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Effect of Surface Roughness on Pressure Drop in Microchannel for Multiphase Flow: A Computational Analysis using ANSYS

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Abstract

This study investigates the influence of surface roughness on pressure drop in microchannel for multiphase flow using computational fluid dynamics (CFD) simulation with ANSYS. Three microchannel models- without roughness, with rectangular roughness, and with triangular roughness - are analyzed at roughness heights from 0.0003m to 0.0007m and inlet velocities from 0.5 ms^{-1} to 2.5 ms^{-1}. The study reveals that surface roughness significantly impacts the pressure drop, with the effect becoming more significant at higher velocities and roughness heights. The microchannel without roughness shows the lowest pressure drop among all. The microchannel with rectangular roughness shows an initial reduction in pressure drop due to enhanced mixing, but as the roughness height increases, the pressure drop rises due to increased turbulence and flow resistance at higher velocities. The microchannel with triangular roughness shows significant increase in pressure drop due to enhanced turbulence and energy dissipation. Notably, the triangular roughness model shows a complex relationship with pressure drop, initially decreasing and then sharply increasing at higher roughness heights.

Keywords: Microfluidics, Multiphase Flow, Computational Fluid Dynamics (CFD)

1. Introduction

The depletion of conventional energy sources in the coming years has led to an intensified focus on energy conservation and the development of alternative energy sources. In light of this, researchers have placed great emphasis on enhancing the efficiency of conventional energy systems and increasing the utilization of renewable energy sources. In order to increase the effectiveness of such systems, modern researchers are focusing more on the thermal management of energy systems. A unique strategy for developing energy-efficient systems is miniaturization. The microchannels is an innovative and cutting-edge device in heat transfer enhancement technology. [1]

Microchannels are particularly well suited for applications where size, efficiency, and performance are key considerations because of their special properties, such as high surface area to volume ratios, higher heat transfer rates, and enhanced mass transfer rates. Microchannels provide intriguing opportunities to improve heat and mass transfer in multiphase flow systems that involve the movement of two or more phases, including interactions between gas-liquid, liquid-liquid, or gas-liquid-solid.

In earlier studies, the definition of microchannels has varied significantly, with researchers offering multiple interpretations. For classification of channels, hydraulic diameter (D_h) of the channel is considered. Microchannels are defined as flow passages that have hydraulic diameters in the range of 10 to 200 micrometers by Kandlikar and Grande [2]. They have classified channels as minichannels, microchannels, transitional channels,

Table 1. The classification of channels given by Kandlikar and Grande [2] and Mehendale et al. [3]

Kandlikar and Grande[2]	Mehendale[3]
Conventional channels: D_h < 42mm	Conventional channels: D_h < 46mm
Minichannels: D_h = 200 μm – 3mm	Compact passages: D_h = 1mm - 6mm
Microchannels: D_h = 10 μm - 200 μm	Meso-channels: D_h = 100 μm - 1mm
Transitional channels: D_h = 0.1 μm – 10 μm	Microchannels: D_h = 1 μm - 100μm

conventional channels and molecular nanochannels. According to Mehendale et al., micro-heat exchangers: D_h= 1 - 100 μm, meso heat exchangers: D_h=100 μm – 1 mm, compact heat exchangers: D_h= 1 - 6 mm and conventional heat exchangers: D_h > 6 mm. [3]. Obot suggested a simpler classification based on the hydraulic diameter of the channel. Microchannels were defined by N. T. Obot as channels with a hydraulic diameter (Dh) of less than 1000m (D_h < 1 mm) [4]. According to Kandlikar & Grande [2] and Mehendale [3], different types of channels are categorized in Table 1 for various hydraulic channel diameters.

2. Methodology

The geometric model of the microchannel has been adapted from the Study of Lee and Mudawar [5], consisting of 21 parallel rectangular microchannel in the test module. In this study, a single micro channel out of 21 channels is considered as computational domain. The microchannel dimension has been set to a width of 215μm, height of 821μm and length of 4.48cm. The rectangular elements are 0.2mm in length, distance between two roughness elements is 0.5mm and total number of roughness elements are 44. The triangular elements are 0.5mm in length, height of a roughness element is 0.2mm, distance between two roughness elements is 0.5mm and total number of roughness elements are 45.

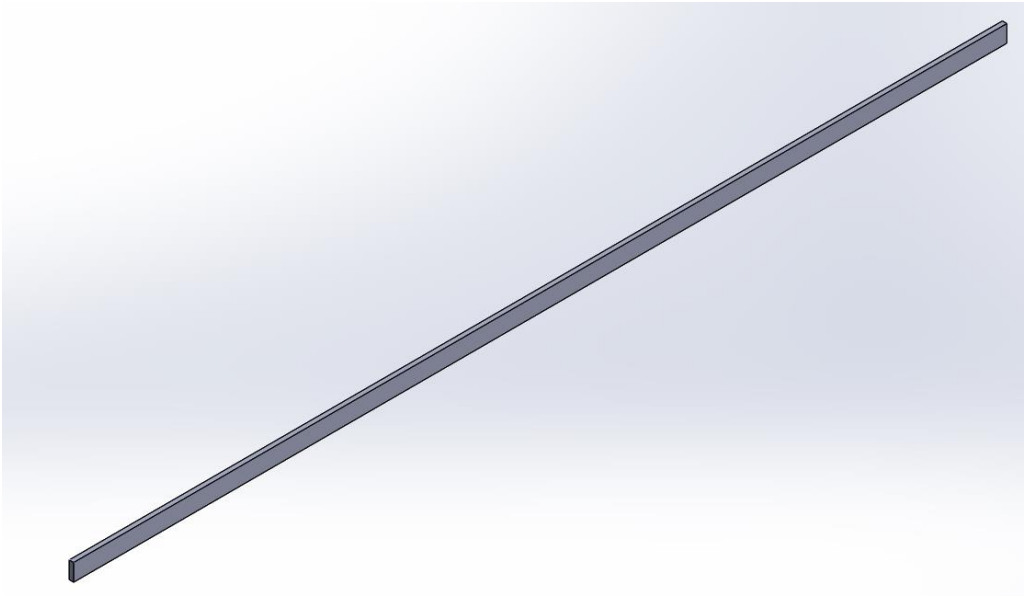


Figure 1. Model of microchannel without roughness element

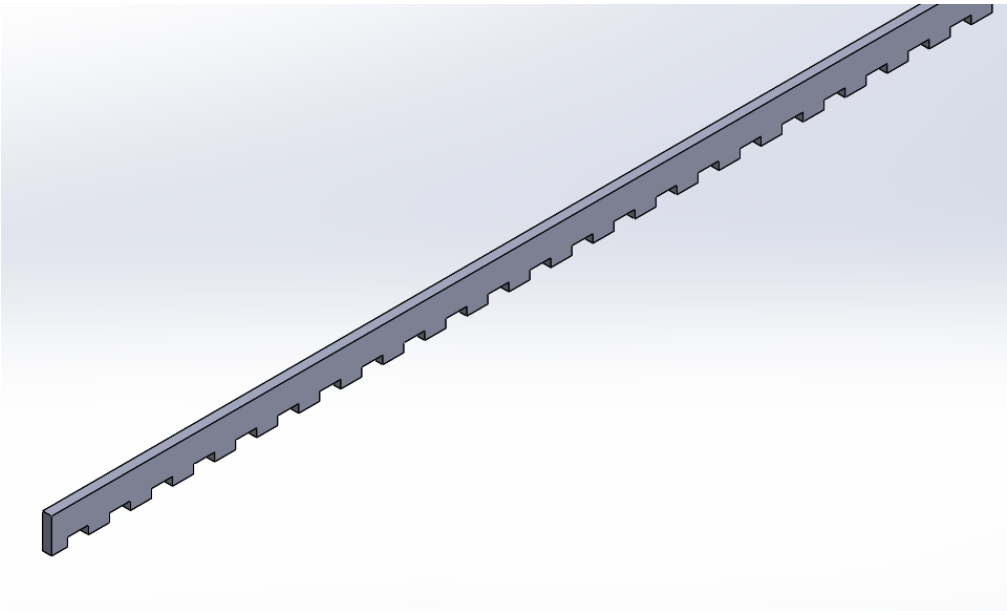


Figure 2. Model of microchannel with rectangular roughness elements

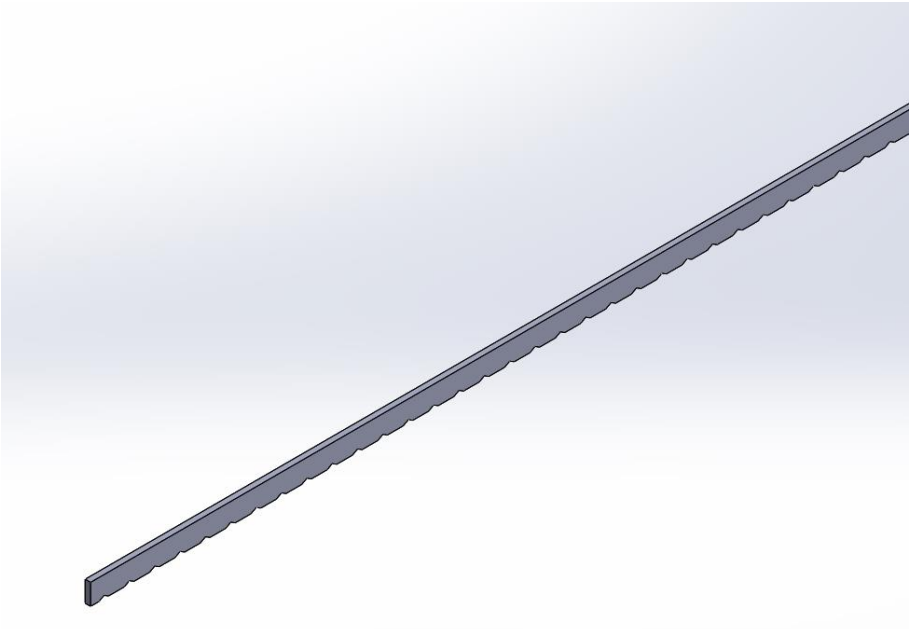


Figure 3. Model of microchannel with triangular roughness elements

In this research, edge sizing technique has been used for meshing. Aluminum is used as the material of the microchannel wall, consisting of density of 2719 kgm^{-3}. For multiphase flow, air and water-liquid is used here consisting of density of 1.225 kgm^{-3} and 998.2 kgm^{-3} respectively. Air has been used as the primary phase and water-liquid as the secondary phase in this study. Surface tension is considered 0.072 Nm^{-1}, suggested by previous literatures.

Volume of Fluid(VOF) method has been used in this research for multiphase flow modeling and for turbulence modeling, standard k-epsilon model is used instead of laminar model. It is a very effective model for turbulent flow simulation, consisting of 2 transport equation. Intensity and viscosity ratio method has been used for turbulence specification model. Standard roughness model has been used, ranging the value of roughness height from 0.0003m to 0.0007m and the value of roughness constant is 0.5. For the wall, no slip boundary condition is applied.

The steady-state conversation for mass and momentum equation used for this study are given by:

Continuity Equation:

$$\nabla . (\rho u) = 0 \tag{1}$$

Momentum Equation:

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

where ρ is the density, u is the velocity vector, p is the pressure and μ is the viscosity. For boundary conditions, fluid velocity and temperature are specified at inlet. No slip condition is applied to the walls. Input at inlet is varied from 0.5 ms^{-1} to 2.5 ms^{-1}.

The study is validated by comparing the numerical data of friction factor obtained from microchannel model without roughness elements with the experimental data by Suwankamnerd and Wongwises [6].

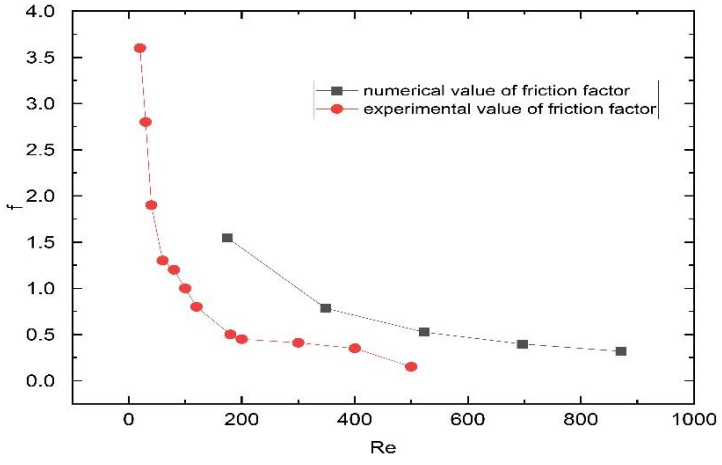


Figure 4. Validation of the numerical analysis

3. Result and Discussion

Figure 5 demonstrates the trends for different velocities for microchannel without surface roughness. It is the baseline for comparison, representing an ideal scenario with minimal frictional resistance and energy dissipation. It exhibits efficient flow characteristics with minimal pressure drop across varying velocities. Across all velocities, the pressure drop decreases as roughness height increases. The trend is consistent due to the minimal frictional resistance and good mixing of phases for no surface roughness in the microchannel. At lower velocities, the flow is predominantly laminar, with minimal turbulence. As velocity increases, the flow remains stable with slight turbulence, but the microchannel effectively reduces energy dissipation, maintaining lower pressure drops even at higher velocities.

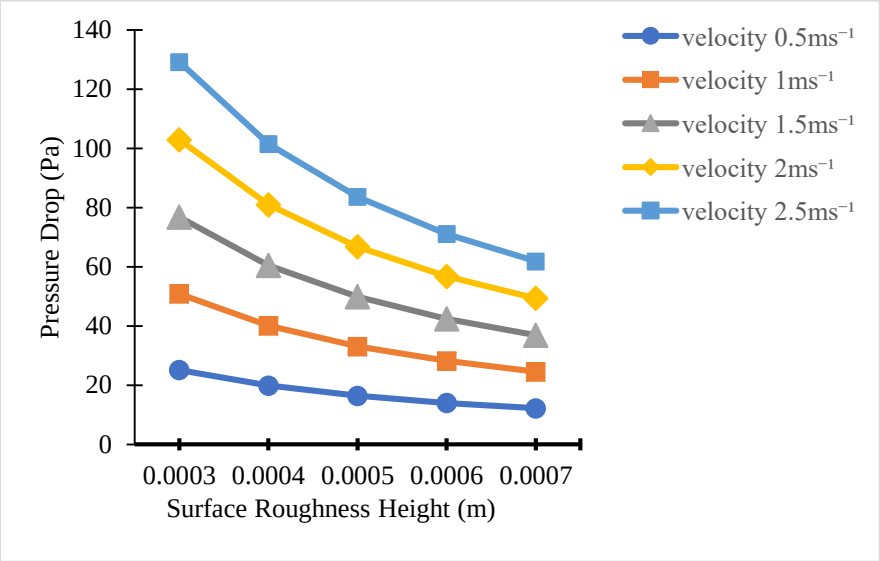


Figure 5. Pressure Drop versus Roughness Height for microchannel with no surface roughness

The trend for rectangular roughness elements differs significantly. As seen from figure 6, at lower velocities, the pressure drop decreases with increasing roughness height due to minimal disruptive effect and stable phase mixing at lower velocities, leading to a reduced pressure drops. But at higher velocities, flow separation and reattachment increase interfacial phase mixing and energy dissipation, leading to higher pressure drop.

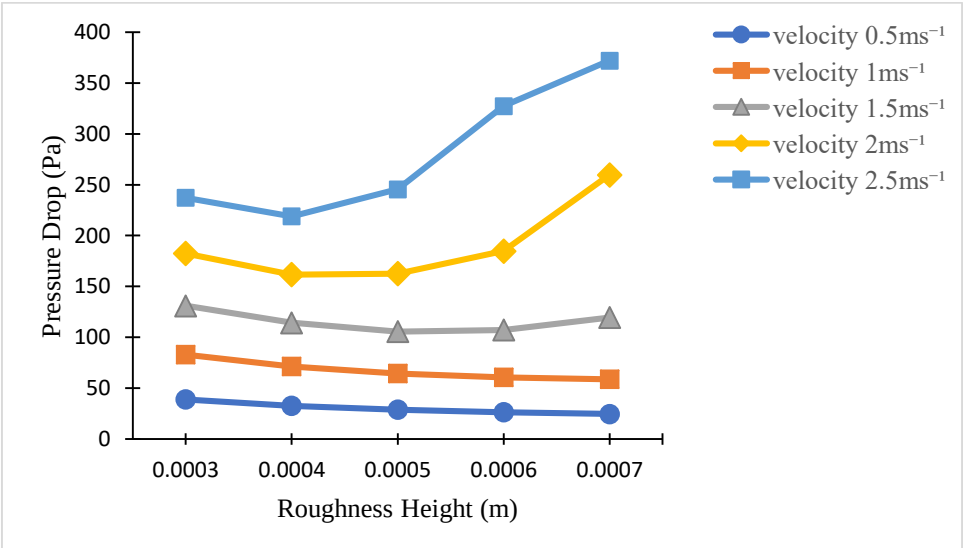


Figure 6. Pressure Drop versus Roughness Height for microchannel with rectangular roughness elements

Analyzing the trend of triangular roughness in microchannel from figure 7, a very complex behavior is observed. The pressure drop generally decreases with increasing roughness height at lower velocities, indicating the minimal resistance to flow and stable phase mixing induced by triangular roughness. At moderate velocities, triangular roughness enhances phase interaction, leading to improved mixing and lower resistance. However, at higher velocities and roughness heights, very chaotic flow occurs, causing flow separation, recirculation zones and significant instability of the phases. This significantly increases the pressure drop.

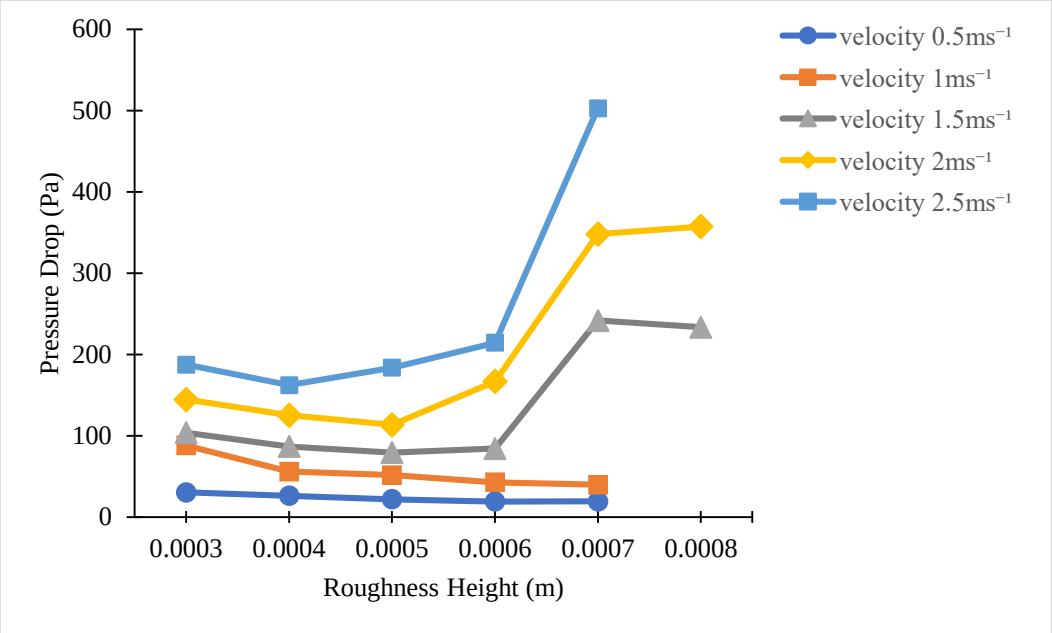


Figure 7. Pressure Drop versus Roughness Height for microchannel with triangular roughness elements

4. Conclusion

This study presents a comprehensive and systematic approach to investigate the effect of surface roughness on pressure drop in microchannels under multiphase flow conditions using ANSYS. Three different microchannel models have been analyzed: one without surface roughness, one with rectangular roughness, and one with triangular roughness. Through a systematic research approach, valuable insights have been obtained into the behavior of pressure drop under varying surface roughness heights and inlet velocities. The findings give valuable insights into the complex interactions between surface roughness and pressure drop characteristics.

The analysis reveals a clear impact of surface roughness on pressure drop. The microchannel without roughness consistently showed the lowest pressure drop, while rectangular roughness initially reduced pressure drop due to stable phase mixing, but increased at higher roughness heights due to flow separation and reattachment, and interfacial phase mixing and energy dissipation. Triangular roughness showed a more complex behavior, with initial decreases in pressure drop followed by significant increases at higher roughness heights due to severe flow disruptions, instable phase mixing, chaotic flow and energy dissipation.

Overall, this research contributes to a deeper understanding of multiphase flow dynamics in microchannels and provides valuable implications for the design and optimization of microchannel-based systems in various industrial applications.

For future research, following recommendations are given:

1. Further investigation across a wider range of surface roughness heights and inlet velocities can provide a more comprehensive understanding of their influence on pressure drop in microchannels.
2. Conducting experimental studies to validate the computational findings will enhance the reliability and applicability of the results.
3. Exploring the coupled effects of surface roughness on pressure drop and heat transfer in 43 microchannels will be valuable for thermal management applications.
4. Investigating optimization strategies to minimize pressure drop while maximizing heat transfer efficiency in microchannel-based systems may lead to significant advancements in various engineering fields.

5. Manufacturing of microchannel is very complex. Future studies can solve this problem and make it easier to manufacture.

5. References

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