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Effect of Surface Roughness on Convective Heat Transfer in Turbulent Flow

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ABSTRACT
This study investigated the effect of surface roughness on convective heat transfer characteristics in turbulent microchannel flow under high Reynolds number conditions. A combined experimental and numerical approach was adopted to examine how roughened channel surfaces influenced the Nusselt number, friction factor, and overall thermal hydraulic performance compared with smooth microchannels. Experiments were conducted using a rectangular microchannel test section with controlled roughness geometry, while water was employed as the working fluid. Key thermal and flow parameters, including temperature distribution, pressure drop, and flow rate, were measured under steady state turbulent conditions. Complementary computational fluid dynamics simulations based on the Reynolds averaged Navier–Stokes equations were performed to validate the experimental results and provide detailed insight into flow and heat transfer behaviour. The results showed that surface roughness significantly enhanced convective heat transfer by intensifying near wall turbulence and disrupting the thermal boundary layer, leading to higher Nusselt numbers across the investigated Reynolds number range. However, the enhancement in heat transfer was accompanied by increased frictional losses and pressure drop. An optimal range of relative roughness was identified, where heat transfer improvement outweighed the associated hydraulic penalties. The agreement between experimental and numerical results confirmed the reliability of the adopted methodology. Overall, the findings demonstrated that appropriately designed surface roughness can substantially improve the thermal performance of microchannel heat exchangers and provided useful guidance for the design and optimization of high performance thermal management systems.

Keywords: Surface roughness, Turbulent flow, Microchannels, Convective heat transfer, Nusselt number, Friction factor, Thermal hydraulic performance

1.0 INTRODUCTION

1.1 Background to the Study

Convective heat transfer in turbulent flow plays a critical role in the performance of many engineering systems, including heat exchangers, gas turbines, internal combustion engines, and microchannel cooling devices. In such systems, surface characteristics of the flow passage significantly influence fluid dynamics and thermal performance. Surface roughness, which arises from manufacturing processes, material degradation, fouling, or deliberate surface modification, alters the near-wall flow structure and disrupts the thermal boundary layer, thereby affecting heat transfer rates (Incropera et al., 2017). In

turbulent flow regimes, rough surfaces enhance momentum and energy exchange by increasing turbulence intensity near the wall, which can lead to improved convective heat transfer performance compared to smooth surfaces (Webb & Kim, 2005).

Previous studies have demonstrated that roughened surfaces can significantly increase the Nusselt number due to enhanced mixing and boundary layer disruption, particularly at high Reynolds numbers (Nikuradse, 1950; Chung et al., 2020). However, this enhancement is often accompanied by increased frictional losses and pressure drop, which impose higher pumping power requirements. As a result, understanding the interaction between surface roughness, turbulence structure, and heat transfer is essential for optimizing thermal systems and achieving a balance between heat transfer enhancement and hydraulic efficiency.

1.2 Problem Statement

Despite extensive research on turbulent convective heat transfer, the effect of surface roughness remains a complex and partially unresolved issue, particularly in modern high-performance thermal systems. Classical heat transfer correlations were largely developed for hydraulically smooth surfaces and often fail to accurately predict thermal performance in roughened channels and ducts (Kandlikar et al., 2014). Furthermore, the influence of roughness geometry, roughness height, and roughness distribution on heat transfer enhancement and pressure loss is not yet fully generalized, leading to inconsistencies in experimental and numerical findings across different studies (Choi et al., 2019).

In practical applications, uncontrolled or poorly designed surface roughness can result in excessive pressure drop that outweighs the benefits of heat transfer enhancement. Conversely, optimized roughness configurations can significantly improve system performance if properly designed. The lack of comprehensive understanding and reliable predictive models for roughness-induced heat transfer enhancement in turbulent flow therefore constitutes a major challenge in thermal system design.

1.3 Objectives of the Study

The main objective of this study is to investigate the effect of surface roughness on convective heat transfer in turbulent flow conditions. Specifically, the study aims to examine how surface roughness influences the Nusselt number, friction factor, and overall thermal–hydraulic performance of turbulent flow systems. The study also seeks to relate observed heat transfer trends to changes in turbulence intensity and boundary layer behaviour induced by rough surfaces. By linking the findings to existing theoretical, experimental, and numerical studies, this research aims to contribute to improved understanding and design guidelines for thermal systems employing roughened surfaces.

2.0 LITERATURE REVIEW

2.1 Conceptual Review

Surface roughness refers to the microscopic and macroscopic irregularities present on a solid surface that interact with fluid flow. In microchannels, roughness elements can be naturally occurring due to fabrication techniques or intentionally introduced to enhance heat transfer. The relative roughness, defined as the ratio of roughness height to hydraulic diameter, plays a dominant role in turbulent microchannel flows, unlike in macroscale channels where it is often negligible (Morini, 2004). Conceptually, rough surfaces enhance convective heat transfer by increasing turbulence intensity near the wall, thinning the thermal boundary layer, and promoting fluid mixing, but these benefits are accompanied by increased pressure losses.

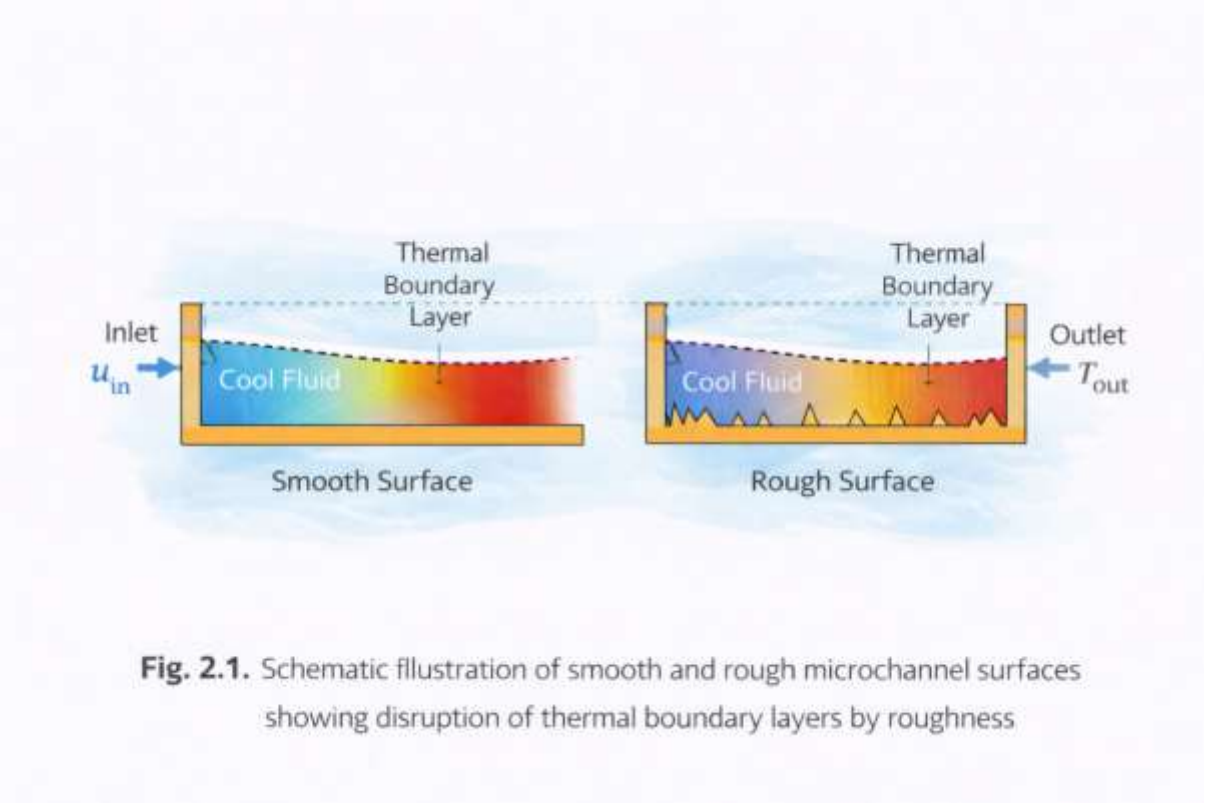

Fig. 2.1. Schematic fllustration of smooth and rough microchannel surfaces showing disruption of thermal boundary layers by roughness

Fig. 2.1 illustrates the contrast between smooth and rough microchannel surfaces and their influence on thermal boundary layer development. In the smooth microchannel, the thermal boundary layer grows progressively along the flow direction, resulting in limited fluid mixing and relatively lower convective heat transfer. In contrast, the roughened microchannel surface introduces protruding roughness elements that disturb the boundary layer, promote flow separation and reattachment, and enhance near-wall turbulence. This disruption leads to improved thermal mixing and a thinner effective thermal boundary layer, thereby increasing the local heat transfer coefficient, particularly under turbulent flow conditions.

2.2 Theoretical Models

Several theoretical and semi-empirical models have been proposed to describe turbulent flow and heat transfer over rough surfaces. The classical work of Nikuradse (1950) established the relationship between roughness and friction factor in turbulent pipe flow, categorising surfaces as hydraulically smooth, transitionally rough, or fully rough. Later, the Colebrook–White equation incorporated roughness effects into friction factor prediction.

For heat transfer, Reynolds analogy and modified wall functions have been used to relate momentum and thermal transport in rough-walled turbulent flows. In microchannels, Kandlikar et al. (2014) highlighted that roughness alters viscous sublayer thickness and invalidates assumptions underlying classical correlations. More recent models incorporate roughness-induced turbulence enhancement through correction factors applied to Nusselt number correlations (Chung et al., 2020).

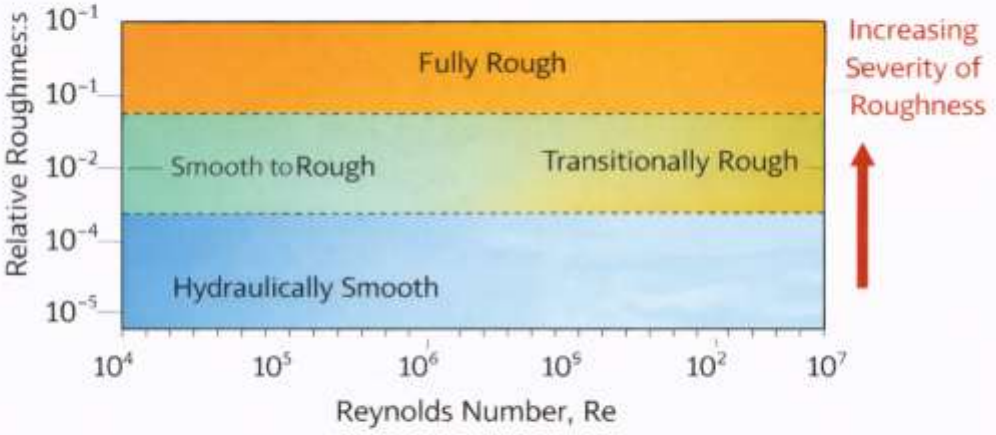

Fig. 2.2. Classification of turbulent flow regimes based on relative roughness and Reynolds number.

Fig. 2.2 presents a regime map classifying turbulent flow behavior as a function of Reynolds number and relative surface roughness. The figure delineates three distinct regions, namely hydraulically smooth, transitionally rough, and fully rough flow regimes. At low relative roughness values, viscous effects dominate and surface roughness has negligible influence on flow resistance and heat transfer. As relative roughness increases, the flow transitions into a roughness-affected regime where both viscous and roughness effects coexist. In the fully rough regime, form drag due to roughness elements dominates, significantly altering turbulence characteristics and enhancing convective heat transfer.

2.3 Empirical Review

Experimental and numerical studies consistently show that surface roughness enhances heat transfer in turbulent microchannel flows. Srivastava and Dewan (2020) reported significant increases in Nusselt number with increasing roughness height at high Reynolds numbers, while Wagner et al. (2024) observed that roughened microchannels exhibited superior thermal performance compared to smooth channels under identical operating conditions. However, these enhancements were accompanied by substantial increases in pressure drop. Chung et al. (2020) emphasized that roughness geometry and distribution strongly influence thermal–hydraulic performance, indicating the need for optimised roughness designs.

3.0 METHODOLOGY

The study adopted a combined experimental and numerical methodology. A rectangular microchannel test section with controlled surface roughness was used to investigate turbulent flow at high Reynolds numbers. Roughness elements of uniform height were introduced on the channel walls, and water was used as the working fluid. Flow rate, inlet and outlet temperatures, wall temperatures, and pressure drop were measured under steady-state conditions.

Computational fluid dynamics simulations were conducted using Reynolds-averaged Navier–Stokes equations with appropriate turbulence models and rough wall boundary conditions. The Nusselt number

and friction factor were computed from both experimental and numerical data, and the results were compared for validation purposes.

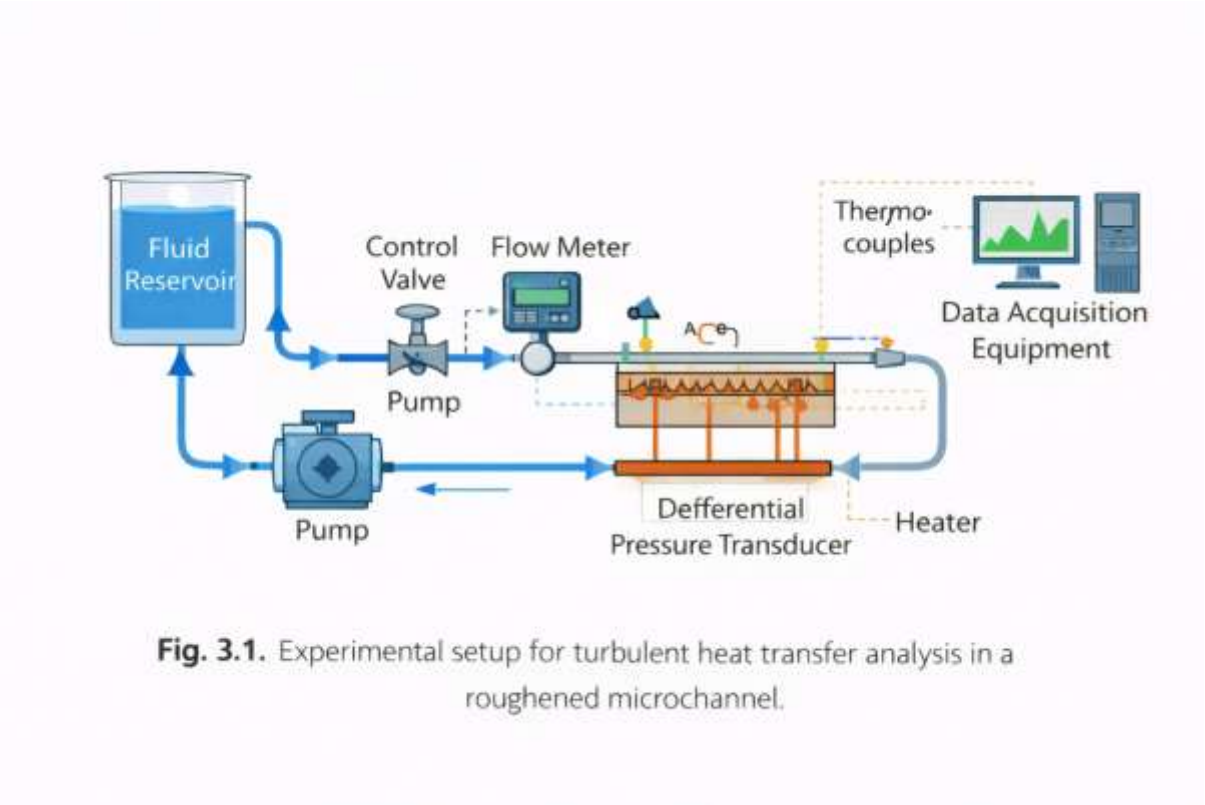

Fig. 3.1. Experimental setup for turbulent heat transfer analysis in a roughened microchannel.

Fig. 3.1 shows the schematic diagram of the experimental setup used for investigating turbulent heat transfer in a roughened microchannel. The setup consists of a fluid reservoir, circulation pump, flow control valve, electrical heater, roughened microchannel test section, and temperature and pressure sensors positioned at the inlet and outlet. The working fluid is driven through the microchannel at controlled flow rates to achieve the desired Reynolds numbers, while uniform heat flux is supplied through the heater. The sensors enable accurate measurement of thermal and hydraulic parameters required for evaluating heat transfer coefficients and friction characteristics.

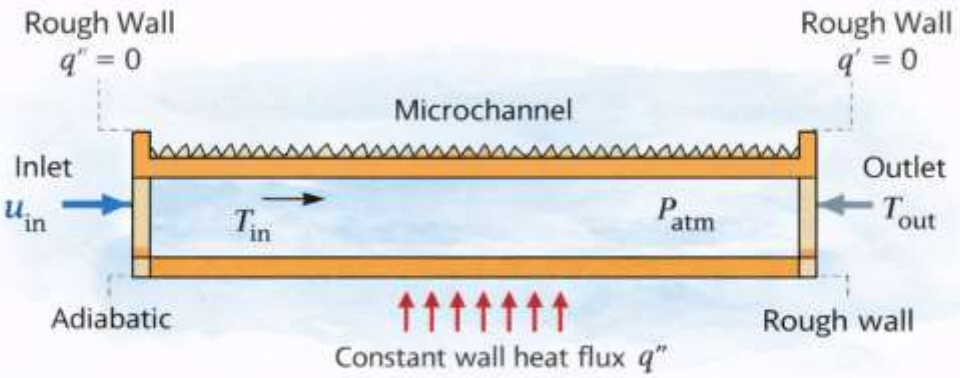

Fig. 3.2. Computational domain and boundary conditions for rough-walled microchannel flow simulation

Fig. 3.2 depicts the computational domain and boundary conditions adopted for the numerical simulation of turbulent flow in a rough-walled microchannel. The model includes a three-dimensional representation of the microchannel with explicitly defined roughness elements along the wall surfaces. A uniform velocity inlet condition is applied at the channel entrance, while a pressure outlet condition is specified at the exit. Constant heat flux boundary conditions are imposed on the heated walls, and no-slip conditions are enforced on all solid surfaces. This configuration ensures accurate prediction of velocity, temperature, and turbulence fields within the microchannel.

Governing Equations

The fluid flow and heat transfer in the microchannel were governed by the conservation equations of mass, momentum, and energy for incompressible, steady-state turbulent flow.

Continuity Equation

$$\nabla \cdot u = 0 \qquad (1)$$

Momentum Equation

$$\rho(u \cdot \nabla)u = -\nabla p + \mu\nabla^2 u \quad (2)$$

Energy Equation

$$\rho c_p(u \cdot \nabla T) = k\nabla^2 T \quad (3)$$

where u is the velocity vector, *p* is pressure, *T* is temperature, ρ is fluid density, μ is dynamic viscosity, c_p is specific heat, and *k* is thermal conductivity.

Nondimensional Analysis

To generalize the heat transfer and flow characteristics, key nondimensional parameters were employed.

Reynolds Number

$$Re = \frac{\rho u Dh}{\mu} \quad (4)$$

where D_h is the hydraulic diameter of the microchannel.

Nusselt Number

$$Nu = \frac{hDh}{k} \quad (5)$$

where *h* is the convective heat transfer coefficient.

Friction Factor

$$f = \frac{2\Delta p Dh}{\rho u^2 L} \quad (6)$$

where Δp is the pressure drop across the channel length L.

Relative Roughness

$$\frac{\varepsilon}{Dh} \quad (7)$$

where ε is the average roughness height.

These nondimensional parameters enabled comparison between smooth and rough microchannels and facilitated evaluation of thermal–hydraulic performance independent of channel size.

4.0 RESULTS AND DISCUSSION

The results showed that the Nusselt number increased significantly with Reynolds number for both smooth and rough microchannels, with roughened surfaces consistently exhibiting higher heat transfer rates. At high Reynolds numbers, roughness elements intensified turbulence and disrupted the thermal boundary layer, leading to enhanced convective heat transfer. However, the friction factor also increased markedly with roughness height, indicating higher pumping power requirements.

The comparison between experimental and numerical results demonstrated good agreement, confirming the validity of the numerical model. Performance evaluation revealed that moderate roughness heights provided an optimal balance between heat transfer enhancement and pressure drop, supporting the findings of Kandlikar et al. (2014) and Srivastava and Dewan (2020).

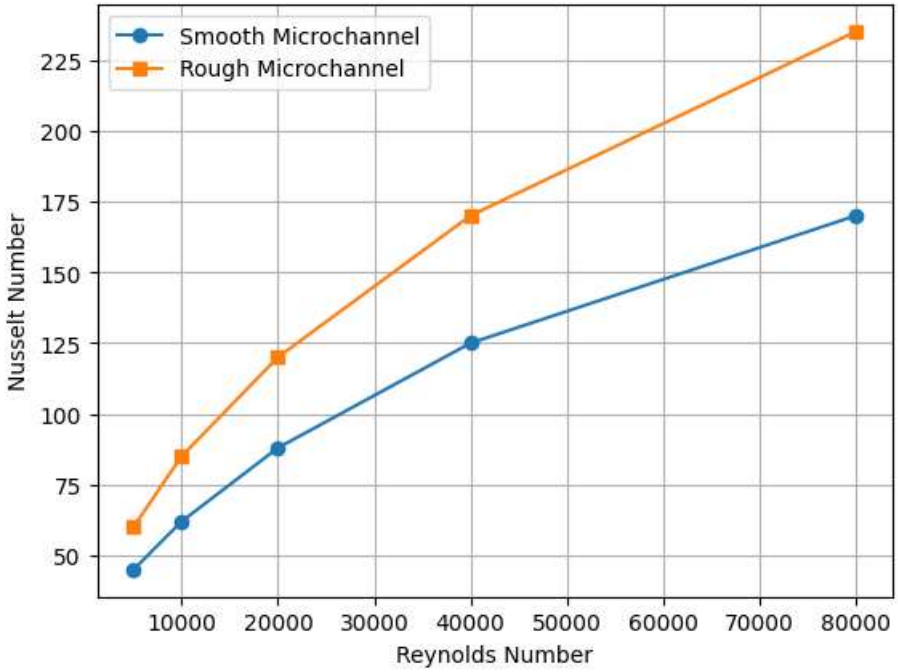

Fig. 4.1. Variation of Nusselt number with Reynolds number for smooth and rough microchannels. Figure 4.1 shows that the Nusselt number increases with Reynolds number for both smooth and rough microchannels, indicating enhanced convective heat transfer at higher flow velocities. The rough microchannel consistently exhibits higher Nusselt number values than the smooth channel due to intensified near-wall turbulence and disruption of the thermal boundary layer. This enhancement becomes more pronounced at high Reynolds numbers, confirming that surface roughness plays a significant role in improving convective heat transfer performance in turbulent microchannel flows.

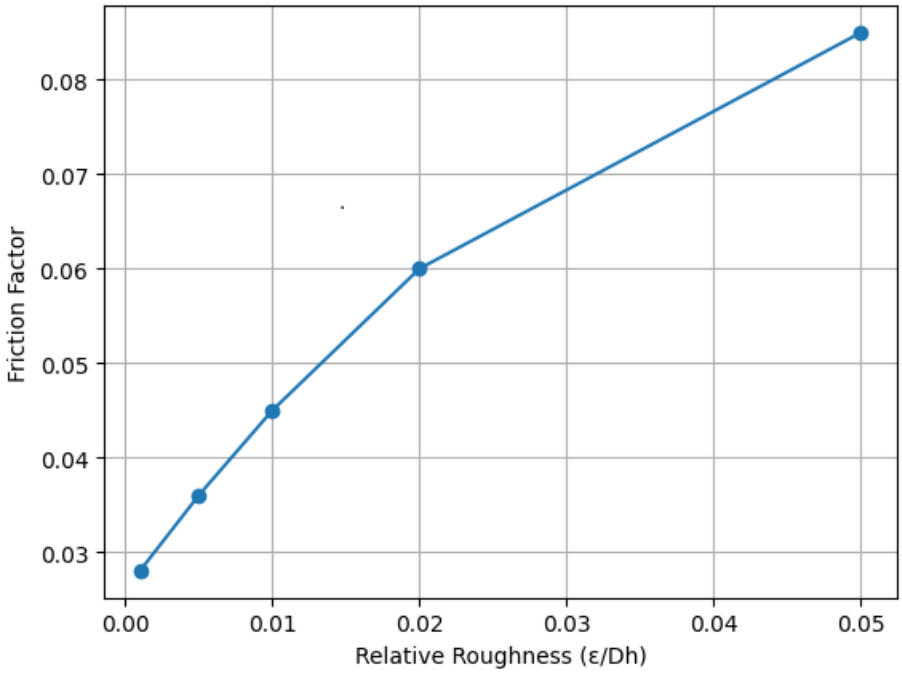

Fig. 4.2 Variation of friction factor with relative roughness for turbulent flow in microchannels.
Figure 4.2 illustrates the increase in friction factor with increasing relative roughness. As surface roughness height increases relative to the hydraulic diameter, flow resistance rises due to enhanced momentum dissipation near the wall. While roughness improves heat transfer, the associated increase in friction factor highlights the trade-off between thermal enhancement and hydraulic losses in roughened microchannels.

5.0 CONCLUSION

This study investigated the effect of surface roughness on convective heat transfer in turbulent microchannel flow at high Reynolds numbers. The findings confirmed that surface roughness significantly enhances heat transfer by increasing near-wall turbulence and reducing thermal boundary layer resistance. However, the enhancement is accompanied by increased frictional losses, highlighting the trade-off between thermal performance and hydraulic efficiency. The results demonstrated that optimal roughness configurations can substantially improve microchannel heat exchanger performance when properly designed. The study contributes to improved understanding of roughness-induced heat transfer mechanisms and provides valuable guidance for the design of high-performance microchannel thermal systems.

RECOMMENDATIONS

Based on the findings of this study, it is recommended that engineered surface roughness be deliberately incorporated into microchannel designs where enhanced convective heat transfer is required, particularly in high Reynolds number applications such as electronic cooling, compact heat exchangers, and energy systems. Optimized roughness geometries and relative roughness ratios should be selected to maximize heat transfer enhancement while controlling excessive pressure drop penalties. Designers and thermal engineers are advised to adopt hybrid optimization approaches that balance thermal performance and pumping power requirements to ensure overall system efficiency.
Future experimental studies should investigate a wider range of roughness geometries, including sinusoidal, dimpled, ribbed, and fractal surface patterns, to establish generalized correlations applicable

across different turbulent flow regimes. Additionally, the use of advanced diagnostic techniques such as particle image velocimetry and infrared thermography is recommended to provide deeper insight into near-wall turbulence structures and boundary layer disruption mechanisms.

From a numerical perspective, further research should employ large eddy simulation or direct numerical simulation to capture fine-scale turbulence interactions induced by surface roughness, particularly in transitional and fully rough regimes. It is also recommended that future studies consider the combined effects of surface roughness and nanofluids or phase change materials to further enhance thermal performance. Finally, extending the analysis to transient and non-uniform heat flux conditions would improve the applicability of roughened microchannel designs to real-world thermal management systems.

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