Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(4):647-658
DOI: 10.1016/S1001-6058(16)60777-1
www.sciencedirect.com/
science/journal/l0016058

Numerical investigation of Reynolds number and scaling effects in micro-channels flows *

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(Received April 9, 2015, Revised May 11, 2016)

Abstract: Compared with conventional channels, experiments of microchannel often exhibit some controversial findings and sometimes even opposite trends, most notably the effects of the Reynolds number and the scaled channel height on the Poiseuille number. The experimental method has still been constrained by two key facts, firstly the current ability to machine microstructures and secondly the limitation of measurement of parameters related to the Poiseuille number. As a consequence, numerical method was adopted in this study in order to analyze a flow in two-dimensional rectangular microchannels using water as working fluid. Results are obtained by the solution of the steady laminar incompressible Navier-Stokes equations using control volume finite element method (CVFEM) without pressure correction. The computation was made for channel height ranging from 50 μm to 4.58 μm and Reynolds number varying from 0.4 to 1 600. The effect of Reynolds number and channel heights on flow characteristics was investigated. The results showed that the Poiseuille numbers agree fairly well with the experimental measurements proving that there is no scale effect at small channel height. This scaling effect has been confirmed by two additional simulations being carried out at channel heights of 2.5 μm and 0.5 μm, respectively and the range of Reynolds number was extended from 0.01 up to 1 600. This study confirm that the conventional analysis approach can be employed with confidence for predicting flow behavior in microchannels when coupled with carefully matched entrance and boundary conditions in the dimensional range considered here.

Key words: Rectangular microchannel, Poiseuille number, control volume finite element method (CVFEM), laminar flow, minichannels

Introduction

The characteristics of flow and heat transfer in micro channels have attracted much attention of researchers because of the rapid developments of microelectromechanical systems (MEMS) and micro total analysis system. These developments have great impacts on the microelectronic cooling techniques, the micro heat exchanger, bioengineering, human genome project medicine engineering, etc..

There are contradictory data concerning flow in this type of channels, such as the compatibility of the friction factor in laminar and turbulent flow with Hagen-Poiseuille law and Blasius equation respectively, valid for channels of ordinary sizes. This leads to difficulty of understanding the idea of the phenomena and causes very disputable discoveries.

Judy et al.[1] measured the friction losses of water, hexane and isopropanol flowing in fused silica capillaries in order to study the effect of the fluid polarity. The capillary diameters ranged from 20 μm to 150 μm. For diameters lower than 100 μm the friction factor deviated from the conventional theory. The friction factor was lower than expected and the deviations were higher for decreasing diameters.

Araki et al.[2] considered nitrogen and helium flows through three different trapezoidal micro-channels having a hydraulic diameter ranging from 3 μm to 10 μm. The friction factor was smaller than that predicted by the conventional theory. These results were contradicted by the experiments of Cui et al.[3] who studied the liquid flow in glass microtubes with diameter varying from 3 μm to 10 μm for $Re = 0.1 - 24$. The friction factor for deionized water was in good agreement with the conventional theory. Baviere et al.[4] presented a solution of deionized water and tap water flowing in rectangular silicon channels with the height of 4.58 μm -21 μm. For the Reynolds number ranging from 0.1 to 300, the friction factor was correctly predicted by the classical theory,

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regardless of the water electrical conductivity. Mokrani et al.[5] conducted an experiment to investigate tap water flowing through flat micro channels with constant width, height ranging between 50 μm and 500 μm. The results reveal that the conventional theory and correlations describing the flow in ducts of large dimension were directly applicable to the micro channel having a diameter between 100 μm and 1 mm. The paper[6] reported the same conclusion.

Ren et al.[7] studied deionized water and aqueous KCl, flow in rectangular silicon microchannels with very large width and heights of 14.1 μm, 28.2 μm and 40.5 μm, the pressure gradient at the same Reynolds number departed from the conventional predictions. The authors concluded that these results confirmed that the electrical-double layer (EDL) effect plays an important role on the pressure drop through small microchannels. Lorenzini et al.[8] analyzed water flowing through stainless steel and fused silica tubes with inner diameter of 29 μm - 508 μm. Fused silica was the smooth tube and stainless steel tube was rougher. Pressure drop experiments were performed over the range of Reynolds number (30-1 000). It was observed that in laminar region the experimental data was in agreement with Poiseuille equation except for micro channels less than 100 μm.

Other techniques, such as numerical simulation might offer alternative solutions and insight to better understand reported findings. For example, Chen et al.[9] investigated numerically the fluid flow in non-circular micro channel heat sink. The cooling fluid in the channel used is deionized water. The geometries for the triangular, rectangular and trapezoidal channel used are 129.6 μm, 40 μm and 158 μm, respectively. The results reveal that the Poiseuille number in micro-channel with a certain cross section remained almost constant and independent of the Reynolds number for fully developed laminar flow which was similar to fluid behavior in conventional channels. Yang et al.[10] presented experimental data on the friction factor for air flowing through microtubes with inside diameter of 86 μm -920 μm. The results indicated a good agreement with the predictions of the conventional theory.

The review of the literature exhibits large scatter and even contradictions in the experimental results. The errors in diameter measurement is speculated to be one of the most important factors for these deviations, because of the size of micro channels, certain common measurement techniques are not available for use in experiments. In order to analyze how the hydrodynamic characteristics can be influenced by inaccuracy in the hydraulic diameter of the micro channels, Hollweg and Oliveski[11] conducted numerical investigation for the single-phase water laminar flow in micro tube $(D_{\text{hyd}} = 130\ \mu\text{m})$. Six cases of inaccuracy were considered: $\pm 1\%$, $\pm 2\%$ and $\pm 3\%$. The results showed that the deviations for the Poiseuille number in micro channels with hydraulic diameter below the nominal value are higher compared with those obtained for the micro channels with hydraulic diameter above the nominal value.

To interpret the roughness effect on the flow in microchannels, Zhang et al.[12] performed experimental work to investigate the friction factor through flat aluminum extruded multiport tube using water as working fluid. Six samples with hydraulic diameter were ranging from 0.48 mm to 0.84 mm and relative roughness ranging from 0.29% to 1.06%. Their experimental results showed that the friction factors all agree with the fully developed correlation in the laminar region. The effect of relative roughness on friction factor seems to be negligible in this study. The latest research of Dai et al.[13] and Huang et al.[14] again confirmed the well known conclusion of Zhang et al.[12].

The literature review also reveals that: (1) hydrodynamic behavior for microchannels with hydraulic diameters greater than 100 μm can be accurately determined from the classical theory, but it is not clear whether the conventional correlations may be employed in rectangular microchannels with hydraulic diameters close to or less than 100 microns, and (2) there is a lack of numerical studies of fluid flow in small channels $(D_{\text{hyd}} \le 100\ \mu\text{m})$. Due to inconsistencies between experimental results and the lack of understanding of the underlying phenomena, the classical Navier-Stokes equations are solved numerically to determine the fluid flow characteristics in micro channel using the control volume finite element method (CVFEM)[19]. the CVFEM uses the advantages of both finite volume and finite element methods. the objectives of the article are: (1) access the capability and accuracy of the CVFEM for prediction of flow characteristics in micro channel. (2) verify the Reynolds number and channel height effects on the deviation of hydrodynamic characteristics such as Poiseuille number, friction factor and pressure drop from the classical correlation in small channels $(D_{hyd} \le 100\ \mu\text{m})$ which usually valid for macro scale flows and finally compare the present predictions with the available experimental data[4,5].

1. Mathematical modeling

1.1 *Geometry and the governing equations*

The experimental investigation that served as an origin for the present numerical model was the work of Baviere et al.[4] and Mokrani et al.[5]. Note that the rectangular channels in Refs.[4] and [5] have very large ratio of width to height. Taking this advantage, we used a simplified two-dimensional geometry shown in (Fig.1), h and L are respectively the height and length of channel. The following assumptions were made for the numerical method: (1) The fluid used is water assumed incompressible, Newtonian and continuum, (2) All the fluid properties are constant, (3) Steady laminar flow character, (4) The effects of gravity and other forms of body forces are negligible.

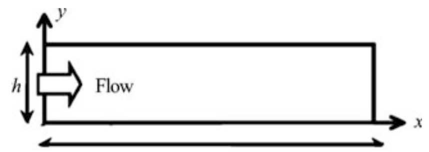


Fig.1 Domain of numerical simulation

The continuity and momentum equations that govern the flow can be written in the form as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x}+\frac{\partial^2 u}{\partial y}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x}+\frac{\partial^2 v}{\partial y}\right) \tag{3}$$

where u, v are the velocity components, ν is the kinematic viscosity and p is the pressure.

1.2 *Boundary conditions*

The continuity and momentum equations are non-linear partial differential equations, subjected to the following boundary conditions:

(1) At the microchannel inlet $(x=0)$, the velocity profile is uniform.

(2) At the inner wall surface: The velocity in top-bottom boundaries is set equal to zero and the fluid flow satisfies no-slip condition at the walls.

(3) At the outlet section flow $(x=L)$: the diffusion flux in the direction normal to the exit is assumed to be zero for velocity while a zero relative pressure is assigned.

1.3 *Numerical method*

In this work a modified version of CVFEM of Saabas and Baliga[15] is adapted to the standard staggered grid in which pressure and velocity components are stored at different points. The CVFEM method is used in order to avoid the spurious oscillations such as the pressure "checkerboard" problem described by Patankar[16].

The control volumes are created by joining the center of each element in the support to the mid points of the element sides that pass through the central node i which creates a close polygonal control volume (see Fig.2). The set of governing equations is integrated over the Control Volume with the use of linear interpolation inside the finite element and the obtained algebretic equations are solved by the Gauss-Seidel iterative technique with successive over-relaxation to improve convergence time. The solution is regarded as converged when the condition $(\phi^{i+1}-\phi^{i})/\phi^{i}\le 10^{-6}$ is satisfied for all independent variables (p, u and v). A FORTRAN code is developed to solve the present problem using a structured mesh of linear triangular.

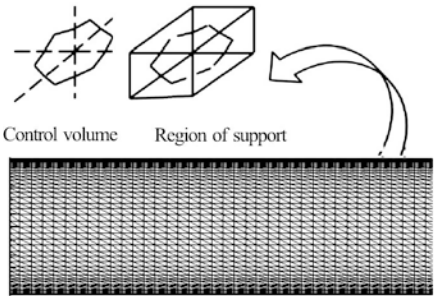


Fig.2 The mesh considered in this work

1.4 *Code validation*

The code was developed to solve u and v velocity fields, pressure field for each of the geometries listed in Table 1. The channel length is chosen so that hydrodynamically developed flow region occupy at the minimum 90% of channel length. The Reynolds number is based on hydraulic diameter D_{hyd}, the fluid viscosity μ and the average velocity u_{ave}. $(D_{\mathrm{hyd}}=15\ \mu\mathrm{m})$ (Eq.(4)). Other values such as friction coefficient, wall shear stress and Poiseuille number (Eqs.(5)-(10)) were calculated once the converged velocity and pressure fields were obtained. The numerical code is tested by choosing the adequate mesh and evaluated by comparing the results with available analytical solutions. It is found that the triangular element number given in Table 1 ensures the grid independent solution. Figure 3 shows a dimensionless velocity profile and 2-D velocity fields for fully developed flow in the channel. The dimensionless velocity here is defined as $u/u_{\max}$, where $u_{\max}$ is the maximum velocity located at the center of the rectangular microchannel. Excellent agreement is found between the present numerical prediction and the analytical solution of Hagen-Poiseuille[17].

Table 1 Geometric dimensions and mesh used in calculations

Channel height, h /μm	L/h	Triangular element number
0.5	20	16 060
2.5	25	16 060
4.58	22	19 260
7.5	30	19 260
14	70	19 260
20.5	50	25 280
50	150	35 000

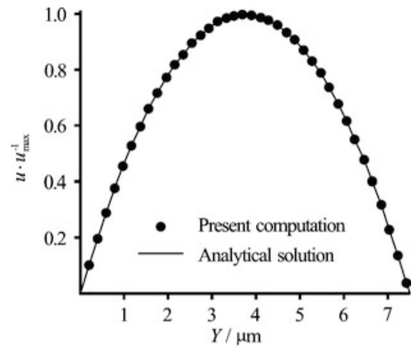


Fig.3(a) Comparison between numerical predictions and analytical solution for fully developed velocity profile

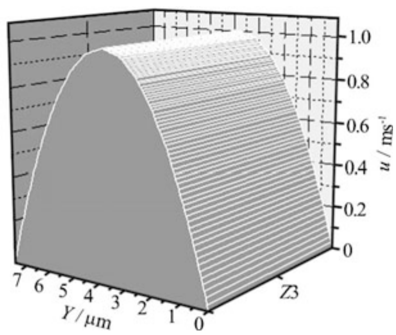


Fig.3(b) 2-D velocity field in channel from the numerical calculation

Reynolds number

$$Re = \frac{\rho u_{\mathrm{ave}} D_{\mathrm{hyd}}}{\mu} \tag{4}$$

Local apparent friction factor

$$f_{\mathrm{app},x} = \frac{2D_{\mathrm{hyd}}}{\rho u_{\mathrm{ave}}^2} \frac{p_{\mathrm{in}} - p_x}{x} \tag{5}$$

Average apparent friction factor

$$f_{\mathrm{app,ave}} = \frac{2D_{\mathrm{hyd}}}{\rho u_{\mathrm{ave}}^2} \frac{p_{\mathrm{in}} - p_{\mathrm{out}}}{L} \tag{6}$$

Poiseuille number

$$Po = f_{\mathrm{app,ave}} Re \tag{7}$$

Local wall shear stress

$$\tau_{\mathrm{app},x} = f_{\mathrm{app},x} \frac{\rho u_{\mathrm{ave}}^2}{2} \tag{8}$$

Average wall shear stress

$$\tau_{\mathrm{app,ave}} = f_{\mathrm{app,ave}} \frac{\rho u_{\mathrm{ave}}^2}{2} \tag{9}$$

For fully developed laminar flow, Eq.(7) can be written as

$$Po = f_{\mathrm{app,ave}} Re = 24 \tag{10}$$

where p_{in}, p_x and p_{out} are respectively the inlet, local and outlet pressure. the subscripts hyd, ave and app refer to hydraulic, average and apparent respectively.

2. Results

A series of numerical simulations have been conducted and the results are presented in order to show the effect of Reynolds number and channels heights on fluid flow characteristic and examine the validity of conventional hydrodynamics on microscale. The flow characteristic of water through microchannel can be interpreted in terms of velocity distributions, pressure drop, friction factor, Poiseuille number and wall shear stress (Eqs.(5)-(10)). Similar to the experimental investigation of Baviere et al.[4] and Mokrani et al.[5], five channel heights 4.58 μm , 7.5 μm, 14 μm, 20.5 μm and 50 μm are considered at first and the Reynolds number varies in a range of 0.4 to1 600 (Table 2). Furthermore, in order to better compare the computational results obtained here with experimental data, the average overall Poiseuille number is analyzed with respect to the variations of the Reynolds number.

Table 2 Reynolds range employed

Channel height, h /μm	Reynolds number, Re
4.58	0.5-7
7.5	0.4 -5
14	1-30
20.5	10-200
50	50-1 600

2.1 *Local fluid flow characteristic*

2.1.1 Velocity and pressure distributions

The developing process of velocity components

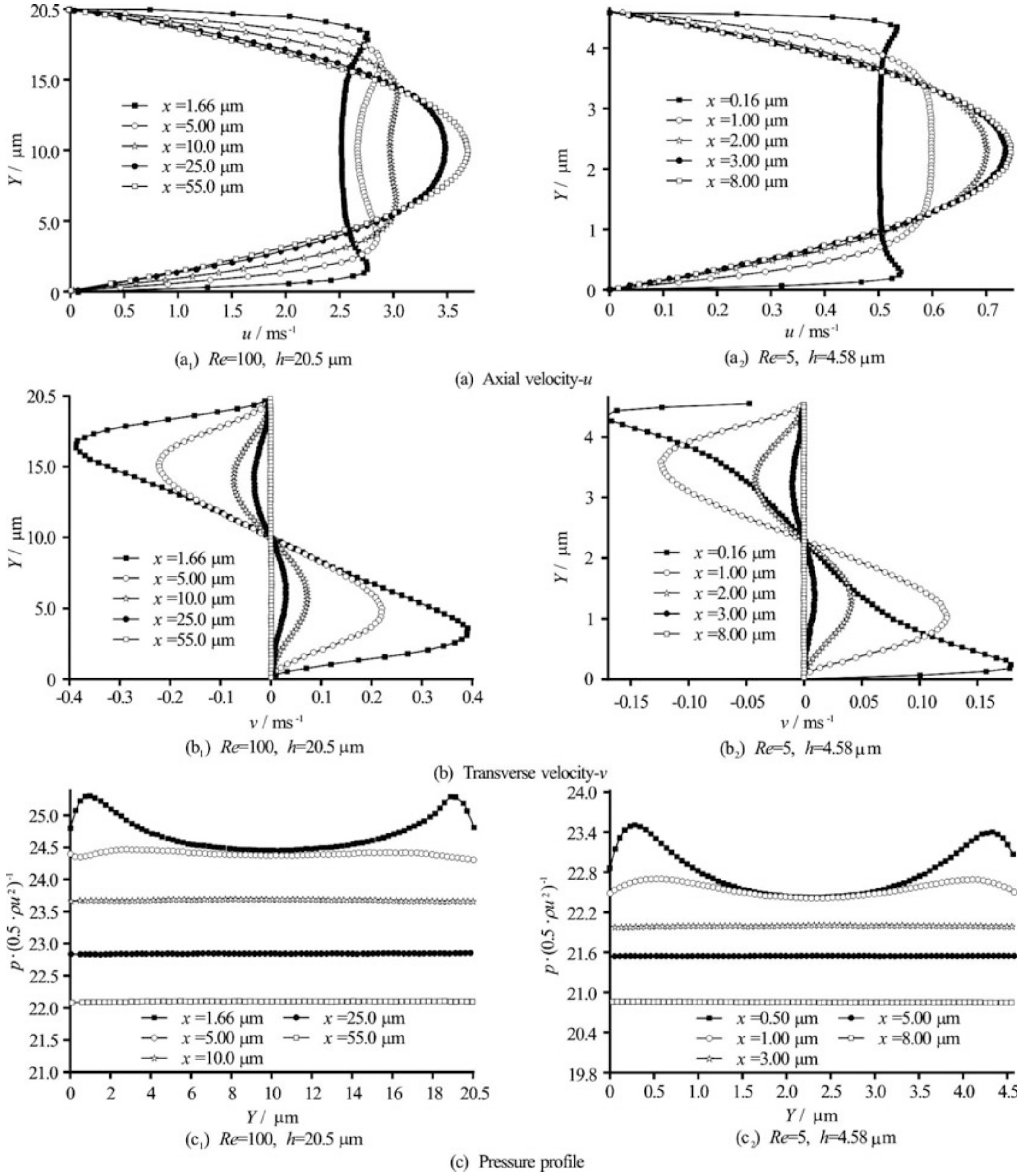
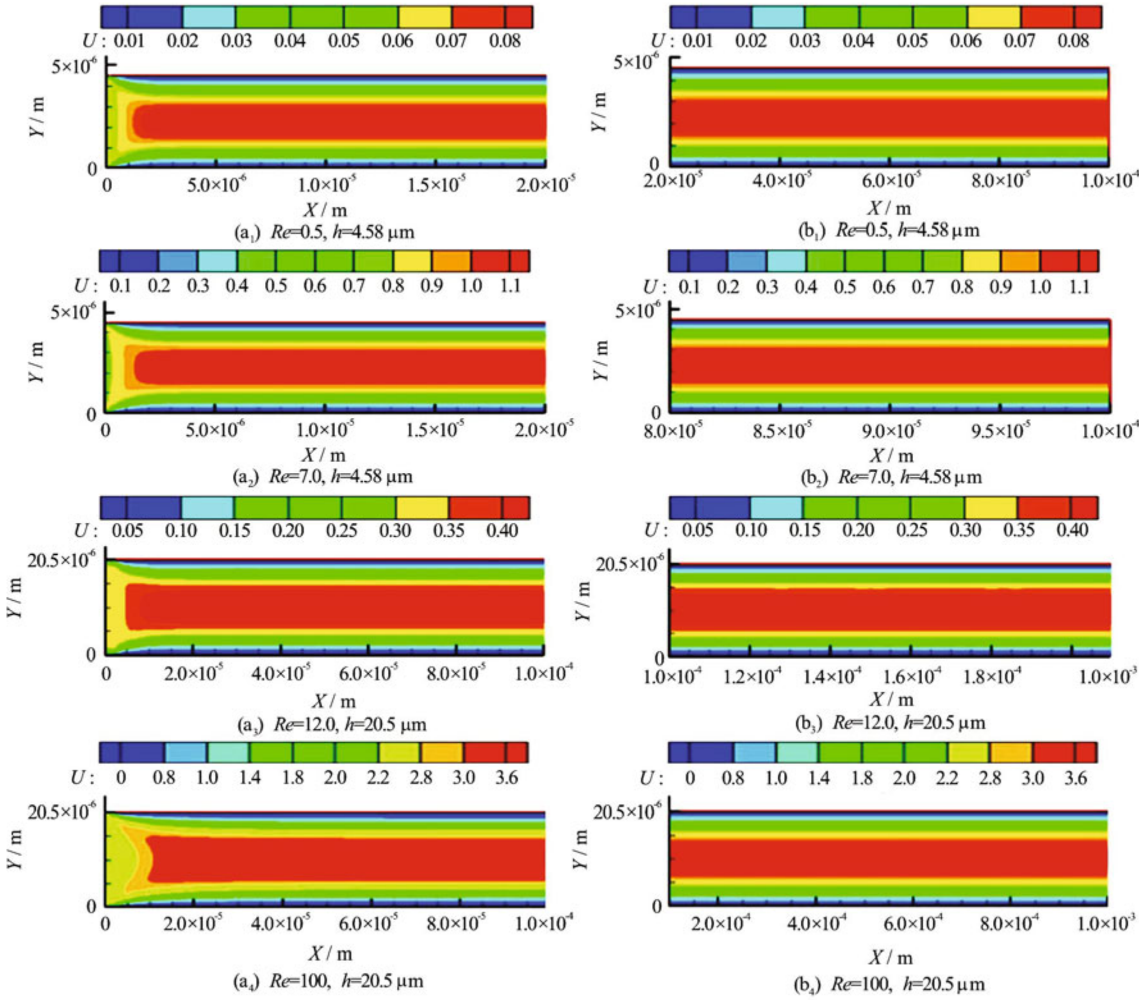


Fig.4 Fully development flows in the channel

(u, v) and pressure gradient at different cross sections along the channel for $h = 4.58\ \mu m$, $Re = 5$ and $h = 20.5\ \mu m$, $Re = 100$ are depicted in Fig.4. The local pressure gradient and velocity maxima can be observed near the wall in the very beginning of entrance region, particularly near the corner region. This is because of the sudden drop of fluid momentum adjacent to the walls due to the no slip boundary condition. As the flow develops along the micro-channel, the u-velocity diminishes in corner region and reaches a maximum in the core region at $(x = 8\ \mu m)$ and $(x = 55\ \mu m)$ for $h = 4.58\ \mu m$ and $h = 20.5\ \mu m$ respectively. At this abscissa, the flow hydrodynamically fully developed, the pressure gradient becomes uniform and the change in v-velocity component is very negligible, it behaves as a 1-D flow. The axial component u-velocity contours plots at different Reynolds number for $h = 4.58\ \mu m$ are shown in Fig.5. We can see that the flow develops gradually along the channel, velocity gradient near the wall becomes low while the maximum velocity appears at the centerline (middle of channel). We can also observe that to get fully developed (maxima velocity) the flow requires traveling certain distance called entrance length. It is visible in the figures that as Reynolds number increases the entrance length increases.



(a) Nearer to the entrance (b) Nearer to the exit

Fig.5 (Color online) u - component of velocity contours plot

2.1.2 Local friction factor, wall shear stress and pressure drop

The distribution of pressure drop, local apparent friction factor $f_{\mathrm{app},x}$ and local wall shear stress $\tau_{\mathrm{app},x}$ with position (x) given for various Reynolds numbers in the two channel ($h = 4.58\ \mu\mathrm{m}$, $h = 20.5\ \mu\mathrm{m}$) can be seen in Fig.6. Notice that each case start at a large wall shear stress but friction number converge approximately to the fully developed value at the exit of channel. The following can be observed as Reynolds number increase:

(1) The entrance length increases.

(2) Highest pressure drop.

(3) The maximum local wall shear stress at the entrance increases.

(4) The maximum local apparent friction number at the entrance diminishes. The local $f_{\mathrm{app},x}$ decrease with increase in fluid kinetic energy (Eq.(5)).

2.2 *Average fluid flow characteristic*

2.2.1 Average wall shear stress and pressure drop

The numerical results of flow resistance and average wall shear stress depending of Reynolds number for water in the microchannel are plotted in Fig.7. The flow resistance was expressed with the aid of value Δp. It can be seen that the pressure drop and wall shear stress are proportional to the Reynolds number, which indicates that the flows were laminar, without any transient effects. An increase of Reynolds number reflecting an increase of the flow resistance and wall shear stress, it is because the friction force increases due to the increase of the average velocity of fluid and the shear stress on the surface of microchannel. This phenomenon is exactly the same as in the conventional-sized channels.

The average friction factors are shown in Fig.8. The value of the friction factor is calculated by means

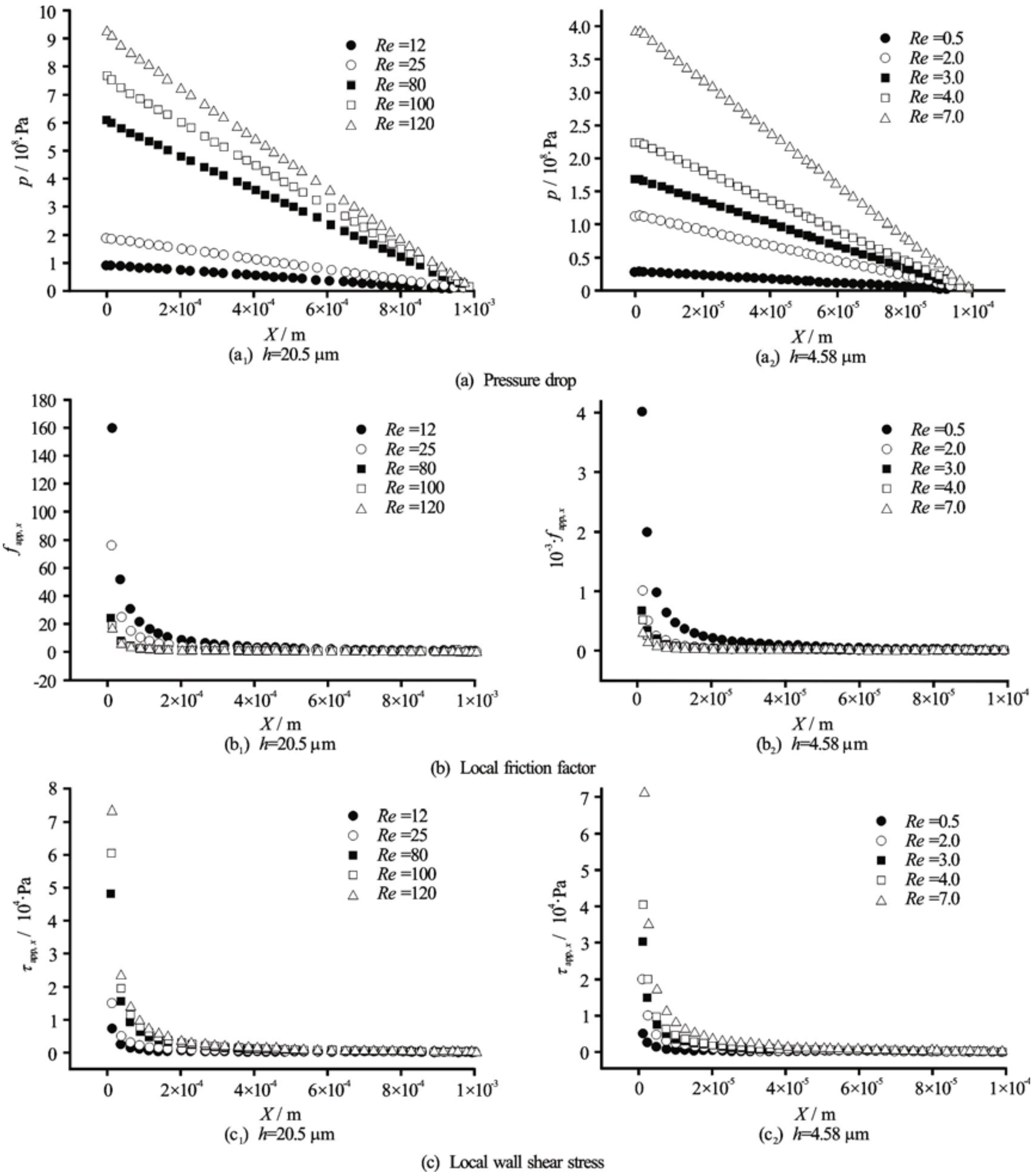


Fig.6 The effect of different Reynolds numbers versus positions

of Eq.(6) which takes into account the pressure drop along the microchannel. The numerical results are compared with the theoretical values described with Eq.(10). It is evident that the present numerical model's predictions agree well with macroscale theory and experimental data. No distinguishable difference in behavior may be seen for all microchannel heights.

2.2.2 Poiseuille number

The comparison of Poiseuille number values between the present numerical study, the theoretical prediction and the experimental work is shown in Fig.9. One can see from Fig.9 that numerical results obtained for Poiseuille number are in good agreement with the value of conventional theoretical prediction ($Po = 24$). There is a difference between the experimental and numerical results but this difference is much lower than the experimental uncertainty of the measurements. The global uncertainty range of these data was between ±7.7% to ±14% in rectangular smooth microchannels of height ranging from 20.5 μm to 4.58 μm. We can see from the computational results plotted that the maximum deviation from the value of $Po = 24$ is less than 4% for the channel with $h = 20.5$ μm, and less than 3% for the channel with $h = 14$ μm. It is satisfying to note that the present results are nearly identical to the numerical results of

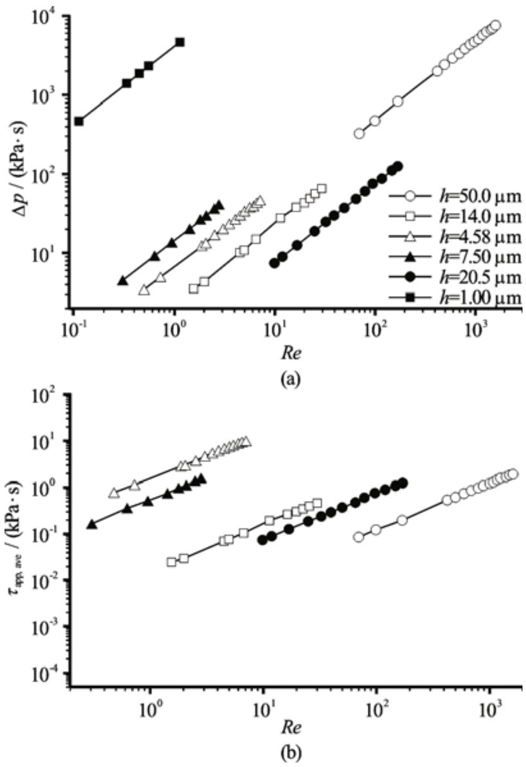


Fig.7 Variation of average wall shear stress and pressure drop with Reynolds number

Tang et al.[18], for the same geometry with a hydraulic diameter $(D_{\text{hyd}} = 4h)$, $h =$ 14.3 μm and 4.58 μm. Tang et al.[18] used lattice Boltzmann method (LBM) to solve fluid flow. The largest deviation for the LBM results from the value of $(Po = 96)$ is less than 3% for the channel with $h = 4.58\,\mu\text{m}$, and less than 2% for the channel with $h = 14\,\mu\text{m}$. In short, the present results confirm that the values of Poiseuille number are independent of Reynolds number for all heights over the full range of Reynolds number studied.

2.3 *The limit of validity of conventional theory in microchannels*

The present results are successfully validated the experimental data[4,5] and confirm that there is no effect of Reynolds number and channel size on hydrodynamic characteristics of flow, typically great as 4.58 μm. The numerical study exist in the literature did not verify this observation even for very lower channel height of 0.5 μm $(D_{\text{hyd}} = 1\,\mu\text{m})$, it is worth checking this from the present study.

For this purpose, we have carried out additional simulations with smaller channel heights of 2.5 μm and 0.5 μm and extended the Reynolds range for all diameters considered before as shown in the Table 3.

Table 3 Additional channel heights and extended Reynolds range

Channel height, h /μm	Reynolds number, Re
0.5	0.01-10
2.5	0.01-10
4.58	0.01-15
7.5	0.01-15
14	0.01-30
20.5	0.01-200
50	0.01- 1 600

Figures 10(a) and 10(b) present results of numerical investigation of Poiseuille number and Darcy frictional factor for water flow in micro-channels with heights varying between 0.5 μm and 50 μm. We can see from both figures that the trend of Poiseuille number and friction factor versus Reynolds number is so much the same as for the conventional theory over the full range of Reynolds number studied (0.01-1 600). The comparison between simulations and theoretical values shows satisfactory agreement for all microchannel heights within an absolute average deviation of 3%. For microchannel heights less than 4.58 μm, some experimenters claim that conventional theory is not applicable to microchannel flow, others indicate that conventional theory is an accurate predictor of microflows. This study supports that the Poiseuille number and the friction factors in rectangular microchannels with a hydraulic diameter ranging between 1 μm and 100 μm are very well predicted by the conventional theory.

3. Discussion

As described in introduction, there have been controversial results about whether the conventional theory can predict friction factors in microchannel or not. The accuracy of friction factors is entirely dependent on the measurement of the parameters related to the pressure drop. Equation (7) shows that the most important parameter of them is the diameter. It means that the error in the measurement of the diameter can lead to the great uncertainty of the friction factor. In spite of its importance, it is not easy to measure the accurate diameter or the height and the width of the microchannels. Agostini et al.[19] and July et al.[20] showed that a 3% uncertainty on channel width and height produces in a friction factor uncertainty of 21% and the experimental uncertainty, dominated by the error in diameter measurements, may induce up to a 20% difference in the evaluation of the Poiseuille number. In addition, in several experimental works, the incorrect evaluation of the manifolds pressure drop could be responsible for the deviation of the experimental friction factor or Poiseuille number from the classical value of laminar

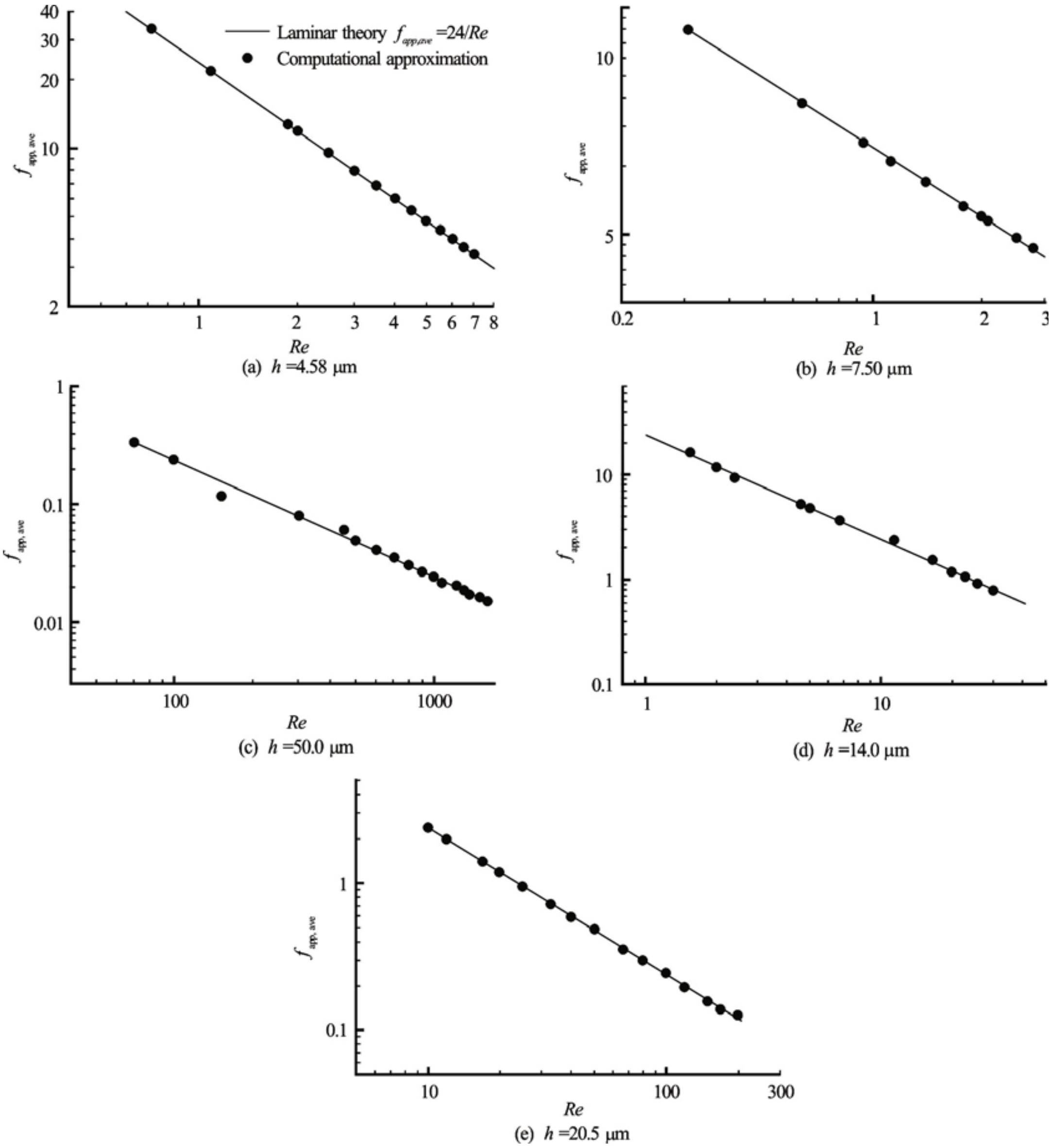


Fig.8 Comparison the present computation and the theoretical predictions for the friction factor

theory. It is instructive to summarize the possible sources of frictional pressure drop deviation from Stokes theory for liquid microscale flow, aside from measurement errors. Two main categories of effects have been put forward to explain the deviations observed in microfluidics: (1) macroeffects such as the entry effects and (2) microeffects such as the effects of the electric double layer (EDL) and viscous dissipation. These effects often negligible in macrochannels could be responsible for some of the deviations observed.

3.1 *The entrance length increases*

There is the question of the fully-developed flow assumption. Some of the discrepancies mentioned above can be explained by entry effects. The Poiseuille number for laminar flows in a channel is constant only for fully developed flows, i.e., when the velocity profile remains unchanged. For higher Reynolds numbers within the laminar regime, the entrance region could extend beyond the channel length. This extension would bring about much higher laminar Poiseuille number than those predicted by fully-developed laminar flow correlations. For the range of Reynolds number considered in the present paper, the entrance length was on the order of 5%-10% of the channel length (Figs.4, 5), so the hydrodynamically fully developed flow condition exists over all microchannels length.

3.2 *Viscous heating*

Depending on the fluid, viscous dissipation may

Table 4 Influence of water conductivity on EDL thickness

Water conductivity, σ /μScm^{-1}	EDL thickness λ^{-1} /nm	EDL thickness to channel diameter ratio $(\lambda^{-1}\cdot D_{\text{hyd}}{}^{-1})$ /%					
		100	41	28	15	9.16	1
De-ionized water $\sigma = 7$	73	0.07	0.18	0.26	0.485	0.8	7.3
1/4 tap water + 3/4 deionized water $\sigma = 70$	23	0.23	0.06	0.08	0.15	0.250	2.3

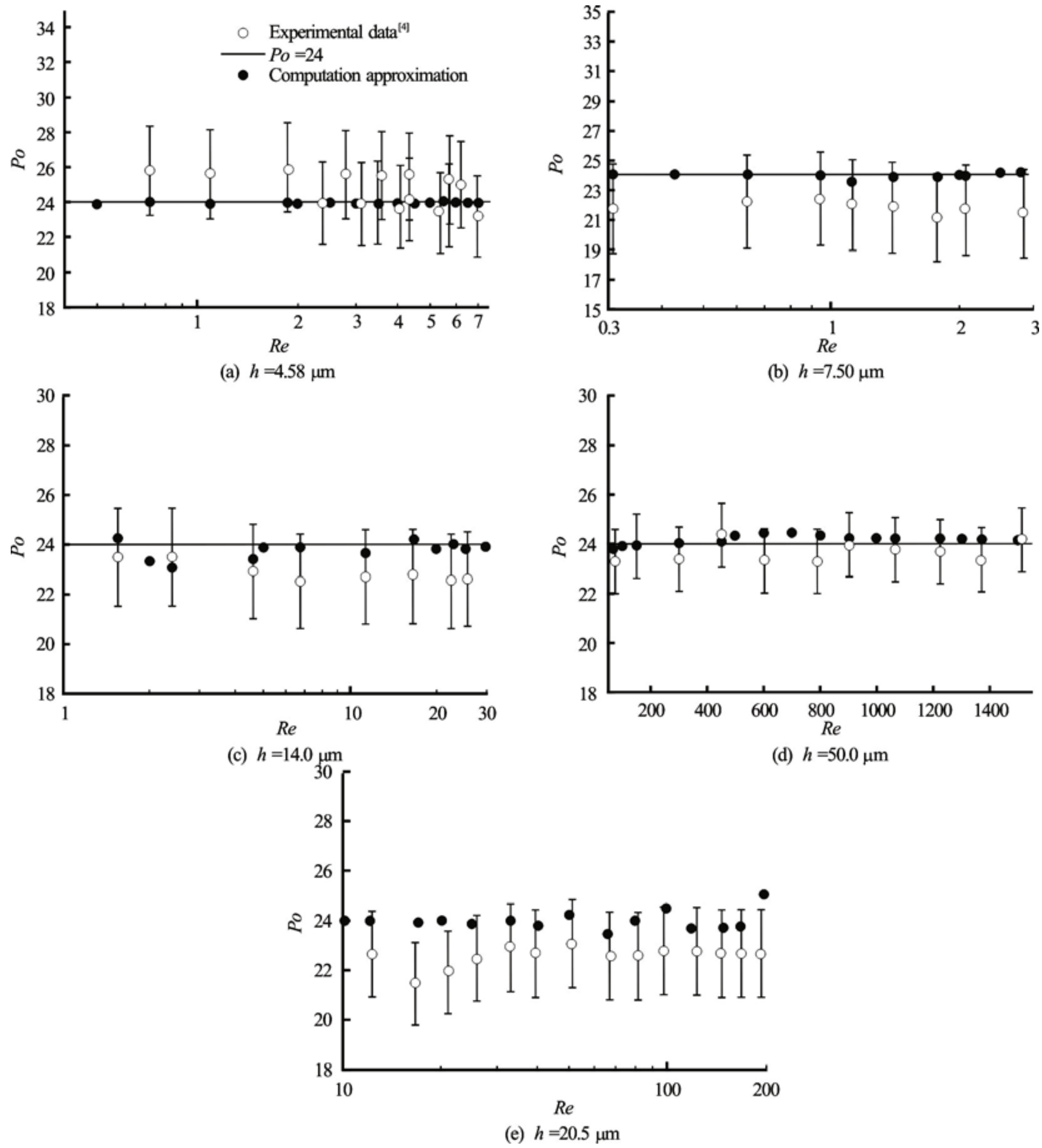


Fig.9 Comparison among the present computation, the theoretical predictions and the experimental data for the Poiseuille number

become significant for decreasing diameter and increasing fluid velocity. The shear induced heating of the fluid results in higher fluid temperatures along the micro channel length and reducing the viscosity. Hence the lower friction factor could mainly be attributed to the temperature effect on the liquid viscosity.

The temperature rise $(\Delta T = T_{\text{out}} - T_{\text{in}})$ can be simply obtained from the first law of the thermodynamics and expressed as: $T_{\text{out}} - T_{\text{in}} = (p_{\text{in}} - p_{\text{out}})/\overline{C_P \rho}$, where $\overline{C_P} = 4.1676\ \text{KJ/KG}\cdot\text{K}$ and $\overline{\rho} = 1\,000\ \text{kg/m}^3$ are

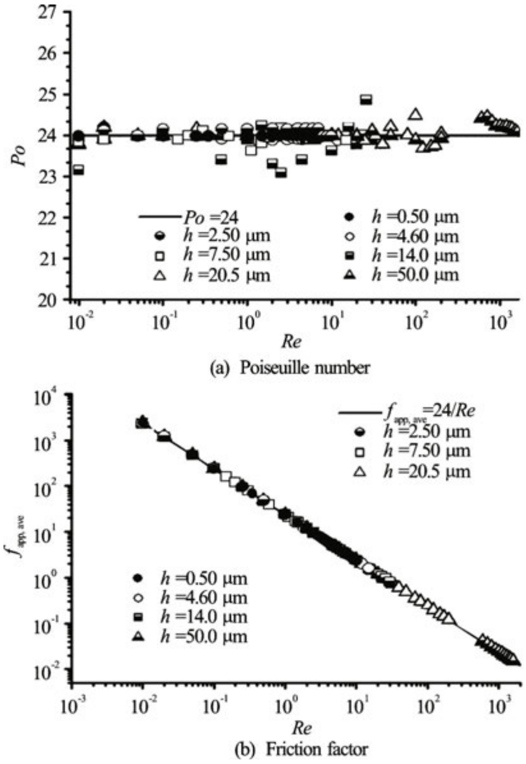


Fig.10 Variations with the Reynolds number for different channel heights

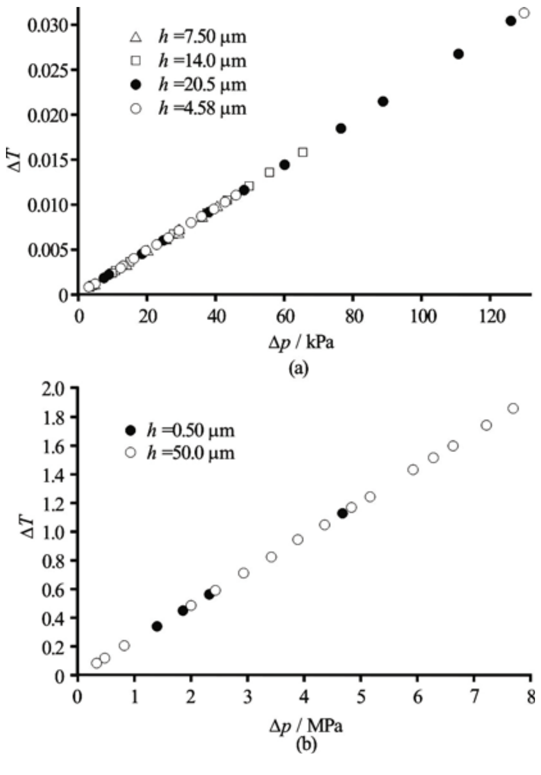


Fig.11 Temperature rise as a function of pressure difference

the average values of specific heat and density of water respectively from the inlet to the outlet. The inlet temperature is 393 K (20°C) and $\Delta p = p_{\text{in}} - p_{\text{out}}$ is the difference between inlet and outlet pressure. Due to viscous heating, the difference between inlet and outlet temperature increases with increasing pressure (velocity) (Fig.11) but never exceeds 2°C for any channel heights, thus we assumed that the viscosity of water remains constant and the viscous heating effect is negligible for the range of Reynolds number investigated in this work. We can also conclude that the variation of pressure from 0.25 MPa to 8 MPa has no influence on the bulk viscosity of water.

3.3 *Electric double layer effects*

Other physical phenomenon that could possibly influence hydrodynamic liquid flows in microstructures is electroviscous effect or the presence of an EDL at channel wall/liquid interface. These interfacial effects are ignored in macroscale fluid mechanics. However, most wall surfaces have electrostatic charges i.e., an electrical surface potential. If the liquid contains very small amounts of ions, the electrostatic charges on the wall surface will attract the counterions in the liquid to establish an electrical field, called the EDL. The EDL leads to an apparent increased fluid viscosity when its thickness is non-negligible compared with characteristic size of channels, in this case the electroviscous effect should be taken into account.

The Debye-Huckel parameter λ_D is used to characterize the EDL thickness effects

$$\lambda_D^{-1} = \sqrt{\frac{K_B T \varepsilon \varepsilon_0}{e^2 n_0 Z_i^2 N_A}}$$

where T is the Absolute temperature (Kelvin, K), the Boltzmann constant $K_B = 1.3806\ \mathrm{J/mol/K}$. N_A and n_0 are the Avogadro number (6.023×10^{23} mol^{-1}) and bulk ionic concentration (mol·l^{-1}) respectively. The charge of proton $e = 1.602\times10^{-19}$ (Colomb, C) and Z is the ionic valence. ε and ε_0 refers to absolute dielectric constant of fluid (8.85×10^{-12} C^2/V/m) and relative dielectric constant of fluid $\varepsilon_0 = 80$ respectively. For water at 20°C and ionic valence $Z=1$, $\lambda_D^{-1} = 1.92\times10^{-7}\sigma^{-1/2}$, σ indicates electric conductivity of water. In order to detect a possible electroviscous effect, we adopted the electric conductivity values measured by Baviere et al.[4] (Table 4). The Table 4 clearly demonstrates that the electrical conductivity of water plays a significant role on the EDL thickness, thus on the viscosity of fluid. The EDL thickness calculated shows that the electroviscous effect can be neglected for all channel diameters studied here. It must be remembered that

EDL effects are relevant only for liquid flows containing ions.

4. Conclusions

Numerical simulations based on the 2-D CVFEM were conducted to predict steady, laminar liquid flow in a rectangular microchannel. The working fluid was chosen to be water. The choice of water helped to ensure that the continuum approach was valid for the study. Our numerical study has successfully validated the experimental data of Baviere et al.[4] and Mokrani et al.[5]. Key findings from the study are as follows:

(1) The numerical results were found to be in good agreement with the experimental data, suggesting that such approaches, when coupled with carefully matched entrance and boundary conditions can be employed with confidence for predicting flow behavior in microchannels.

(2) The present numerical simulations show that there is no size effect on hydrodynamic behavior when the channel spacing is reduced from 50 μm down to 0.5 μm (hydraulic diameters100 μm -1 μm) in the range of Reynolds number and electrical conductivity considered here.

(3) Numerical simulations turned out to be very helpful as a complement to the interpretation of experimental data, where complex measurement techniques are obviously not possible.

Acknowledgements

The authors acknowledge the support from MESC laboratory (Laboratoire de Mécanique Energétique et systèmes de conversion) and U.S.T.H.B University (Code Number of Research Project J0300220130012).

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