

THERMAL PERFORMANCE ANALYSIS OF NANOFLUID FLOW IN ASYMMETRIC SPIDER-WEB MICROCHANNEL HEAT SINKS

Vu Sy Ky¹, Le Phuong Hao¹, Nguyen Thi Tham¹, Pham Thi Ha¹, Luu Dinh Thi¹,
Le Viet Anh¹

Received: 18 May 2026/ Accepted: 20 July 2026/ Published: 30 July 2026

<https://doi.org/10.70117/hdujs.E11.7.2026.1395>

Abstract: Microchannel heat sinks have attracted significant attention for advanced thermal management of high-heat-flux devices, where enhancement of heat transfer performance remains a critical challenge. In this study, a detailed thermal analysis of nanofluid flow and heat transfer in asymmetric spider-web microchannel heat sinks is presented using a two-dimensional numerical framework. The effects of microchannel geometric asymmetry and nanofluid properties on convective heat transfer characteristics are systematically investigated.

The governing continuity, momentum, and energy equations are solved to evaluate key thermal performance indicators, including the Nusselt number, temperature distribution, and thermal resistance, over a range of Reynolds numbers and nanofluid types at a fixed nanoparticle volume fraction of $\phi=0.1\%$. Numerical validation is achieved through grid independence analysis and comparison with established heat transfer correlations reported in the literature.

The results demonstrate that the asymmetric spider-web configuration promotes enhanced thermal mixing and temperature uniformity, leading to improved heat transfer performance compared to conventional microchannel designs. The use of nanofluids further intensifies convective heat transfer, although at the expense of increased pressure drop. The present study provides physical insight into the coupled effects of geometry-induced flow redistribution and nanofluid-enhanced thermal transport, offering useful guidance for the thermal design of micro-scale heat dissipation systems.

Keywords: Numerical heat transfer, nanofluid flow, asymmetric microchannels, spider-web microchannel, CFD simulation, pressure drop.

1. Introduction

The rapid miniaturization and increasing power density of modern electronic and energy systems have imposed stringent requirements on advanced thermal management technologies. Microchannel heat sinks have emerged as highly effective solutions due to their large surface-area-to-volume ratio and capability to dissipate high heat fluxes under laminar

¹Faculty of Engineering and Technology, Hong Duc University, Thanh Hoa; Email: vusyky@hdu.edu.vn

flow conditions [1-3]. However, the thermal performance of conventional straight microchannels is often limited by boundary layer development and non-uniform temperature distribution, motivating the exploration of innovative microchannel geometries [4,5]. Recent review studies have further highlighted the critical role of microchannel heat sinks in next-generation electronic cooling systems and summarized recent advances in structural optimization and heat-transfer enhancement techniques [21,22].

Among various geometric modifications, bio-inspired and network-based microchannel designs have demonstrated promising potential for improving heat transfer through enhanced flow redistribution and secondary flow generation [6-8]. Spider-web-inspired microchannel structures, characterized by interconnected radial and circumferential flow paths, have recently attracted attention owing to their ability to promote fluid mixing and thermal homogenization [9,10]. Nevertheless, systematic thermal analysis of asymmetric spider-web microchannel configurations remains scarce, particularly under realistic laminar flow conditions relevant to microscale heat dissipation devices.

In parallel, the use of nanofluids has been widely investigated as an effective approach for enhancing convective heat transfer due to their superior thermal transport properties compared to conventional working fluids [11-13]. Numerous studies have reported that the addition of nanoparticles can significantly increase the effective thermal conductivity and Nusselt number in microchannel flows [14-16]. However, this enhancement is often accompanied by increased viscosity and pressure drop, necessitating a careful thermal-hydraulic assessment [17,18]. Recent reviews have further confirmed that nanofluids remain promising working fluids for compact cooling systems, particularly when combined with advanced microchannel geometries [21][24-26]. From a thermal analysis perspective, understanding the coupled influence of nanofluid properties and microchannel geometry is essential for optimizing overall thermal performance.

Most existing studies on nanofluid flow in microchannels have focused on symmetric channel layouts or simplified geometries, while the combined effects of geometric asymmetry and network-type microchannel architectures have not been adequately addressed [19]. Furthermore, recent reviews have emphasized the need for further investigations into complex microchannel networks and thermo-hydraulic optimization strategies that simultaneously consider heat-transfer enhancement and pressure-drop penalties [22-25]. Fundamental heat-transfer principles and transport mechanisms governing such systems remain essential for interpreting thermal performance trends [20].

In this context, the present work aims to provide a comprehensive thermal performance analysis of nanofluid flow in asymmetric spider-web microchannel heat sinks using a two-dimensional numerical framework. The effects of Reynolds number, nanofluid type, and geometric asymmetry on temperature distribution, Nusselt number, thermal resistance, and pressure drop are investigated at a fixed nanoparticle volume fraction of $\phi=0.1\%$. The results offer physical insight into geometry-induced thermal enhancement and nanofluid-assisted heat transfer, contributing to the thermal design of micro-scale heat dissipation systems.

2. Mathematical Modeling

2.1. Geometry and Computational Domain

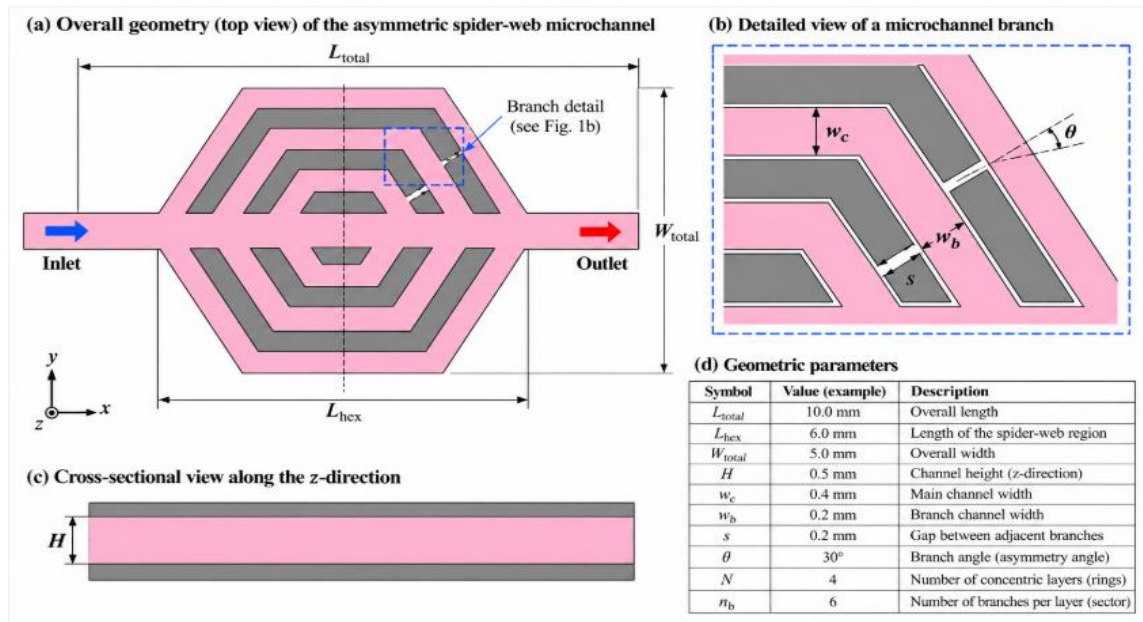


Figure 1. Schematic geometry and principal dimensions of the asymmetric spider-web microchannel: (a) overall geometry; (b) detailed view of the branch-channel structure; (c) cross-sectional view along the zz -direction; and (d) principal geometric parameters

The geometry of the asymmetric spider-web microchannel considered in this study is illustrated in Fig. 1. The proposed configuration consists of a main channel interconnected with multiple branches arranged in a spider-web pattern. The asymmetric configuration is introduced by applying a prescribed branch deviation angle, resulting in a non-symmetric flow network.

As shown in Fig. 1(a), the overall computational geometry is characterized by the total length L_{total} , the characteristic width of the spider-web region L_{hex} , and the overall width W_{total} . A detailed view of the branch-channel configuration is provided in Fig. 1(b), where w_c , w_b , s , and θ define the main-channel width, branch width, spacing between adjacent branches, and branch deviation angle, respectively. The channel height H is defined in the transverse z -direction, as shown in Fig. 1(c). The principal geometric parameters used in the present study are summarized in Fig. 1(d).

2.2. Governing Equations

The behavior of nanofluid flow and heat transfer in the asymmetric spider-web microchannel is described by the classical conservation equations:

Continuity equation: To ensure mass conservation for incompressible fluid flow:

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

where $\vec{u} = (u, v)$ represents the velocity vector in the x and y directions.

Momentum equation (Navier-Stokes): Under Newtonian flow and no external body forces, the steady-state momentum equations are written as:

$$\rho_{nf} (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \mu_{nf} \nabla^2 \vec{u} \quad (2)$$

where: ρ_{nf} is the density of the nanofluid; μ_{nf} is the dynamic viscosity; p is the pressure field.

These equations model the inertia-viscous balance of the nanofluid as it navigates through the microchannel geometry, including the side branches and main channel.

Energy equation: The temperature distribution within the fluid is governed by the steady-state energy equation:

$$\rho_{nf} c_{p,nf} (\vec{u} \cdot \nabla T) = k_{nf} \nabla^2 T \quad (3)$$

where ρ_{nf} , μ_{nf} , $c_{p,nf}$, and k_{nf} denote the effective density, viscosity, specific heat, and thermal conductivity of the nanofluid, respectively; $\vec{u}$ is the velocity vector, p is pressure, and T is the fluid temperature.

2.3. Nanofluid Thermophysical Properties

The effective thermophysical properties of the h-BN/water nanofluid are obtained from standard mixture models [1,2]:

Density:

$$\rho_{nf} = (1 - \phi) \rho_f + \phi \rho_p \quad (4)$$

Heat capacity:

$$(\rho c_p)_{nf} = (1 - \phi) (\rho c_p)_f + \phi (\rho c_p)_p \quad (5)$$

Viscosity (Einstein model):

$$\mu_{nf} = \mu_f (1 - \phi)^{2.5} \quad (6)$$

Thermal conductivity (Maxwell model):

$$k_{nf} = k_f \cdot \frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)} \quad (7)$$

Here, ϕ is the nanoparticle volume fraction, and subscripts f , p , and nf represent base fluid, particle, and nanofluid, respectively. For this study, $\phi = 0.1\%$, with water as the base fluid and h-BN nanoparticles providing enhanced thermal conductivity.

The effective thermophysical properties of the h-BN/water nanofluid are evaluated using classical mixture models that have been extensively validated for thermal analysis of dilute nanofluids. The Maxwell model is employed to estimate the effective thermal conductivity, while the Einstein relation is used to account for viscosity enhancement.

These models provide a physically consistent description of thermal transport enhancement without introducing empirical fitting parameters, which aligns with the thermal analysis focus of the present work.

2.4. Characteristic Parameters

The heat transfer and hydrodynamic performance of the microchannel are characterized using two non-dimensional numbers:

Reynolds number (Re):

$$Re = \frac{\rho_{nf} u_{in} D_h}{\mu_{nf}} \quad (8)$$

Nusselt number (Nu):

$$N_u = \frac{hD_h}{k_{nf}} \quad (9)$$

where u_{in} is the inlet velocity, D_h is the hydraulic diameter defined as:

$$D_h = \frac{4A}{P} \quad (10)$$

with A the cross-sectional area and P the wetted perimeter. The local convective heat transfer coefficient is calculated from the temperature gradient at the wall:

$$h = \frac{k_{nf}}{(T_w - T_m)} \left(\frac{\partial T}{\partial n} \right)_{wall} \quad (11)$$

where T_w is wall temperature, T_m is bulk mean temperature, and $\left(\frac{\partial T}{\partial n} \right)_{wall}$ is the temperature gradient normal to the wall.

2.5. Boundary Conditions

The computational domain of the asymmetric spider-web microchannel consists of a velocity inlet, a pressure outlet, and solid channel walls. The flow is assumed to be steady, laminar, incompressible, and Newtonian. The boundary conditions applied in the numerical simulations are described as follows.

At the inlet, a uniform velocity profile is imposed at the channel entrance. The inlet velocity is specified according to the Reynolds number, which varies from 100 to 1000. The inlet fluid temperature is maintained at a constant value:

$$T_{in} = 293K \quad (12)$$

At the outlet, a pressure boundary condition is applied with zero gauge pressure:

$$p_{out} = 0 \quad (13)$$

This condition allows the flow to develop naturally and ensures numerical stability at the channel exit.

At the channel walls, a no-slip velocity condition is enforced:

$$\vec{u}_{wall} = 0 \quad (14)$$

In addition, all solid walls are subjected to a uniform and constant heat flux given by:

$$q'' = 1 \times 10^5 \text{ W/m}^2 \quad (15)$$

This thermal boundary condition represents a constant heat generation rate typically encountered in microelectronic cooling and MEMS applications.

3. Results and Discussion

3.1. Velocity Distribution

Figure 2 presents the velocity magnitude contours within the asymmetric spider-web microchannel for different Reynolds numbers. The flow field is strongly influenced by the repeated branching and merging of the main and secondary flow paths. As the fluid enters the spider-web region, the flow is redistributed between the radial and circumferential branches, resulting in spatial variations in velocity magnitude.

At low Reynolds numbers, the flow remains predominantly laminar, and the velocity field is relatively smooth. With increasing Reynolds number, the velocity gradients near the

branch junctions become more pronounced. Local acceleration occurs in the narrower branch sections, whereas relatively low-velocity regions develop near the junctions and channel corners. These flow redistribution effects increase fluid mixing and contribute to the disruption of the thermal boundary layer.

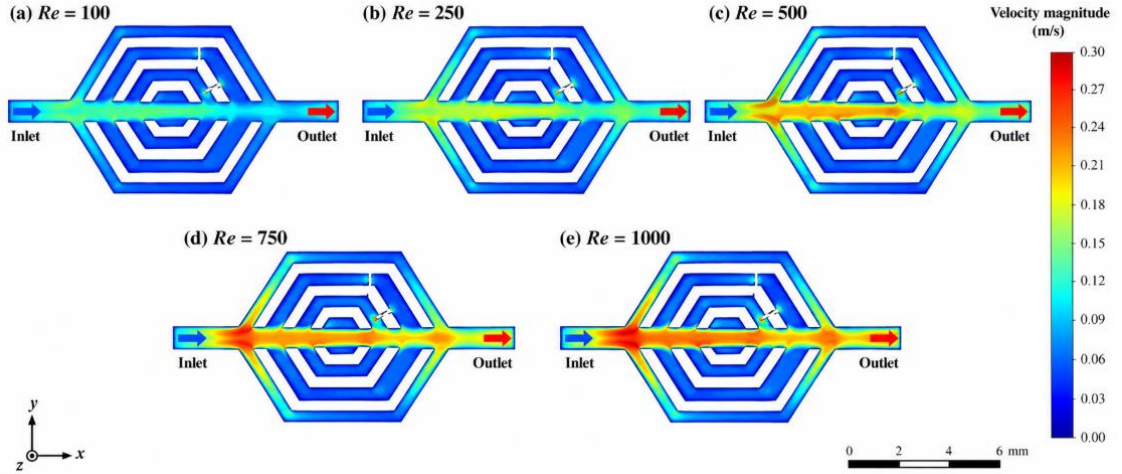


Figure 2. Velocity magnitude contours in the asymmetric spider-web microchannel at different Reynolds numbers

3.2. Temperature Distribution

Figure 3 shows the corresponding temperature contours under uniform wall heat flux. At low Reynolds numbers, the fluid remains in the heated region for a longer residence time, resulting in a relatively higher bulk-fluid temperature. Increasing the Reynolds number enhances convective heat removal and reduces the temperature rise of the fluid. The repeated branching of the spider-web geometry further promotes thermal transport by continuously redistributing the fluid between different flow paths.

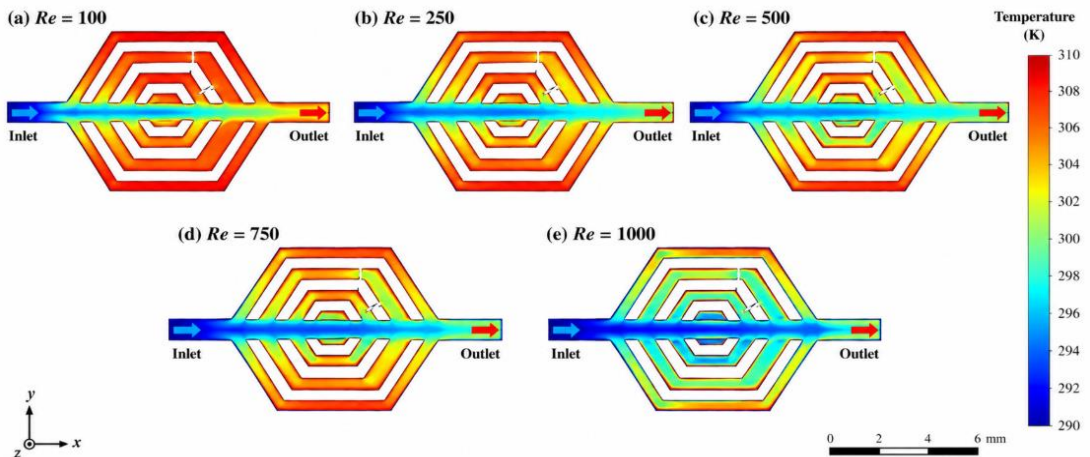


Figure 3. Temperature contours in the asymmetric spider-web microchannel under uniform wall heat flux at different Reynolds numbers

3.3. Static Pressure

Figure 4 presents the static pressure distribution within the asymmetric spider-web microchannel. The pressure decreases progressively from the inlet toward the outlet, with localized pressure variations occurring near the branch junctions. These variations are associated with flow acceleration, deceleration, and changes in flow direction.

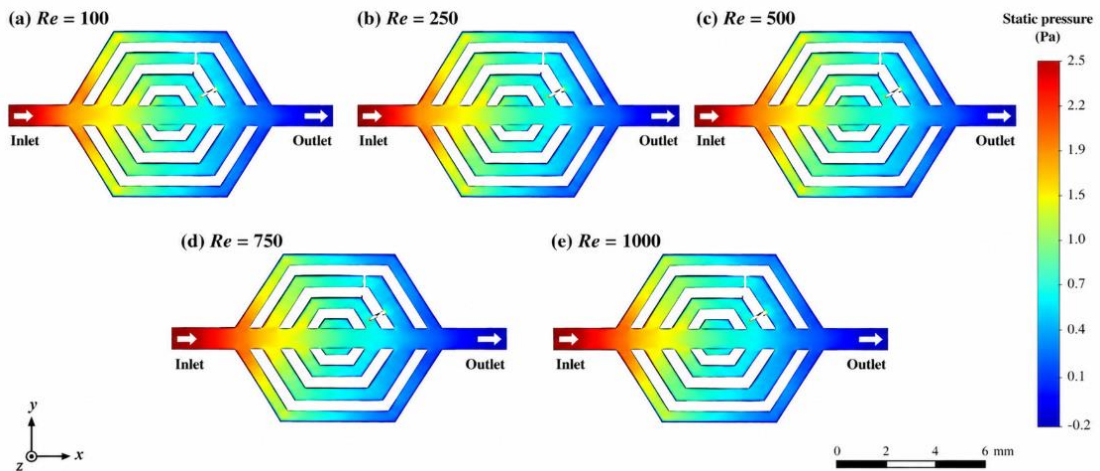


Figure 4. Static pressure contours in the asymmetric spider-web microchannel at different Reynolds numbers

3.4. Effect of Nanofluids

Table 2 summarizes the thermal and hydraulic performance of the asymmetric spider-web microchannel using h-BN/water, Al₂O₃/water, CuO/water, and SiO₂/water nanofluids. The comparison considers the enhancement in thermal conductivity, the corresponding increase in viscosity, the average Nusselt number, and the pressure drop across the microchannel.

Table 2. Summary of nanofluid performance (h-BN, Al₂O₃, CuO, SiO₂).

Nanofluid	Thermal conductivity enhancement (% vs. water)	Viscosity increase (% vs. water)	Average Nusselt number	Pressure Drop, ΔP (Pa)	Performance evaluation
h-BN/water	+22%	+9%	$1.25 \times Nu_{water}$	2.05	Best overall performance
Al ₂ O ₃ /water	+18%	+15%	$1.18 \times Nu_{water}$	2.10	Good enhancement, higher flow resistance
CuO/water	+20%	+19%	$1.20 \times Nu_{water}$	2.15	Strong heat transfer, highest hydraulic penalty
SiO ₂ /water	+10%	+5%	$1.10 \times Nu_{water}$	2.00	Good stability, limited thermal enhancement

The results indicate that the addition of nanoparticles improves the thermal transport characteristics of the working fluid. Among the investigated nanofluids, h-BN/water provides the most favorable overall thermal performance, with an approximately 22% enhancement in effective thermal conductivity and a relatively moderate viscosity increase of approximately 9% compared with water. The corresponding average Nusselt number is approximately 25% higher than that of the base fluid.

$\text{Al}_2\text{O}_3/\text{water}$ and CuO/water also provide significant heat-transfer enhancement. However, their higher viscosity increases the hydraulic resistance of the microchannel. In particular, CuO/water exhibits the largest viscosity increase among the investigated fluids and consequently produces the highest pressure drop.

$\text{SiO}_2/\text{water}$ shows the smallest increase in viscosity and therefore the lowest hydraulic penalty. Nevertheless, its relatively modest improvement in thermal conductivity results in a lower heat-transfer enhancement compared with h-BN/water.

These results indicate that the selection of a nanofluid should consider both thermal and hydraulic characteristics. A nanofluid with high thermal conductivity does not necessarily provide the optimum overall performance if the associated increase in viscosity produces excessive flow resistance.

3.5. Pressure Drop and Flow Resistance

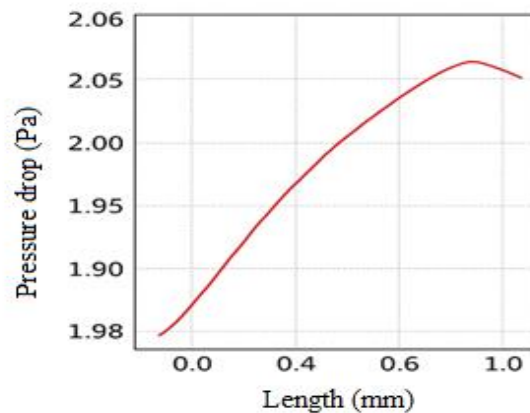


Figure 4. Pressure drop across the asymmetric spider-web microchannel for different nanofluids.

Figure 4 presents the pressure-drop characteristics of the asymmetric spider-web microchannel. The pressure drop is defined as the difference between the inlet and outlet pressures:

$$\Delta P = P_{in} - P_{out} \quad (16)$$

The asymmetric spider-web geometry introduces additional hydraulic resistance because the fluid repeatedly changes its flow direction and redistributes between the main channel and the interconnected branches. These geometric features result in local acceleration, deceleration, and flow redistribution, which contribute to the overall pressure loss.

As shown in Figure 4, the pressure drop remains relatively low for all investigated nanofluids under the considered operating condition. The illustrative values range from approximately 2.00 to 2.15 Pa. $\text{SiO}_2/\text{water}$ produces the lowest pressure drop of approximately 2.00 Pa, whereas CuO/water produces the highest value of approximately 2.15 Pa. The latter behavior is consistent with the higher viscosity associated with CuO nanoparticles.

The pressure-drop difference among the nanofluids is relatively small compared with their differences in thermal transport properties. This suggests that h-BN/water may provide a favorable compromise between heat-transfer enhancement and hydraulic resistance.

4. Conclusions

A comprehensive numerical investigation of nanofluid flow and heat transfer in asymmetric spider-web microchannels has been presented. A two-dimensional CFD model was developed to analyze the coupled thermal and hydraulic characteristics under laminar flow conditions. Grid independence and validation against established correlations confirmed the reliability of the numerical framework.

The results demonstrate that geometric asymmetry in spider-web microchannels significantly enhances convective heat transfer by promoting fluid mixing and increasing local velocity gradients. The use of nanofluids further improves thermal performance, as reflected by higher Nusselt numbers, particularly at moderate Reynolds numbers. However, the enhancement is accompanied by an increase in pressure drop, highlighting the importance of balancing thermal benefits against hydraulic penalties.

At the selected nanoparticle volume fraction of $\phi=0.1\%$, the nanofluids provide enhanced thermal transport compared with the base fluid, while the associated increase in viscosity introduces an additional hydraulic penalty. The findings emphasize the importance of simultaneously considering heat-transfer enhancement and flow resistance when selecting a working fluid for asymmetric microchannel heat sinks.

The present study provides quantitative insights and design guidance for optimizing asymmetric microchannel configurations in advanced thermal management applications, particularly where compact and efficient cooling solutions are required.

References

- [1] Tuckerman, D.B.; Pease, R.F.W.(1981), *High-performance heat sinking for VLSI*. IEEE Electron Device Lett. 2:126-129.
- [2] Kandlikar, S.G. (2005), *High flux heat removal with microchannels-A roadmap of challenges and opportunities*. Heat Transfer Eng., 26:5-14.
- [3] Garimella, S.V.; Singhal, V.; Liu, D. (2006), *On-chip thermal management with microchannel heat sinks and integrated micropumps*. Proc. IEEE, 94:1534-1548.
- [4] Morini, G.L. (2004), *Single-phase convective heat transfer in microchannels: A review of experimental results*. Int. J. Therm. Sci., 43:631-651.
- [5] Xia, G.; Zhai, Y.; Cui, Z.(2011), *Numerical investigation of flow and heat transfer in microchannel with different geometric structures*. Appl. Therm. Eng., 31:259-266.
- [6] Bejan, A., Lorente (2008), S. *Design with constructal theory*. Wiley.
- [7] Chen, Y., Zhang, C.; Shi, M. Wu, J. (2012), *Numerical simulation of laminar flow and heat transfer in microchannel heat sink with longitudinal vortex generators*. Appl. Therm. Eng., 44:84-95.
- [8] Wang, X.Q., Mujumdar, A.S. (2007), *Heat transfer characteristics of nanofluids: A review*. Int. J. Therm. Sci., 46:1-19.
- [9] Li, X.; Fan, Y.; Wang, X. (2019), *Bio-inspired spider-web-like microchannel heat sink for enhanced heat transfer*. Int. J. Heat Mass Transf., 133:1005-1017.

- [10] Zhang, H.; Tang, G.H. (2017), *Thermal performance of fractal microchannel heat sinks*. Energy Convers. Manag., 149:106-116.
- [11] Choi, S.U.S. (1995), *Enhancing thermal conductivity of fluids with nanoparticles*. ASME FED, 231:99-105.
- [12] Buongiorno, J. (2006), *Convective transport in nanofluids*. J. Heat Transf., 128:240-250.
- [13] Das, S.K., Choi, S.U.S., Yu, W., Pradeep, T. (2007), *Nanofluids: Science and Technology*; Wiley.
- [14] Akbarinia, A., Laur, R. (2009), *Investigating the thermal performance of nanofluids in microchannels*. Int. J. Heat Fluid Flow, 30:706-719.
- [15] Bianco, V.; Chiacchio, F.; Manca, O.; Nardini, S. (2009), *Numerical investigation of nanofluids forced convection in circular tubes*. Appl. Therm. Eng., 29:3632-3642.
- [16] Maïga, S.E.B., Palm, S.J., Nguyen, C.T., Roy, G., Galanis, N. (2005), *Heat transfer enhancement by using nanofluids in forced convection flows*. Int. J. Heat Fluid Flow 26:530-546.
- [17] Pak, B.C., Cho, Y.I. (1998), *Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles*. Exp. Heat Transf., 11:151-170.
- [18] Duangthongsuk, W., Wongwises, S.(2009), *Measurement of temperature-dependent thermal conductivity and viscosity of TiO₂-water nanofluids*. Exp. Therm. Fluid Sci. 33:706-714.
- [19] Mohammed, H.A., Gunnasegaran, P., Shuaib, N.H. (2011), *Influence of channel shape on the thermal and hydraulic performance of microchannel heat sink*. Int. Commun. Heat Mass Transf., 38:474-480.
- [20] Incropera, F.P., DeWitt, D.P., Bergman, T.L., Lavine, A.S. (2011), *Fundamentals of Heat and Mass Transfer*, 7th ed.; Wiley.
- [21] Dwivedi, A., Khan, M.M., Pali, H.S. (2023), *A comprehensive review of thermal enhancement techniques in microchannel heat exchangers and heat sinks*. Journal of Thermal Analysis and Calorimetry, 148:13189-13231. DOI: 10.1007/s10973-023-12451-3.
- [22] Zhang, X., Ji, Z., Wang, J., Lv, X. (2023), *Research progress on structural optimization design of microchannel heat sinks applied to electronic devices*. Applied Thermal Engineering, 235:121294. DOI: 10.1016/j.applthermaleng.2023.121294.
- [23] Singh, S., Malik, A., Mali, H.S. (2023), *A critical review on single-phase thermo-hydraulic enhancement in geometrically modified microchannel devices*. Applied Thermal Engineering, 235:121729. DOI: 10.1016/j.applthermaleng.2023.121729.
- [24] Jan, M., Butt, M.M., Hassan, M.M. (2023), *Fluid flow characteristics and heat transfer performance in microchannel heat sinks: A review*. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, DOI: 10.1177/09544089221142436.
- [25] Du, L., Hu, W. (2023), *An overview of heat transfer enhancement methods in microchannel heat sinks*. Chemical Engineering Science, 280:119081. DOI: 10.1016/j.ces.2023.119081.
- [26] Ghani, U., Wazir, M.A. et al. (2024), *Microchannel Heat Sinks-A Comprehensive Review*. Electronic Materials, 5(4):249-292. DOI: 10.3390/electronicmat5040017.