



Fluid Dynamics and Transport Phenomena

Gas–liquid two-phase flow in serpentine microchannel with different wall wettability

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ABSTRACT

Gas–liquid flow in serpentine microchannel with different surface properties exhibits drastically different flow behavior. With water and air as working fluids, the method of numerical simulation was adopted in this paper based on CLSVOF (coupled level set and volume of fluid method) multiphase model. After verifying the reasonability of the model through experiment, by changing wall properties and Re number ($Re < 1500$), the influences of contact angle and surface roughness on flow regime and Po number were discussed. Moreover, the difference of pressure drop between curve and straight microchannel was also calculated. Beyond that, the combined effect of curve channel and wall properties on flow resistance was analyzed. This paper finds that wall properties have great influence on gas–liquid flow in microchannels not only on flow regime but also flow characteristics. Meanwhile, the pressure drop in curve microchannels is larger than straight. It is more beneficial for fluid flowing when the straight part of microchannel is hydrophilic smooth wall and curve part is hydrophobic with large roughness.

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1. Introduction

Microchannel has great application prospect in the fields of natural science and chemical engineering, and kept high speed development. Meanwhile, microchemical technology which increasingly attracts attention of scholars has become one of the important development directions of chemical engineering [1,2]. According to the statics in literature, due to excellent heat and mass transfer ability, many reactions that cannot be achieved in conventional channel can be implemented in a microreactor [3]. At present, microreactor has been widely used in chemical researches, and the application of it in commercial production is also increasing day by day. Especially for gas–liquid two-phase flow which is widely applied in the chemical industry [4], petroleum industry [5] and photochemical reactions [6]. As basic transport, it determines the performance and efficiency of microdevices to a great extent. Up to now, domestic and foreign academic circles have carried out extensive researches and owned a better understanding of fluid flow characteristics. However, there are still many technical difficulties in the manufacture of microdevices including wall load of the catalyst and automatic control of the system [7]. It is necessary to carry out deep and integrated researches on wall surface of microchannel and interfacial phenomena. Among various issues calling for further study, wall properties have attracted our interests a lot.

As an important part of microchemical technology, gas–liquid microcontact system has been widely studied both by experiment and in theory [3–5,8]. A common conclusion has been drawn: wall properties (roughness and wettability) are one of the reasons that cause heat transfer and flow characteristics of microchannel different from conventional ones. On the basis of experiment and detailed numerical simulation, we adopted a Y type convergence serpentine microchannel with two curve channels which is different from traditional microchannel to explore two-phase flow. The present research is mainly focused on two aspects: one is the influence of contact angle and roughness on flow regime and characteristics; the other is combined effect of curve and wall properties on fluid flow in serpentine microchannel.

In the studies of gas–liquid flow in conventional straight microchannels with hydrophilic smooth wall surface, most of the conclusions about main flow regime were confirmed. When the channel diameter reduces to 50 μm and 100 μm , the bubbly and slug–annular flow regimes cannot be discriminated and only some diverse slug flow were noticed; when the channel diameters are 250 μm and 530 μm , the flow patterns were analogous to those in channels with large diameter [9–11].

As for surface properties, a myriad of studies have also been performed. To investigate water flow kinematics when passing through super-hydrophobic superfluids, Ou [12,13] conducted a series of tests. Their findings revealed that pressure drop reduces up to 40% and apparent lengths larger than 20 μm were obtained when using ultra-hydrophobic surfaces. Sung and Yun [14] studied gas–liquid flow in microchannels with hydrophobic and hydrophilic surfaces both by means of experiment and numerical simulation. The results showed

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that wall properties influenced the presence of working fluid: when one channel had hydrophobic wall surface, liquid water would exist in two corners of hydrophilic preferentially. Peng *et al.* [15] calculated size distribution and maximum radius of droplet with hydrophilic–hydrophobic surface experimentally, and it was observed that with hydrophobic region width increasing, the maximum radius and density of droplet on hydrophobic region decreased. To study the effects of contact angle on water behavior, Cai *et al.* [16] analogue the mobility of water droplets in straight microchannels. They found that water flowed faster on hydrophobic wall surfaces.

Wong [17] analyzed the mixing phenomena of fluid in T microchannel, and found that different geometries are the main causes of second and vortex flow. Numerical method was used by Song *et al.* [18] to study the droplet dynamics in hydrogen fuel cell with serpentine microchannel. The results of numerical simulation demonstrated that serpentine microchannel which had straight hydrophilic walls and curved hydrophobic surfaces could enhance water flow capacity in comparison with the other two cases: the channel surface was all hydrophilic or hydrophobic. Park and Ansari [19,20] found that serpentine shape has good mixing performance at high Reynolds number.

Due to the complexity and specialty of serpentine microchannel structure, although the effects of wall properties had been mentioned in numerous literatures, the significant effect of roughness and wettability on fluid flow in microchannel is not coordinated with the existing experimental and analytical results. The present paper uses numerical simulation to explore flow regime map under different operation conditions and the influence of contact angle and roughness on flow resistance at the first part. In the second part, the combined influences of curve part and wall properties on *Po* number are investigated.

2. Experiment

In the experiments, the model of serpentine microchannel with a converging shape of 90 degree Y-junction was firstly made on the monocrystalline silicon circle which was as a mold to process the groove on polydimethylsiloxane (PDMS) by using the method of soft lithography process. And then it was integrated with glass by means of the ionic reaction bond.

Fig. 1 indicates the schematic of serpentine microchannel adopted in our experiment. It was made of two inlet channels used for introducing continuous fluid and three main microchannels, the length of which are 10 mm and 50 mm, respectively. And the angle between two inlet microchannels is 90°. At the same time, there are two curved channels of semicircular structure to connect main microchannels. The inner diameter of that is 3 mm, and the outer is 4.6 mm. All microchannels have a rectangular cross section (800 μm × 100 μm).

The experiment was carried out using pressure driven method, meanwhile to capture the clear flow pattern image, high-speed camera was adopted to shoot by us with backlit tricolor light pipe (color temperature is 6400 K). And the microchannel was horizontally placed in vertical plane. By adjusting gas and liquid phase flow rate which were fed into inlets 1 and 2 respectively, we could observe stable flow patterns under different working conditions and then collected data.

All experiments were carried out under normal temperature and pressure.

3. Numerical Simulation

3.1. Governing equations

There are several methods to follow the interface of two incompatible fluids including Level Set (LS), Volume of Fluid (VOF), Phase Fields, Front Tracking and Lattice Boltzmann [21]. The most widely used methods of simulating gas–liquid flow with complicated interfaces in literature are LS and VOF. Both of the two methods belong to interface capture algorithm which can describe the geometric characteristics of the interface by solving a scalar function on each grid, and have a strong topological expression ability and processing ability. However, the definition of two scalar functions is different. VOF method solved the equation by tracking phase volume fraction in every cell. While in LS method, the material interface with time motion is considered as a zero equivalent of a function. As a whole, VOF method is better in volume conservation, but is complex in interface reconstruction. The overall effect of interface captured by LS is better but the calculation time is consuming.

In order to conquer the shortcomings of LS and VOF method, CLSVOF coupled LS and VOF method was adopted in this paper. This method combines advantages of the two methods, which overcomes the problem that the mass transfer is not conserved in the LS method and phase function is not continuous at the interface in VOF method. This method has unique advantages of accurate calculation of interfacial normal vector and curvatures without physical quantity loss.

ANSYS FLUENT (version 15.0, Ansys, USA), a commercial software based on finite volume method for numerical simulation and the CLSVOF method were used to capture two-phase interface. The surface tension of volume in momentum equation was in view of continuum surface force (CSF) proposed by Brackbill *et al.* [22]. Immiscible and incompressible gas–liquid flow control equations are shown as below.

Equation of continuity:

$$\frac{\partial \rho}{\partial \tau} + \nabla \rho \mathbf{u} = 0 \quad (1)$$

Equation of momentum:

$$\frac{\partial (\rho \mathbf{u})}{\partial \tau} + \nabla (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \mu \cdot [\nabla \mathbf{u} + (\nabla \mathbf{u})^T] + \rho \mathbf{g} + \mathbf{F}_\sigma \quad (2)$$

where $\mathbf{u}$ is the velocity vector, ρ is the density, p denotes pressure, and μ is the dynamic viscosity of fluid. $\mathbf{F}_\sigma$ is the surface tension force of volume based on the continuum surface force (CSF) method.

$$\mathbf{F}_\sigma = \sigma k(\varphi) \nabla(\varphi) \quad (3)$$

$$k(\varphi) = \nabla \cdot \frac{\nabla \varphi}{|\nabla \varphi|} \quad (4)$$

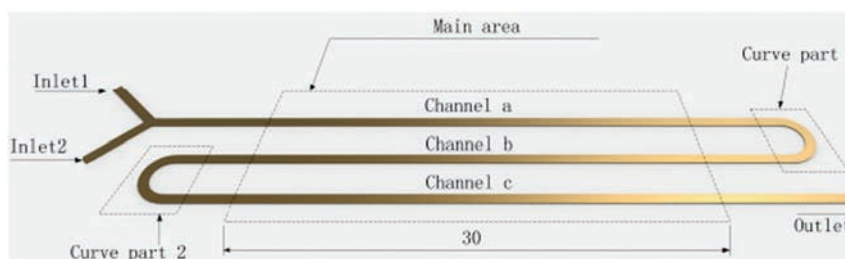


Fig. 1. Sketch map of 3D serpentine microchannel geometry adopted in the experiment and numerical simulation.

$$\delta(\varphi) = \begin{cases} 0, & |\varphi| \geq a \\ \frac{1}{2a} \left(1 + \cos \frac{\pi\varphi}{a} \right), & |\varphi| < a \end{cases} \quad (5)$$

Mixture properties:

$$\rho(\varphi) = \rho_G + (\rho_G - \rho_L)H(\varphi) \quad (6)$$

$$\mu(\varphi) = \mu_G + (\mu_G - \mu_L)H(\varphi) \quad (7)$$

$$H(\varphi) = \begin{cases} 0, & \varphi < -a \\ \frac{1}{2} \left[1 + \frac{\varphi}{a} + \sin \left(\left[1 + \frac{\varphi}{a} + \sin \left(\frac{\pi\varphi}{a} \right) \right] \right), & |\varphi| \leq a \\ 1, & \varphi > a \end{cases} \quad (8)$$

where G denotes gas phase and L denotes liquid. $H(\varphi)$ is the smoothed Heaviside function.

Equation of VOF function:

$$\frac{\partial \alpha_L}{\partial \tau} + \mathbf{u} \cdot \nabla \alpha_L = 0 \quad (9)$$

$$\frac{\partial \alpha_G}{\partial \tau} + \mathbf{u} \cdot \nabla \alpha_G = 0 \quad (10)$$

where α_L is the volume fraction of liquid phase and α_G is the volume fraction of gas phase.

Equation of LS function:

$$\frac{\partial \varphi}{\partial \tau} + \mathbf{u} \cdot \nabla \varphi = 0 \quad (11)$$

$$\varphi(\mathbf{x}, \tau) = \begin{cases} d & \text{if } \mathbf{x} \text{ in the liquid phase} \\ 0 & \text{if } \mathbf{x} \text{ in the interface} \\ -d & \text{if } \mathbf{x} \text{ in the gas phase} \end{cases} \quad (12)$$

where φ is distance function, $\mathbf{x}$ is vector of position, d displays the minimum distance of $\mathbf{x}$ from interphase at τ time.

3.2. Solution

Structured hexagram elements were used to mesh 3D geometry model by ICEM and then loaded into ANSYS FLUENT processor to calculate. The flow was regarded as incompressible because of the low gas velocity. Each inlet is set to a constant velocity boundary for introducing gas or liquid phase and boundary condition of outlet was outflow. The influence of wall wettability and relative roughness was considered by changing contact angle and roughness. Other flow parameters were inferred from internal.

In our simulation, air was used as gas phase and water as liquid phase. Before simulating, the whole flow field was full of water and initial speed was specified to zero. During the process of simulation, we set first-order implicit time stepping of unsteady term and Pressure-implicit with Splitting of Operators (PISO) algorithm for coupling pressure-velocity. As for pressure term, pressure staggering option (PRESTO) scheme was adopted. Meanwhile, scheme of second-order up-wind and geometric construction were used for momentum formula and volume fraction, respectively. During simulating, we need to adjust time step, maximum iterations each time step and relaxation factors carefully to guarantee convergence and keep Courant number below 0.5. The results of simulation were handled by integrated processor of Fluent or ANSYS CFD-post.

3.3. Grid independence

To adapt the complex surface, we use 12 body mesh which can adapt mesh number and complexity of cross section well. To minimize the influence of grid size on results of simulation, we compared the length of

bubble in serpentine microchannel under two different typical operation conditions by increasing grid number which was shown in Fig. 2. It turns out that when the quantity of grid was over 100000, length changes of bubble were insignificant. Considering the calculation time and precision, the number of elements we adopted was 110000.

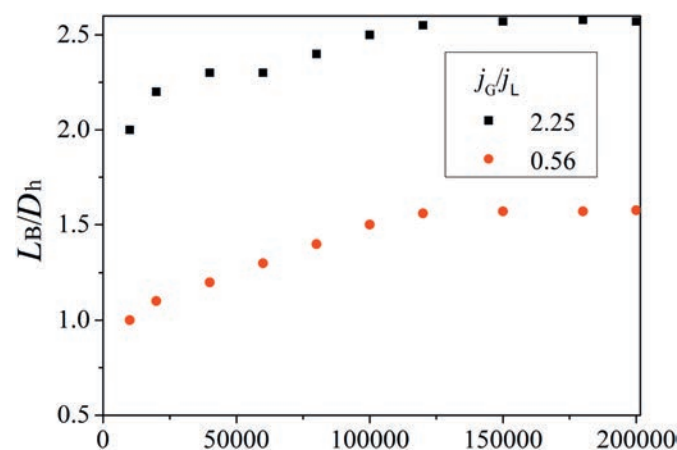


Fig. 2. Mesh dependence of bubble length (Gas phase: air; liquid phase: water. $\theta = 110^\circ$, $\sigma = 0.072 \text{ N} \cdot \text{m}^{-1}$, $\mu_L = 0.001003 \text{ kg} \cdot (\text{m} \cdot \text{s}^{-1})^{-1}$).

4. Variation of Numerical

To validate the reliability of the numerical simulation method adopted by us, we also carried out a flow visualization experiment in our microchannel device, which can also be examined from another paper of us [8]. The results of experiment and numerical simulation were showed in Fig. 3 under the same operating conditions.

From Fig. 3, we can observe some typical flow patterns and a new flow pattern named attaching-wall flow which is different from conventional flow in straight microchannel. Due to the influence of inertia effect, there is a thin layer of airflow which is attached to the wall. And the air flow is inclined to lateral wall surface in curve I, while it is opposite in curve II. At the same time, a comparison between the numerical simulation and experimental results on Taylor bubble length and flow regime map under different gas and liquid velocity were depicted in Figs. 4 and 5. It should be noted that the method of classifying flow pattern was by visual observation and previous literature. The parameters for plotting data in our paper were gas and liquid velocities.

The simulated transition lines and bubble lengths were shown consistent with experimental data. And we also compared length data of experiment with that calculated by previous correlations [23,24] as shown in Fig. 5. Obviously, the forecast of Qian [23] is more suitable for this serpentine microchannel. These results confirm our correctness of simulation to predict gas-liquid flow behavior in serpentine microchannel.

5. Results and Discussions

5.1. Contact angle

5.1.1. Flow regime maps under different contact angle

Two-phase for air-water flow regime maps under different contact angles (36° , 150°) were constructed in Fig. 6, using velocity of gas and liquid as abscissa and ordinate. Every flow map is consisted of more than 150 simulation results under different operation conditions.

Comparing Figs. 4 and 6, some different flow patterns are observed under different contact angle serpentine microchannel. For example,

Flow pattern	Experimental results	Simulation results
(a) Slug Flow ($j_G=1.389\text{m}\cdot\text{s}^{-1}$, $j_L=0.122\text{m}\cdot\text{s}^{-1}$)		
(b) Annular Flow ($j_G=3.681\text{m}\cdot\text{s}^{-1}$, $j_L=0.694\text{m}\cdot\text{s}^{-1}$)		
(c) Attaching-wall Flow ($j_G=1.042\text{m}\cdot\text{s}^{-1}$, $j_L=0.035\text{m}\cdot\text{s}^{-1}$)		
(d) Taylor Flow ($j_G=0.8\text{m}\cdot\text{s}^{-1}$, $j_L=0.5\text{m}\cdot\text{s}^{-1}$)		

Fig. 3. Comparison of typical flow pattern between experimental results and simulation results under the same working condition (Gas phase: air; liquid phase: water. $\theta = 110^\circ$, $\sigma = 0.072\text{ N}\cdot\text{m}^{-1}$, $\mu_L = 0.001003\text{ kg}\cdot(\text{m}\cdot\text{s}^{-1})^{-1}$).

when the wall is super-hydrophobic namely the contact angle is more than 150° , some flow regimes like wall flow and wave flow which can be seen respectively from 110° and 36° are absent. In order to further test the influence of contact angle, Fig. 7 shows the transition lines of flow regime. The transition lines for the same contact angle are identified by line style, and for the same flow regime are identified by color.

From Fig. 7, we can see that when the contact angle increases from 36° to 150° , the bubbly-slug transition boundary shifts towards higher j_L , and at the same time the slug-annular transition line shifts towards lower j_G . Overall results, the slug flow pattern extends along two coordinate directions. The expansion area of slug flow regime can be interpreted as below:

On the one hand, due to the characteristic of hydrophobic wall, the contact area between water and wall surface is small which contributes

to larger contact area between gas and water. Especially in super-hydrophobic microchannel, the contact area of gas and liquid can reach 90% of the total area based on Ou's [13] conclusions. Because the resistance of air–water contact area is lower than that of liquid–solid surface, the general resistance in serpentine microchannel with larger contact angle decreases significantly compared with hydrophilic microchannels. On the other, the delayed transition lines in super-hydrophobic microchannels contributed to slip flow on the wall which leads to smaller pressure drop. Meanwhile, as an important factor of flow transition in microchannels, shear stress in super-hydrophobic microchannel is smaller than others due to large contact area. On the basis of the above two spots, energy dissipation of two-phase gas–liquid flow is smaller in microchannel with larger contact angle which attributed to a more difficult flow regime transitions.

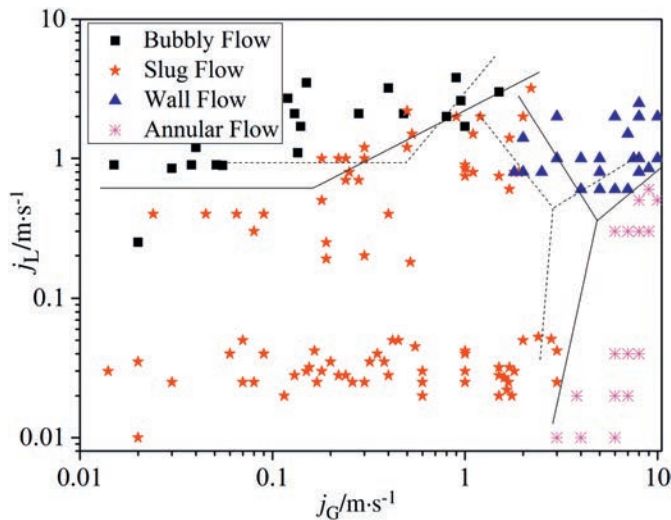


Fig. 4. Comparison of flow regime map between experiment and simulation results under different operational conditions (Gas phase: air; liquid phase: water. $\theta = 110^\circ$, $\sigma = 0.072\text{ N}\cdot\text{m}^{-1}$, $\mu_L = 0.001003\text{ kg}\cdot(\text{m}\cdot\text{s}^{-1})^{-1}$).

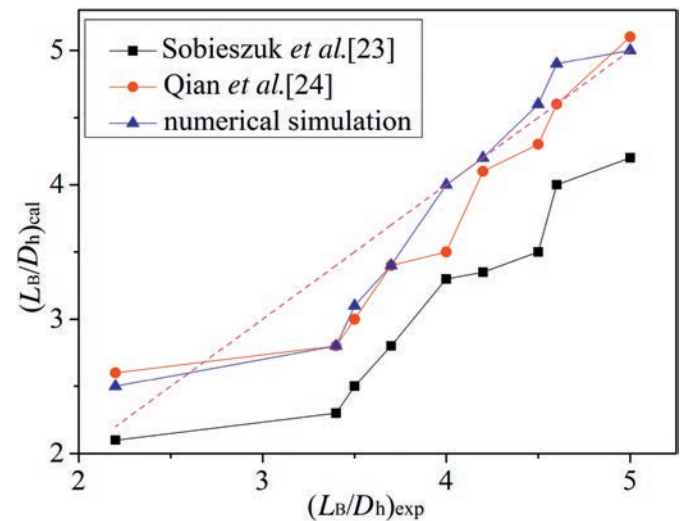


Fig. 5. Comparison of numerical simulation results, experienced formula and experimental results of bubble length.

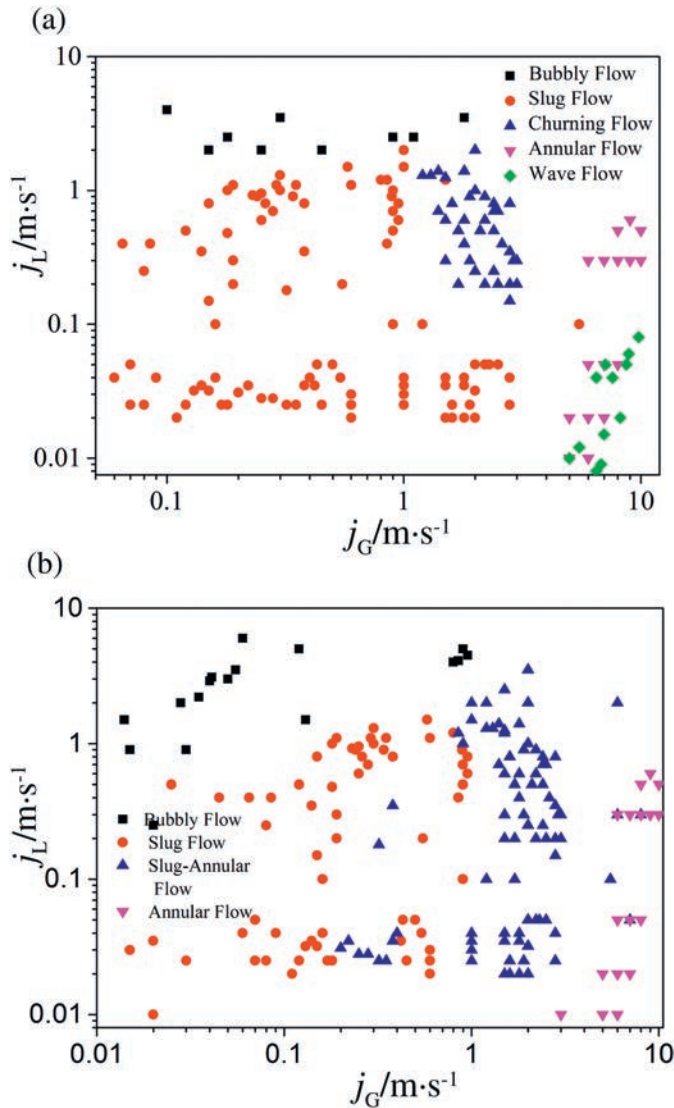


Fig. 6. Flow regime map for contact angle is 36° for (a) and 150° for (b).

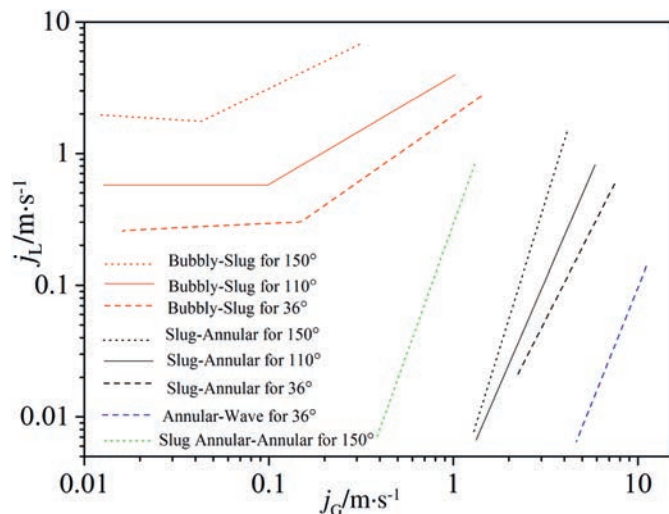


Fig. 7. Effect of contact angle on flow regime transition lines (Gas phase: air; liquid phase: water. $\theta = 110^\circ$, $\sigma = 0.072 \text{ N} \cdot \text{m}^{-1}$, $\mu_L = 0.001003 \text{ kg} \cdot (\text{m} \cdot \text{s}^{-1})^{-1}$).

5.1.2. Length of Taylor bubble under different contact angle

We analyzed the influence of contact angle on bubble length under 3 groups of liquid phase, whose glycerin solution are 20%, 60% and 80%, respectively. The results were shown in Fig. 8.

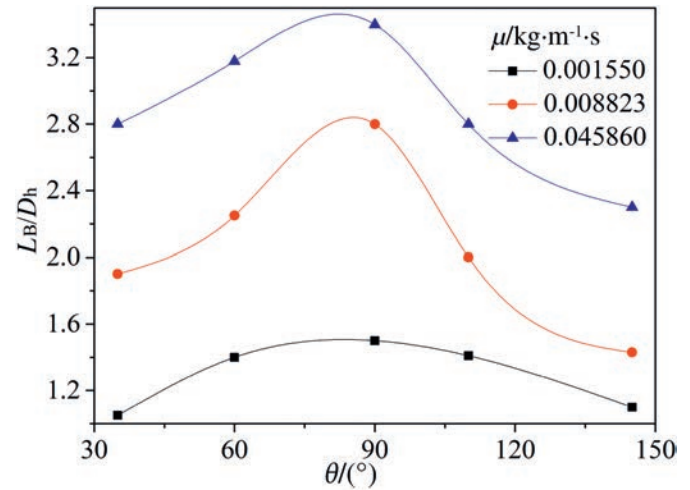


Fig. 8. Influence of contact angle on bubble length of various surface tensions ($j_G = 0.6 \text{ m} \cdot \text{s}^{-1}$, $j_L = 0.89 \text{ m} \cdot \text{s}^{-1}$).

As shown in Fig. 8, at a given viscosity of glycerin solution, the length of bubble was distributed like parabolic. And when the contact angle is 90° , it becomes the maximum. We can use the formula of Yang to analyze the reasons:

$$\gamma_{LV} = \frac{\gamma_{SV} - \gamma_{SL}}{\cos \theta} \quad (13)$$

$$F = \gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{SL} \quad (14)$$

where γ_{LV} , γ_{SV} and γ_{SL} are surface tension between liquid and air, wall and air, wall and liquid, respectively. F is wettability tension.

From formula (14), we can see that in the wetting system ($\theta < 90^\circ$), wall adhesive force diminishes with contact angle increasing, contributing to a decrease of general resistance, which is conducive to form bubble. While in the non-wetting system ($\theta > 90^\circ$), surface tension between liquid and air decreases as contact angle increasing, leading to an easier rupture of the bubble, which is the only conservative force to hinder the rupture of bubble.

When the viscosity of solution is relatively high, the influence of contact angle on bubble length is not as significant as low viscosity solution. For example, the contact angle changes from 90° to 110° , the bubble length decreases substantially in a low viscosity solution contrary to a nearly insignificant decrease of that in a relatively high viscosity solution. The change of bubble length in high viscosity solution was not as significant as low liquid viscosity. The reason of that is when fluids flowing in high liquid viscosity, the effect of surface tension is not that obvious in comparison with shear stress in the process of bubble rupture, which we have mentioned before.

5.1.3. The influence of contact angle on Po

Po number is taken as the parameter to analyze the characteristics of fluid flow, the definition is as follows:

$$Po = fRe = \frac{2D_h^2}{\mu u_m} \left(\frac{\Delta p}{L} \right) \quad (15)$$

u_m is the mean velocity of fluid, $\Delta p/L$ is the mean pressure drop gradient along the direction of process, but, not constant. In this paper, the relationship between Po and Re number is calculated under different contact angles, Fig. 9 shows the results.

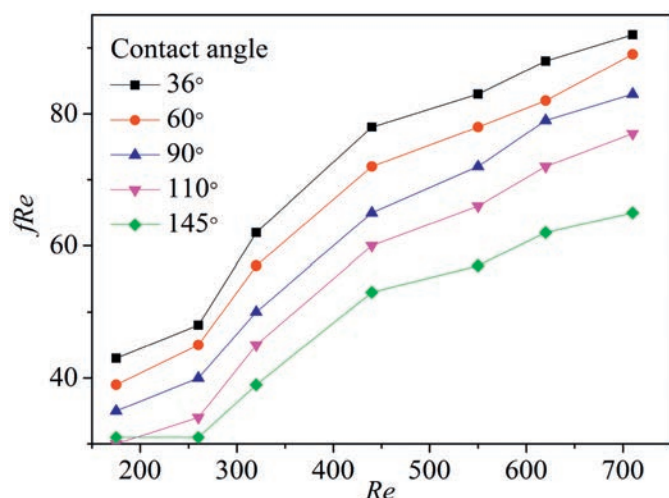


Fig. 9. Effect of contact angle on Po number under various Re .

From Fig. 9, we can find that with contact angle increasing, the number of Po decreased. For hydrophobic wall (contact angle is greater than 90°), especially the super hydrophobic surface, air–water contact area accounted for most of the total area of the channel as we mentioned before. Because gas–liquid flow resistance is smaller than that between liquid and solid, the Po number of two-phase gas–liquid flow in hydrophobic wall surface is lower than that of hydrophilic surface. Meanwhile, it can be analyzed that as the Re number increases, the air between the convex of hydrophobic surface will gradually overflow which leads to the increase of contact area between water and wall and weakens the hydrophobic wall drag effect. Thus, the Po number changes smoothly.

5.2. The effect of relative roughness on Po

To explore the influence of roughness on flow characteristics of the fluid, the relationship between Po number and Re number is calculated under different relative roughness conditions. The results are shown in Fig. 10.

In Fig. 10, the vertical axis represents the ratio of Po number between rough and smooth surface. Obviously, the number of Po is not relevant

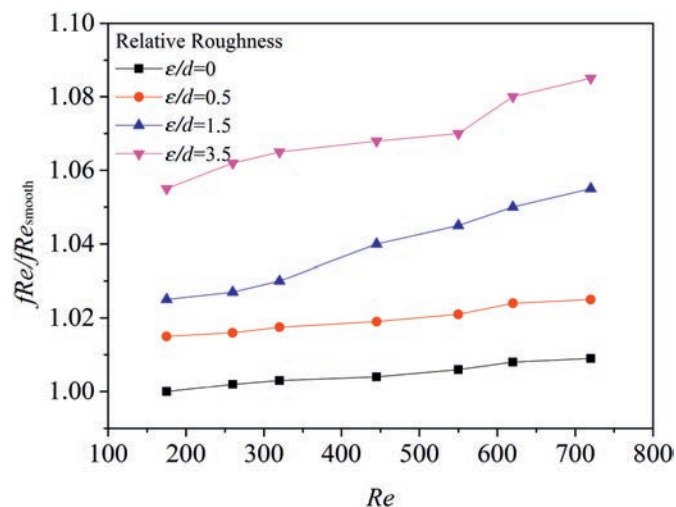


Fig. 10. Effect of the relative roughness on Po number under various Re .

with Re . Compared with conventional scale channel with rough surface, there is no significant effect on fluid flow in the recirculation zone between microchannel roughness element, and more obvious vortex with the increase of Re number, as mentioned by literature [25]. But we can find that Po number increases when relative roughness is increasing compared with smooth wall. As the experimental material used in this paper is hydrophobic wall, we conduct the following analysis:

Surface hydrophobicity is determined by both of the surface chemical composition and surface roughness. The classical Young Eq. (13) only considered improving the hydrophobic property by changing wall chemical composition, while Wenzel *et al.* [26] introduced the roughness r into Young formula to obtain contact angle calculation equation of the Wenzel model:

$$\cos \theta_w = r \cos \theta_c \quad (16)$$

θ_w is rough surface apparent contact angle and θ_c is intrinsic contact angle of the desired surface. By formula (16) we can see that, when the roughness increases, the contact field between liquid and wall surface decreases, so as to enhance the surface hydrophobicity. For two phase flow, liquid phase will cause more energy loss in the dry wall with large roughness, which leads to a larger pressure drop and Po number.

5.3. Comparison of pressure drop between straight and curve microchannel

Turning curves were part of model adopted in this paper. Therefore, flow of gas–liquid in serpentine microchannel is more complex than that in conventional straight microchannels. For the sake of studying the effect of bend microchannel on pressure drop in microchannel, the numerical calculation method is adopted in this paper. The pressure drop of gas liquid flow was calculated for the same length under the same operating conditions in straight and curved microchannel, respectively. The results are shown in Fig. 11.

Curve will change behaviors of fluid flow, adjust the distribution of the two phases, and influence calculation method of pressure drop. As we can see from Fig. 11, gas–liquid flow pressure drop in microchannels with curve is higher than that in straight microchannel. Pierre [27] thinks that flow resistance of turning curve is mainly composed of two parts, one part is pressure drop caused by fluids to turn, and the other is caused by friction. This also explains the phenomena shown in Fig. 11.

In addition to the above findings, the turning curve is mainly to strengthen the disturbance in the microchannel, raise the fluid velocity, and also increase the slip ratio of gas–liquid flow. As we all know, on air–liquid interface, slip flow will occur and flow resistance of water will be reduced when fluids passing through microchannel. Therefore, it can be inferred that slip flow is a key factor to reduce flow resistance of hydrophobic surfaces in microchannel. On the basis of experimental results acquired by Ning [28], the value of pressure drop becomes larger with the increase of slip length which is part of slip flow. Therefore, it can be concluded that due to the existence of turning curve, slip ratio and pressure drop increase.

6. Combined Effect

6.1. Combined influence of roughness and contact angle on Po

A large number of studies have indicated that surface roughness has different effects on two-phase flow in microchannel: 1) By changing the contact field of fluid and wall, the distribution of fluid in the vicinity of roughness element is affected. 2) Through the slip phenomenon, fluid flow resistance is changed. For further study, the combined influences of surface wettability and roughness on gas–liquid flow in serpentine

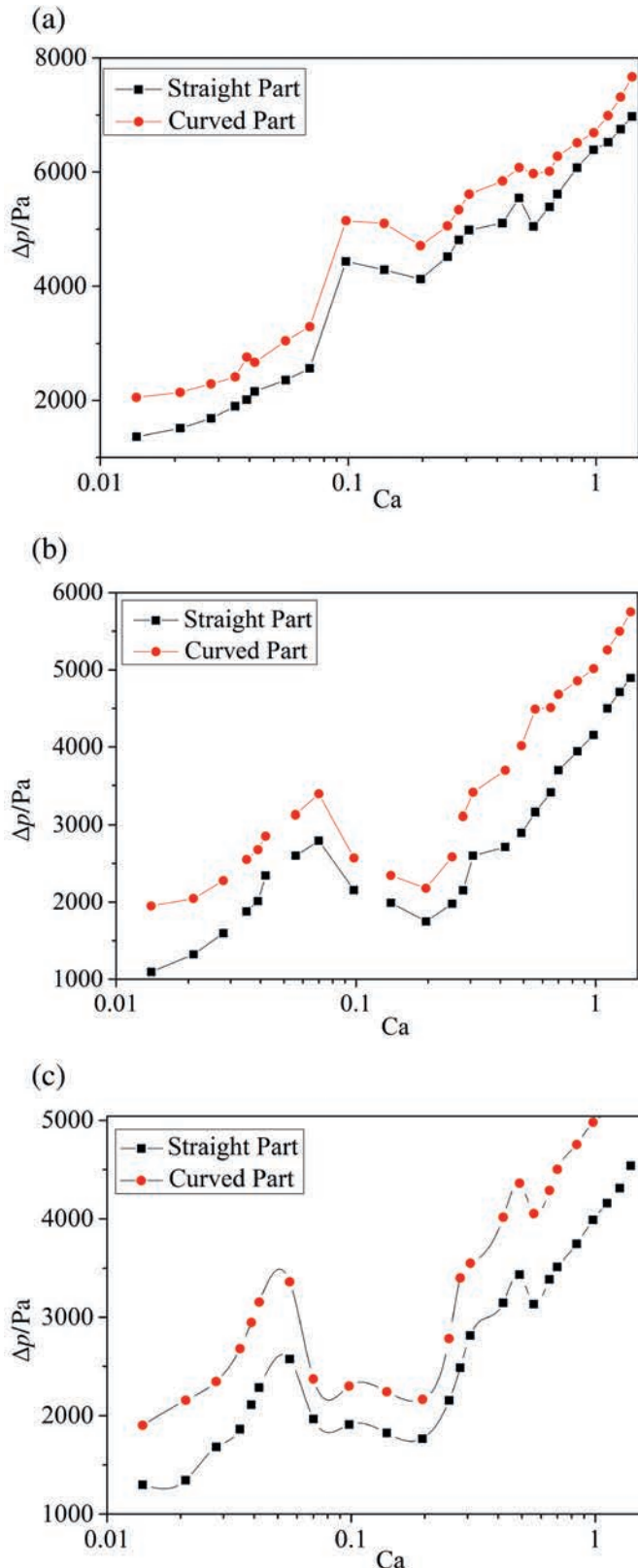


Fig. 11. Comparison of pressure drop between straight and curved part for contact angle (a) = 36°, (b) = 110°, (c) = 150° (Gas phase: air; liquid phase: water. $\sigma = 0.072 \text{ N} \cdot \text{m}^{-1}$, $\mu_l = 0.001003 \text{ kg} \cdot (\text{m} \cdot \text{s}^{-1})^{-1}$).

microchannel will be discussed. The effect of roughness on Po number in microchannel with hydrophilic and super hydrophobic wall is shown as Fig. 12.

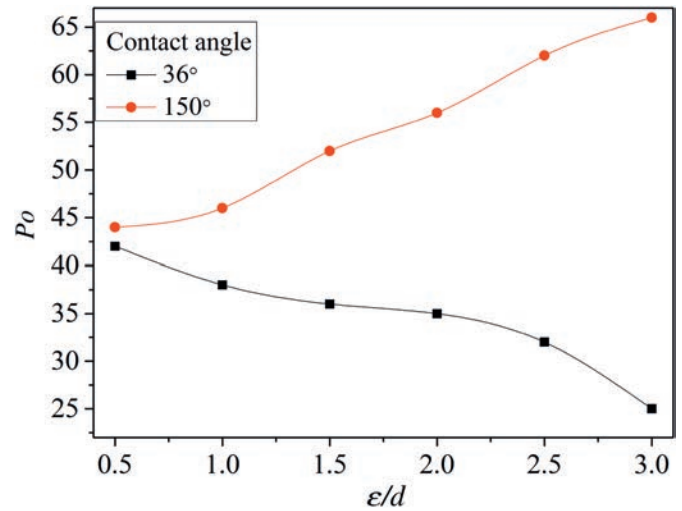


Fig. 12. The combined influence of contact angle and roughness on Poiseuille number.

As shown by Fig. 12, when the roughness is changed, the variation trends of Po number under hydrophilic and super hydrophobic wall are opposite. The reasons for this phenomenon can be explained mainly in the following two aspects:

- 1) On the one hand, through the above formula (16) we can also find that the increase of roughness will raise liquid solid contact angle of hydrophobic surface, thereby enhancing its hydrophobicity; while as for hydrophilic wall, it will reduce the contact angle of liquid and wall surface and make the hydrophilicity better. Moreover, liquid phase in the super hydrophobic wall cannot fill the groove between roughness elements, so partial gas will be retained between liquid and solid, which reduces the contact area between liquid and solid greatly. As we have mentioned before, gas-liquid flow resistance is lower than that between liquid and solid, as a result, with the increase of roughness, the Po number of super hydrophobic wall is decreased. It also verifies the formula proposed by Cassie and Baxter [29]:

$$\cos \theta_w = f_1 \cos \theta_1 + f_2 \cos \theta_2 \quad (17)$$

They believe that contact surface of super hydrophobic wall is composed of wall and air. f_1 and f_2 are surface area fractions of these two kinds of medium, θ_w is the surface contact angle, θ_1 and θ_2 are contact angles of liquid phase between gas phase and wall surface.

- 2) On the other hand, the increase of roughness can raise the slip length of super hydrophobic wall, which can reduce flow resistance. However, it has the opposite effect on hydrophilic wall, even occurs negative slip phenomenon.

6.2. Combined effect of curve and wall properties on Po

Due to the particularity of serpentine microchannel structure, the combined effect of wall surface properties and curve on flow characteristics of fluid in microchannel is analyzed as follows.

From Fig. 13 we can find that, the number of Po in microchannel inlet declines rapidly and the effect of roughness on two-phase flow in curve is weak. We can attribute this to the entrance effect, which is the result of large pressure drop at the Y junction when gas and liquid phase gathering. At the same time, at the exit of microchannel, when the turning curve is smooth, Po number increases rapidly; when the turning curve has a certain degree of roughness, the value changes opposite. Hu

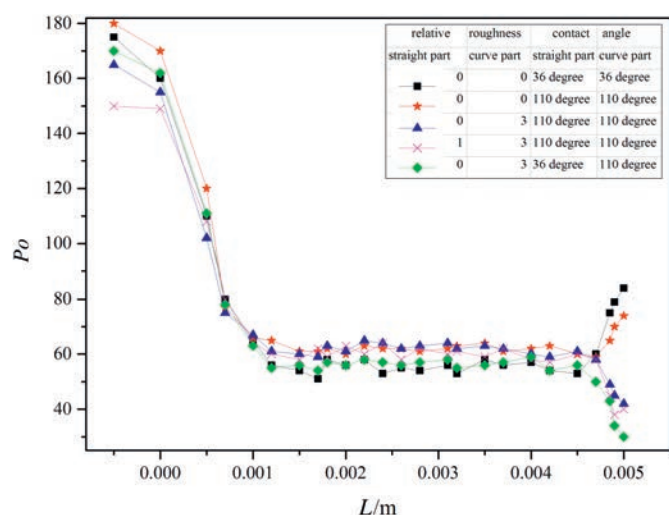


Fig. 13. The combined effect of gas-liquid flow in serpentine microchannel on Po number.

[30] believes that the existence of roughness destroys export effect, so its impact on Po number can be derived from curve lines of Fig. 13. Further observing the effect of contact angle and roughness on fluid flow in curve microchannel, we can find that Po number in the hydrophobic surface is smaller than that in hydrophilic surface, and reasons were stated above.

For the hydrophobic wall surface, when the roughness of curve is the same, the larger the roughness of straight microchannel, the lower the Po number; when the microchannel is hydrophilic smooth surface, the curve part is hydrophobic wall with larger roughness, Po number is smaller and the amplitude of the outlet is the largest. This is due to the double effect of turning curve and roughness on fluid flow. When Re number is small, the existence of turning curve will not change the flow pattern, but generating the second flow due to its special structure. When fluids flow through curve part, the second flow makes bubbles of inner wall not to be transported to the center of the channel and the outside of the wall surface, which leads to an accumulation of gas in the inner wall and an increase of flow resistance. When increasing the roughness of outer surface, Po number can be reduced by changing contact area and increasing slip ratio. This is consistent with the conclusions drawn by Song *et al.* [18]: They believe that hydrophilic wall surface of straight microchannel can prevent liquid phase from covering gas diffusion layer, while the hydrophobicity of curved channel wall can reduce the saturation of water, which is more favorable to the flow of fluid.

7. Conclusions

Through the analyses, several conclusions can be derived as follows:

- 1) Contact angle has a great influence not only in flow regime but also transition lines and bubble length. When it increases, the slug flow region expands. In the wetting system, the length of bubble grows with it increasing; while in the non-wetting system, the change is opposite.
- 2) Po decreases with contact angle increasing. As for hydrophobic wall, the number of Po increases with wall roughness increasing. However, when roughness changed, the change of Po number of the hydrophilic wall and the super hydrophobic wall is opposite.

- 3) The pressure drop in curve channel is larger than straight, but is lower in hydrophobic channel than hydrophilic channel. When the straight part of microchannel has hydrophilic smooth wall, and turning curve has hydrophobic with large roughness wall, Po number is smaller.

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