The investigation of the height effect of a slit microchannel with a textured wall on its hydrodynamic drag

A S Lobasov¹,², A V Minakov¹,²
¹ Siberian Federal University, 79 Svobodny pr., Krasnoyarsk, 660041, Russia
² Institute of Thermophysics SB RAS, 1 Lavrentyev pr., Novosibirsk, 630090, Russia
perpetuityrs@mail.ru

Abstract. The numerical investigation of the fluid flow in a slit microchannel with a textured wall was carried out. The effect of the channel height on the hydrodynamic drag coefficient, as well as on the pressure drop in such channel and the effective slip length on the wall for various Reynolds numbers, are presented in the paper. The channel length was 100 µm, and its height was varied from 25 µm to 500 µm. The Reynolds number was varied from 0.1 to 100. The main studied characteristics were compared to the similar ones obtained for a channel with normal walls (no-slip conditions). It was found that the pressure drop in such textured microchannel was lower as compared to a conventional channel for any of its heights and for any Reynolds numbers. The dependences of the relative pressure drop, effective slip length, and drag coefficient on the Reynolds number were obtained for different channel heights. The drag coefficient was described as 20/Re for the average values of the channel height. A correlation that describes the dependence of the friction factor on the Reynolds number for small and large heights of the channel was proposed. The accuracy of the proposed correlation was about 90%.

1. Introduction
Currently, there is a worldwide tendency to miniaturize various devices and equipment. Intensive research into microfluidic equipment over the past two decades has been driven by the ability to use a range of advantages that result from the unique behaviour of the fluid at micro-scale. At the microscale level, the properties of liquid are becoming more and more controllable, and it is also possible to exercise control over various processes carried out in microfluidic conditions.

The small internal volume also allows reduction in the amount of sample required for analysis or reaction. This is especially useful when rare and valuable substances or samples are used, as well as when a large number of samples are available for biological and chemical analysis and screening in a limited small volume [1].

However, all the advantages of miniaturization of hydrodynamic systems are often offset by one significant drawback: as the transverse dimension of the channel decreases, its hydraulic resistance increases significantly. For example, the velocity of a water flow in a microchannel with an average hydraulic diameter of 10 µm at Reynolds number equal to one will be equal to 0.1 m/s, and the pressure drop in a channel of such a transverse size and length of 10 cm will be about 3.2 atm. This disadvantage can be overcome by using the superhydrophobic effect. This effect is achieved by modifying the surface of the channel walls: applying regular or irregular structures. Contact angles of wetting of such surfaces can reach 120-150 degrees. At such angles, the velocity of the fluid on the wall becomes nonzero, that is, slip conditions are implemented. In this case, a drop of liquid contacts
only a small part of the solid surface, and wetting occurs with the participation of atmospheric air captured by the surface irregularities. As it was shown in many studies [2-10] the critical parameters affecting the fluid flow and heat transfer in the absence of wetting are the type of texture, its shape and location, the curvature of the liquid-gas interface (an indirect parameter), and the Reynolds/Peclet number. In light of the above, it is obvious that the development and optimization of surface textures are necessary to improve the thermohydraulic characteristics of microchannels. Thus, the studies of possibility of using superhydrophobic surfaces in order to reduce the hydraulic resistance of microchannels are extremely urgent. However, the effect of microchannel sizes is usually not considered in any way. In this case, the height of the channel can significantly affect its hydrodynamic characteristics, especially in the presence of superhydrophobicity on the wall. Therefore, in this work, we studied the effect of this parameter on the hydrodynamic drag coefficient, as well as on the pressure drop in such channel and the effective slip length on the wall for various Reynolds numbers.

2. The computational domain and the mathematical model
After a literature review and preliminary studies, it was found that the effect of channel wall textures on the flow of a single-phase fluid is provided when the average roughness size is more than 5% of the characteristic size of the microchannel. For a two-phase interaction of a fluid flow with an interlayer of capillary-retained air, the roughness effect is manifested at the order of 0.5% of the characteristic microchannel size, and in some cases even at smaller sizes. A three-dimensional microchannel of the rectangular cross-section was considered. Periodic boundary conditions were set on the sidewalls of the channel, so the channel width was assumed to be infinite. The texturing areas were squares with a side of 1 μm and were staggered with longitudinal and transverse steps also equal to 1 μm. Its scheme is shown in figure 1, where the red squares correspond to no-slip conditions (the textures on the channel wall), and the black squares correspond to slip conditions (the absence of the textures on the channel walls). As one can see, the bottom wall is a combination of texturing areas with no-slip boundary conditions and free surface areas simulate air caverns between textures. In the free surface sections, the velocity slip of the flow on the wall was specified using the zero shear stress condition. The no-slip conditions were set on the upper wall. The calculations were carried out for various Reynolds numbers, and the obtained results were compared with the usual non-textured channel. A series of calculations for the flow of water in a slit microchannel with a length of 100 μm was carried out. The height was varied in the range from 2.5 μm to 100 μm. The mesh detail was about 1 million cells: this amount was enough to obtain a mesh-independent solution. The Ansys Fluent CFD package was used.

Figure 1. The scheme of the textured wall of the microchannel. Red squares for no-slip conditions.

To solve the posed problems the theoretical approach based on the computational fluid dynamics methods, namely, on the numerical solution of the unsteady Navier-Stokes equations, was used:
For any of its height, the pressure drop depends nonlinearly on the Reynolds number for various dimensionless channel heights is shown in figure 2. As one can see from the figure, the relative pressure drop depends nonlinearly on both the Reynolds number and the relative heights. At the same time, as the relative height of the channel increases the behaviour of the relative pressure drop dependence on the Reynolds number changes. For the smallest channel height, the slope of this curve is negative, for a channel height of 5 μm, the curve is substantially parallel to the horizontal axis, and, starting from a height of 7.5 μm, the slope of the curve becomes positive and increases with increasing the channel height. The use of a textured wall allows reduction in the hydrodynamic losses in such a microchannel by an average of 32%.

Another important characteristic is the effective slip length of the velocity on the wall, which is defined as the ratio of the average velocity on the wall to the average velocity gradient on this wall: \[ l_{eff} = \frac{<u_n>}{<\nabla u \cdot n>}. \] Since the flow of a Newtonian fluid is considered in this case, the velocity gradient is determined from Newton rheological law: \[ <\tau> = \mu (\nabla u \cdot n). \] In turn, the shear stress \( <\tau> \) is proportional to the pressure drop in the channel. As a result, the effective slip length in the microchannel will be determined as follows: \[ l_{eff} = \frac{2 <u_n>}{\mu \cdot l} (\Delta \rho h), \] where \( \mu \) is the dynamic viscosity of the fluid, \( l, h \) are the length and height of the channel, accordingly, \( \Delta \rho \) is the pressure drop in the channel. The dependence of the effective slip length on the Reynolds number for various dimensionless channel heights is shown in figure 3a. As one can see, the effective slip length on the wall decreases nonlinearly with decreasing the channel height. Moreover, the dependence on the Reynolds number is rather weak. However, it is not entirely correct to make such a comparison, since the channel height changes significantly. Therefore, the dependence of the relative effective slip length on the Reynolds number is considered (see fig. 2b). That value is obtained as a result of dividing the
effective slip length by the channel height. As one can see from the figure, the largest value of the relative effective slip length is observed for the channel with the smallest height, and that value decreases with an increase in the Reynolds number. Its average value is about 15%. For channels with heights of 5 μm and 7.5 μm, a slight decrease in this value is also observed with an increase in the Reynolds number, and, starting from a channel height of 10 μm, the value of the relative effective channel length does not depend on the Reynolds number. For the largest channel height of 100 μm, the relative effective slip length is about 3% of the channel height.

Figure 2. The dependence of the relative pressure difference on the Reynolds number for different relative heights.

Figure 3. The dependence effective slip length (a) and relative effective slip length (b) on the Reynolds number for different relative heights.
Further, the influence of microchannel wall texturing on the hydrodynamic drag coefficient is investigated. The dependence of that value on the relative microchannel height at different Reynolds numbers is shown in figure 4a. According to the theory, the friction factor for a slit channel is $24/Re$, that is, it should be a straight line in the coordinates used in figure 4a. As it can be seen, for the average values of the relative channel height, this dependence is indeed a straight line. However, for large and, especially, small values of the relative channel height, this dependence begins to deviate from the straight line. Moreover, the larger the Reynolds number, the stronger this deviation. At the same time, even straight sections do not correspond to the theoretical values of the friction factor: they are well described as $\lambda_{\text{eff}} = 20/Re$, which is shown in figure 4a as dotted lines for the corresponding Reynolds numbers. The relative channel height $l/h$ is used in figure 4, where $l$ is the length of the slit channel equal to 100 μm, and $h$ is the channel height.

**Figure 4.** The dependence of the hydrodynamic drag coefficient on the relative height of the microchannel for various Reynolds numbers (a) and the comparison of the pressure drop in the channel obtained as a result of the calculation and using the proposed correlation (b).

Such behaviour of the hydrodynamic drag coefficient value for a microchannel with a textured wall is consistent with the results of studies of the relative pressure drop dependence given above. After processing all the results obtained, a correlation that describes the behavior of the drag coefficient is proposed: $\lambda_{\text{eff}} = 4.631/Re^{0.025} \cdot (2.3027 - \ln(l/h)) - 14.325/Re^{0.935} \cdot (l/h)^{-0.5} + 24/Re$. If divide the hydrodynamic drag coefficient of a conventional channel (equal to $24/Re$) by the same value for a channel with a textured wall, then the values of the relative hydrodynamic drag coefficient, numerically equal to the relative pressure drop, can be obtained. Comparing the relative pressure drop obtained using the proposed correlation with the calculation results, it is found that the proposed correlation describes the results obtained with an accuracy of about 90%. This can be seen from fig. 3b, where the dotted line indicates a deviation of ± 10%.

4. Conclusion
A superhydrophobic phenomenon during the fluid flow through microchannel due to channel wall texturing is considered. It is found as a result of literature review, that, in recent years, the study of highly and superhydrophobic microtextured surfaces has attracted great interest, therefore, such investigations are extremely relevant. The geometries and grids of straight rectangular microchannels with chess-wise roughnesses and free surface areas simulating air voids between textures are
constructed. In the free surface sections, the flow velocity slip on the wall is specified using the zero shear stress condition. The number of cells in these grids is about 8 million. It is found that the pressure difference in such a microchannel is also less than in a conventional channel for any of its heights and for any Reynolds numbers. The relative pressure drop depends nonlinearly on both the Reynolds number and the relative heights. The use of a textured wall allows reduction in the hydrodynamic losses in such a microchannel by an average of 32%. The relative effective slip length on the wall decreases nonlinearly with increasing channel height. Moreover, the dependence on the Reynolds number is rather weak. The largest value of the relative effective slip length is about 15%; it is observed for the channel with the smallest height. For the largest channel height of 100 μm, the relative effective slip length is about 3% of the channel height. The influence of microchannel wall texturing on the hydrodynamic drag coefficient is investigated. As it is mentioned above, according to the theory, the friction factor for a slit channel is $24/Re$. However, for a textured microchannel, this value is also well described as $20/Re$. For large and, especially, small values of the relative channel heights, this dependence begins to deviate from that ratio, and the larger the Reynolds number, the stronger this deviation. After processing all the results obtained, a correlation that describes the behavior of the drag coefficient was proposed: $\lambda_{\text{eff}} = 4.631/Re^{0.925} \cdot (2.3027 - \ln(l/h))^{0.5} + 24/Re$. Comparing the relative pressure drop obtained using the proposed correlation with the calculation results, it is found that the proposed correlation describes the results obtained with an accuracy of about 90%. Thus, it can be concluded that the use of textured surfaces allows reduction in the pressure drop in microchannels and an increase in their energy efficiency.

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