A friction factor in rectangular microchannel of 100 μm depth

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Abstract. The dependence between the shear stress and integral flow parameters such as fluid flow rate still remains unclear for different microchannel geometries. We present results of the numerical simulation of the 3D fluid flow in a microchannel with a rectangular cross section. Basing on the experimental measurements of the pressure drop the fluid flow and the shear stress are analyzed in detail giving the correlations for the friction factor. The results show that the shear stress for a numerical calculation can be estimated using friction factor from the well-known formula with a slight deviation due to wall and corner effects which can be important with the reduction of microchannel size.

1. Introduction

Optimizing the design of microfluidic systems requires a clear understanding of the fluid transport mechanisms in both laminar and turbulent fluid flows. Many works had been done during past decades devoted to investigations of fluid flow and measurements of the pressure drop in microchannels [1-3]. However, the influence of parameters such as shear stress on microchannel walls or the friction factor for some microchannel geometries are still remain unclear. Due to small size of microchannel the shear stress at the boundary of the microchannel significantly affects the nature of the flow and the throughput of the microchannel.

Decreasing of the shear stress is one of the ways to increase microchannel throughput, which is important for different devices such as lab on chip, valves and pumps in molecular analysis and medicine, cooling systems [1]. Rothstein overviewed different ways to create superhydrophobic surface which is mainly governed by the boundary geometry [2]. It was exemplified by using superhydrophobic surfaces with topographical patterns and described applying Navier slip boundary condition. The contrast wettability or biphilic surfaces for smooth walls is another solution for drag reduction [3].

The shear stress for a Newtonian fluid at an element parallel to a flat plate is given by the formula:

\[ \tau(y) = \mu \frac{\partial u}{\partial y} \]  

where \( \mu \) is the dynamic viscosity, \( u \) is the flow velocity along the boundary. However, to find the shear stress from this equation the flow velocity \( u \) have to be known.

Friction factor is another variable that can characterize throughput of a microchannel. Here we use the friction factor to compare our results with other works and experimental results. The following equation gives the shear stress dependence on the friction factor [4]:

\[ \tau = \frac{1}{8} \rho f V |V| \]
where \( \rho \) is the density, \( V \) is the flow velocity, \( f \) is the friction factor.

The friction factor, or sometimes the Darcy friction factor can be estimated from dimensional analysis [5]:

\[
    f = \frac{\Delta p (D/4)}{\left( \frac{\rho \cdot V^2}{2} \right)}
\]  

where \( D \) is the hydraulic diameter, \( l \) is the length of the channel. The article [6] contains the overview of the friction factors from literature for different Reynolds numbers, compressible and incompressible flow. They showed agreement between standard laminar incompressible flow predictions and measured results for water.

In this paper we investigate the impact of the pressure drop, fluid flow rate and temperature for water on the shear stress in the microchannel with a rectangular cross section of \( 241 \times 101 \mu m^2 \). It is important to investigate the shear stress dependence on microchannel parameters before implementing any artificial boundary condition. We assume that the shear stress is the same on all boundaries of the microchannel.

2. Experiment and calculation

We consider a microchannel with rectangular cross section. The width, height and length of the microchannel were \( 242.26 \pm 0.005 \mu m, 101-115 \mu m, 10 \pm 0.5 \text{ mm} \), respectively. We conducted the experiment to investigate the shear stress in dependence on different parameters such as flow rate and inlet temperature. Water was used as a test liquid. Inlet liquid temperature was varied: \( 40^\circ \text{C}, 60^\circ \text{C}, 80^\circ \text{C} \). Also, the measurements at the room temperature were made. The pressure drop was measured by pressure transducer parallel to the microchannel. The friction factor was obtained from equation 3.

The shear stress in the microchannel was found numerically using Ansys CFD parametric calculation for laminar 3D flow by the SIMPLE method with a residual parameter of \( 10^{-7} \). The microchannel mesh grid was performed from hexagonal elements with \( 4 \mu m \) side size. The fluid density, viscosity, pressure drop in the microchannel, and the shear stress at the boundary in the direction of the flow were set. Verification was made using grid convergence method and by variation of different parameters and calculation method. Also, the microchannel geometry measurement error impact on the calculation results was checked. Optimal parameters were selected. Figure 1 shows the comparison between “noSlip” boundary condition and the boundary condition with adjusted shear stress (19.35, 55, 88, 120, 158 Pa for 1, 3, 5, 7, 10 ml/min flow rate, respectively).

![Figure 1](image.png)

**Figure 1.** The dependences of the flow rate on the pressure drop for water at the room temperature.
The parametric calculation was performed to find the shear stress by iterative method. The shear stress was set as a parameter and at the first iteration was estimated using equation 2 and appropriate friction factor from the literature. The value determined in the numerical calculation was the volumetric fluid flow rate. And the pressure drop was considered as a known parameter. By setting the average shear stress on the boundaries iteratively the volumetric fluid flow rate was compared with the experimental results until coincidence.

3. Results
The obtained results on shear stress via flow rate are shown in . The shear stress was obtained from Ansys CFD parametric calculation. Figure 3 shows log-log plot of the dependences of the friction factor on the Reynolds number which were obtained from numerical calculation by using equation 2 and from experimental results by using equation 3. Partial slip condition has been used for calculations.

![Figure 2](image1.png)  
**Figure 2.** The dependence of the shear stress on the flow rate for water at different temperatures.

![Figure 3](image2.png)  
**Figure 3.** The dependence of the friction factor on the Reynolds number for water.

The results show good agreement with the theory for laminar regimes. The dependence of the shear stress on the flow rate for water can be useful in further numerical calculations. shows deviation between the friction factor from the numerical calculation and the friction factor from the experiment for high Reynolds numbers, in the transition region from laminar to turbulent regime.

and show the field of velocity vectors in the cross section of the microchannel. Some corner effect can be observed. The vectors on the boundaries, shown in , have opposite direction due to adjusted average shear stress on all microchannel boundaries, for more physical results the shear stress on the boundaries should be set as a function.
Conclusion
Flow in a rectangular microchannel has been numerically investigated. Basing on the experimental data on the pressure drop the shear stress is calculated for laminar 3D flow and analyzed in detail. The results show that the shear stress for a numerical calculation can be estimated using well-known friction factor with slight deviation for high Reynolds number. For more precise result, which can be important for a smaller channel size, the shear stress should be defined as a function of wall and corners properties and geometry.

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