EFFECT OF WALL ROUGHNESS ON THERMAL PERFORMANCE OF WAVY MICROCHANNELS

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Abstract: Effect of wall roughness on the thermal performance of wavy microchannels is numerically investigated in this paper. Parametric study of two-dimensional laminar fluid (water) flow and heat transfer characteristics in micro-sized wavy channels (500 µm wide, 20 mm long) was performed by varying the values of maximum roughness magnitude (ε) and intensity (r_i) for a *Re* of 100. Thermal performance for a constant heat flux of 47 W/cm^2 was compared for different values of ε (0-50 µm) and r_i (of 0-50% over a smooth surface). Based on the comparison with the corresponding smooth-walled wavy microchannels, it was found that both Nusselt number and pressure drop increased with ε as well as r_i, while the overall thermal performance was found to decrease with increased roughness (and intensity). The results showed that including wall roughness in the numerical simulations is important to accurately predict the performance of microchannels when the order of roughness magnitude approaches the channel size.

Keywords: microchannels, wavy channels, roughness, forced convection, single-phase

INTRODUCTION

The maximum heat flux of a single-chip high performance multiple purpose unit will reach up to 47 W/cm^2 by the end of 2010 [1], which will be very difficult to meet with the cooling efficiency of traditional fans. This increase in power density leads to significant thermal management problems. One of the solutions proposed is to enhance heat transfer by utilizing single phase fluid flow in microchannels. Various passive enhancement techniques were suggested in the literature to boost the performance of microchannel flows including the use of wavy surfaces for channel walls. Wavy channels are easy to manufacture and offer a passive, cost-effective means to realize improved thermal performance. They were traditionally employed in high Reynolds number (*Re*) flows and recently in creeping flows in microfluidics and mixing applications. They were more recently investigated for cooling of microelectronics [2,3] but none of the prior studies analyzed the effect of wavy wall roughness on thermal performance. Surface roughness is inevitable in nature to any manufacturing/fabrication process and might become an important consideration especially as the channel hydraulic diameters scale down to microscale. Artificial roughness was included in prior work using specified regular contours/shapes for roughness in straight microchannels. Some of the examples are provided in ref. [4-6]. They found that inclusion of roughness in the simulations results in an increase in the pressure drop without affecting the heat transfer significantly. But geometrically regular roughness representation is suitable only under ideal conditions. The flow dynamics under practical conditions might have a different impact on performance prediction when the surface roughness is irregular. Moreover, the impact of roughness on the overall performance (combined effect of pressure drop, heat transfer coefficient and surface area increase) was not directly considered in any of the prior work. Therefore, the effect of arbitrary wall roughness, which more closely mimics the practical surface roughness, on the overall thermal performance for two-dimensional laminar flow in wavy microchannels is numerically investigated in this paper.

NUMERICAL MODEL

Geometry

The wavy channel geometry considered, consisted of crests and troughs facing each other alternately by a phase of 180^0 (serpentine channel), was analyzed for thermal performance dependence on maximum roughness magnitude (ε) and intensity (r_i). The schematic and the nomenclature of the channel are shown in Fig. 1.

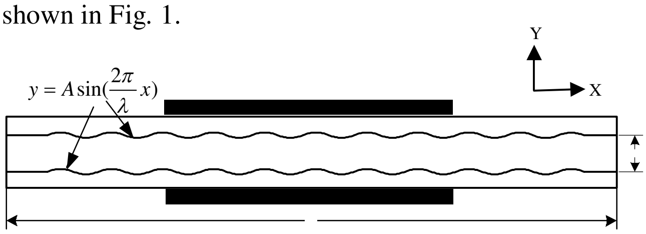


Fig. 1: Schematic of wavy microchannel.

Roughness Generation

Arbitrary roughness was generated using Gaussian distribution as given in the description below.

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (1)$$

Setting μ=0, $\sigma = \frac{1}{\sqrt{2\pi}}$; then, $f(x) = 1$ when x=0.

Accordingly, the roughness channel wall function ($y*$) can be obtained as given below.

$$y^{*}=y+\varepsilon \cdot f(2\sigma) \tag{2}$$

In addition, r_i was set as a percentage of mean roughness i.e., (1- r_i) % roughness is less than $\varepsilon \cdot f(2\sigma) = 0.135\varepsilon$. Figure 2 shows the examples of arbitrary roughness geometries generated.

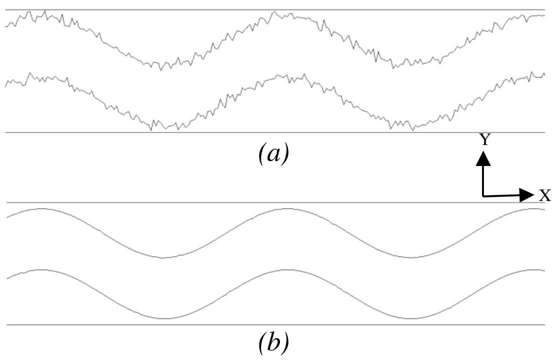


Fig. 2: Rough-walled wavy channels with (a) 50% roughness and (b) 5% roughness over a smooth-walled wavy channel.

Assumptions

1. Flow is laminar and steady
2. No thermophysical property variation with temperature.
3. Fluid is incompressible, Newtonian and viscous.
4. No velocity-slip at the walls.
5. Temperature and heat flux continuity at all the solid boundaries.

Boundary Conditions

Commercial CFD software, FLUENT [7], was used to solve the flow and temperature fields. For the flow simulations, a constant fluid inlet velocity was specified, along with the outlet pressure. For thermal simulations, a constant fluid inlet temperature was specified and all the walls were assumed as insulated. Heat sources were assumed at the channel center in the flow direction on the outside surfaces (straight surfaces) of the two wavy walls as shown in Fig. 1.

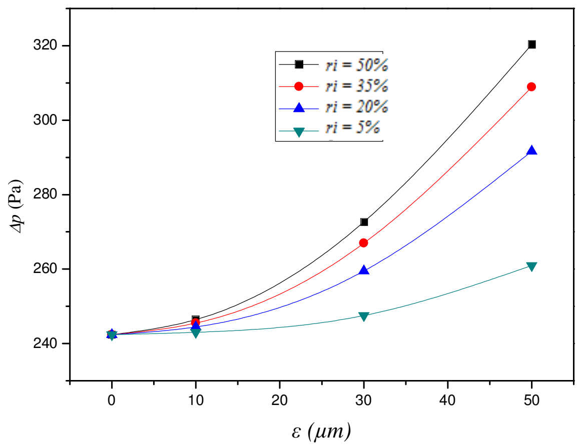
Meshing and Grid Independency

A triangular meshing scheme was used for all the simulations. Various grids of sizes from 50,000 nodes to 3.1 million nodes were employed for checking the mesh independency of the solution. The difference in the flow pressure drop and the Nusselt numbers between the solutions on the grids with 0.78 million nodes and 3.1 million nodes was found to be about 0.44% and 0.21% respectively. Hence, to save computation time and memory, grid sizes of around 0.78 million nodes were used for all the simulations in this study. A relative error of less than 10^{-8} was assumed as the convergence criteria for velocity and pressure variables, while $\varepsilon < 10^{-12}$ was assumed for temperature. The velocity-pressure coupling was achieved using SIMPLEC [8] method.

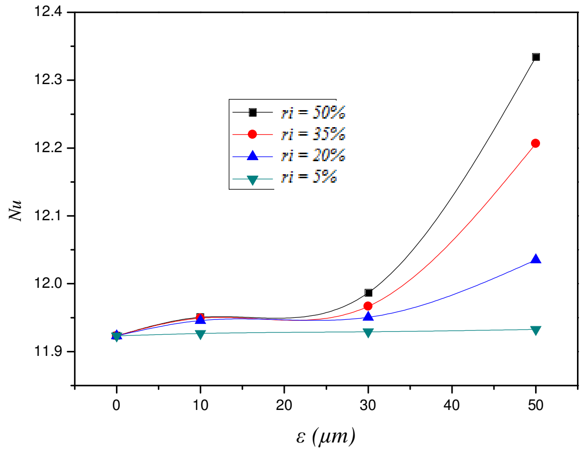
RESULTS AND DISCUSSION

Parametric study of ε and r_i for a *Re* of 100 (suitable for electronics cooling applications without resulting in high pressure drops [3]) was performed for a wave amplitude of 100 µm. A 500 µm wide, 20 mm long wavy channel was considered with a wavelength of 2 mm. Thermal performance for a constant heat flux of 47 W/cm^2 (from a 1 cm X 1 cm heater located at the channel axial center) was compared for different values of ε (0-50 µm) and r_i (of 0-50% over a smooth surface) and the results are plotted in Fig. 3. Performance Factor (*PF*) was defined as shown below [9] under the condition of constant pumping power.

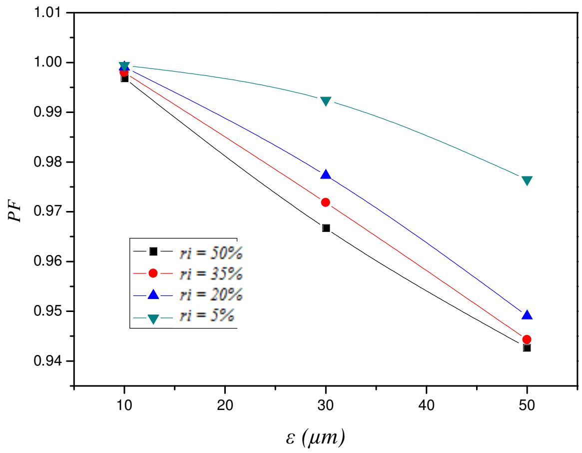
$$PF = \frac{\left(\dfrac{Nu_w}{Nu_s}\right)}{\left(\dfrac{\Delta P_w}{\Delta P_s}\right)^{\frac{1}{3}}} \tag{6}$$



(a) Effect of ε on pressure drop (Δp) for various r_i



(b) Effect of ε on wall averaged Nusselt number (Nu) for various r_i

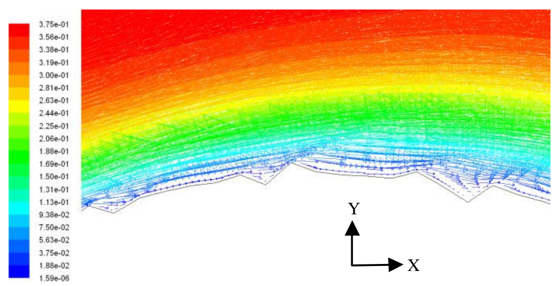


(c) Variation in PF with ε for different r_i

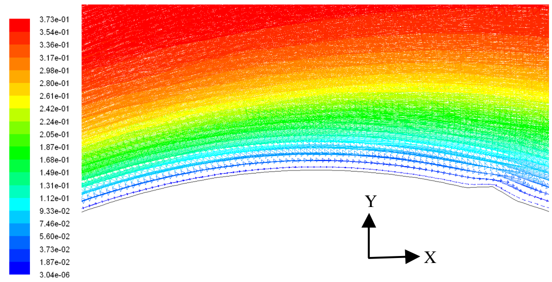
Fig. 3: Results from the parametric study

In Eq. (6), subscript *w* represents wavy channel with roughness while subscript *s* represents a smooth walled wavy channel. Based on the comparison with the corresponding smooth-walled wavy microchannels, it was found the rough-walled counterparts showed inferior performance. As shown in Fig. 4, the inclusion of surface roughness in the simulations was found to affect the local flow field. Secondary flows with local recirculation zones were observed in random roughness pits and were more pronounced in channels with large/more roughness. Accordingly, it was found that both Nusselt number and pressure drop increased with ε as well as r_i, while the overall thermal performance, *PF*, was found to decrease with increased roughness (and intensity) due to a higher sensitivity of pressure drop to roughness compared to heat transfer. This can be observed from Fig. 3 as well, that low ε has less impact on heat transfer but significantly affects the pressure drop. The reason for this behavior is explained below.

It must be noted that the wall averaged Nusselt number included the additional surface area due to roughness. Increase in the surface area and local mixing in the flow result in improved heat transfer, but flow separation due to roughness decreases heat transfer to the fluid. This conjugate effect accounts to only a marginal improvement in the heat transfer performance compared to the pressure drop increase (roughness peaks protrude into the flow resulting in a continuous increase in the pressure drop).



(a)



(b)

Fig. 4: Velocity vectors (scale is in m/s) in rough-walled wavy channels with (a) 50% roughness (showing local flow recirculation) and (b) 5% roughness over a smooth-walled wavy channel.

It is worthwhile to note from Fig. 4 that vortex interaction and periodic flow mixing (due to regularly spaced and well-defined geometrical roughness), which contribute to an increase in heat transfer in addition to affecting the pressure drop, are missing in the current result plots. Hence, performance prediction will be more accurate and practical when roughness is introduced arbitrarily as in the present work.

CONCLUSION

Effect of wall roughness on the overall thermal performance for two-dimensional laminar flow in wavy microchannels is numerically investigated in this paper.

The results of the parametric study showed that including wall roughness in the numerical simulations is important to accurately predict the performance of microchannels (here, wavy microchannels) where the order of roughness magnitude can be comparable to the channel size depending on the manufacturing/fabrication process employed. Without the inclusion of roughness, it was observed that the overall performance (including the combined effect of pressure drop, heat transfer coefficient and surface area increase) would be over-predicted by as much as 6% under the considered geometrical and flow conditions.

The observations of the numerical simulations performed in this paper could be helpful in gaining fundamental insight of flow thermohydrodynamics in rough-walled channels and, in general, would lead to a better understanding of the effects and importance of including surface roughness in future similar analyses.

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