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NUMERICAL STUDY ON THE INFLUENCE OF SURFACE MODIFICATION ENHANCING THERMAL PERFORMANCE AND OPTIMIZATION IN MICROCHANNEL HEAT EXCHANGERS

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ABSTRACT

Numerical investigations on the thermal performance of microchannel heat sinks featuring pin-fin surface modifications have been performed using Computational Fluid Dynamics (CFD) simulations. The simulations have been carried out to assess the flow and heat transfer behavior across 55 distinct microchannel configurations with varying pin fin heights with water as the coolant medium. The performance of pin-fin-enabled microchannels was compared against conventional flat microchannel to quantify the enhancement effects. Two fin heights (40 µm and 60 µm) were examined in laminar flow regime across Reynolds numbers ranging from 500 to 2000. Results indicate that the integration of pin fins significantly improves thermal response by amplifying heat transfer surface area and inducing localized flow disturbances. The channel configuration with 60 µm fin height demonstrated optimal performance, achieving a notable increase in the Nusselt number and overall heat transfer efficiency. These findings suggest that surface modifications through pin fins, even with water as a base fluid, can substantially enhance the thermal capability of microchannel heat exchangers and are suitable for compact, high-performance cooling applications.

I. INTRODUCTION

The electronic industry has witnessed a progressive rise in the demand of portable electronic systems and MEMS in the recent decades. The ancient cooling systems lack in high performance and effective thermal management solutions become incapable to meet such surging demands. Accordingly, Microchannel Heat Sinks (MCHs) has evolved as a potential solution for high heat flux dissipation with a compact size scale advantage. The MCHs basically creates higher surface area to volume ratio and possibly produced fluid mixing inside the channels. There has been constant research to improve the heat transfer enhancement of MCHs. The addition of pin fins in the heat transferring surface of MCHs has been one of the attractive modifications in this direction.

Pin fins serve to increase the surface-to-volume ratio, hinder the thermal and velocity boundary layers and elevate fluid mixing. In the early phase of microchannel research, Tuckerman and Pease introduced MCHs as a promising technique for dissipating heat from microelectromechanical systems (MEMS). In the subsequent years researchers explored various MCHs geometries to optimize heat transfer performance to improve cooling efficiency [1]. Jyoti Singh and R.P. Sugavaneshwar studied the effectiveness of pin fins in MCHs and reported that optimal fin configurations can achieve up to 50% higher Nusselt numbers compared to conventional designs. This study provides critical insights design of pin fin enabled micro channels [2].

Compared the thermal performance of mini- and microchannels under identical working conditions and demonstrated that pin-fin microchannels (PF-MCs) exhibit superior hydrothermal performance relative to conventional microchannels (CMCs). Their findings emphasized the need for optimizing geometric configurations to balance heat transfer enhancement and flow resistance [3]. Haridas, D. and C.B. Sobhan investigated convective heat transfer in mini-channels using digital interferometric techniques and reported localized thermal gradients across the channel. Their results showed that flow conditions and channel dimensions significantly influence heat transfer performance [4].

Demonstrated that an increase in the number of channels, cross-sectional area and hydraulic diameter in microchannel heat sinks significantly enhances thermal performance. Surface temperature dropped from 361 K in a basic rectangular model to 324 K in the 11-channel design configuration marking a 188% improvement over the basic configuration [5]. Further experimental work by Haridas et al. on wavy microchannels revealed that surface modifications could enhance thermal transfer due to surface area and secondary flow effects under laminar conditions [6]. Numerical Simulations performed by N.B. Sukhor et al. on micro-pin fin heat sinks using water as the base fluid confirmed the effectiveness of structural modifications in boosting thermal performance [7].

Hasan and Muter numerically heat sinks with different fin geometries and coolants. The results emphasized significant heat transfer enhancements can achieved using conventional coolants like water with optimized geometries [8]. |Used CFD and machine learning to analyze flow behaviour and heat transfer in MCHs with pin fins embedded in the channel. The simulations predicts improved heat transfer with increasing flow speed while wider spacing between fins reduces both heat transfer and pressure drop. This study also emphasized the potential of Neural Network algorithms combined with CFD for better channel optimization [9]. Introduces an adaptive pin-fin microchannel (A-MCHS) with phase-change fins that shrink above 313.15 K enabling intelligent flow regulation at hotspot regions.

Compared to fixed pin-fin designs, A-MCHS improves local heat transfer by 37.9%, and enhances average Nusselt number by 7.4%. It also reduces pressure drop by 10.7% demonstrating efficient, self-regulating cooling and energy savings for high heat flux applications [10]. Showed that a V-shaped rib angle of 35° significantly enhances thermal performance with a Nusselt number of 13.81 at Re-300 compared to 8.12 at 90° [11]. Tomar, P., & Kumar, demonstrated that diamond-shaped pin fin with a height of 2.5 mm improve heat transfer 5 times and thermal performance by 340% compared to smooth channels. Optimal performance occurs at a fin height of 2.5 mm with Reynolds numbers ranging from 1500 to 4000 [12]. Inserted pillars into MCHs to stimulate heat transfer by four times with the highest Nusselt number achieved in configuration P75 configuration [13].

Found that smaller taper angles (15°) is very efficient at low Re while large taper angles (30°) excel at higher Re for enhancing heat transfer. The optimal taper angle of 30° achieved the highest THPP of 1.77 underscoring the need to balance thermal and hydraulic efficiency for MHS designs [14]. Proposed adaptive pin-fins microchannel (A-MCHS) to improve thermal performance by 37.9% in hotspot regions. The configuration increases average Nusselt number by 7.4%, and reduces the maximum chip surface temperature by 3.12 K. It also decreases pressure drop by 10.7% offering enhanced cooling and energy savings for high heat flux electronic chips [15]. Ali, N., et al., showed that semi-elliptical pin-fins (SEPFs) enhance heat transfer efficiency in MCHs with a maximum THPP of 1.41 for an aspect ratio of 1.0 at a Reynolds number of 300.

However, flow disturbances increase pressure drop and the minimum THPP value occurs for SEPF with $\Psi = 0.36$ at Re = 900 [16]. Alnaimat, F.,et al., found that incorporating square-shaped fins in microchannel heat sinks improves thermal performance by reducing thermal resistance. Optimizing fin size, space and channel size can enhance thermal efficiency with smaller fins, reduced spacing and certain channel configurations providing higher Figures of Merit (FOM) by balancing heat transfer enhancement with pressure drop [17]. Ehsani, H., et al., discovered that perforated pin fin systems (especially those with three square holes) enhance thermal efficiency by 16.63% compared to non-perforated pin fins. AIML enabled CFD analysis effectively predicts thermal performance with a low mean absolute error of 2.25%.

This study pay way for future of CFD simulations assisted by artificial intelligence and machine learning methods for improved accuracy and effective computational cost [18]. Lee, Y. J., & Kim, S. J., showed that the Manifold Microchannel (MMC) with fins improves thermal-hydraulic performance by reducing thermal resistance by 40% and consequently increasing the heat transfer coefficient by 20%. The system performs with a 5 fold increase in Coefficient of Performance (COP) at a flow rate of 300 ml/min for heat fluxes up to 1.2 kW/cm² [19]. Muhammad Anas Wazir., et al., revealed that the MC-Mixed pin fin configuration enhances convective heat transfer by 50% at Re = 1000 and achieves the highest TPF ($\eta = 1.4$) at Re = 600. Geometric optimization using Response Surface Methodology (RSM) provides optimal pin dimensions for both base wall and mixed configurations [20].

Fluid flow and heat dissipation were examined by A. Kumar., et al using the finite volume method in conjunction with computational fluid dynamics and heat transfer theory [21]. A. Fetuga., et al and O. T. Olakoyejo., et al examined the combined effects of advanced working fluids and optimised heat sink configurations can enhance heat transfer in thermal management systems, improving thermal-hydraulic performance and reducing entropy generation [22], [23]. Extending prior studies the authors analyze the impact of pin-fin height on velocity fields and its interaction with the thermal transport characteristics in a water-cooled microchannel heat exchanger. The study primarily focused on the role of physical geometry modifications on hydro-thermal performance of the system. Simulations are conducted across Reynolds numbers ranging from Re = 500–2000 all lies within the laminar flow regime.

The microchannel heat sinks were designed with copper walls and has dimensions of 600 µm in length, 265 in µm width and 62 in µm height concentrating to a hydraulic diameter of 100 µm. A constant heat flux of 100 W is applied to the heated surface with a coolant flow at constant inlet temperature of 300 K. The flow conditions are maintained under forward-biased. Pin fins are introduced to the microchannel to improve the performance and to create hindrance in the thermal boundary layers by forced convection. The analysis is performed for about four distinct Reynolds numbers from 500 to 2000 to study the laminar flow regimes and establish the correlations of velocity, temperature, pressure drop and convective heat transfer mechanism. By isolating the influence of geometric parameters, the study contributes to optimizing microchannel heat sink designs for reliable and efficient cooling applications. The findings of this study provide new insights into how pin-fin geometry and induced flow structures govern heat transfer enhancement in water-cooled microchannels.

These insights enable a systematic optimization of microchannel geometry and operating conditions to balance thermal efficiency and performance factors, offering practical design guidance for MEMS-based thermal management systems. By enhancing the thermal efficiency and design innovation of microchannel heat exchangers, this work aligns with SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation and Infrastructure).

II. MODELLING AND SETUP

II.1 COMPUTATIONAL MODELLING

II.1.1 Geometric Model:

The presented numerical simulation has been performed for two variations of microchannel heat sink geometries to investigate the functional ability of the pin fins on heat transfer and fluid flow behavior: The first geometry is a MCHs without any surface modifications (Fig 1 a) whereas the second geometry has been designed as a MCHs with pin fin enabled heating surface (Fig 1 c). The MCHs without pin fins is considered as the reference channel for comparison of thermal efficiency. Both the MCHs are constructed with a rectangular cross section as depicted in Figure 1 a.

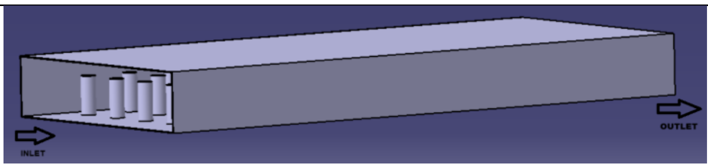
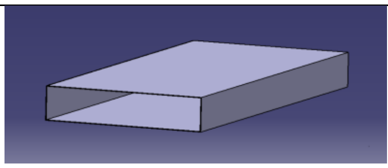


Figure 1a: Computational Domain.
Source: Authors, (2026).



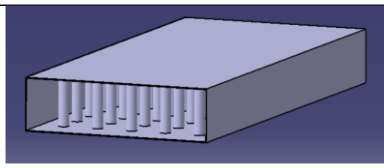


Figure 1b: Plain Channel.
Source: Authors, (2026)

Figure 1c: Channel with Pinfins.
Source: Authors, (2026)

The MCHs with pin fins has designed with 55 uniformly placed circular fins on the bottom heated plate of the channel. Pin fins are indulged in the geometry to promote fluid mixing and to enhance heat dissipation. Moreover, fin heights are altered to check the difference in the resulting heat transport. These geometrical design parameters will allow to establish the correlation with design parameter and flow mixing with in the channel. The design dimensions of the channel and the boundary conditions adopted for the simulation are summarized in Table 1.

Table 1: Geometrical Specifications of the Microchannel.

Symbols	Dimensional values (µm)
L_{ch}	600
W_{ch}	265
H_{ch}	62
d_p	15
S_p	50
h_p	60, 40
N_p	55
Heat Flux q	100 W/m2
Inlet Temperature	300K
Outlet Pressure	0 Pas

Source: Authors, (2026).

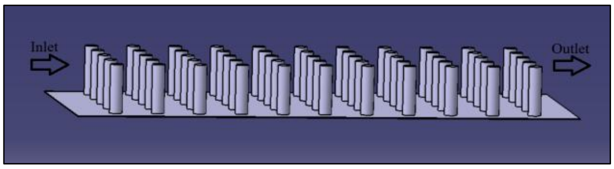


Figure 2: Pin fin arrangement on Heat Plate.
Source: Authors, (2026)

The total heat plate area is approximately 55 mm^2. The spacing between the fins (Sp), the diameter of the fins (dp) remains constant throughout the simulation. The height of the fin (hp) is varied for two different fin heights. The geometry and the entire simulation is performed with the use of a commercial software ANSYS Fluent. Figure 2 shows the top view of the pin fin arrangement.

II.1.2 Computational Modelling:

The simulation has been performed for steady state conditions by using pressure-based analysis. The entire analysis is performed in laminar regime. This model allows to predict the flow characteristics and omit the complications caused in the turbulence regime. The boundary conditions for this analysis are framed with the velocity as inlet and the pressure as outlet. The post processing part consists of the solver settings which are set to the Finite Volume Method, SIMPLEC method and the second order upwind methods. The fundamental equations are solved to the residual range below 10-6 .

This means that the Navier-Stokes equations are solved till they reach a stable value. The boundary layer is assumed with no slip condition and a heat flux of about 100 W/m2 is subjected to the bottom plate of the channel. The inlet temperature is set to 300K and the pressure at the outlet is 0 Pascal. Water is chosen as a working fluid with a density of 1000 kg/m3. To ensure differentiation between the channel walls and the heat plate behavior based on its thermal properties, the materials are differentiated. The channel walls are made of Aluminium and the heat plate is of Copper. The physical properties of the materials used in the computation has been mentioned in the Table 2.

Table 2: Properties of the Materials.

Material Properties	Copper	Water
Density [ρ] (kg/m3)	8978	998
Dynamic Viscosity [μ] (kg/ m/ sec)	-	0.00103
Specific Heat Capacity [Cp] (J/ Kg/ K)	386	4184
Thermal Conductivity [K] (W/ m/ K)	387.6	0.6

Source: Authors, (2026).

II.1.3 Mesh Independence Study

The mesh independence study is the crucial section of the CFD simulation process which entails in finding the most favorable mesh size for the efficient heat transfer analysis. The mesh size has been characterized by analyzing three different meshes: Course, Reference and Fine mesh. The mesh quality straightforwardly influences the fundamental equations and mostly around the inflated regions of the pins. The study is made to frame out the precise results and simultaneously constrain the computational time and cost. The study parametric are same for all the three comparative mesh sizes (Fig 3a-c).

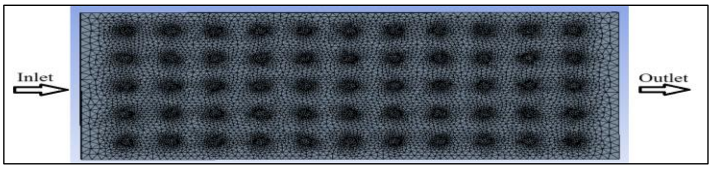


Figure 3a: Reference Mesh.
Source: Authors, (2026)

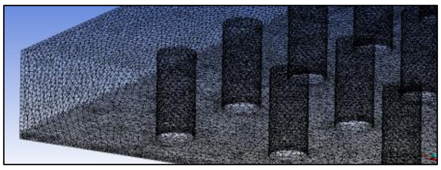


Figure 3b: Fine Mesh.
Source: Authors, (2026)

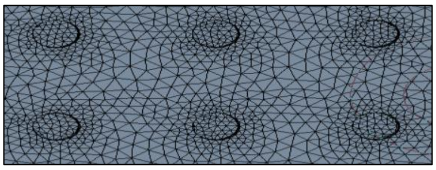


Figure 3c: Coarse Mesh.
Source: Authors, (2026)

These illustrations give the utmost reliable mesh value which compromises all the requirements of an effective heat transfer system. The reference mesh is chosen for the next stage simulations as it accommodates both accuracy and computational benefits. The fine mesh gives more accuracy however fails in the computational aspect. The coarse mesh satisfies the computational time and cost but the accuracy of the results is been compromised. So the reference mesh is taken as the optimal mesh size for this study (refer Table 3)

Table 3: Mesh types and Its findings.

S.No	Type of Grid	No: of elements	Computational time (hrs.)	Friction factor deviation (Δf)
1	Reference	2.625 x 106	3.80	2.25%
2	Fine	3.167 x 106	5.35	1.825%
3	Coarse	1.889 x 106	1.46	4.35%

Source: Authors, (2026).

The table also gives the reason for choosing the reference mesh, as it takes the convergence factor as the friction factor for additional calculation of the mesh size. The deviation in the friction factor, the computational time, the number of elements is the criteria taken into consideration.

III. METHODOLOGY

III.1 COMPUTATIONAL METHODOLOGY

This study employs ANSYS Fluent 2022 R2 for all the simulations performed . The software enables the detailed analysis of solid–fluid interaction through a three-dimensional conjugate heat transfer model. This coupling allows for an accurate representation of heat conduction within the solid domain (channel walls and pin fins) and convection in the fluid domain (flowing water), thereby providing an in-depth note of the thermal behavior within the microchannel. The simulation is carried out under steady-state conditions, assuming a fully developed and laminar flow regime throughout the computational domain. The subsequent conditions are formed to simplify and accurately represent the conjugate heat transfer problem:

- The fluid (water) is considered incompressible and Newtonian, implying that its viscosity remains constant and density does not change significantly with pressure or temperature.
- The flow is steady, meaning that all physical properties such as velocity, temperature, and pressure are independent of time.
- As the heat transfer is driven by forced convection, the effects of natural convection, radiation, and gravitational forces are considered negligible and excluded from the analysis.
- The flow is assumed to be laminar across all Reynolds numbers investigated (500 to 2000), ensuring a smooth and orderly fluid motion throughout the channel.

These assumptions align with typical microchannel flow characteristics and ensure numerical stability while maintaining a high degree of physical accuracy.

III.2 MATHEMATICAL MODEL

The fundamental equations are:

Continuity Equation

To effectively ensure that mass is conserved in the fluid domain, Continuity equation is employed. This equation shows that mass within a certain volume remains constant and also implies that the minute changes in mass will directly relate to the boundary flows.

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

In the case of incompressible flows, when the density is constant, this equation relates the mass flow rate with velocity and the flow boundaries. This equation changes the approach towards the fluid behaviour and enhances the analysis.

Momentum Equation

This equation is basically rooted from the Newton's second law and it describes the relation and balance between pressure and viscous forces acting on the fluid.

$$\rho_l \left(\vec{u} \cdot \nabla \vec{u} \right) = -\nabla p + \mu_l \nabla^2 \vec{u} \tag{2}$$

This inertial term denotes the change in velocity with space due to the movement of the fluid. As a result, this equation describes the fluid dynamics under varying conditions.

Energy Equation (Liquid)

The energy equation plays an important role in governing both the convective and conductive heat transfer within the fluid domain.

$$\rho_l C_{pl} \left(\vec{u} \cdot \nabla T_l \right) = k_l \cdot \nabla^2 T \tag{3}$$

By this we can analyse the thermal energy of the fluid which is essential in optimizing the thermal behaviour

Energy Equation (Solid)

The energy equation in the solid region denotes the heat flow in the channel walls and the pin fins.

$$\nabla (k_s \cdot \nabla T_s) = 0 \tag{4}$$

In this region, the convective heat transfer is absent and it is completely governed by conduction.

III.3 PARAMETER EVALUATIONS

Hydraulic Diameter D_h:

In microscale systems like microchannel heat sinks, the hydraulic diameter replaces the conventional diameter to determine the flow behaviour, especially in non-circular cross sections.

$$D_h = \frac{4A}{2P}$$

$$D_h = \frac{4(W_{ch} \times H_{ch})}{2(W_{ch} + H_{ch})} \tag{5}$$

Reynolds Number Re:

The dimensionless number which determines the flow phase. It is the ratio of inertial and viscous forces.

$$Re = \frac{\rho_l u_l D_h}{\mu_l} \tag{6}$$

Heat Transfer Rate:

The rate of heat transfer between the walls of the channel and the fluid is calculated subsequently,

$$h = \frac{q}{T_w - T_f} \tag{7}$$

Nusselt Number Nu:

A dimensionless quantity which influences the thermal performance factor directly is the Nusselt number.

$$Nu = \frac{hD_h}{k} \tag{8}$$

Friction Factor f:

The friction factor is calculated due to the presence of the pin fins which cause resistance to the flow.

$$f = \frac{2D_h \Delta p}{L\rho u_{in}^2} \tag{9}$$

Thermal Performance Factor TPF:

TPF is the balance in the heat transport and Δp of the system.

$$TPF = \frac{Nu/Nu_o}{(f/f_o)^{1/3}} \tag{10}$$

If the TPF is > 1, then the system has a good heat transfer enhancement.

IV. RESULTS AND DISCUSSIONS

The following sessions presents a detailed discussion of the observations from the numerical simulations performed on a microchannel with pin fin enabled heated walls. The results are presented in the form of velocity and temperature variations along the channel's axial length, heat transport rates and Δp. The results discussed the possible explanations of the velocity streamline and thermal streamline distributions and the corresponding thermal characteristics.

IV.1 VELOCITY STREAMLINES

The evaluation of the velocity streamlines in the micro pin fin enabled channels offers significant insights into fluid flow and heat transfer performance in these surface modified MCHS. In the steady-state simulation carried out in this manuscript, the velocity appears uniform throughout the process and stays constant over time. A key factor in the velocity distribution is the channel's structural model; even with the same Reynolds number (Re), narrower passages produce higher velocities while wider sections display lower velocities. Furthermore, pin fins enhance heat transfer coefficients by changing the local velocity profile and positively contributing to the velocity range (Fig. 4a,b & 5a,b). Furthermore, the flow behaviour and flow rearrangements are strongly influenced by the pin height.

The simulations were conducted for two distinct fin heights, to investigate the flow manipulation over pin height (60 µm at Re 500 (Fig 4 a); Re 2000 (Fig 5 a) and 40 µm at Re 500 (Fig 4 b); Re 2000 (Fig 5 b)). Velocity vortices form around the pin fins due to the varying local velocities change the streamline nature of the inlet velocity. The flow separates across the fins, mainly affecting the surface flow towards the middle of the channel. Increased velocity occurs mostly around the fins due to redirection, and flow detachment happens near the fins, which operate as obstruction to the flow pattern. As the fin height rises, the SA available for fluid contact also increases, which instinctively improves heat transfer efficiency. Variations in fin height alter the flow pattern, creating vortices and splashes and promoting fluid mixing.

Enhanced fluid mixing leads to higher heat transfer rates, thereby increasing thermal performance. By positioning the ideal channel, the overall efficiency and TPF can be increased even though a higher fin height does cause a greater pressure drop (Fig. 4a). Higher fins are clearly correlated with higher velocity at the centre of the channel, as shown by the cross-sectional planar view. When the pin height is 60 µm instead of 40 µm, streamlines exhibit more vortices and reach higher velocities (Fig. 4) (Fig. 5). Additionally, it is observed that flow detachment and reattachment are more noticeable at the inlet section and drastically decrease as the flow approaches the outlet section. This phenomenon is common in both the pin heights. Thus, the evolution of velocity streamlines with different pin heights concludes that when the Re is high and the fin height is at maximum, the VBL redistribution also increases. This condition stimulates fluid mixing, resulting in enhanced heat transfer and better thermal performance along with pressure drop.

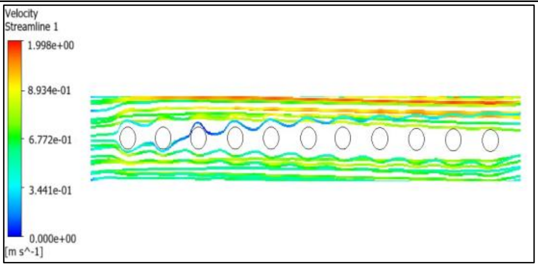


Figure 4a: Velocity streamlines on the microchannel with fin height of 60 µm at Re 500.
Source: Authors, (2026).

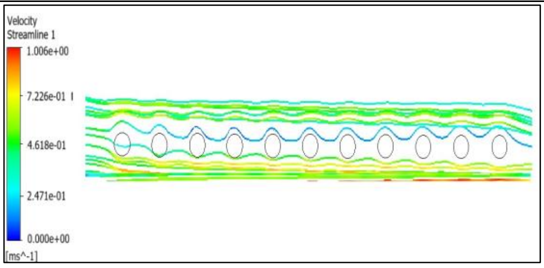


Figure 4b: Velocity streamlines on the channel with fin height of 40 µm at Re 500.
Source: Authors, (2026).

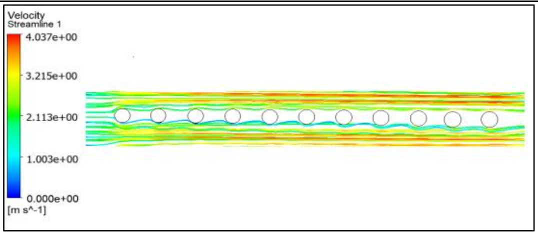


Figure 5a: Velocity streamlines on the microchannel with fin height of 60 µm at Re 2000.
Source: Authors, (2026).

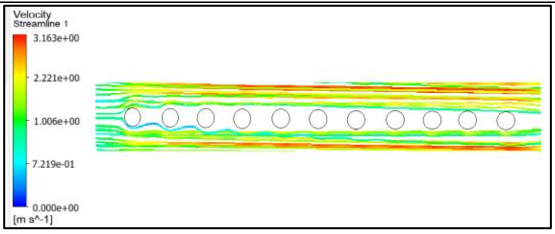


Figure 5b: Velocity streamlines on the microchannel with fin height of 40 µm at Re 2000.
Source: Authors, (2026).

At a Reynolds number of 2000, the velocity streamlines become more intense and complex due to increased inertial forces. With the 60 µm pin fins, the flow exhibits significant detachment and reattachment around the fins, creating flow mixing and high-velocity in the narrow gaps (Fig 5 a, b). The greater height of the fins increases blockage and enhances interaction with the fluid , leading to accelerated flow around the fins and improved fluid mixing, which contributes to better thermal performance. Instead, produces high pressure drop and makes it inefficient for a thermal system. In contrast, the 40 µm pin fins display relatively less intense streamline patterns when compared to fin 60 µm. The flow remains neither aligned nor distracted with the direction of the channel, and the disturbance caused by the fins is less pronounced. While this results in considerably high pressure drop, it also leads to reduced mixing and thermal enhancement. In both scenarios, flow disturbances are more prominent near the inlet and gradually stabilize toward the outlet. However, the taller fins (60 µm) with low Re (Fig 4a) induce stronger streamline evolution and create better heat transfer conditions.

IV.2 TEMPERATURE CONTOURS

The integration of fins within MCHS significantly enhances heat transportation productivity, as indicated in the higher temperature gradients observed along the channel length near the surface of the channel. The presence of fins not only modifies the flow dynamics but also directly contributes to improved thermal performance by increasing the efficient heat exchange surface area. Among the various fin design parameters, fin height serve a critical part in determining the thermal characteristics of the system. By increasing the surface area available for fluid contact, taller fins promote a steeper temperature gradient across the channel. This increase in the surface area-to-volume ratio is particularly beneficial in microchannel applications, where maximizing heat exchange within a limited space is essential.

Fin height variation has a direct impact on fluid flow behaviour, improving mixing and, as a result, thermal boundary layer distribution. This effect is particularly apparent at the outlet, where taller fins are associated with higher outlet temperatures (Fig. 7 & 9). The temperature contours make it easy to see how the TBL changes as the fluid travels downstream close to the outlet. The temperature gradients that have been observed, verify that the addition of fins considerably modifies the flow and temperature fields by encouraging the expansion of the TBL and increasing the total heat transfer rate. Furthermore, the height and arrangement of the fin have a significant effect on the thermal-fluidic performance of the system. A constant inlet fluid temperature of about 300 K is used at the start of the simulation.

As the working fluid travels through the channel, it absorbs heat from the heated base plate, causing a progressive temperature rise along the channel length. The interaction between the fluid and the pin fins facilitates greater heat absorption, resulting in noticeable temperature increases downstream. This interaction also leads to flow separation and detachment, which improves the temperature gradient due to induced mixing. As a result, the temperature distribution across the channel becomes more uniform, indicating effective convective heat transfer. A comparison between fins of 60 µm and 40 µm in height reveals that the taller fins (60 µm) disrupt and redirect the flow more effectively, leading to superior thermal performance (Fig 7 & 9).

These taller fins create more pronounced flow disturbances, contributing to a more uniform temperature field and enhancing overall heat dissipation. In contrast, the shorter fins (40 µm) allow the fluid to pass through with minimal disruption, resulting in reduced interaction and lower heat transfer rates (Fig 6 & 7). The findings of this study demonstrate that fins with an optimal height of 60 µm strike a balance sufficiently disturbing the flow constructively without causing excessive temperature peaks (Fig 7). This configuration creates a more uniform thermal field and efficient heat dissipation, making it a promising design for high-performance microchannel heat sinks.

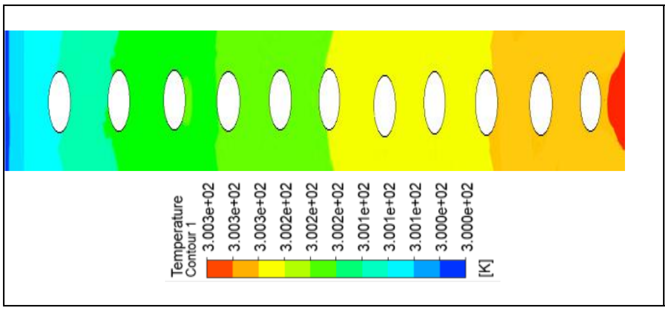


Figure 6: Temperature Profile on the channel with fin height of 40 µm at Re 500.
Source: Authors, (2026).

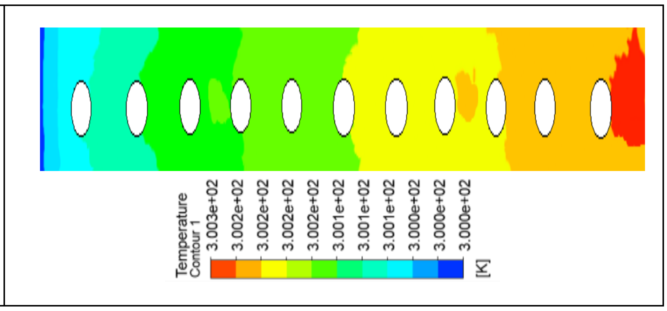


Figure 7: Temperature Profile on the channel with fin height of 60 µm at Re 500.
Source: Authors, (2026).

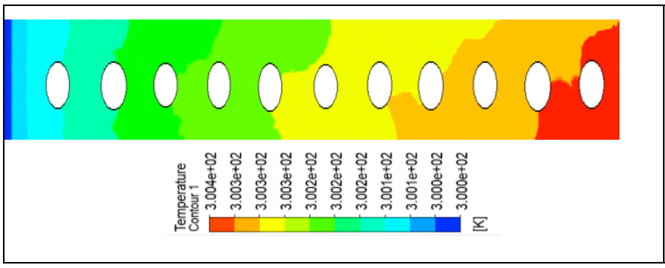


Figure 8: Temperature Profile on the channel with fin height of 60 µm at Re 500.
Source: Authors, (2026).

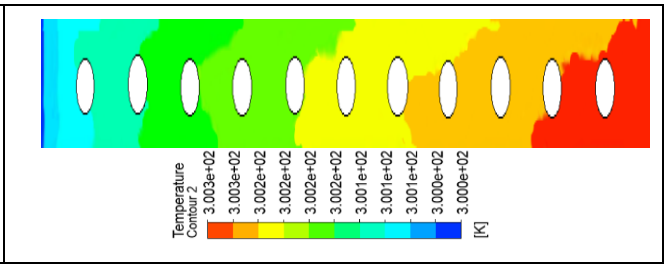


Figure 9: Temperature Profile on the channel with fin height of 60 µm at Re 2000.
Source: Authors, (2026).

IV.3 EFFECT OF PIN FINS ON BOUNDARY LAYER DISTRIBUTION

The incorporation of pin fins within microchannel configurations is essential for elevation of thermal performance of the system. One primary advantage of using fins is that significant improvement in the SA:V ratio available for heat exchange. By extending the solid-fluid interface, pin fins create additional pathways for heat to transfer from the channel walls to the working fluid. Furthermore, the presence of pin fins disrupts the smooth flow of fluid through the channel. This disruption alters the growth of the TBL, promoting greater convective heat transfer. As the fluid interacts with the fins, localized flow separation and reattachment occur, enhancing fluid agitation and mixing.

These changes in flow behavior contribute to improved thermal interaction between the fluid and the channel surfaces. Pin fins also play a critical role in achieving temperature uniformity within the channel. By enhancing fluid mixing, they help distribute the absorbed heat more evenly by reducing the formation of localized hot spots. This results in a more uniform temperature field along the channel, which is beneficial for both thermal management and the structural integrity of heat-sensitive systems. However, it is important to note that pin fins introduce resistance to flow. The obstruction they create leads to an increased pressure drop across the channel. While this can be seen as a drawback, it is usually accompanied by a simultaneous increase in heat transfer capability.

The greater the resistance and fluid interaction, the more heat is transferred to the fluid, resulting in improved thermal performance (Fig 10). It has also been seen from Fig 10 that the fins placed in the inlet section has better heat dissipation capacity as compared to the outlet section of the channel. There is a significantly temperature variation along the fin surface along the height of the pin as more fluid is in touch with the upper surface of the fin. In conclusion, pin fins positively contribute to the operation of microchannel heat sinks by increasing surface area, disrupting flow to enhance convective heat transfer, and promoting uniform temperature distribution. Despite the higher pressure drop they cause; the trade-off is justified by the significant improvement in heat dissipation.

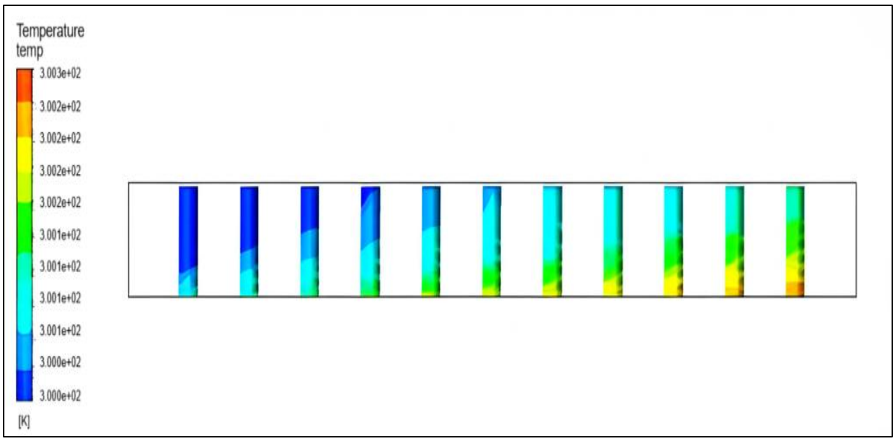


Figure 10: Effect of Temperature Distribution along the Fins.
Source: Authors, (2026).

Figure 11: Wall Shear-Induced Flow Diversion Around a Single Pin Fin at Varying Reynolds Numbers (a) 60 µm Re 2000; (b) 40µm Re-2000; (c) 60µm Re 500; (d) 40µm Re500.
Source: Authors, (2026).

The impact of wall shear forces on the flow diversion behaviour around a single pin fin under various geometric and flow conditions is shown in Figure 11. The intensity of the streamline colors highlights how changes in pin height and Reynolds number impact fluid deviation by revealing shear related velocity gradients. The flow is clearly strongly diverted and the pin fin is surrounded by dense streamlines that curve sharply. The obvious bending indicates a strong fluid to fin surface interaction and a high shear influence (Fig. 11 (a)). Despite a high Reynolds number, the reduced pin height leads to less pronounced deviation of the streamlines. The flow bypasses the shorter pin more easily, resulting in a comparatively weaker shear-induced diversion (Fig 11 (b)). At a lower Reynolds number, the bending of streamlines around the taller pin is still observable, but the overall flow energy is reduced. As a result, diversion patterns become less intense and more fluid (Fig. 11 (c)). Because of the negligible wall shear effects caused by the lower velocity and pin height, there is very little flow deflection in this case (Fig 11 (d)). In conclusion, flow behaviour is greatly influenced by both pin height and Reynolds number. While lower Reynolds numbers reduce the energy available for such diversion, a higher pin height increases wall shear-induced flow diversion.

IV.4 NUSSELT NUMBER

The Nusselt number (Nu) is a critical non-dimensional parameter for assessing flow induced heat transfer in relation to contact induced fluid-solid interface. (Fig 12) illustrates a comparative analysis of Nu values as a function of Re for three configurations: a plain microchannel without fins, a finned channel with a pin height of 40 µm, and a finned channel with a pin height of 60 µm. The results clearly show that the inclusion of pin fins elevates the convective heat transfer rate across all Reynolds numbers simulated. This improvement is due to the stimulated SA provided by the fins which intensifies the thermal interplay amidst the fluid and solid. Additionally, the fins help disrupt the boundary layer and promote localized mixing, thereby improving the mechanisms of convective heat transfer.

As demonstrated in (Fig 12) the Nu augments steadily with Re for all cases, which is consistent with the expected behavior of forced convection in laminar and transitional flow regimes. However, channels equipped with pin fins exhibit significantly higher Nusselt numbers compared to the baseline configuration without fins. Among the finned options, the design with a pin height of 60 µm consistently shows the highest Nu, indicating superior thermal performance. This enhancement is particularly noticeable at lower Reynolds numbers (i.e., Re = 500) where the effects of increased surface area and induced mixing are more pronounced due to weaker inertial forces. Although the relative improvement decreases slightly as the Re increases, the performance advantage of the taller fins (60 µm) remains evident across the range.

Overall, the findings confirm that increasing fin height improves the convective heat transfer rate (approx.. 60%) leading to higher Nusselt numbers. The configuration with a pin height of 60 µm offers the most effective thermal enhancement and is therefore ideal for microchannel heat sink applications that require better heat dissipation performance. The variation of the heat Transfer Gain Ratio (Nu/Nu_0) with Reynolds number for channels incorporating pin fins of 40 µm and 60 µm heights are shown in Fig 13. Nusselt number denoted by Nu for finned configurations, while Nu_0 denotes the value for a plain channel without fins. This ratio yields a normalized measure of heat transfer gain due to the inclusion of fins, independent of baseline performance.

The graph shows that, particularly at low Reynolds numbers, both finned configurations significantly outperform the plain channel in terms of heat transfer. Interestingly, the 60 µm fin consistently outperforms its 40 µm counterpart in terms of gain ratio, with the biggest improvement seen at Re = 500. This suggests that in lower flow regimes, the advantages of increased surface area and improved convective mechanisms are more potent. The relative gain from pin fins, however, slightly decreases as the Reynolds number rises, indicating the diminished impact of structural improvements under higher inertial forces. The findings show that although both fin heights improve thermal performance, the 60µm configuration is more efficient, especially when convective improvements are most advantageous.

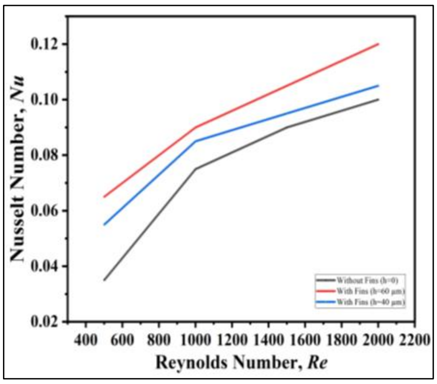


Figure 12: Variation of Nusselt number along various Reynolds numbers
Source: Authors, (2026).

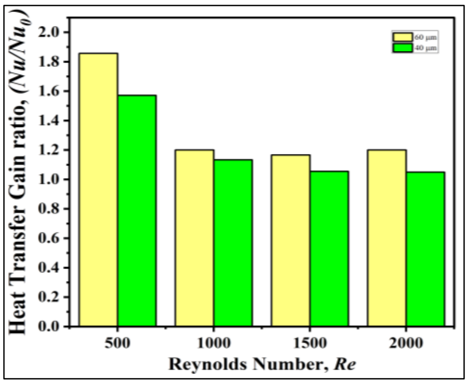


Figure 13: Heat Transfer Gain Ratio (Nu/Nu_0) vs Reynolds Number
Source: Authors, (2026).

IV.5 FRICTION FACTOR F

The friction factor is a non-dimensional parameter that quantifies the resistance a fluid encounters due to wall shear and geometric constraints within a channel. Figure 14 illustrates the deviation of friction factor with Re for three cases: a smooth channel without fins, and channels with pin fins of heights 40 µm and 60 µm. The presence of pin fins introduces additional obstacles within the channel which increases flow resistance and contributes to a higher pressure drop. These structural intrusions increase viscous drag as Figure 14 illustrates, channels with fins consistently show higher friction factors when compared to the smooth channel. The channel with 40 µm fins exhibits the highest friction factor across all Reynolds numbers among the tested configurations. This is explained by the development of recirculation zones, which increase wall shear stresses, and a stronger blockage effect. Despite having taller fins, the 60 µm fin configuration exhibits lower friction factors. This may be due to more efficient flow redirection and reduced wake interference at higher Reynolds numbers. For all cases, the frictional factor drops steadily with rise in Re, due to reduced influence of viscous forces in higher flow regimes.

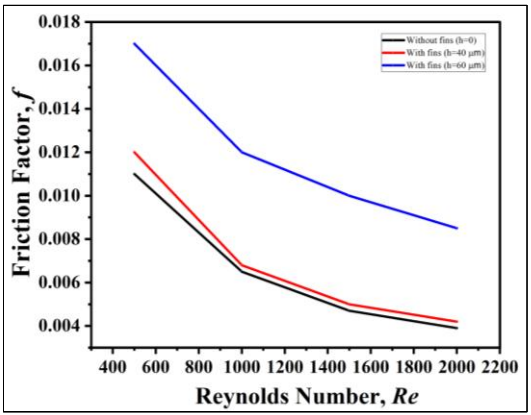


Figure 14: Friction factor vs Reynolds number.
Source: Authors, (2026).

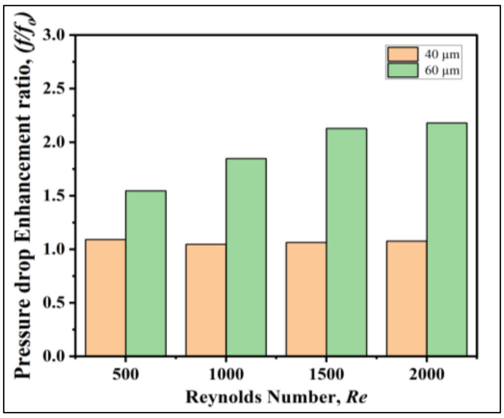


Figure 15: Pressure drop enhancement ratio vs Re for pin fins of 40 µm and 60 µm heights.
Source: Authors, (2026).

However, Finned channels exhibit higher resistance than the smooth configuration, but the relative differences between configurations are still consistent. These results highlight the fact that integrating fins can cause heat transfer, but it also raises the pressure drop. Therefore, choosing fin geometries for microchannel heat sinks requires striking a balance between hydraulic performance and thermal enhancement. The relationship between the pressure drop enhancement ratio (f/f_0) and the Reynolds number for pin fins of heights 40 µm and 60 µm (Fig 15). f_0 represents the friction factor of a plane channel while f denotes the friction factor for the pin fin configurations. The enhancement ratio increases with the Reynolds number for both fin heights, indicating that the pressure resistance rises due to the flow obstruction caused by the fins.

The 60 µm fins shows higher pressure drop across all Reynolds numbers, which can be attributed to greater blockage and surface area. Although this leads to increased flow resistance, it notably improves convective heat transfer. In contrast, the 40 µm fins exhibit a more moderate increase in pressure, achieving a balance between thermal performance and pumping power. These findings emphasize that integrating pin fins enhances heat transfer but also increases Δp which made it crucial to balance thermal performance with hydraulic efficiency when selecting fin geometries for microchannel heat sinks. Achieving this balance ensures optimal system performance without excessive pumping power requirements.

IV.6 THERMAL RESISTANCE:

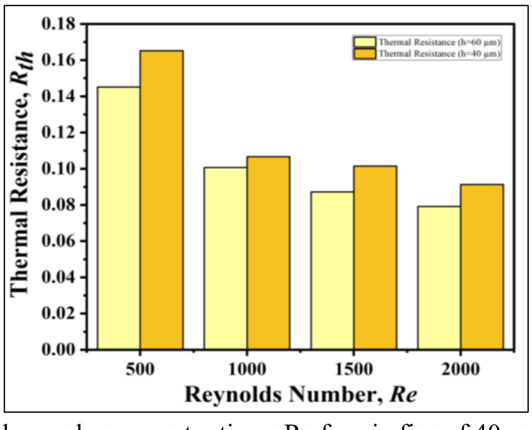


Figure 16: Pressure drop enhancement ratio vs Re for pin fins of 40 µm and 60 µm heights.
Source: Authors, (2026).

The relationship between thermal resistance (Rth) and Reynolds number (Re) for pin fin heights of 40 µm and 60 µm is clearly demonstrated in (Fig 16). The Thermal resistance lowers as Re rises for both fin heights, denoting a significant improvement in heat dissipation at higher flow rates.

Among all Reynolds numbers, the 60 µm fin configuration consistently exhibits lower thermal resistance than the 40 µm fin. This distinctively indicates superior thermal performance which in turn attributed to the expanded surface area. The most substantial reduction in thermal resistance occurs between Reynolds numbers of 500 and 1000, after which the decrease slows down, but the trend remains evident. This data confirms that taller fins (60 µm), in conjunction with higher flow rates, enhance convective heat transfer and make the system significantly more thermally efficient.

IV.7 THERMAL PERFORMANCE FACTOR:

The thermal performance factor (TPF) is a key metric employed to assess the balance between heat transfer enhancement and the resulting flow resistance. It is typically derived from the ratio of the Nu to f which allows for a comprehensive assessment of both thermal and hydraulic performance in a single criterion. The TPF varies with Re for three different channel configurations: a smooth channel, a channel with pin fins of height 40 µm, and a channel with pin fins of height 60 µm (Figure 17). The results clearly demonstrate the positive impact of incorporating pin fins on overall thermal performance. The reference channel without fins consistently shows the lowest thermal performance across all Reynolds numbers.

This is primarily due to its limited surface area and lack of mechanisms to disrupt flow. In contrast, adding pin fins significantly enhances thermal performance through improved convective heat transfer and better fluid mixing. Notably the configuration featuring 60 µm fins achieves the highest thermal performance factor among the tested setups. This improvement can be attributed to the larger SA in connection with the fluid, which allows for higher heat transfer rates without a surplus hike in Δp. The taller fin geometry promotes greater flow disturbance and thinning of the TPF, thus optimizing the balance between heat transfer and flow resistance.

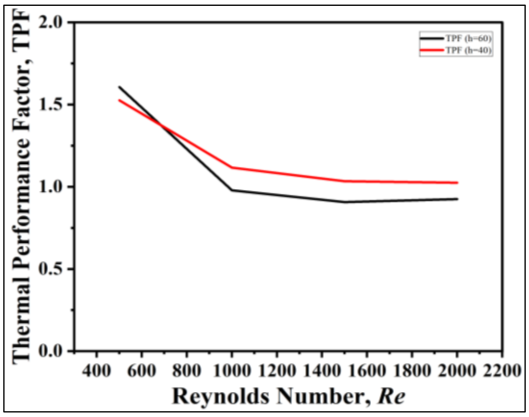


Figure 17: Thermal Performance Factor vs Reynolds number.
Source: Authors, (2026).

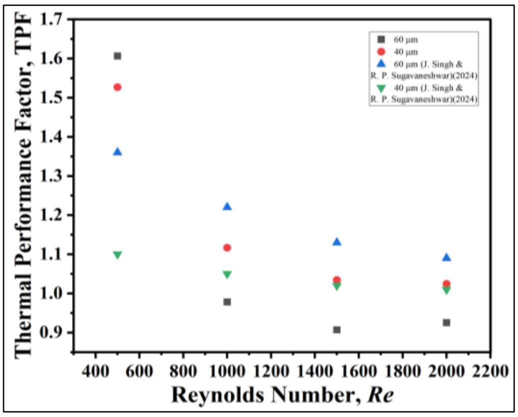


Figure 18: Thermal Performance Factor vs Reynolds number.
Source: Authors, (2026).

The configuration of 40 µm fins shows a moderate improvement over the non fin configuration but is still less effective than the 60 µm fins. This highlights the importance of fin geometry, specifically the height in determining overall system efficiency. The trends observed in Figure 17 reinforce the idea that optimal fin design is crucial for maximizing thermal performance in microchannel applications. The validation of the Thermal Performance Factor (TPF) for two fin heights (40 µm and 60 µm) in comparison to published results by J. Singh & R. P. Sugavaneshwar [3] (Fig 18). The validation clearly shows the comparison made on both the works. The following points states the comparison performed:

- The TPF values from this study closely correspond with the results reported by J. Singh & R. P. Sugavaneshwar confirming the accuracy and credibility of the numerical model.
- For both fin heights, the deviations are minimal at higher Reynolds numbers, which validates the thermal behavior captured in the simulation.
- The TPF consistently decreases with increasing Re in both datasets by reaffirming the trend that higher flow rates reduce the thermal enhancement relative to frictional losses.
- The strong alignment in performance trends supports the reliability and consistency of the simulation setup, meshing, and boundary conditions with previously established results.

IV.8 INTERNAL EFFICIENCY OF THE SYSTEM

The variation of internal efficiency is expressed as the ratio of Nusselt number to friction factor (Nu/f), with Re for three channel configurations: a smooth channel (0 µm), and channels with pin fins of 40 µm and 60 µm heights (Fig 19). Internal efficiency is a critical performance indicator as it balances heat transfer enhancement (Nu) against the pressure drop penalty (f) by offering insight into overall thermal-hydraulic effectiveness.

The internal efficiency increases with Reynolds number for all configurations, indicating improved convective heat transfer performance at higher flow rates. Among the three cases, the channel with 60 µm fins consistently demonstrates the highest internal efficiency followed by the 40 µm fin configuration, while the smooth channel perform least efficiently. The superior performance of the 60 µm fins can be attributed to their larger surface area and enhanced flow disruption which intensify thermal mixing without a proportionally high increase in pressure drop.

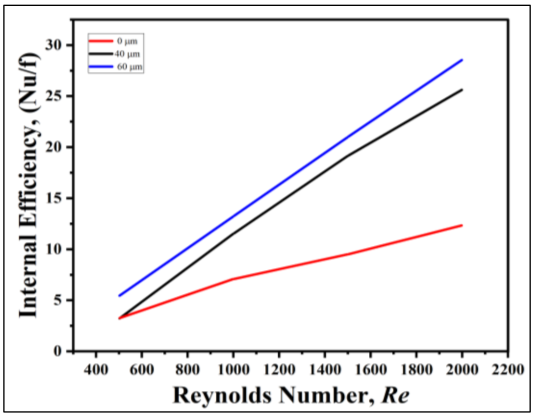


Figure 19: Internal Efficiency vs Reynolds number.
Source: Authors, (2026).

These results highlight that increasing fin height not only boosts heat transfer but also maintains a favorable balance with the associated pressure loss, making it a promising design choice for high-performance microchannel heat sinks. Notably at Re - 500, the 60 µm pin fin configuration achieves a desirable combination of moderate pressure drop and elevated thermal performance establishing it as an efficient and balanced solution for microchannel heat transfer systems.

V. CONCLUSIONS

This study presents a detailed numerical investigation into the augmentation of heat transfer in microchannels with the use of pin fins. The research employed computational fluid dynamics (CFD) simulations to analyze over 55 different heat sink configurations. Two distinct fin heights, both with identical diameters, were evaluated under consistent boundary conditions to assess their thermal performance. The results indicate that the fin height matching the full channel height (60 µm) delivers optimal thermal performance. Among the various flow conditions examined, a Re of 500 combined with the 60 µm fin height exhibited the most efficient thermal behavior, achieving substantial heat transport enhancement while upholding manageable flow resistance.

The introduction of pin fins significantly increased the Nusselt number and improved the overall thermal characteristics compared to conventional channel geometries without fins. This optimal configuration not only produced a higher Nusselt number but also resulted in a greater friction factor, highlighting the trade-off between thermal enhancement and pressure drop. Despite the increased pressure loss, the configuration with 60 µm pin fins achieved up to 60% higher thermal performance compared to the baseline case without fins, demonstrating its considerable advantage in thermal efficiency. Overall, the findings confirm that a fin height of 60 µm at a Reynolds number of 500 provides robust and consistent performance across varying operating conditions, making it highly suitable for high-efficiency thermal management applications.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Methodology: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Investigation: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Discussion of results: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Writing – Original Draft: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Writing – Review and Editing: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Resources: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Supervision: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.
Approval of the final text: Sorna Latha, Divya Haridas and Karthik Jayanarasimhan.

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