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Research article

Numerical simulation of heat transfer and pressure drop in fluid flow through conical microchannels

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Abstract

This study presents a numerical investigation of laminar flow and heat transfer in conical microchannels using computational fluid dynamics (CFD). The performance of the microchannel is examined over a range of Reynolds numbers, as well as different inlet, outlet, and total channel lengths. The results show that the pressure drop exhibits a coupled dependence on both inlet length and Reynolds number. Increasing the inlet length leads to an average reduction of 19% in pressure drop for every 1-mm increase, whereas increasing the Reynolds number produces an average increase of 37.5% for every 300-unit increment. The heat-transfer coefficient decreases with increasing inlet length but increases with increasing Reynolds number. On average, a 300-unit rise in Reynolds number leads to a 10.17% increase in the heat-transfer coefficient, while a 1-mm increase in inlet length results in a 52.5% decrease. The temperature difference between the inlet and outlet is found to be primarily governed by the Reynolds number, with negligible sensitivity to inlet length; for every 300-unit increase in Reynolds number, this temperature difference decreases by approximately 25%. The outlet length also influences both pressure drop and heat-transfer coefficient, following similar trends: a 300-unit increase in Reynolds number results in an average increase of 55.73% in pressure drop and 10.32% in heat-transfer coefficient. Overall, the results demonstrate that geometric variations and flow conditions significantly affect the hydrodynamic and thermal behavior of conical microchannels, providing useful insights for the design and optimization of micro-scale thermal systems.

Keywords: Microchannels, Heat transfer, Pressure drop, Reynolds number, Constant heat flux, Numerical simulation.

1- Introduction

With advancements in technology across various fields, microchannels have emerged as essential components for a wide range of applications. The trend towards miniaturization necessitates effective management of heat flux to ensure the reliability and stability of devices, particularly in sectors such as medical technology and microelectro mechanical systems (MEMS) [1]. Efficient heat removal is crucial for the performance of central processors, as operating at elevated temperatures can lead to immediate failures and significantly reduce their lifespan. In extreme cases, overheating can even result in complete failure or melting of the processor on the mainboard [2]. As technology continues to evolve and devices become increasingly compact, the demand for effective heat dissipation solutions such as microchannel heat sinks will intensify [3].

Heat sinks are pivotal in dissipating thermal loads, and innovative designs, including corrugated and convergent channels, have been shown to enhance heat transfer rates and cooling performance. For instance, Monavari et al. [4] investigated the thermal and hydrodynamic behavior of cooling fluids in heat sinks that combined corrugated and convergent microchannels. Their findings indicated that while channel corrugation can significantly improve heat transfer performance, there is a threshold beyond which additional corrugation does not yield further benefits.

Hosseini et al. [5] investigated the behavior of micron-sized suspended particles (10–19 μm) in straight microchannels by examining the combined effects of inertial and Magnus forces using a quasi-3D simulation approach, which reduced computational time by 88%. Their results showed that increasing the particle diameter and Reynolds number accelerates the attainment of equilibrium particle trajectories, while variations in the channel aspect ratio alter the lateral equilibrium positions of the particles within the flow.

Sanei et al. [6] examined the influence of aluminum oxide nanoparticles on forced convection heat transfer rates in laminar flow through microchannels. Their simulations, based on a single-phase model and finite difference method, demonstrated that increasing nanoparticle concentration and Reynolds number significantly enhanced the average Nusselt number and heat transfer rates.

Joseph and Tom [7] focused on an immiscible liquid-liquid system for reactive extraction, emphasizing the effectiveness of slug flow patterns in microreactors. Their study achieved a 2.2 to 2.3-fold improvement in extraction efficiency under specific ultrasonic conditions, highlighting the active effects in laminar flow regimes. Chandra et al. [8] numerically studied the hydrodynamics of two-phase flows in Y-connecting microchannels, revealing that slug volumes decrease linearly with increasing flow rates, with more pronounced effects observed in smaller hydraulic diameters.

Lin et al. [9] conducted a numerical investigation of flow boiling on microfin, microporous, and smooth surfaces in microchannels, finding that microfin surfaces significantly enhance heat transfer coefficients compared to smooth surfaces due to capillary effects and induced vortices from nucleated bubbles.

Given the wide range of emerging applications of microchannel technologies, there is a continuing need to investigate the behavior of different fluid types—including single-phase, multiphase, Newtonian, and non-Newtonian flows—within these confined geometries. Conical microchannels are particularly attractive in space-limited applications. For instance, in drug-delivery and microneedle systems, a conical geometry enables localized and controlled transport of therapeutic agents from the wider inlet region toward the targeted tissue near the tip [10,11]. Likewise, in precision manufacturing and microscale cooling, converging conical channels can operate as miniature nozzles that generate focused fluid jets to enhance heat removal and improve tool performance. These examples highlight the functional advantages of conical microchannel configurations in practical engineering and biomedical systems.

The operational efficiency of these conical microchannels is influenced by their geometric dimensions, including length, angle, and inlet/outlet widths, which directly affect heat transfer and pressure drop characteristics. Despite the significance of these factors, there has been limited research on the impact of geometric parameters on heat transfer and pressure drop in conical microchannels. Previous studies have primarily concentrated on enhancing heat transfer through methods such as nanoparticle addition, fin enhancement, and surface modification, with insufficient attention given to the geometric influences on single-phase flow dynamics. Therefore, this research aims to numerically investigate the effects of geometric dimensions on heat transfer rates and pressure drop in conical microchannels.

2- Numerical simulation

2-1- Problem description

The present study investigates laminar fluid flow and convective heat transfer within a two-dimensional microchannel by numerically solving the governing conservation equations of mass, momentum, and energy. The computational domain consists of an inlet section with a length of 4.5 mm, an outlet section with a length of 3.5 mm, and a channel height of 1000 mm. The geometry is modeled as a two-dimensional representation of the microchannel cross-section to reduce computational cost while preserving the essential flow and thermal characteristics.

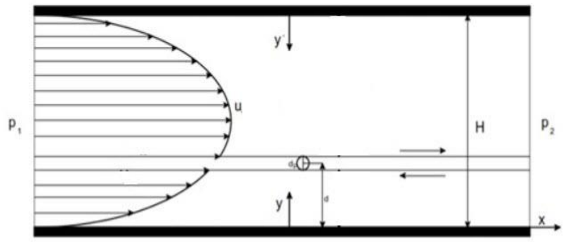

Fig. 1 Schematic figure of investigated geometry

The simulation framework is based on the following assumptions. The flow is considered steady-state, laminar, single-phase, Newtonian, and incompressible, with constant thermophysical properties throughout the domain. Thermal effects arising from natural convection, radiation heat transfer, and viscous dissipation are neglected. The walls of the microchannel are assumed to be impermeable and subject to a prescribed thermal boundary condition, while a uniform velocity and temperature profile are imposed at the inlet. At the outlet, a zero-gradient condition is applied for both velocity and temperature to represent fully developed flow conditions.

The numerical simulations were carried out in Fluent Software employing a pressure-based solver under laminar flow conditions. Under these assumptions, the numerical model enables a systematic investigation of the influence of geometric parameters and Reynolds number on pressure drop and heat-transfer behavior within microchannel configurations.

2-2- Governing equations

In this study, we solve the conservation equations governing mass, momentum, and energy within a two-dimensional microchannel geometry. The microchannel is characterized by an inlet length of 4.5 mm, an outlet length of 3.5 mm, and a height of 1000 mm. Several assumptions underpin the simulation framework: the solution field is strictly two-dimensional, the fluid is treated as Newtonian and incompressible, and its properties remain constant despite temperature variations. Additionally, heat transfer mechanisms such as radiation and natural convection are disregarded, and the flow is assumed to be single-phase, steady-state, and laminar. The governing equations can be expressed as follows: the mass conservation equation ensures mass continuity, the momentum conservation equation (Navier-Stokes) accounts for fluid motion, and the energy conservation equation describes thermal dynamics in the system [12].

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

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

$$\rho C_p\left(\vec{u}.\nabla\right)T=k\nabla^2 T \tag{3}$$

2-3- Boundary condition

For the numerical solution, we employ the Coppel algorithm to establish a relationship between pressure and velocity, while the upper quadratic method is utilized to separate terms in the conservation equations for effective numerical integration [13]. Boundary conditions are crucial for accurately modeling the system: at the inlet, we impose hydrodynamic conditions with a specified inlet velocity $u=V_{in}$, $v=0$, and a constant temperature T=300K. A constant heat flux boundary condition of $q_w=23800\ W/m^2$ is applied at the wall, while the outlet boundary is defined with a gauge pressure of $P_{gage\ out}$=0. The working fluid in this study is pure water, characterized by the following properties [14]: density of 997 kg/m³, viscosity of 0.0008542 Pa·s, thermal conductivity of 0.5979 W/(m·K), and specific heat capacity of 4179 J/(kg·K).

2-4- Grid convergence and validation

To ensure the reliability and independence of the simulation results, we employ the Grid Convergence Index (GCI) method. This approach requires the use of two or three different grid levels to assess the convergence of the numerical solution. The grid index *i* is assigned values of 3 for coarse, 2 for medium, and 1 for fine grids. The ratio of the number of cells between successive grids is defined as $r_{i-1,i}=(N_{i-1}/N_i)^{1/3}$, while the relative error is calculated as $\varepsilon_{i-1,i}=f_{i-1}-f_i\ /f_i$, where *f* represents the key parameter, specifically the pressure drop in this study [15]. Richardson extrapolation is then applied to obtain the exact value of (*f*) as the distance between grid levels approaches zero [16].

$$f_{exact}=f_1+\frac{f_1-f_2}{r_{12}^P-1} \tag{4}$$

$$GCI_{i-1,i}^{fine}=\frac{F_s\left|\varepsilon_{i-1,i}\right|}{r_{i-1,i}^P-1} \tag{5}$$

The GCI is calculated using a confidence factor (F_s = 1.25) and an apparent degree of separation *P*, determined through an iterative process.

$$P=\omega P+(1-\omega)\frac{\ln\beta}{\ln r_{12}},(\omega=0.5) \tag{6}$$

$$\beta=\left(r_{12}^P-1\right)e_{23}\Big/\left(r_{23}^P-1\right)e_{12} \tag{7}$$

$$e_{i-1,i}=f_{i-1}-f_i \tag{8}$$

The absolute error $e_{i-1,i}$ between grid levels is used to verify grid independence, with the criterion that if (α≈1), the grid is considered sufficiently fine. Table 1 summarizes the parameters related to the GCI method, including grid sizes, the number of cells, pressure drops, and calculated errors.

$$\alpha = \frac{r_{12}^{P} GCI_{12}^{fine}}{GCI_{23}^{fine}} \tag{9}$$

The results indicate that the coefficient α is close to one, confirming grid independence. Furthermore, the small differences in pressure drop results between the fine, medium, and coarse grids suggest that the medium grid is adequate for further simulations.

To assess the reliability of the numerical model, the simulation results were validated against the experimental data reported by Briclot et al. [17]. In their study, the authors examined the thermal and hydrodynamic behavior of Al_2O_3–water nanofluid flow in a microchannel over a range of Reynolds numbers spanning the laminar–turbulent transition region, providing detailed measurements of pressure drop and heat transfer characteristics. The close agreement between our numerical predictions and the reported experimental trends confirms the accuracy of the present simulation framework for modeling laminar microchannel flows. As shown in Table 2, the estimated pressure drop from our simulation aligns reasonably well with the experimental values, demonstrating the effectiveness of our numerical approach. This validation reinforces the reliability of the simulation results for predicting fluid dynamics and heat transfer in the microchannel under the specified conditions.

3- Result and discussion

Figure 2 illustrates the relationship between pressure drop and inlet height in the microchannel, with the outlet height held constant at 3.5 mm across various Reynolds numbers. The data reveal a clear trend: as the inlet length of the microchannel increases, the pressure drop consistently decreases. This behavior can be attributed to the reduced fluid velocity and turbulence as the flow path lengthens, allowing for a smoother flow profile and less resistance. Conversely, the pressure drop exhibits a significant increase with higher Reynolds numbers, which is expected due to the increased inertial forces dominating over viscous forces in the fluid. Specifically, our analysis shows that for every increase of 300 units in the Reynolds number, there is an average increase of approximately 37.5% in the pressure drop.

Moreover, the results indicate that for each 1 mm increment in the inlet length, the pressure drop decreases by about 19%. This decrease highlights the importance of microchannel design in optimizing flow characteristics; longer inlet lengths can effectively mitigate pressure losses, thereby enhancing overall system efficiency. These findings emphasize the critical interplay between microchannel geometry and flow dynamics, providing valuable insights for the design of more efficient microfluidic systems.

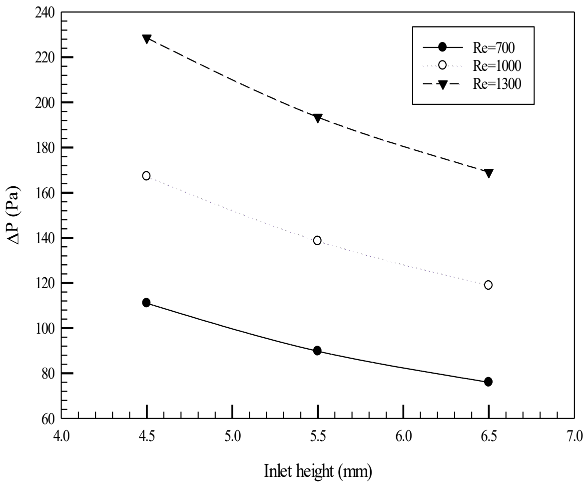

Fig. 2 Pressure drop variation with inlet length.

Table 1: Parameters related to the GCI method

α	$GCI_{i-1,i}^{fine}$	$r_{i-1,\,i}$	$\lvert\varepsilon_{i-1,\,i}\rvert$	Pressure drop (Pascal)	Number of cells	Grid size
0.9788	4.31	1.83	0.0212	96.91	2500	Coarse (*i*=3)
	1.57	1.89	0.0641	103.55	9000	Medium (*i*=2)
	-	-	-	105.79	30000	Fine (*i*=1)
Difference between fine and medium grid: 2.12%						
Difference between medium and coarse grid: 6.41%						
Exact solution of pressure drop based on Richardson extrapolation: 107.12						
Difference between medium grid and exact solution: 3.33%						

Table 2: Validation of the results of the solution

Ref.	[17]	present study
Pressure drop	110.25	103.55
Reynolds number: 700, Working fluid: water-aluminum oxide 4% , Wall temperature: flux 23800 W/m2 (constant).		

Figure 3 demonstrates the variation of the convective heat transfer coefficient as a function of the inlet height of the microchannel, while maintaining a constant outlet height of 3.5 mm across various Reynolds numbers. The data reveal a notable trend: as the inlet length of the microchannel increases, the convective heat transfer coefficient decreases. This reduction can be attributed to the longer flow path, which leads to increased thermal resistance and less efficient heat transfer between the fluid and the channel walls. In contrast, as anticipated, the convective heat transfer coefficient exhibits an increase with rising Reynolds numbers. This trend is consistent with the observed behavior of pressure drop; higher Reynolds numbers indicate a more turbulent flow regime, enhancing the mixing of fluid layers and promoting better heat transfer.

Quantitatively, our analysis indicates that for every increase of 300 units in the Reynolds number, the convective heat transfer coefficient experiences an average increase of approximately 10.17%. This relationship underscores the significance of flow dynamics in influencing thermal performance within microchannels. Conversely, the results also show a substantial decrease of about 52.5% in the heat transfer coefficient for each 1 mm increase in inlet length. This stark contrast highlights the critical role of microchannel design parameters in optimizing heat transfer efficiency. Overall, these findings emphasize the intricate balance between flow characteristics and thermal performance, providing essential insights for the development of more effective microfluidic systems.

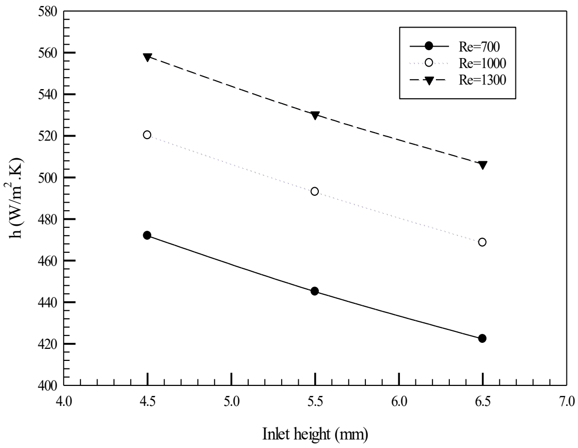

Fig. 3 Variation of convective heat transfer coefficient with inlet height.

The simulation results indicate that the temperature difference between the inlet and outlet of the microchannel is independent of the inlet length, depending solely on the Reynolds number. This relationship is clearly illustrated in Fig. 4. Specifically, for Reynolds numbers of 700, 1000, and 1300, the observed temperature differences between the inlet and outlet are 19 °C, 13 °C, and 10 °C, respectively. This data reveals an average reduction of 34.5% in temperature difference as the Reynolds number increases.

The observed trend can be attributed to the constant heat flux boundary condition applied in the model. As the Reynolds number rises, the convective heat transfer coefficient also increases, enhancing the efficiency of heat transfer from the fluid to the surrounding environment. Consequently, this improved heat transfer leads to a smaller temperature gradient between the inlet and outlet. The results underscore the critical role that flow dynamics play in thermal performance within microchannels, highlighting how higher flow rates can facilitate more effective thermal management. Overall, the findings suggest that optimizing the Reynolds number can significantly influence thermal outcomes in microchannel systems, making it a vital consideration in the design and operation of such devices.

Figure 5 presents the relationship between pressure drop and outlet height of the microchannel, maintaining a constant inlet height of 4.5 mm across various Reynolds numbers. The data reveal a significant trend: as the outlet height increases, the pressure drop consistently decreases. This behavior can be attributed to the reduced resistance to flow as the cross-sectional area of the outlet expands, allowing the fluid to exit the microchannel more easily. Conversely, as expected, the pressure drop increases with rising Reynolds numbers. This increase is due to the greater inertial forces at higher velocities, which enhance turbulence and frictional losses within the channel.

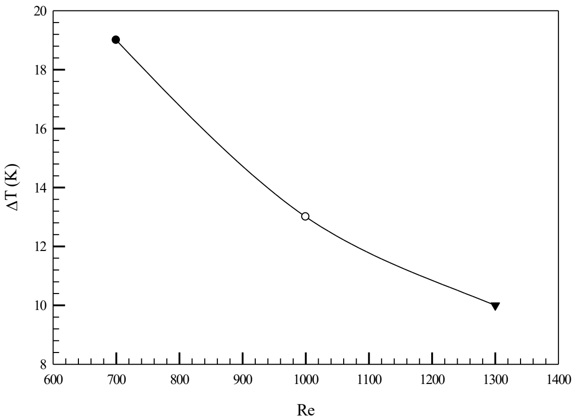

Fig. 4 Variations in temperature difference with Reynolds number.

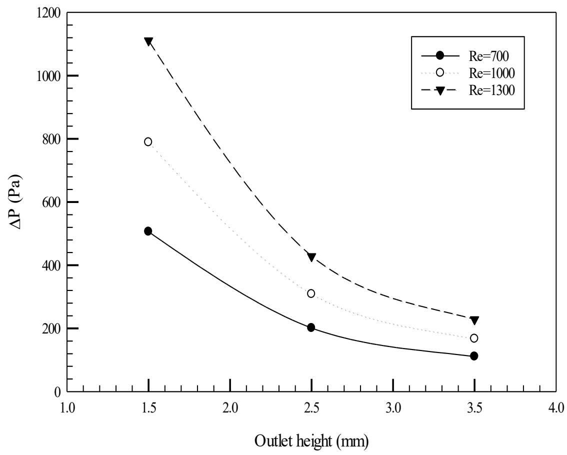

Fig. 5 Pressure drop variation with microchannel outlet height.

Quantitatively, the analysis indicates that for every increase of 300 units in the Reynolds number, there is an average increase of approximately 55.73% in the pressure drop. This substantial increase underscores the impact of flow regime changes on pressure losses in the microchannel. Additionally, the results show a notable decrease of about 60.19% in pressure drop for each 1 mm increase in outlet height. This decrease emphasizes the importance of outlet design in optimizing flow characteristics and minimizing pressure losses. Overall, these findings highlight the critical interplay between microchannel geometry and fluid dynamics, providing valuable insights for the design of more efficient microfluidic systems. By carefully considering both inlet and outlet dimensions, engineers can significantly enhance the performance and efficiency of microchannel applications.

Figure 6 shows the variation of the convective heat transfer coefficient with respect to the microchannel outlet length, while maintaining a constant inlet height of 4.5 mm across different Reynolds numbers. The data indicate a clear trend: as the outlet length of the microchannel increases, the convective heat transfer coefficient decreases. This decline can be attributed to the increased thermal resistance associated with longer flow paths, which reduces the efficiency of heat transfer between the fluid and the channel walls. In contrast, as anticipated, the heat transfer coefficient increases with rising Reynolds numbers. This increase is a result of enhanced turbulence in the flow, which promotes better mixing and more effective heat transfer.

Quantitatively, the analysis reveals that for every increase of 300 units in the Reynolds number, there is an average increase of approximately 10.32% in the convective heat transfer coefficient. This relationship underscores the significance of flow dynamics in influencing thermal performance within microchannels. Conversely, the results also indicate that a 1mm increase in the microchannel outlet length leads to a substantial decrease of about 56.6% in the heat transfer coefficient. This dramatic reduction highlights the critical impact of outlet design on thermal efficiency. Overall, these findings emphasize the intricate balance between microchannel geometry and thermal performance. By optimizing both the outlet length and the Reynolds number, engineers can significantly enhance the effectiveness of heat transfer in microfluidic systems, leading to improved performance in various applications.

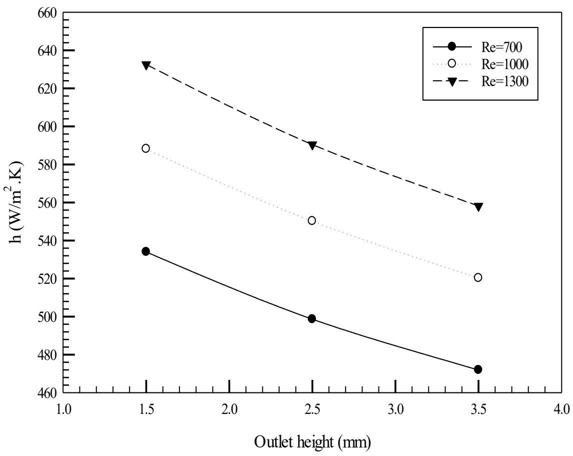

Fig. 6 Changes in heat transfer coefficient according to the length of the microchannel outlet.

The findings from this study indicate that, consistent with previous observations, the temperature difference between the inlet and outlet of the microchannel is independent of the outlet length and is determined solely by the Reynolds number. Specifically, for Reynolds numbers of 700, 1000, and 1300, the temperature differences recorded between the inlet and outlet are 19 °C, 13 °C, and 10 °C, respectively. This pattern reinforces the notion that flow dynamics, particularly those associated with varying Reynolds numbers, play a crucial role in influencing thermal gradients within the microchannel.

Figure 7 explains the variations in pressure drop as a function of microchannel length. In constructing these graphs, it is important to note that the inlet and outlet lengths are held constant at 4.5 mm and 3.5 mm, respectively. Within the studied range, the results reveal a significant trend: for every increase of 300 units in the Reynolds number, there is an average increase of approximately 56.5% in pressure drop. This substantial rise in pressure drop is indicative of the increased frictional losses and turbulence associated with higher flow velocities.

Moreover, the analysis shows that as the microchannel length increases from 0.5 mm to 1 mm, there is an average increase of about 77% in pressure drop across various Reynolds numbers. This dramatic increase underscores the impact of microchannel geometry on flow resistance, highlighting the importance of careful design considerations in optimizing microfluidic systems for efficient operation. Overall, these results provide valuable insights into the interplay between thermal and hydraulic performance in microchannels, emphasizing the necessity of optimizing both temperature differences and pressure drops to enhance the efficiency of microfluidic applications.

Figure 8 demonstrates the variation of the convective heat transfer coefficient with respect to microchannel length, while maintaining fixed inlet and outlet lengths of 4.5 mm and 3.5 mm, respectively, across different Reynolds numbers. The data reveal a clear trend: the heat transfer coefficient increases as the length of the microchannel increases. This enhancement can be attributed to the extended interaction time between the fluid and the channel walls, which allows for more effective heat transfer.

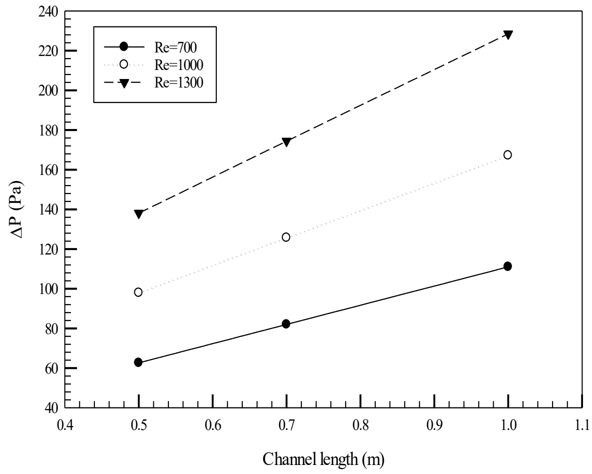

Fig. 7 Pressure drop variation with microchannel length.

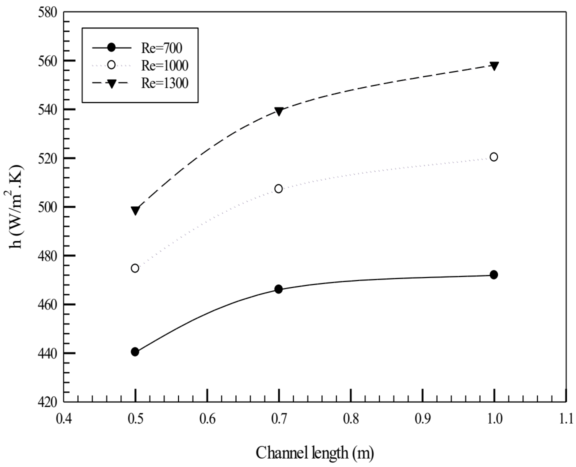

Fig. 8 Changes in heat transfer coefficient according to the length of the microchannel.

In addition to the effect of channel length, the results also confirm that the heat transfer coefficient rises with increasing Reynolds number, a relationship that is consistent with the observed trends in pressure drop. Specifically, the analysis indicates that for every increase of 300 units in the Reynolds number, there is an average increase of approximately 73.7% in the heat transfer coefficient. This significant increase highlights the role of flow dynamics in improving thermal performance, as higher Reynolds numbers typically correspond to increased turbulence and better mixing within the fluid.

Moreover, the findings show that an increase in microchannel length from 0.5 mm to 1 mm results in an average increase of about 7% in the heat transfer coefficient. This relatively modest increase suggests that while longer channels can enhance heat transfer, the incremental benefits may diminish beyond a certain length. Overall, these results underscore the importance of optimizing both the length of the microchannel and the flow conditions to maximize the convective heat transfer coefficient. By carefully considering these factors, engineers can significantly improve the thermal efficiency of microfluidic systems, leading to more effective heat management in various applications.

Figure 9 illustrates the variations in the temperature difference between the inlet and outlet flows of the microchannel, with fixed inlet and outlet lengths of 4.5 mm and 3.5 mm, respectively, across different channel lengths and Reynolds numbers. The data reveal a notable trend: as the length of the microchannel increases, the temperature difference between the inlet and outlet generally rises. This increase can be attributed to the extended residence time of the fluid within the channel, allowing for more effective heat exchange and a greater thermal gradient.

Conversely, the results indicate that as the Reynolds number increases, the temperature difference tends to decrease. Specifically, for every increase of 300 units in the Reynolds number, there is an average reduction of approximately 31.5% in the temperature difference between the inlet and outlet. This reduction is likely due to the enhanced mixing and turbulence associated with higher Reynolds numbers, which can lead to more uniform temperature distributions within the fluid and thus a smaller temperature gradient.

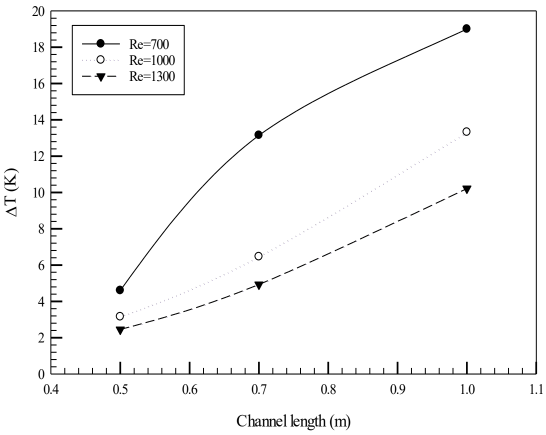

Fig. 9 Variations of the fluid temperature difference between the inlet and outlet depending on the length of the microchannel.

Furthermore, the analysis shows that when the channel length is increased from 500 mm to 1000 mm, the temperature difference increases significantly—by about five times. This dramatic rise underscores the critical impact of channel length on thermal performance, suggesting that longer microchannels can facilitate greater heat transfer efficiency under certain conditions.

Overall, these findings highlight the intricate relationship between channel geometry, flow dynamics, and thermal performance in microchannels. By optimizing both the Reynolds number and channel length, engineers can effectively manage temperature differences, leading to improved thermal efficiency in microfluidic applications.

4- Conclusion

The numerical simulations conducted in this study yielded several significant findings regarding the behavior of fluid flow and heat transfer in microchannels. One of the primary observations is that as the inlet length increases, the pressure drop across the microchannel decreases. In contrast, an increase in the Reynolds number leads to an increase in pressure drop. Specifically, for every 300 units increase in the Reynolds number, there is an average increase of 37.5% in pressure drop. Additionally, an increase of 1 mm in the microchannel inlet length corresponds to a 19% decrease in pressure drop, indicating that longer inlet lengths can enhance flow efficiency.

The heat transfer coefficient exhibits an inverse relationship with respect to the inlet length, decreasing as the inlet length increases while increasing with rising Reynolds numbers. On average, for every 300 units increase in Reynolds number, the heat transfer coefficient increases by 10.17%. However, every additional millimeter in the microchannel inlet length results in a substantial decrease of 52.5% in the heat transfer coefficient, highlighting the complex interplay between flow characteristics and thermal performance.

Interestingly, the temperature difference between the inlet and outlet is independent of the inlet length and is solely a function of the Reynolds number. The simulations indicated that for every 300 units increase in the Reynolds number, there is a 25% reduction in the temperature difference between the inlet and outlet. This finding suggests that optimizing flow conditions can significantly influence thermal gradients. Similar trends were observed regarding outlet length. As the outlet length increases, the pressure drop decreases, while an increase in Reynolds number results in a rise in pressure drop. Specifically, for every 300 units increase in Reynolds number, the pressure drop increases by 55.73%. Furthermore, a 1 mm increase in microchannel outlet length leads to a notable 60.19% decrease in pressure drop, reinforcing the importance of microchannel design in managing flow resistance.

The heat transfer coefficient also decreases with increasing outlet length, while it increases with higher Reynolds numbers. On average, for every 300 units increase in the Reynolds number, there is a 10.32% increase in the heat transfer coefficient. In contrast, for every 1 mm increase in the microchannel outlet length, the heat transfer coefficient decreases by 56.6%, further illustrating the critical balance between channel dimensions and thermal performance. The results indicate that for every increase in channel length from 0.5 mm to 1 mm, there is an average increase of 77% in pressure drop across various Reynolds numbers. This significant increase emphasizes the need for careful consideration of channel dimensions in microfluidic applications.

Lastly, the study demonstrated that increasing the channel length from 500 mm to 1000 mm results in a remarkable fivefold increase in the temperature difference. This finding highlights the potential for optimizing channel length to enhance thermal management. In conclusion, the insights gained from this numerical simulation provide a comprehensive understanding of the factors affecting pressure drop, heat transfer coefficients, and temperature differences in microchannels. These results underscore the importance of optimizing both the inlet and outlet configurations, as well as the Reynolds number, to achieve efficient thermal management in microfluidic systems. Future research could explore the implications of these findings in practical applications, aiming to enhance the design and performance of microchannel-based technologies.

The main motivation of this study was to provide a systematic understanding of how geometric parameters—specifically the inlet length, outlet length, and total channel length—interact with the Reynolds number to influence pressure drop, heat-transfer coefficient, and temperature distribution in conical microchannels. Unlike most previous studies that focused primarily on either flow hydrodynamics or thermal behavior in uniform or straight microchannels, the present work emphasizes the combined analysis of flow and thermal performance in non-uniform conical geometries, and quantifies the sensitivity of key performance indicators to geometric variations. The originality of this research lies in establishing scaling-type relationships and percentage-based performance trends for each geometric parameter over a practical range of Reynolds numbers, thereby offering engineers and designers an interpretable basis for selecting microchannel dimensions according to the desired trade-off between pressure losses and heat-transfer enhancement. Overall, the findings demonstrate that seemingly small geometric modifications can result in significant variations in both hydraulic and thermal behavior, highlighting the importance of geometry-based optimization in future microchannel design and micro-thermal management applications.

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