

## Effect of Geometric and Thermophysical Properties of Porous Medium on Thermal Performance of a Finned Microchannel Heat Sink

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### Abstract

This study numerically and three-dimensionally investigates the thermal performance of a microchannel heat sink integrated with a porous medium. Three different microchannel geometries—including square, circular, and finned—are considered, with conductive heat transfer modeled in the solid regions. Numerical simulations are performed using ANSYS Fluent and the finite volume method. The Reynolds number range in this study is between 50 and 1000, representing laminar flow conditions. The effects of a newly designed porous fin, variations in microchannel geometry, heat flux distribution, porosity, Darcy number, and the ratio of solid to fluid thermal conductivity within the porous medium on the thermal performance of the microchannel heat sink are evaluated. Results indicate that the square microchannel heat sink exhibits superior thermal performance compared to other geometries. The thermal performance of the system is directly influenced by the spatial distribution of heat flux on the active surface, which plays a key role in enhancing heat transfer.

Furthermore, the use of porous fins improves the thermal performance of the microchannel heat sink, with the degree of enhancement depending on porous medium properties such as porosity, Darcy number, and the thermal conductivity ratio. Among these, the thermal conductivity ratio of the porous medium significantly affects system performance. Notably, employing a porous medium with porosity varying as a function of position along the flow direction (z-axis) can improve thermal performance by approximately 38%. This study clearly demonstrates that variations in porous medium characteristics, especially porosity and thermal conductivity, can have substantial impacts on the thermal performance of microchannel heat sink systems.

**Keywords:** Microchannel-heat sink; Porous medium; Fin geometry; Porous medium properties; Thermal performance.

### 1. Introduction

In recent years, micro-electro-mechanical systems (MEMS) have gained widespread applications in fields such as aerospace, automotive engineering, biomedical devices, precision instruments, and electronic equipment, owing to their small dimensions, lightweight structure, low energy consumption, and fast response. One of the key components of these systems is the microchannel, which is utilized for fluid transport, thermal management, component cooling, and material transfer. Mini- and microchannels also play a crucial role in the performance of compact heat exchangers, particularly in the cooling of high-power-density chips and electronic devices.

However, one of the major challenges in employing microchannels lies in the reduction of heat transfer rates caused by increased thermal resistance, which in turn decreases the overall thermal efficiency of MEMS-based systems. A promising approach to address this challenge is the incorporation of porous media within microchannels. Such structures can significantly enhance heat transfer by increasing the effective surface area, promoting fluid mixing, and reducing

thermal resistance.

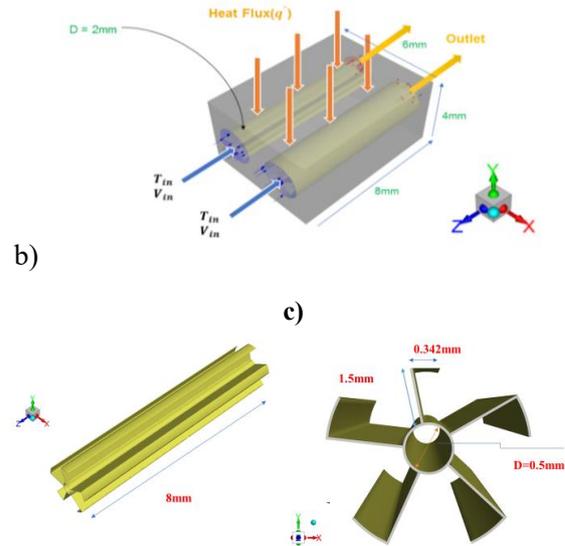
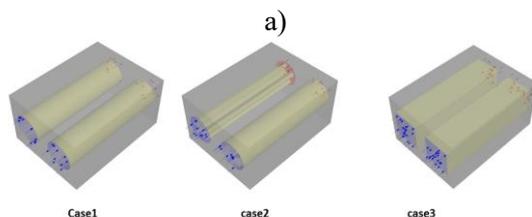
Hong and Yan [1] investigated a channel with variable height and width for enhancing the thermal performance of a microchannel heat sink. Their results indicated that a narrowing-width channel exhibited a more uniform temperature distribution and lower average temperatures compared to parallel-wall channels with narrowing heights. Seif and Nikaein [2] numerically studied the effects of particle size and Brownian motion on the thermal performance of a rectangular microchannel heat sink using alumina, zinc oxide, and copper oxide nanoparticles dispersed in an ethylene glycol–water base fluid. Fani et al. [3] analyzed the heat transfer of a water–copper oxide nanofluid in a trapezoidal microchannel heat sink by employing a two-phase model that accounted for Brownian motion. They reported that Brownian diffusion increased with both temperature and nanoparticle volume fraction, while it decreased with increasing particle diameter. Duryodhan et al. [4] conducted numerical and experimental investigations of single-phase liquid flow in converging and diverging trapezoidal microchannels. Their numerical simulations, carried out in three dimensions,

demonstrated that converging–diverging microchannels provide superior thermohydraulic performance compared to channels with constant cross-sectional areas. Hu et al. [5] examined the heat transfer characteristics of water–phase-change material (PCM) suspensions in a microchannel. The incorporation of PCM nanoparticles enhanced heat transfer and improved performance indices by more than 40%, although at higher flow rates the addition of nanoparticles led to reduced heat transfer. Moreover, In the present work, the effect of incorporating a porous medium into finned microchannel heat sinks is investigated. Three-dimensional numerical simulations are conducted for microchannels with square, circular, and finned geometries, taking into account heat conduction within the solid regions. The simulations are carried out using the finite-volume method implemented in ANSYS Fluent. The study evaluates the effects of various parameters—including fin incorporation, channel geometry, spatial distribution of heat flux, porosity, Darcy number, and the ratio of thermal conductivity in the porous medium—on the thermal performance of microchannel heat sinks.

## 2. Methodology

A schematic of the investigated microchannel heat sinks (MCHS) is illustrated in Figure 1. In this study, three different geometries, including circular (Case 1), finned (Case 2), and square (Case 3), are selected as representative configurations, as shown in Figure 1. Water is used as the cooling fluid, while both the porous medium and the solid substrate are assumed to be made of steel. The detailed dimensions of the microchannels are presented in Figure 1(b). In addition, a schematic of the fin employed in Case 2, along with its dimensions, is shown in Figure 1(c). The coolant enters the channel with a uniform inlet velocity  $V_{in}$  and uniform temperature,  $T_{in}$ . The Reynolds number of the flow is varied within the range of 50 to 1000. A no-slip boundary condition is imposed on all solid walls. All the walls of the heat sink are considered thermally insulated, except for the top surface, where a uniform heat flux is applied.

This study aims to evaluate the effect of introducing a porous medium on the thermal performance of MCHS. The flow is assumed to be three-dimensional, steady, incompressible, and laminar.



**Figure 1(a) Schematic of the microchannel heat sink (MCHS) configurations under study. b) Boundary conditions of the problem, (c) Schematic of the fin used in Case 2**

The governing equations were solved using the finite volume method, with a second-order upwind scheme employed for discretization. In addition, the SIMPLE algorithm was applied to achieve pressure–velocity coupling. For all simulations, the continuity, momentum, and energy equations were solved iteratively until the residuals dropped below  $1e-6$ .

Generating an appropriate computational grid is crucial for obtaining accurate and reliable results. To ensure grid independence, the temperature distribution on the heated surface (the surface subjected to the applied heat flux) was examined. As the number of grid elements increases, their size decreases, leading to improved solution accuracy. This refinement process was continued until no significant change was observed in the temperature distribution of the heated surface. For the grid-independence test, several meshes with different element sizes were examined. Figure 2(a) illustrates the variations of the heated surface temperature and the outlet fluid temperature for different meshes. Based on these results, a mesh with 374,822 nodes was selected for further analysis. A view of the selected mesh is shown in Figures 2(a) and 2(b). For all cases with modified microchannel geometries, grid-independence tests were performed, and the number of nodes for each case is presented in Figure 2(c).

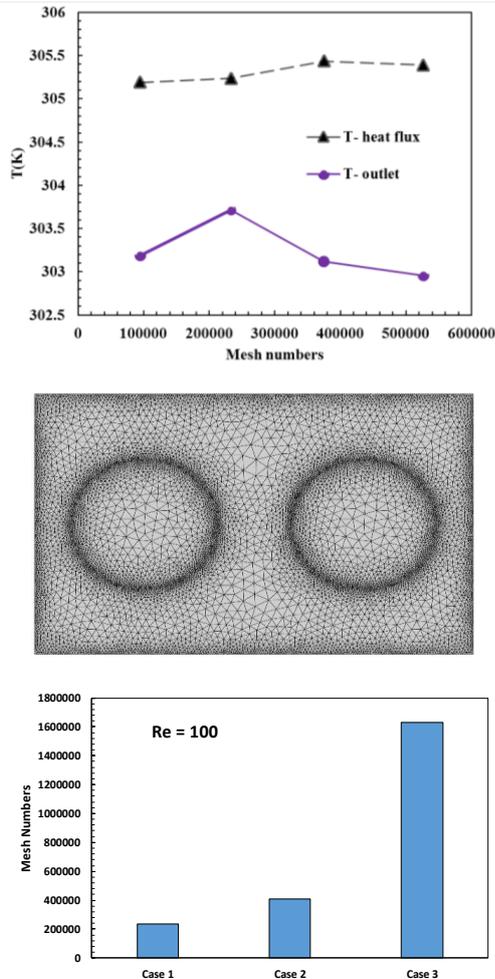


Figure 2(a) Grid independence study, (b) View of the selected mesh, (c) Number of nodes for each geometry

### 3. Discussion and Results

In this study, numerical simulations were employed to investigate the effects of microchannel geometry, variations of heat flux on the heated surface, and the use of porous media with different properties on the thermal performance of microchannel heat sinks. The influence of microchannel geometry, its variations, and Reynolds number on the performance of the microchannel heat sink was evaluated, and the results are presented in Figures 3 and 4. The geometry of the microchannel plays a key role in improving heat absorption and dissipation by affecting the flow pattern and temperature distribution. The results indicate that changing the microchannel geometry from circular to square enhances the heat dissipation capability. Although the cross-sectional area is the same in both cases, the wall effect and the resulting variations in velocity and temperature fields improve heat transfer, thereby lowering the temperature of the heated surface. This trend is clearly observed in the temperature variations shown in Figure 4(a). The thermal resistance of the square microchannel heat sink is approximately 14.5% lower than that of the circular microchannel heat

sink. In another case, where fins were employed inside the microchannel, a reduction in thermal resistance between about 13.1% and 32.8% compared to the baseline case was observed. The presence of fins modifies the fluid flow pattern and temperature distribution, leading to enhanced thermal performance. Attaching fins to the heat transfer walls increases the effective heat transfer surface area, resulting in a reduction in the heated surface temperature.

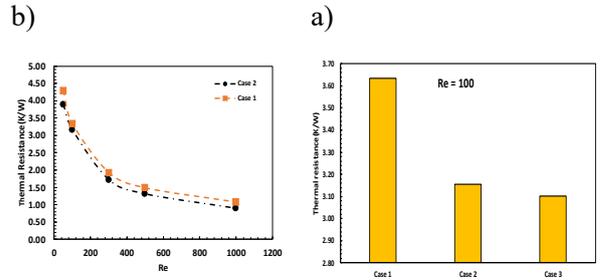


Figure 3(a) Thermal resistance of the microchannel heat sink for different cases (b) Thermal resistance as a function of Reynolds number for Case 1 and Case 2

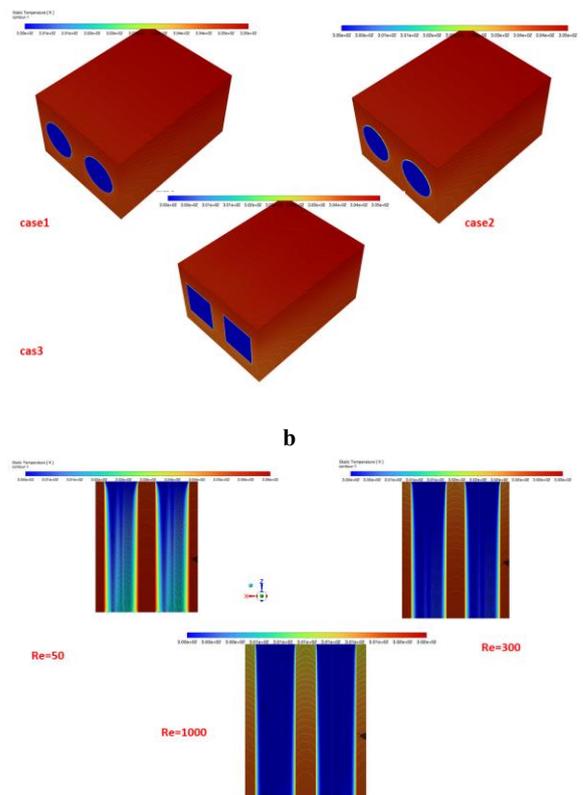


Figure 3(a) Temperature contours for different cases (b) Temperature contours for various Reynolds numbers in Case 2

Figure 4 illustrates the variation of thermal resistance with Reynolds number for Case 1 and Case 2. Increasing the Reynolds number leads to a higher mass flow rate of the coolant and a reduction in convective

thermal resistance, thereby enhancing heat absorption from the heated surface and reducing its temperature. Figure 4(b) confirms this trend and shows that an increase in Reynolds number from 50 to 1000 reduces the thermal resistance by approximately 72% to 74%. However, increasing Reynolds number also raises the pressure drop, which was found to be about three times higher compared to the baseline case. The sensitivity of the microchannel heat sink (MCHS) performance to spatial variations of porosity within the microchannel has been investigated. Three porosity distributions along the z-direction were considered, and the results are clearly presented in Figure 7(d). In Case P1, the porosity decreases linearly with the flow direction. In Case P2, the porosity increases linearly along the flow direction. In Case P3, the porosity first increases, reaching a maximum value at  $z=4\text{mm}$ , and then decreases; this variation is modeled as a quadratic function of position. In all cases, the porosity varies along the channel length. In Case P1, as porosity  $\varepsilon$  increases in the flow direction, the effective thermal conductivity of the porous region decreases while convective heat transfer increases. This enhances the overall heat transfer, improves the heat absorption capability of the microchannel, and reduces the heated surface temperature. Consequently, this configuration outperforms the other cases, improving the thermal performance of the MCHS by approximately 38.25% compared to the case without a porous medium.

#### 4. Conclusions

This paper presented a numerical investigation of the thermal performance of microchannel heat sinks integrated with a porous medium. Three-dimensional simulations were conducted for different microchannel geometries (square, circular, and finned), accounting for heat conduction in the solid regions. The simulations were carried out using ANSYS Fluent based on the finite volume method. Various parameters were examined, including the effect of fins, changes in channel geometry, heat flux distribution, porosity, Darcy number, and the ratio of thermal conductivity in the porous medium on the overall performance of the MCHS. The main findings can be summarized as follows:

The thermal performance of the MCHS strongly

depends on its geometry. Flow and temperature fields are directly affected by channel shape. For example, the thermal resistance of the square and finned MCHS is reduced by about 14.5% and 13.1–32.8%, respectively, compared to the baseline circular case. The spatial distribution of heat flux on the heated surface significantly influences thermal performance. A uniform heat flux distribution can reduce thermal resistance by about 19–57%. Integrating a porous medium improves the thermal performance of the MCHS by approximately 6–20% compared to the case without a porous medium. Selecting appropriate materials for the porous matrix can further enhance performance by up to 20%. Increasing porosity and decreasing Darcy number both lead to higher thermal resistance, highlighting the strong relationship between porous medium properties and system performance. Employing a porous medium with spatially varying porosity along the flow direction can further improve thermal performance, reducing thermal resistance by up to ~38%. In conclusion, this study clearly demonstrates that integrating porous media with microchannel heat sinks—particularly through optimal selection of materials and porosity distribution—can significantly enhance system thermal performance.

#### 5. References

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