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Numerical analysis of distinction boundary of surface roughness and wall blocks in laminar pressure-driven flow within the rugged microchannels

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ABSTRACT: In the present study, a laminar pressure-driven flow within a microchannel consisting of two parallel flat plates with rugged walls has been simulated. The walls' surface ruggednesses have sinusoidal profiles with relative heights of $0 \le h/H \le 0.15$. The governing equations in a two-dimensional general coordinate are solved using the finite-volume method in a non-uniform grid with the maximum orthogonality of the grid lines adjacent to the rugged boundaries. In the first step, the surface ruggednesses of the wall are divided into two categories: surface roughness and wall blocks. Then, the boundary of surface roughness from wall blocks is determined by defining and applying two qualitative and quantitative criteria. According to the qualitative criterion, when the surface ruggedness is of the order of surface roughness, the pressure distribution at the centerline remains as linear as a perfectly smooth microchannel. But when the surface ruggednesses are of the order of wall blocks, however, the pressure distribution at the centerline is oscillating. Also, on the quantitative criterion, the average shear and normal forces just adjacent to the rugged surfaces are accurately calculated and compared. According to the results, in laminar flow within the rugged planar microchannels, $h/H|_{cr}$ is 0.042 which is independent of Δp.

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1. Introduction

Surface ruggedness is a feature of the surface of the walls. When the height of the surface ruggedness is much less than the characteristic length of the channel (channel height), it is called surface roughness. But when the surface ruggednesses are of the order of the height of the channel, the use of surface roughness term for them does not seem to be correct. In this case, it is necessary to address the ruggednesses on the wall as wall blocks and analyze the flow in the channel with the wall blocks, just like the flow in a convergent-divergent channel.

In all previous numerical studies, the distinct boundary between the terms surface roughness and wall blocks has not been determined. In other words, there is not enough attention to the use of a suitable word for surface ruggedness, so that very high ruggednesses are sometimes considered as surface roughness. Therefore, the first purpose of this paper is to determine the distinction boundary between the two terms of surface roughness and wall blocks for pressure-driven flow. Then the effect of surface roughness on this flow within a microchannel is investigated.

2. Problem Statement

In this paper, a two-dimensional laminar pressure-driven flow between two parallel plates (as a microchannel) with sinusoidal surface ruggednesses (in unit depth) is investigated numerically. The schematic of the problem is shown in Fig. 1, in which height, length and relative ruggednesses of the microchannel are H, L=10H, and $0 \le h/H \le 0.15$, respectively. $p_1 = p_{in}$ and $p_2 = 0$ are the pressures at the inlet and the output of the microchannel, respectively. The governing equations are the Navier-Stokes equations for a Newtonian fluid in a microchannel for the incompressible and steady-state. The boundary conditions of the problem are the non-slip flow and $\frac{\partial^2 p}{\partial n^2} = 0$ on the walls and the flow development at the inlet and outlet of the microchannel.

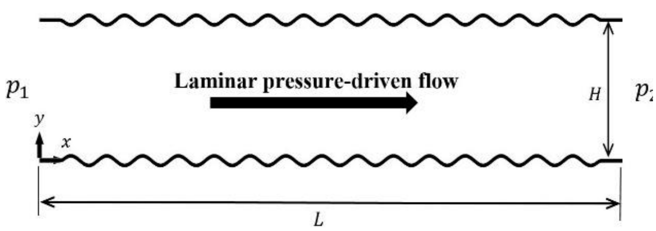

Fig. 1. Schematic of a two-dimensional laminar pressure-driven flow within a microchannel with sinusoidal surface ruggednesses

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3. Numerical Method

In this study, the 2D governing equations and the corresponding boundary conditions are solved by the use of the finite-volume method with collocated variables in a non-uniform body-fitted grid with the maximum orthogonality of the grid lines adjacent to the boundaries. The SIMPLE scheme links the velocity and pressure fields, and the Rhie-Chow interpolation scheme is used to calculate the moving mass at the faces of the control volumes to avoid the probable checkerboard pressure field. The concurrent evaluation of the diffusive and convective terms at the faces of the control volumes is performed using a hybrid scheme.

4. Results and Discussion

In microchannels, when a laminar flow of fluid passes near a rugged surface, two qualitative and quantitative criteria can be established to detect surface roughness from the wall blocks.

4.1. Qualitative criterion

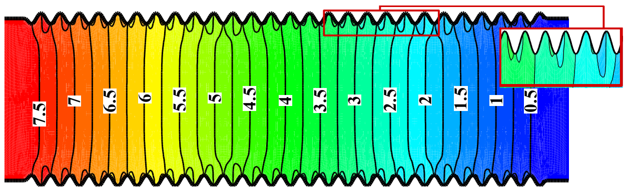
In this criterion, the effectiveness of the pressure distribution at the microchannel centerline from the surface ruggedness is evaluated. Figs. 2 and 3 compare this ineffectiveness and effectiveness.

4.2. Quantitative criterion

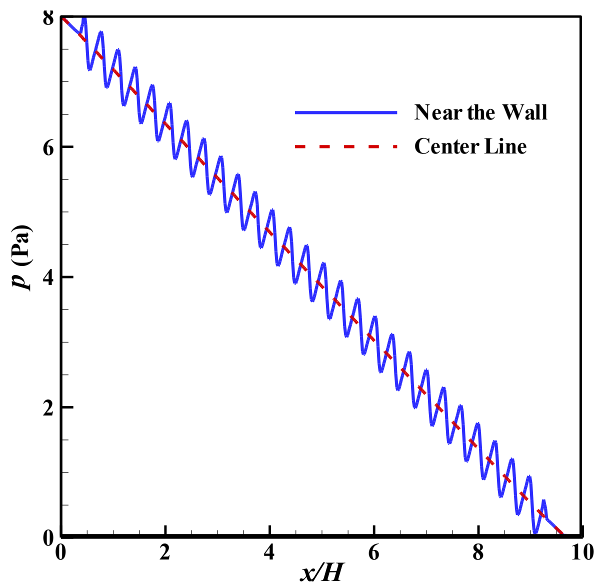
On the quantitative criterion, the average normal and shear forces in the horizontal direction of x just adjacent to the rugged surfaces are accurately calculated in the form of Eqs. (1) and (2) and compared for different relative ruggednesses.

$$\overline{F_{N,x}} = \frac{2}{L_c}\int_{i=1}^{i=I_{max}} \left\{ \begin{matrix} \mu\left(\frac{\partial u}{\partial \xi}\xi_x + \frac{\partial u}{\partial \eta}\eta_x\right)A_{nx} \\ -pA_{nx} \end{matrix} \right\}\Bigg|_{i,1 \text{ or } Nj} d\xi_{i,1 \text{ or } Nj} \quad (1)$$

$$\overline{F_{S,x}} = \frac{2}{L_c}\int_{i=1}^{i=I_{max}} \left\{ \mu\left(\frac{\partial u}{\partial \xi}\xi_y + \frac{\partial u}{\partial \eta}\eta_y\right)A_{ny} \right\}\Bigg|_{i,1 \text{ or } Nj} d\xi_{i,1 \text{ or } Nj} \quad (2)$$



(a)

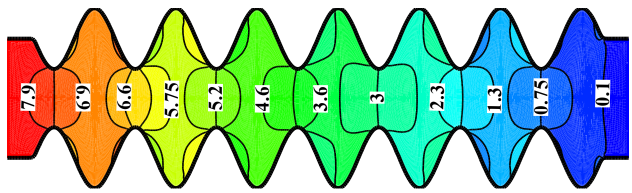


(b)

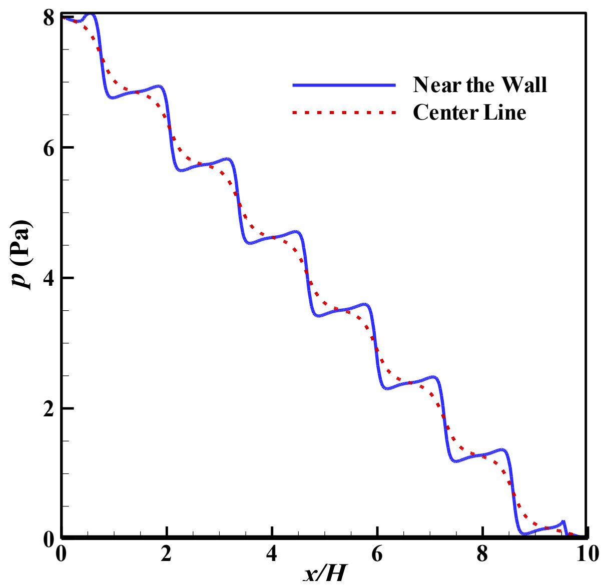
Fig. 2. Distribution of pressure along the microchannel with walls with the small relative ruggedness of h/H=0.02

a) Pressure field contours along the microchannel

b) Pressure distribution near the wall and the centerline of the microchannel



(a)



(b)

Fig. 3. Distribution of pressure along the microchannel with walls with the high relative ruggedness of h/H=0.15

a) Pressure field contours along the microchannel

b) Pressure distribution near the wall and the centerline of the microchannel

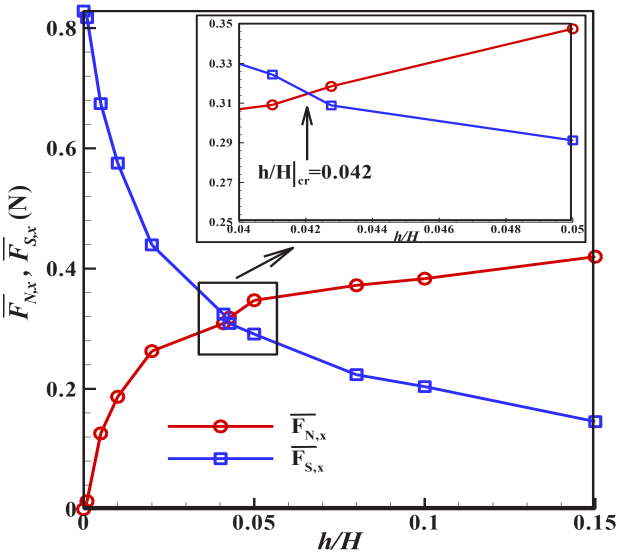


Fig. 4. Variations of $\overline{F_{N,x}}$ and $\overline{F_{S,x}}$ in terms of h/H

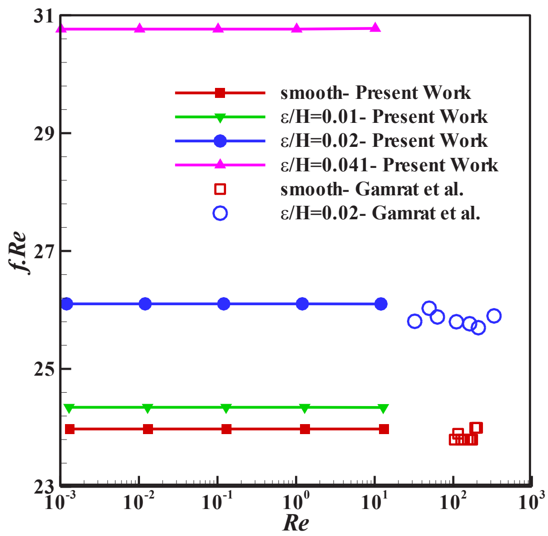


Fig. 5. Variations of fRe in terms of Re for different ε/H

4.1. Qualitative criterion

In this criterion, the effectiveness of the pressure distribution at the microchannel centerline from the surface ruggedness is evaluated. Figs. 2 and 3 compare this ineffectiveness and effectiveness.

4.2. Quantitative criterion

On the quantitative criterion, the average normal and shear forces in the horizontal direction of x just adjacent to the rugged surfaces are accurately calculated in the form of Eqs. (1) and (2) and compared for different relative ruggednesses.

Fig. 4 illustrates the variations of $\overline{F_{N,x}}$ and $\overline{F_{S,x}}$ in terms of different ruggednesses. The graphs of these two forces intersect at *h/H*=0.042. Hence, the critical relative ruggedness of $h/H|_{cr}$ = 0.042 is the distinct boundary between the surface roughness and the wall blocks which is independent of Δp and *Re*.

4.3. Investigation of the effect of surface roughness on the flow in the microchannel

In this section, 2D laminar pressure-driven flow between two parallel plates with a surface roughness of 0.001≥ε/H ≥0.041 is investigated. The effect of roughness on the laminar pressure-driven flow dynamic is considered as the most important objective in this paper. According to the results, the minor surface roughness of about 0.41μm reduces $\dot{m}$ by 22.3% compared to that in a completely smooth microchannel.

Also, Fig. 5 shows that *fRe* increases with increasing ε/H but is independent of Re. Similar behavior is observed in the experimental results of Gamrat et al. [1].

According to the above results, the following correlation can be defined:

$$fRe = 24\left[1+\frac{\varepsilon}{H}+144.4\left(\frac{\varepsilon}{H}\right)^2\right] \quad (3)$$

5. Conclusions

In the present study, the distinction boundary of surface roughness and wall blocks in laminar pressure-driven flow between two parallel flat plates was determined by defining and applying two qualitative and quantitative criteria. Based on the quantitative criterion, $h/H|_{cr}$ is 0.042 which is independent of *Δp* and Re. The results showed that unlike the macro-scale pressure-driven flows, the effect of surface roughness on the laminar flow inside microchannels is not negligible and increase the friction factor and decrease the flow rate.

References

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