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Numerical study of roughness effect on fluid flow in rectangular microchannels

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***Abstract*— The roughness within microchannels can be a significant factor affecting the fluid flow characteristics. In this study, numerical modelling is used to investigate the impact of roughness on velocity distribution and pressure drop in laminar flow. The CFD tool COMSOL is used to perform the simulation within a range of Reynolds number (10<Re<800). It has been shown that the pressure drop increases in rough microchannels as in large channels. Also, it was found that the transition to the turbulent flow begin at Re=800 and not at Re=2100 as in conventional theory at macro-scaled channels.**

***Keywords*— roughness, microchannels, Computational Fluid Dynamics (CFD), pressure drop**

I. Introduction

Microchannels are one of the essential geometry in microfluidic systems. In literature, different classifications were done to define the microchannels. Obot [1] and Pandey [2] classified the microchannels as the channels having a hydraulic diameter less than 1mm. In the last few decades, these systems have emerged as an important area in research aimed at the development of micro devices. Among various microfluidic systems [micro-coolers, micro-reactors, micro-biochips…], rectangular channels are widely used to improve heat transfer, enhance mixed efficiency and shift fluid flow direction [3, 4]. These small devices are currently used in different fields, due to their advantages such as compactness, lightweight and higher surface/volume ratio compared with other macro-scale systems [5]. Therefore, different studies are done in order to investigate the flow behaviour through microchannels in regards of the importance of the fundamental understanding of flow characteristics such as velocity distribution and pressure drop in design and process control.

Despite the numerous investigations, contradictory experimental results exist and lead to questionable discoveries about the micro-effects on the flow characteristics [6, 7]. These discrepancies are due to the existence of surface roughness at most cases

Thus, a computational approach can be useful to understand the basic physics of the problem. In numerical process, any effect can be easily neglected and the analysis of the problem would be possible.

For the single-phase flow, the studies on pressure drop in microsystems are based on the comparison of the friction factor, f, and the friction constant C*, defined as in equation (1), with their values at macro scales channels.

$$C^{*}=f.Re \qquad (1)$$

In one part, this comparison showed that the friction constant C* is different from its values in conventional channels. Different experimental studies showed that friction factor, f, in microchannels is less than its values in microchannels [8, 9, 10, 11]. Also, the friction constant, C*, so the pressure drop is found more than the pressure drop in macro scales channels [10, 11, 12, 13, 14]. In another part, other researches showed a good agreement with the theoretical results of pressure drop [15, 16, 17, 18].

Table.1 illustrates the discrepancies of the existing results of the friction factor and pressure drop through microchannels [19].

TABLE.1

THE DISCREPANCIES BETWEEN THE EXISTING STUDIES ABOUT THE FRICTION FACTOR FOR THE SINGLE PHASE FLOW.

Investigator	$f>f_{theory}$	$f\cong f_{theory}$	$f<f_{theory}$
Wu and Little [12]	✓		
Pfahler et al. [15]		✓	
Choi et al. [8]			✓
Peng et al [9]			✓
Yu et al. [10]	✓		✓
Peng and Peterson [11]	✓		✓
Mala et al [13]	✓		
Lee et Lee [16]		✓	
Faghri and Tumer [17]		✓	
Tu and Hrnjak [14]	✓		
Liu and Garimella[18]		✓	

In this paper, we focus our attention on the analysis of the surface roughness effects on the fluid flow characteristics in microchannels.

Here, we will take advantage of the flexibility of the CFD tools in order to isolate and estimate the magnitude of the roughness effect. In particular, we will verify if it is possible to detect simple relationships between roughness, velocity distribution and pressure losses if these effects are sensitive to the geometrical details. Also, the effect of roughness on a rectangular microchannel will be verified by a comparison with a smooth channel.

II. CFD MODELLING

The comparison of the state of surface is held in a rectangular microchannel with different hydraulic diameter. The geometric methodology and mathematical model of the numerical study are detailed below.

A. Geometry

The smooth and rough rectangular microchannels used for this study are presented in Fig.1. wc, hc and L are respectively the width, the depth and the length of the channel.

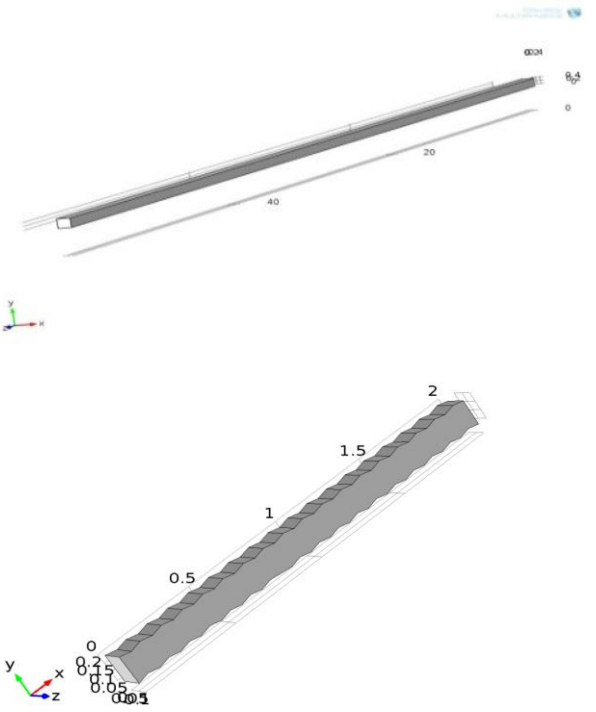


Fig. 1 Problem geometry of a smooth and rough rectangular microchannels

Surface roughness is explicitly modelled through a number of peaks and valleys of specified form. Real roughness may assume many different shapes, depending on the material properties and the manufacturing process; here, as shown in figure 1, the roughness is presented with triangular peaks with a random size distribution. Peak spacing and height is assumed to be uniform along the channel as shown in figure 1. The relative roughness height ε is defined as the ratio between the average of the peak heights and the hydraulic diameter. Values of ε ranging from ε = 5.0% to to 15% will be considered.

Each structural parameter is independently adjusted while fixing other variables in order to study its effect on the pressure drop through the microchannel. The investigated parameters are illustrated in Table.2.

TABLE.2

THE BASIC AND INVESTIGATED STRUCTURAL PARAMETERS OF MICROCHANNEL MODEL.

	Variables	**Basic**	**Investigated parameters**
Microchannel structural parameters	L (mm)	58, 20	-
	Wc (µm)	555	300-800
	Hc (µm)	488	100-400
	Dh (µm)	519	150-550
	α	0.85	0.13-0.97
	Re	35	1-400
	ε (%)	10	5, 10, 15

B. Mathematical Model

In this study, for an incompressible and Newtonian fluid, the mathematical model is based on the Navier-Stokes equations. Isothermal conditions are assumed for a laminar single-phase flow where the viscous dissipation, the pressure work, and the gravity are neglected [22]. Therefore, the steady state equations (2, 3) are written as follows:

Mass conservation

$$\nabla(\rho.u)=0 \tag{2}$$

Momentum conservation

$$\rho.u.(\nabla u)=-\nabla p+\nabla\mu.\left[\nabla u+(\nabla u)^{T}\right] \tag{3}$$

p and u are, respectively, the pressure (Pa) and the velocity (m/s).

This set of nonlinear equations has been solved according to the following boundary conditions:

- At the microchannel inlet, fluid velocity profile is assumed uniform and constant.
- At the microchannel outlet, no viscous stress condition is chosen and an atmospheric pressure is set.
- At the walls, slip condition is neglected since the working fluid is liquid water with constant properties taken at 20 °C: the density is ρ=999.56kg/m3 and µ=0.00101Pa.s is the value of the dynamic viscosity.

The mathematical forms of the boundary conditions are shown in equations (4)-(6), where $\vec{n}$ is the boundary normal unit vector pointing out of the domain.

$$\vec{u}_{in}=-u_0\vec{n} \tag{4}$$

$$P_{out}=0,\ \mu\left(\nabla\vec{u}+(\nabla\vec{u})^{T}\right).\vec{n} \tag{5}$$

$$\vec{u}_{wall}=0 \tag{6}$$

The Pressure drop is evaluated through the variation of the friction factor vs. the hydraulic diameter D_h and aspect ratio α and Reynolds number Re, defined respectively in equations (7), (8) and (9) [23].

$$D_h = \frac{2.w_c.h_c}{(w_c+h_c)} \tag{7}$$

$$\alpha = \frac{h_c}{w_c} \tag{8}$$

$$Re = \frac{\rho.u_{avg}.D_h}{\mu} \tag{9}$$

In equation (9), u_{avg} is the average velocity (m/s). The friction factor is calculated as in equation (10):

$$f = \frac{2.D_h.\Delta p}{\rho.L.(u_{avg})^2} \tag{10}$$

Δp is the pressure difference along the channel considered at the fully developed flow region in order to neglect the entrance effects.

The friction factor can be determined, as in equation (11), by the model proposed by Shah and London [23], for laminar incompressible fluid flow in straight rectangular channel.

$$f=(96/Re).\begin{bmatrix} 1-3.3553.\alpha+1.9457.\alpha^2 \\ -1.7012.\alpha^3+0.9564.\alpha^4-0.2537.\alpha^5 \end{bmatrix} \tag{11}$$

The relative roughness height ε is defined as the ratio between the average of the peak heights, h, and the hydraulic diameter Dh.

$$\varepsilon = \frac{h}{D_h} \tag{12}$$

C. *Numerical method and validation*

The single-phase steady-state laminar flow module in COMSOL Multiphysics 5.0 was used to perform the CFD simulations. COMSOL implements finite element method (FEM) for solving the partial differential Navier-Stokes equations (2-3). COMSOL uses the GMRES (Generalized Minimal Residual) method to solve the linearized equations. The discretization of both pressure and velocity components was of the first order, which is the default setting for the laminar flow interface in COMSOL.

Different grid distributions have been tested to ensure the grid independence results. The selected grid, for this study, is an unstructured grid consisted of of 50293 coarse (triangular, quadrilateral, prism and tetrahedral) elements predefined by COMSOL for dynamic fluids was used to discretize the computational domain. The refinement of the mesh does not change significantly (by an error of 10^{-3}) for the velocity at the centreline region, and the computational model is stable. The coarse grid is chosen in order to reduce the time resolution and to gain the memory capacity of the computer.

COMSOL utilized an iterative scheme to solve the governing partial differential equations. The prescribed converging tolerance was 0.001.

III. Results and Discussion

A. *Friction factor in smooth microchannel*

The computational data of friction factor are compared to the theoretical data calculated by the correlation of Shah and London formulated in equation (11). The numerical results are shown in Fig.2 and in Fig.3.

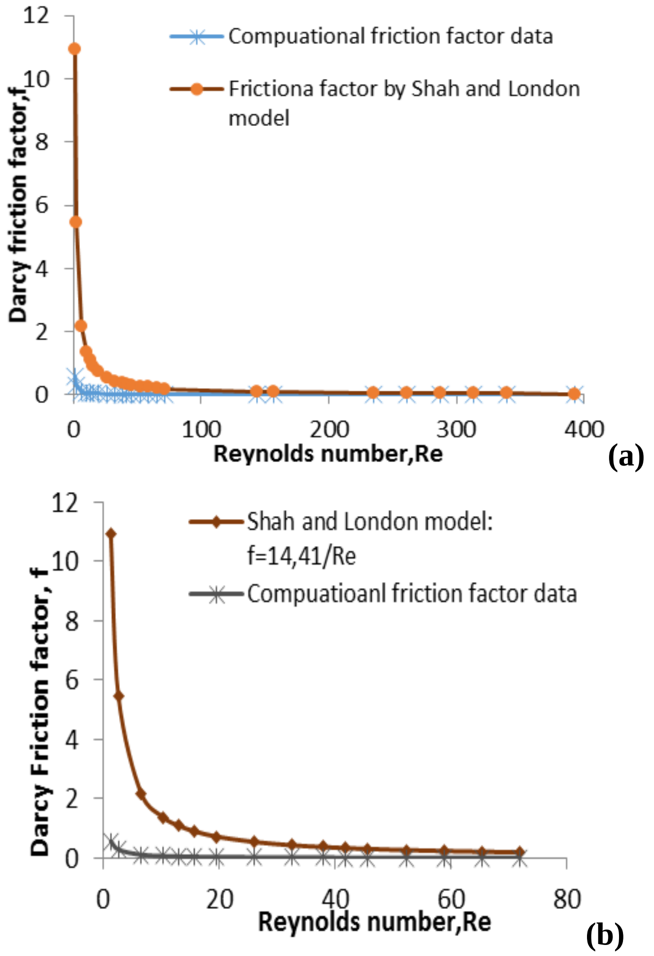


Fig. 2 Friction factor with Reynolds number, Re, in rectangular microchannel with Dh=133µm.

The comparison of the friction factor data, f, for Reynolds number range ≤ 400 is presented in Fig.2.a. It shows that the friction factor has the same behaviour as the theoretical friction factor defined in macro-scaled channels, but a difference is important between the two data for the Reynolds number range less than 50 (Re<50), which is detailed in Fig.2.b.

Fig.3 presents the friction factor in the range of the Reynolds number, Re <100 at the form of f versus Re log-log plot presented by COMSOL Multiphysics.

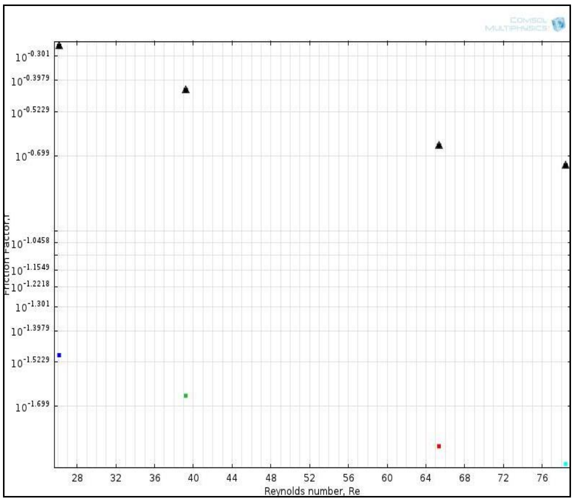
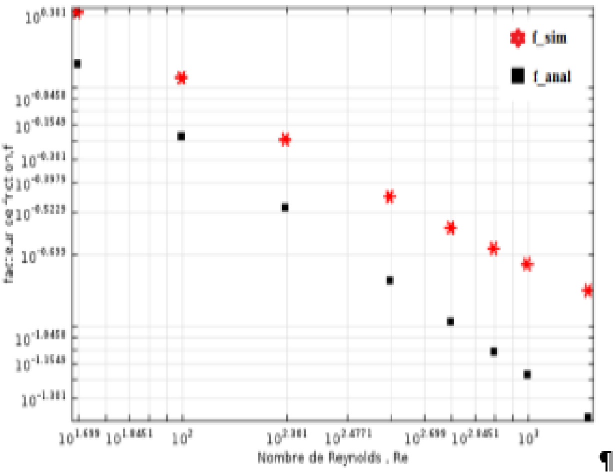


Fig. 3 Friction factor in rectangular microchannel with hydraulic diameter of 519µm for Re< 100: triangle for theoretical data and square for computational data.

In laminar single-phase flow, the friction factor is proportional to the Reynolds number. This result is similar to theoretical ones at macro scale channels. The difference between the two data reduces with the increase of the Reynolds number. In rectangular microchannels, for low Reynolds number<100, the friction factor is less than its predicted value in macro-scale channels.

B. *Friction factor in Rough microchannel*

The following figure shows the effect of the roughness on the friction factor vs the Reynolds number in rectangular microchannel. the two plots are deduced from the numerical study on the same channel with a hydraulic diameter D_h=200µm and with a length of L=30mm, with different relative roughness one is 10% and the other is 15%.



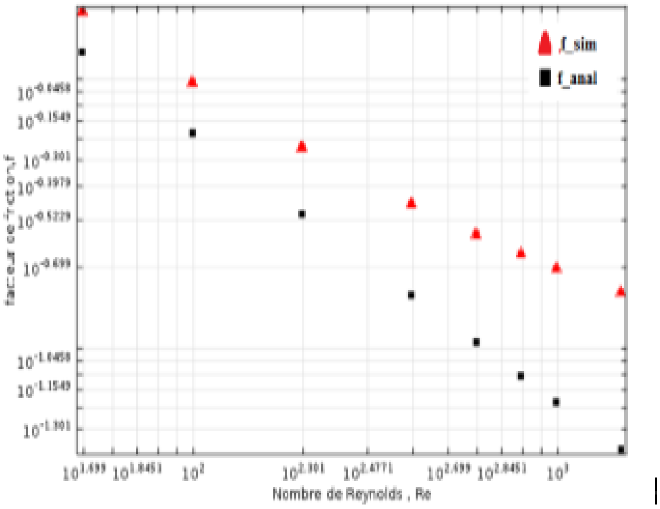


Fig. 4. Effect of the roughness on the friction factor in rectangular microchannel for two relative roughness: 10% and 15%.

The comparison of the friction factor evolution in laminar flow found by simulation and by the analytical model of Shah and London yields to find that the friction is no longer linear with the Reynolds number and presents a deviation to be parabolic from Re=600 for channel with ε=10% and for Re=500 for channel with ε=15%.

So, the roughness on microchannels makes the transition to turbulence earlier: for Reynolds number less than the conventional theory in laminar flow at Re=2000.

IV. Conclusion

For laminar single-phase flow, frictional pressure drops have been computed from the Navier- Stokes equations over a Reynolds number range 1 ≤Re≤ 400 in smooth and rough rectangular microchannels with the hydraulic diameter range of 150µm≤D_h≤550µm, in the aspect ratio range 0.3≤α≤0.97 and with two values of a relative roughness 10% and 15%. This set of equations is solved by Finite Element Method (FEM) and the solution assumed to converge at a relative tolerance ≤ 10^{-3}. The following conclusions are obtained after this numerical investigation:

- For lower Reynolds number, the computational data of frictional pressure drop in rectangular micro-channel are less than the predicted data. For higher Reynolds number (Re> 100), the computational data agree well with the theoretical data presented by Shah and London model for macro- scaled rectangular channels.
- The transition to turbulence flow is forwarded in rough rectangular microchannels in comparison with the conventional theory where the transition begins at Re=2000.

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