© Journal of the Technical University - Sofia
Plovdiv branch, Bulgaria
"Fundamental Sciences and Applications"
Vol. 32, 2026

Numerical Analysis of Fluid Flow and Heat Transfer in Wavy Microchannels with Pin Inserts

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Abstract: Effective thermal management is essential for maintaining reliability and performance of modern electronic devices as heat generation increases with system miniaturisation. This study presents a numerical investigation of fluid flow and heat transfer in wavy microchannel heat sinks with circular pin inserts of varying heights ranging from 0 to 0.4 mm. A 3D conjugate heat transfer model was developed in ANSYS Fluent to evaluate thermal-hydraulic performance with Reynolds numbers ranging from 300 to 800. The microchannels were examined with wave amplitudes of 0, 150, and 250 μm. Water was used as the coolant and a constant heat flux of 50 W/cm2 was applied at the base of the heat sink. Key performance indicators including the Nusselt number, friction factor, and performance evaluation criterion were used to assess heat transfer enhancement and flow resistance. Results show that channel waviness significantly improves heat transfer, with the 250 μm amplitude channel outperforming the straight and 150 μm channels. Increasing pin height further enhances the Nusselt number, reaching about 15% higher than the smooth channel, although it also increases the pressure drop. The best overall thermal-hydraulic performance was obtained for a wavy microchannel with 250 μm amplitude and a pin height of 0.1 mm.

Keywords: Microchannel, Heat Sink, Pin insert, Nusselt number, Performance evaluation criteria

1. Introduction

Electronic devices have become an important part of the world today. Most modern-day items are powered using this technology, from devices as small as the phones in our pockets to the gigantic rockets that blast into space. Controlling rising temperatures becomes critical during the operation of such devices to ensure that microprocessors and electronic systems run smoothly and continuously. Researchers are in a tighter spot when it comes to cooling electronics by natural convection due to the ever-increasing compactness of electronic systems. This can result in a hot spot, which may cause the system to fail or ignite. Consequently, thermal management is a critical component of achieving the intended performance within the specified operating conditions. It is anticipated to be a significant challenge for a variety of electronic technologies in the near future [1,2].

 Online ISSN 2603-459X

There are two main approaches to optimising the thermal-hydraulic performance of microchannel heat sinks, which are the external (active) methods and internal (passive) methods. The external method involves using sources of energy to modify the microchannel's fluid flow characteristics. This approach includes the vibration of the working fluid and the application of electrostatic fields. Internal methods involve altering the fluid used or the microchannel design, which includes the microchannel cross-section, waviness, and inserts in the flow path [3]. Kaewchoothong & Gonsrang [4] numerically examined the thermal-hydraulic performance of air-cooled microchannels that were furnished with curved pin-fins with multi-convex profiles. The simulations were conducted, with a uniform heat flux applied to both the fin surfaces and the end wall. The findings indicated that the internal flow was significantly altered by the introduction of cross-sectional convexity, which resulted in impingement enhancement, secondary vortices strengthening, and wake region suppression. Zhong et al. [5] conducted numerical simulations of the heat transfer process in microchannels with fully walled channels under the laminar flow regime. The heat flux was 100 W/cm^{2}, and the inlet Reynolds number ranged from 300 to 800. Their results demonstrated a considerable improvement in the heat transfer process in the fully wavy wall microchannels as compared with the smooth wall microchannels, yet there was an associated rise in the flow resistance. Nevertheless, the overall performance was enhanced.

Several research have been conducted on the effects that obstructions in the form of pin inserts have on the heat transfer performance of wavy microchannels. This has helped in the effort to make the microchannel heat sinks more efficient. Nevertheless, research on the effects of pin heights in wavy microchannels is limited, resulting in a gap that requires additional investigation. Hence, this research work looks to perform a numerical assessment and characterize the thermal-hydraulic performance of microchannels with pin inserts of varying heights.

2. Methodology

2.1 Geometry of the Model

The microchannel heat sink has, as shown in Fig. 1, a geometry of 25 mm by 25 mm. It consists of 60 individual channels of both straight and wavy geometry. Each microchannel has a constant width, W_c of 200 μm, a height, H_c of 400 μm, and a length of 25 mm. The substrate thickness, that is the width of the bottom wall is given as 100 μm, while the microchannel wall half-thickness is 100 μm.

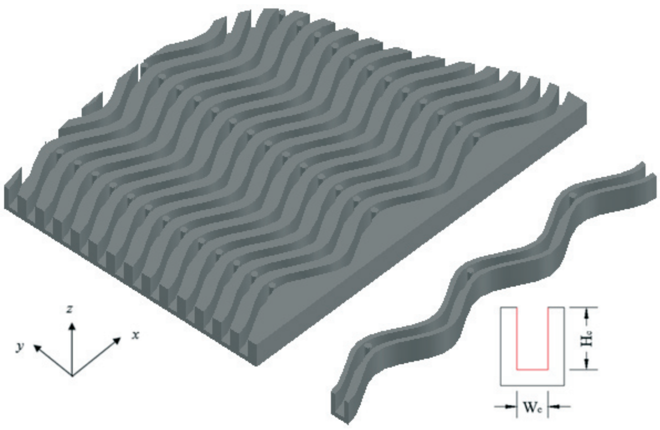

Fig. 1: Schematics of cut-section of the wavy microchannel heat sink, and its computational unit with pin inserts.

$$y = A\sin\left(2\pi\frac{x}{\lambda}\right) \tag{1}$$

where A is the amplitude and varies between values of either 150 or 250 μm, while the straight channel was assumed to have its amplitude equal to 0 μm. Each wavy microchannel consists of ten periodic wavy units with a wavelength, λ, of 2.5 mm.

The pin inserts are circular in geometry and have a constant width of 133 μm. They are 10 in number and are placed at one wavelength interval along the length of the channel. The height of the pin insert, however varies for various cases: 0 μm (channel floor without pin), 100, 132, 200, 300, and 400 μm. This corresponds to 0, ¼, ⅓, ½, ¾ and full height of the channel. The heat sink is made of copper, and the coolant used to remove heat load from the microchannel is water.

2.2 Governing Equations

The heat sink's cooling performance was investigated using a three-dimensional solid-fluid conjugate heat transfer model. The governing equations for the heat transfer and flow can be expressed as follows:

Mass conservation equation:

$$\nabla.\left(\rho u\right) = 0 \tag{2}$$

Momentum equation:

$$\left(u.\nabla\right)\rho u = -\nabla p + \mu\nabla^2 u \tag{3}$$

Energy equation:

$$u.\nabla T = \frac{k}{\rho c_p}\nabla^2 T \tag{4}$$

and the energy equation for the solid domain is

$$\nabla^2 T = 0 \tag{5}$$

2.3 Boundary Conditions and Numerical Setup

The outlet pressure was specified as one standard atmospheric pressure. A uniform heat source with a constant heat flux of 50 W/cm² was applied to the bottom wall of the heat sink. The other walls were assumed to be adiabatic. Temperature and heat flux were also assumed to be continuous at the fluid-solid interfaces.

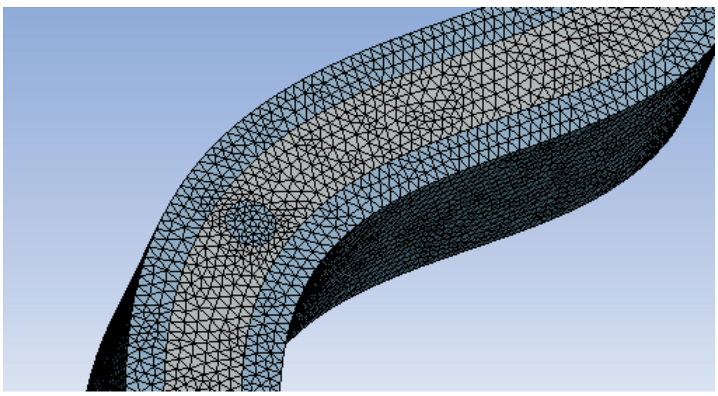

Fig. 2: Mesh distribution of the computational domain

The momentum and energy governing equations were discretized using the second-order upwind method within ANSYS Fluent 22. To connect the pressure and velocity components, the SIMPLE algorithm is employed. The momentum and pressure-based continuity equations were all solved using the SIMPLE technique. The residuals have convergence conditions of the order of 10e-6 for energy, velocity, and continuity parameters. A mesh size of 0.03 mm was used, and to ensure a high-quality mesh across the entire domain, edge sizing and tetrahedron meshing were employed in the solid geometry, while the quadrilateral and hexagonal mesh methods were used for the fluid domain (Fig. 2).

2.4 Data Reduction

To evaluate the thermal-hydraulic performance of the microchannel, the average Nusselt number and friction factor of the microchannel heat sink were estimated as follows [7,8]:

The Nusselt number:

$$Nu = \frac{hD_h}{k} \tag{6}$$

The friction factor

$$f = \frac{\left({dp}/{dx} \right) D_h}{0.5 \rho U^2} \tag{7}$$

The average heat transfer coefficient is evaluated from

$$h = \frac{q}{N\left(A_{cb} + A_{cs}\right)\left(T_w - T_m\right)} \tag{8}$$

where N represents the total number of microchannels for a heat sink, Acb is the bottom surface area of the microchannel, Acs is the other areas available for convection in a single microchannel, Tw stands for average wall temperature, and Tm is the mean fluid temperature.

The thermal-hydraulic performance of a microchannel can be measured using a metric called Performance Evaluation Criteria (PEC). This combines the Nusselt number and the friction factor of the microchannel as such:

$$PEC = \frac{{Nu}/{Nu_0}}{\left({f}/{f_0} \right)^{1/3}} \tag{9}$$

3. Results and Discussion

3.1 Validation

The accuracy of the numerical method used for solving flow and heat transfer in wavy microchannels was validated using the same geometrical detail and operating conditions as the experimental work reported by Sui et al. [6]. Numerical methods were used to find out the Nusselt number and friction factor. Figs. 3 and 4 present the Nusselt number and friction factor of the numerical study as against the experimental work. There is a variation of 10-15% for the Nusselt number and 5-10% for the friction factor. The deviations do not fall short of those observed for similar numerical components of the same study by Sui et al. [6].

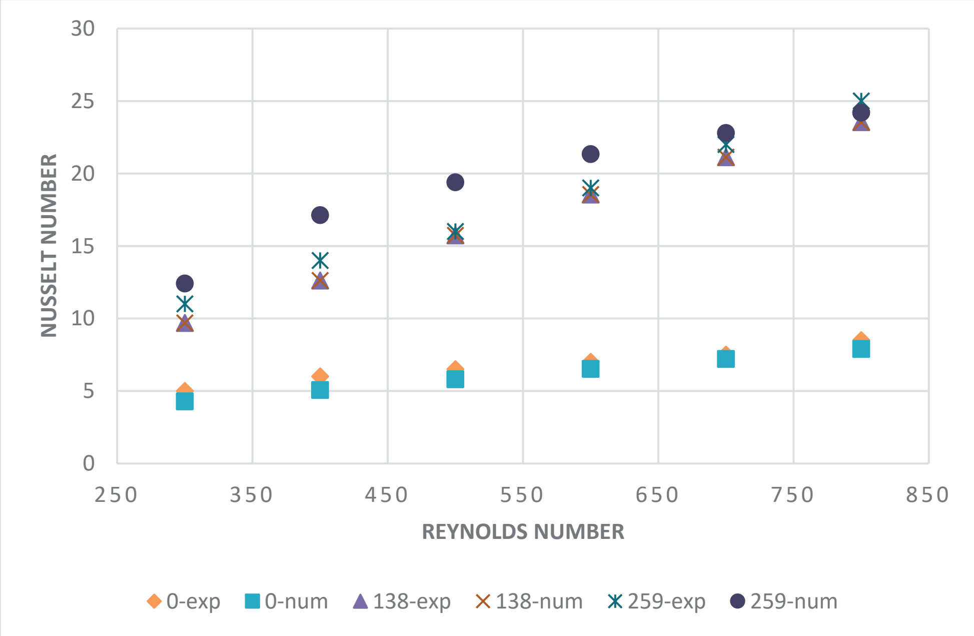

Fig. 3: Nusselt number validation

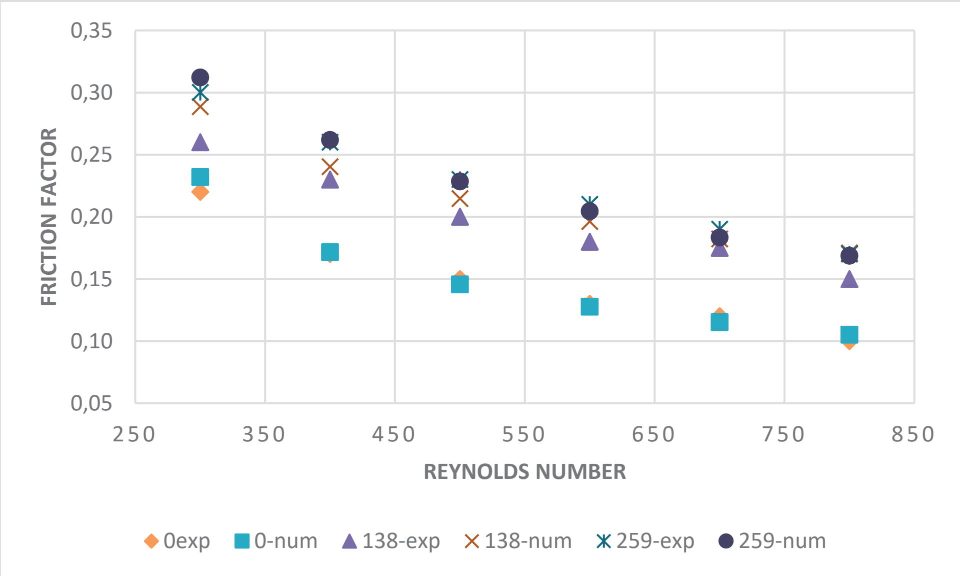

Fig. 4: Friction factor validation.

3.2 Velocity Distribution

Fig. 5 shows the plots of velocity at various sections, namely: 6.25, 12.5, and 18.75 mm. It also shows the pin inserts at heights of 0.1, 0.2, and 0.3 mm, respectively. The pin insert causes a flow obstruction, and flow velocity increases at the obstruction and normalizes in the unobstructed regions. This is to adhere to the law of conservation of mass. This expansion and reduction contribute to the heat-transfer capability of the microchannel.

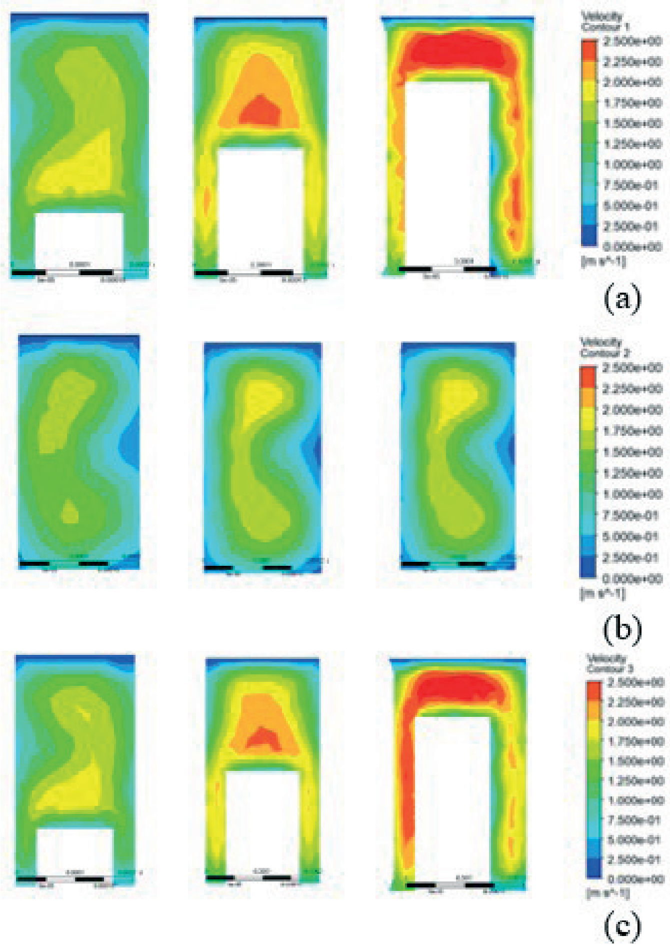

Fig. 5: velocity plots at cross-sections of microchannels with pin height of 0.1mm, 0.2mm, 0.3mm at (a) 6.25 mm, (b) 12.5 mm, (c) 18.75 mm along the microchannel length

3.3 Heat Transfer

This numerical analysis analyses the heat transfer capabilities of the microchannel with pin heights of 0.1, 0.2, 0.3, and 0.4 mm over a Reynolds number range of 300-800. Fig. 6 shows channels with a pin height of 0.4mm. The 250 μm channel features a higher Nusselt number with a 20% increase compared to the 0 μm channel. The Nusselt number of the 150 μm channel is 12% larger than that of the straight (0 μm) channel. It can be deduced that an increase in the wavelength of the channel causes an increase in the Nusselt number.

Also, increasing the pin height results in an increase in the Nusselt number, as shown in Fig. 7, which compares the varying heights of pin inserts in a microchannel of wavelength 250 μm. When compared to the 250 μm microchannel with a pin height of 0 mm (without pin), the Nusselt number increases by 9, 13, 15, and 15% for pin heights of 0.1, 0.2, 0.3, and 0.4 mm, respectively

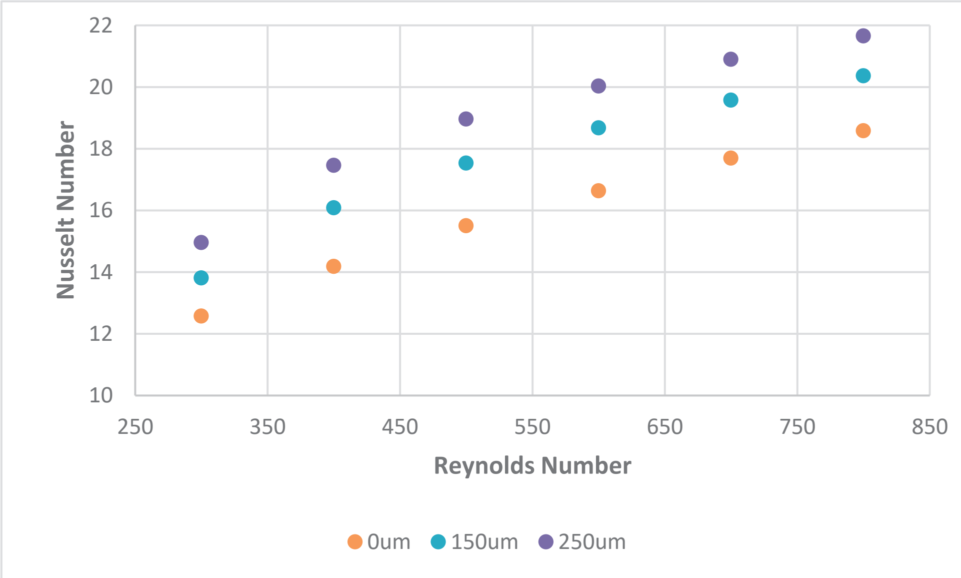

Fig. 6: Nusselt number of microchannels with pin height of 0.4mm

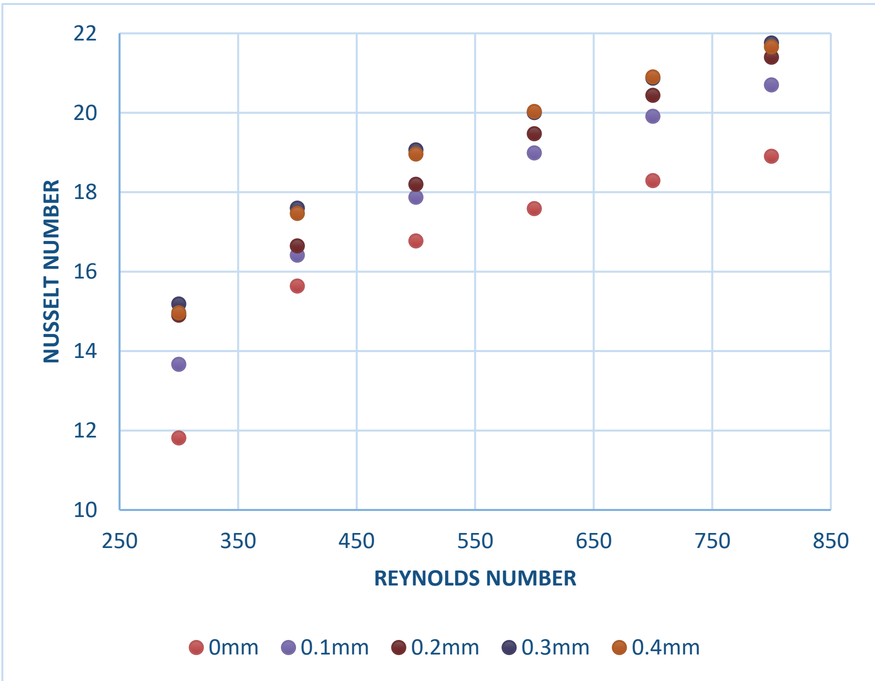

Fig. 7: Nusselt number of microchannels with wavelength 250µm

3.4 Friction Factor

The friction factor is a measure of the resistance to the flow of fluid in a channel. Comparison of the flow friction capabilities of the microchannel with pin heights of 0.1, 0.2, 0.3, and 0.4 mm over a Reynolds number range of 300-800. From Fig. 8, the friction factor of microchannels with pin inserts of 0.4 mm. It can be seen that the friction factor decreases with an increase in Reynolds number. However, the friction factor increases with increased wavelength. The 150 µm channel has a 5% difference from the 0 µm channel, while the 250 µm channel has a 12% difference.

Fig. 9 shows that the pin inserts of 0.4mm have the highest friction factor recorded. The smooth channel has the lowest friction factor, which implies the lowest pressure drop. There is a 20%, 59%, 117% and 220% increase for the 0.1, 0.2, 0.3, and 0.4 mm pin insert, respectively.

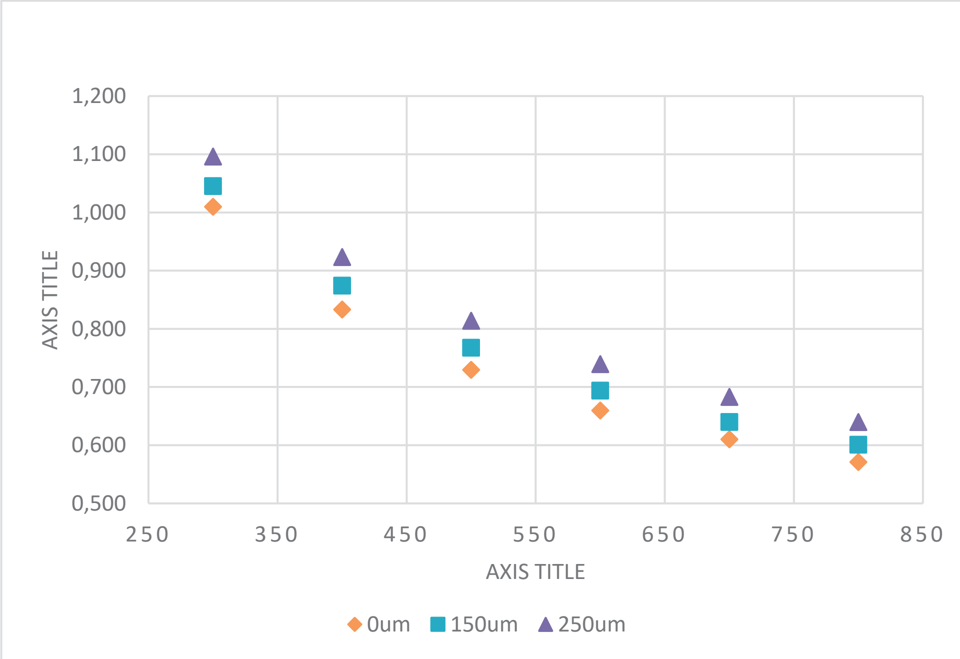

Fig. 8: Friction factor of microchannels with pin height of 0.4mm

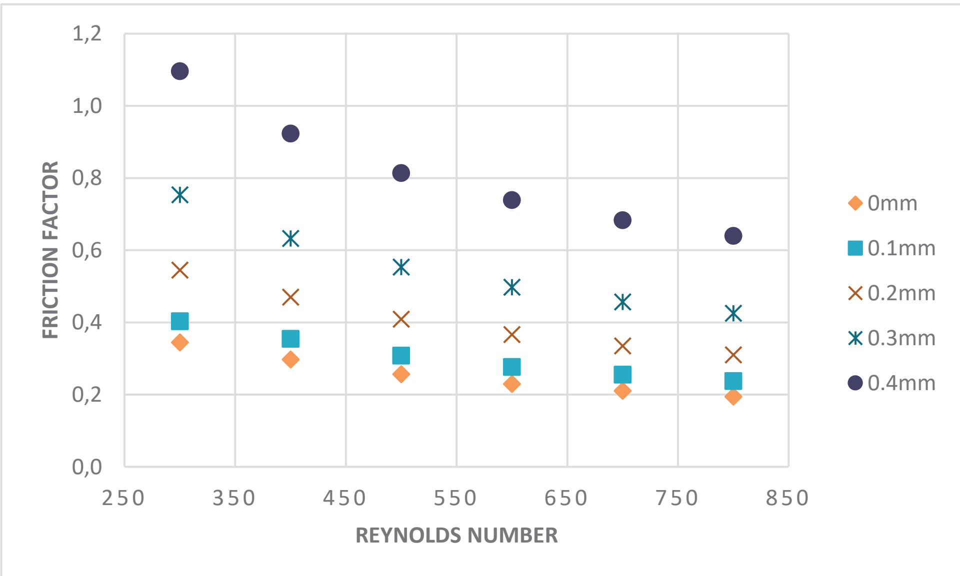

Fig. 9: Friction factor of microchannels with a wavelength of 250μm

3.5 Thermal-Hydraulic Performance

The PEC essentially evaluates the Nusselt Number, which represents the effectiveness of heat transfer in the microchannel, and compares it with the friction factor, which represents the resistance to flow in the microchannel. The PEC values show how the heat transfer and pressure drop performance of the wavy microchannel varies with different geometrical parameters. A higher PEC value indicates a more efficient heat exchanger, as it implies a better heat transfer performance relative to the pressure drop penalty. As indicated in Fig. 10, it is shown that the PEC values increase with respect to increasing wavelength and reduce as the Reynolds number increases. The highest peak seen is at Reynolds number of 300 and an amplitude of

250 μm. Fig 11 shows PEC values of a microchannel of wavelength 250 μm. It is seen that the higher the height of the pin insert, the lower the value of the PEC. Higher PEC values are seen at microchannels with no pin insert or a pin height of 0.1 mm.

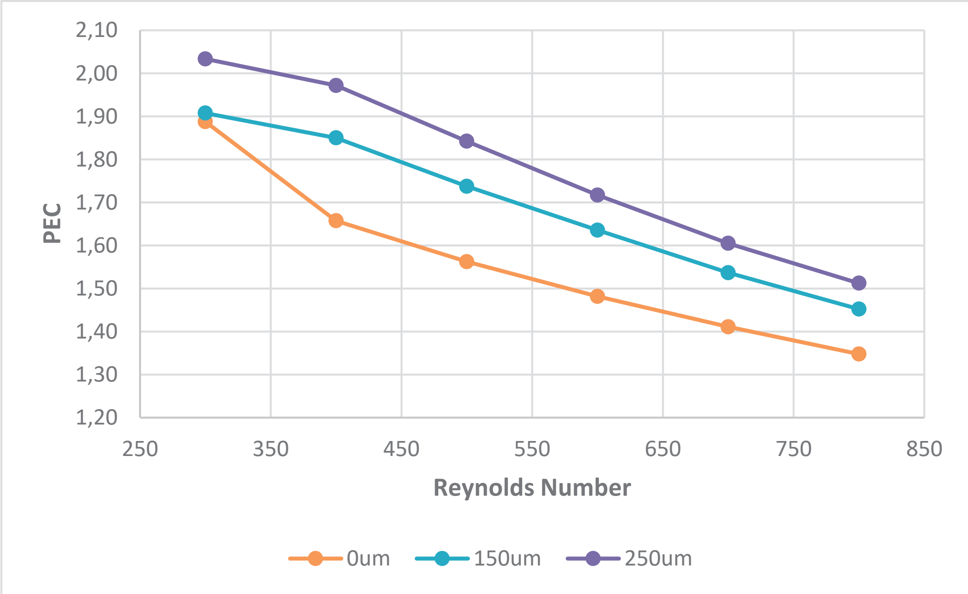

Fig. 10: PEC of microchannels with a pin height of 0.4 mm

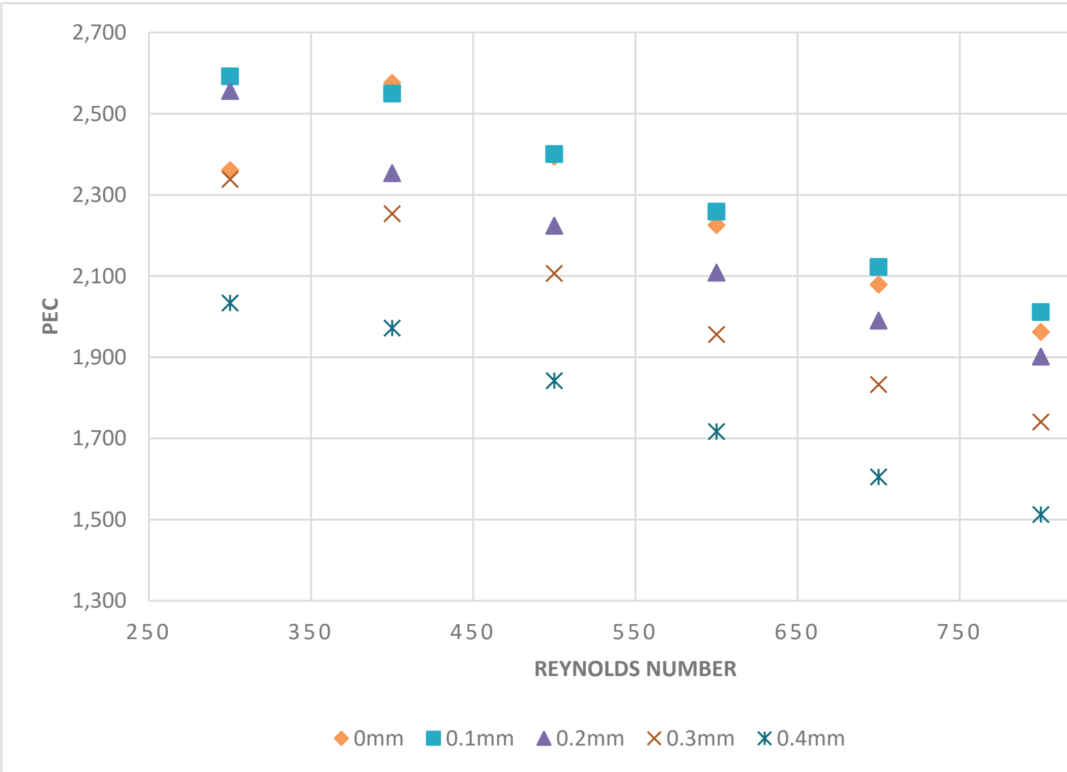

Fig. 11: PEC of microchannels with a wavelength of 250 μm

4. Conclusions

The fluid flow and heat transfer characteristics of a wavy microchannel with pin insert heights of 0.1, 0.2, 0.3, 0.4 mm were numerically carried out in this study. For each of these channels, the overall thermal-hydraulic performance with wavelengths of 2.5 mm and wave amplitudes 0, 150, and 250 μm was carried out. The results showed that the waviness had a positive effect on thermal performance, with the 250 μm microchannel having better performance than the straight and 150 μm channels.

The results also showed that the higher the height of the pin insert, the better the thermal performance of the channel. The peak performance was obtained for a pin height of 0.4 mm, which is 15% higher than that of the smooth channel. The pressure drop, however, was at its best performance in smooth channels. It is discovered that the presence of pin inserts causes a drop in pressure, with the highest pressure drop recorded for pin inserts of height 0.4 mm. In terms of overall thermal-hydraulic performance, the microchannel with a wavelength of 250 μm and a height of 0.1 mm. offers the best performance. Future work should focus on the real-world implementation of the proposed geometry, including the impact of manufacturing tolerances.

References

1. Gönül A (2025) Enhancement of heat transfer characteristics in wavy microchannel heat sinks with streamlined micropins within convergent-divergent flow passages. *Appl Therm Eng* 258: 124574.

2. Kumar M, Gupta R (2022) Case Studies in Thermal Engineering Numerical investigation of the performance of rectangular micro-channel equipped with micro-pin-fin. *Case Stud Therm Eng* 32: 101884.

3. Hajialibabaei M, Saghir MZ (2022) A critical review of the straight and wavy microchannel heat sink and the application in lithium-ion battery thermal management. *Int J Thermofluids* 14: 100153.

4. Kaewchoothong N, Gonsrang S (2026) Thermal – fluid optimization in hybrid microchannels : Merging wavy wall patterns with curved pin-fin arrays. *Appl Therm Eng* 288: 129515.

5. Zhong S, Zhang C, Fan A (2025) Numerical study on heat transfer enhancement of laminar flow in fully wavy wall microchannels. *Appl Therm Eng* 266: 125782.

6. Sui Y, Lee PS, Teo CJ (2011) An experimental study of flow friction and heat transfer in wavy microchannels with rectangular cross section. *Int J Therm Sci* 50: 2473–2482.

7. Lin L, Zhao J, Lu G, et al. (2017) Heat transfer enhancement in microchannel heat sink by wavy channel with changing wavelength/amplitude. *Int J Therm Sci* 118: 423–434.

8. Oyewola OM, Petinrin MO, Sanusi HO (2023) Flow and Heat Transfer Characteristics in Channels With Piriform Dimples and Protrusions. *Front Heat Mass Transf* 20.