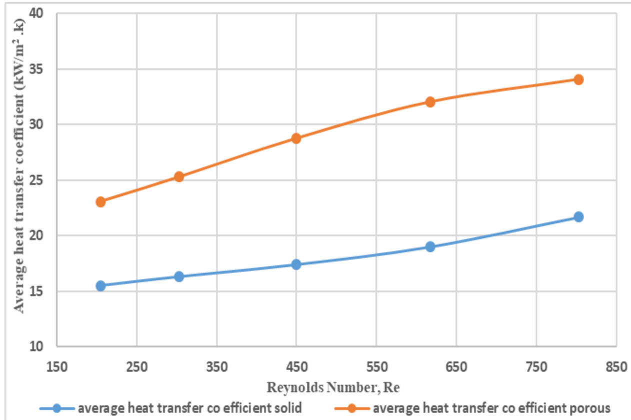
Figure 6(c) illustrates the Nusselt number (Nu) as a function of inlet velocity for porosity levels of 0.40 and 0.662. The Nusselt number increases with inlet velocity for both porosity levels, with a more significant rise observed at the higher porosity (0.662). Higher porosity improves fluid flow and interaction within the fins, enhancing convective heat transfer (Abouei,2013). Nevertheless, this also results in a higher pressure drop, underscoring the need for optimization to balance thermal efficiency with fluid resistance (Rahman,2025), (Hossain,2025).

4. Conclusion

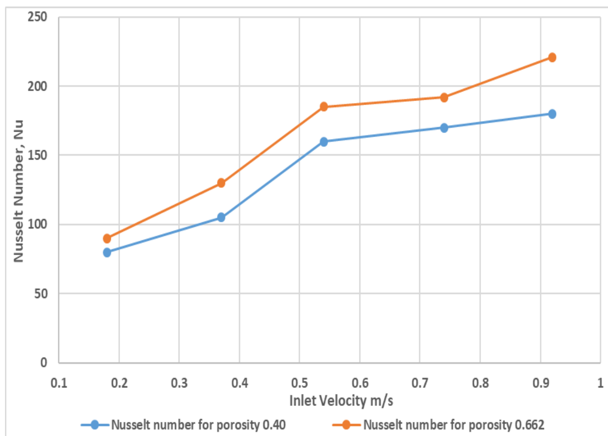
The study successfully demonstrates the potential of double layered sinusoidal heat sinks with porous fins for enhanced thermal management in microelectronics. The outcomes are listed below:

i. The integration of porous materials significantly improves heat transfer, with an increase of 1.5 times compared to conventional non-porous designs.
ii. The porous fins substantially improve heat dissipation by increasing the surface area for fluid interaction. This leads to a higher coefficient of convective heat transfer, particularly at higher Re.
iii. Despite the enhanced heat transfer, the pressure drop remains within acceptable limits, and balances thermal performance with fluid flow resistance.
iv. The porous fin design significantly reduces thermal resistance, ensuring more efficient cooling of high-density electronic systems.

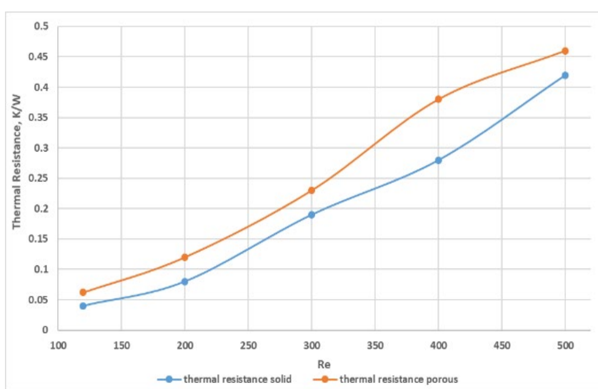
v. The numerical model was validated with experimental data, showing a maximum error of just 4.79%, confirming the accuracy of the simulation results.



(a)



(b)



(c)

Figure 6. (a) Relationship between the average coefficient of heat transfer and Reynolds number for both porous and solid heat sinks, (b) Variation of Nusselt Number by porosity, and (c) Relationship between the average coefficient of heat transfer and Reynolds number for both porous and non-porous heat sinks.

These results suggest that porous fins are a promising solution for improving heat dissipation in compact systems. Future research could explore the long-term performance and durability of these designs, as well as potential applications in other high-performance sectors where efficient thermal management is vital.

5. Future Recommendations

The system works well and accurately for the intended purpose. To enhance the system some future improvements can be made.

I) **Intramuscular EMG sensor:** Skin contact EMG receives meager, noisy signals. Intramuscular EMG sensors would provide much cleaner and useful signals, with much more fine motor movements.

II) **Better, Specialized Micro-controllers:** Arduino Uno is a commercially available microcontroller which is adequate for our purpose, but more specialized micro-controllers can do more complex feature extractions which can correlate to much higher variety of motor functions without a restrictive number of electrodes.

III) **More suitable limb actuators:** Using more advanced biotech actuators such as Artificial Muscles or Fine Movement Servo Motors instead of DPDT and a DC motor.

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