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Influence of feature size of micro-scale channel on ink flow characteristics①

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Abstract

Under the micro-scale condition, feature size of the channel is one of the main factors influencing the fluid flow characteristics. In printing process, ink thickness in the extrusion zone formed by two ink rollers may reach micron scale. Compared with macroscopic fluid, the velocity field and the pressure field of fluid may change when the feature size of fluid channel reaches micron scale. In order to control printing quality, it is necessary to research the influence of feature size on ink flow characteristics in micro scale. This paper analyzes it in theory, and then numerical simulation of an ink flow model with different feature sizes is carried out in no slip condition. The influence of the feature size on the ink flow characteristics and the wall shear force are obtained. Besides, the ink flow model with different feature sizes is simulated numerically in slip condition, and the influence of feature size on ink flow characteristics is obtained. Finally, by comparing and analyzing the above results, it can be concluded that both the ink velocity and pressure at the inlet of the extrusion zone are inversely proportional to the feature sizes whether in slip condition or not. And the ink velocity in slip condition is larger than that without slip, the pressure at the inlet of the extrusion zone is less than that in no slip condition. Within the micro-scale range, the ink velocity difference between the two conditions cannot be ignored. Therefore, it is necessary to consider slip when analyzing the influence of feature size of micro-scale channel on ink flow characteristics.

Key words: ink flow, feature size, velocity slip, velocity, pressure

0 Introduction

With the development of science and technology and the improvement of people's living standard, there is an increasing demand for printing products in recent years. Thus in the printing process, the key to ensure the quality of printing products is controlling ink flow characteristics and maintaining uniformity, stability and suitability of ink transfer[1-3].

In the inking system of offset press, hard and soft ink rollers are arranged alternately. Among the rollers, the material of hard roller is carbon steel, and the soft roller is made of steel core and covered with rubber. In the process of ink transfer, the ink flow channel is formed by the interaction of ink fluid and ink rollers. When the ink key opening of the offset press is 0.48mm, the process of ink transfer is simulated and analyzed by Sun[4]. Results show that the thickness of the ink passed to the paper is 0.5μm. A channel with feature size below 100μm is taken as the division standard of microchannel, which is proposed by Chung and Kawaji[5]. And it has reached micro-scale range in the ink transfer process. The factors influencing fluid flow in microscale are different from those in macroscale, such as scale effect and velocity slip. The feature size of a channel is one of the factors that affects fluid flow. In macroscopic scale, velocity slip can be neglected. However, the slip cannot be neglected in microscopic scale. At present, there are many researches on the ink transfer process, but none of them consider the microscale effect. Zhang[6,7], et al have numerically simulated the process of ink flow, but the velocity slip is not considered. The channel size varies with the pressure between two rollers. Therefore, it is of great significance to research the influence of channel feature size on ink flow characteristics under slip condition for controlling printing quality.

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1 Theoretical analysis of the influence of micro-scale feature size on ink flow characteristics

In this paper, two-dimensional Poiseuille laminar fully developed flow is taken as an example[8]. The influence of feature size on ink flow characteristics is analyzed in two cases, which are under the conditions of slip and no slip (see Fig. 1).

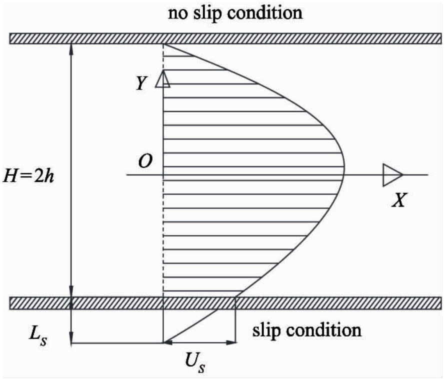


Fig. 1 Diagram of the slip velocity

Velocity distribution under no slip condition is

$$u_x = \frac{h^2}{2\mu}\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right)\left[1 - \left(\frac{y}{h}\right)^2\right] \tag{1}$$

In the formula, p is pressure, h is half of the flow channel height, and μ is liquid viscosity.

Eq. (1) shows that without considering the slip, the ink flow velocity u_x is related to the ink channel feature size $2h$. As a result, u_x varies with the feature size of the channel.

In 1823, Navier[9] presented a flow control equation for macro flow, which was widely used in fluid mechanics. Meanwhile, he pointed out that it was allowed that the flow fluid had a small velocity slip related to the solid surface. That is Navier boundary condition:

$$u_s = u_f - u_w = L_s \left.\frac{\partial u}{\partial y}\right|_{\text{wall}} \tag{2}$$

The model is called linear slip length model, where u_s is slip velocity, u_f is fluid velocity, u_w is wall velocity, and L_s is slip length. Considering the boundary velocity slip, the velocity distribution is

$$u_x = \frac{h^2}{2\mu}\left(-\frac{\mathrm{d}p}{\mathrm{d}x}\right)\left[1 - \left(\frac{y}{h}\right)^2\right] + u_s \tag{3}$$

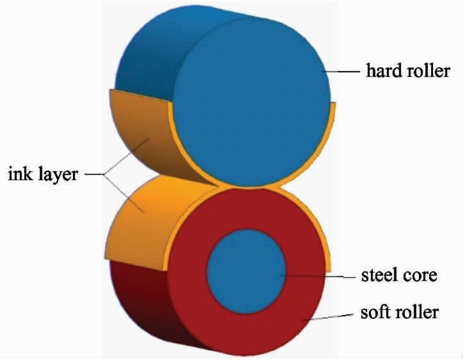
It can be seen from Eq. (3) that when the feature size h changes, the fluid velocity under slip condition also changes.

Due to the uncertainty of the influence extent of velocity slip on the results in microscale before the simulation analysis, ink flow models of feature size are numerically analyzed under two conditions, which are slip and no slip. Thus the influence of feature size on the velocity field and pressure field is obtained. And by contrast, it determines whether slip should be considered when the influence of feature size on ink flow characteristics is analyzed.

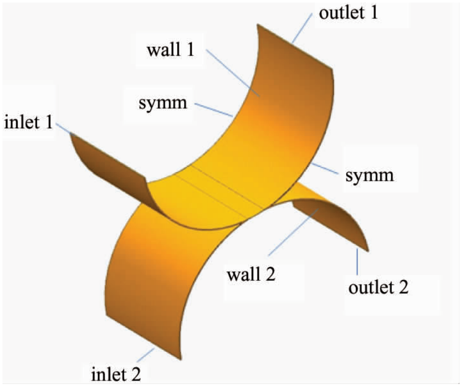
2 Numerical analysis of influence of feature size on flow characteristics of ink under no slip condition

2.1 Ink flow model and mesh generation

Zhang[6] obtained an ink flow model with feature size of 0.02mm, which was based on liquid-solid coupling relationship. In the model, the wall internal diameter is 30mm, the initial ink thickness at inlet and outlet is set to 0.08mm, and the center distance of two rollers is 29.95mm. With the center distance of two rollers and the wall diameter remaining unchanged, the ink flow models under different feature sizes are obtained by enlarging or decreasing in multiples. The shape of the model is shown in Fig. 2, and the specific dimensions of each model are illustrated in Table 1. As seen from Fig. 2(a), the ink layer is attached to the surface of two ink rollers, and the micro-scale channel



(a) Ink layer between two rollers



(b) Ink layer

Fig. 2 Ink flow model

Table 1 The initial data of different ink models

Number of models	Initial inlet ink thickness (mm)	Ink thickness in extrusion zone (mm)	Initial outlet ink thickness (mm)
1	0.04	0.01	0.04
2	0.08	0.02	0.08
3	0.16	0.04	0.16
4	0.32	0.08	0.32
5	0.64	0.16	0.64

is formed by the extrusion of two ink rollers. This paper builds ink flow models as Fig. 2(b). To a great extent, mesh quality affects the speed and accuracy of calculation. Therefore, in order to get grids of good quality, this paper uses a specialized fluid mesh generation software ICEM CFD to mesh each ink flow model. And hexahedral structured mesh is obtained by block partitioning.

2.2 Setting of boundary conditions and ink physical parameters

Inlet and outlet are set as pressure inlet and pressure outlet respectively. Inlet pressure is 0 and outlet is static pressure. Two end faces of axial direction are set as symmetrical boundaries (symm). In order to simplify the problem, variables should be reduced and influence of the velocity difference on the simulation results should be eliminated, the speeds of two wall surfaces are all set to 200r/min and its linear speed is 0.314m/s. Both of them are set under no slip condition. In this calculation, the calculation model is a standard k-epsilon one and the SIMPLE method is used for coupling of pressure and velocity. Because this analysis does not consider energy relation, the ink physical parameters are set as constant. The ink viscosity is set to 10.2Pa · s and the density is set to 1012.98kg/m^3.

2.3 Analysis of simulation results

Fig. 3 and Fig. 4 show the pressure nephogram and velocity nephogram of the 0.01mm ink model in no slip condition respectively.

As seen from Fig. 3 and Fig. 4, without considering the slip, the maximum pressure of the ink appears at the inlet of the extrusion zone, and the maximum tension appears at the outlet. Besides, the maximum velocity appears in the middle of the ink layer along the thickness direction in micro-scale channel.

The trends of pressure and velocity distributions in other feature sizes are similar to those of Fig. 3 and Fig. 4, but differ only in magnitude. As shown in Table 2, the characteristic data of the ink at each feature size is extracted.

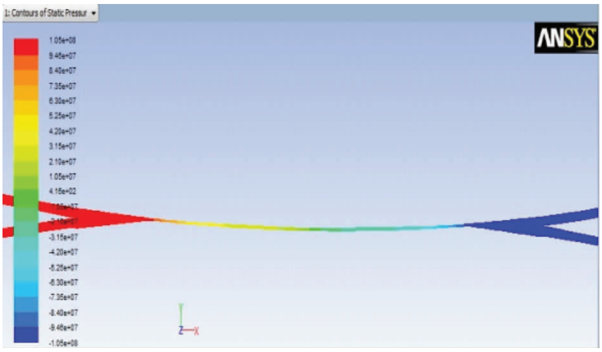


Fig. 3 Pressure nephogram of the 0.01mm ink model

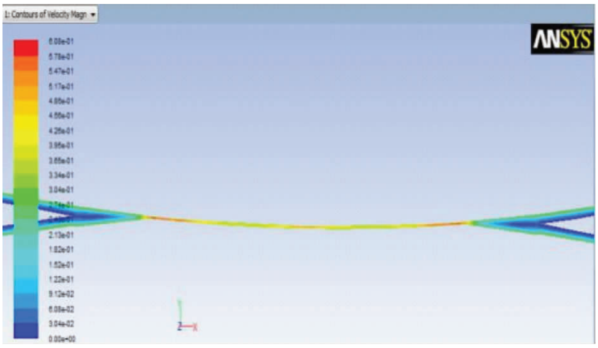


Fig. 4 Velocity nephogram of the 0.01mm ink model

Table 2 The characteristic data of different ink models

Feature size (mm)	Max pressure (MPa)	Max tension (MPa)	Max velocity (m/s)	Wall shear stress (MPa)
0.01	105.1	105.1	0.557	0.600
0.02	34.5	34.5	0.546	0.350
0.04	10.3	10.3	0.523	0.178
0.08	2.9	2.9	0.494	0.081
0.16	0.8	0.8	0.448	0.034

Fig. 5 shows the velocity distribution in the middle of the ink flow channel along the direction of ink layer thickness with different feature sizes under no slip condition. Nodes represent position off the middle of the ink layer. Node 0 stands for the middle of the ink layer along the thickness direction. And nodes −20 and 20 represent respectively upper wall (wall1) and lower wall (wall2).

As seen from Fig. 5, when ignoring the velocity slip at the solid-liquid interface, the ink velocity near two walls is the same as each other. And its value is equal to the linear speed of the rotating wall. The ink velocity increases with the decrease of channel feature size.

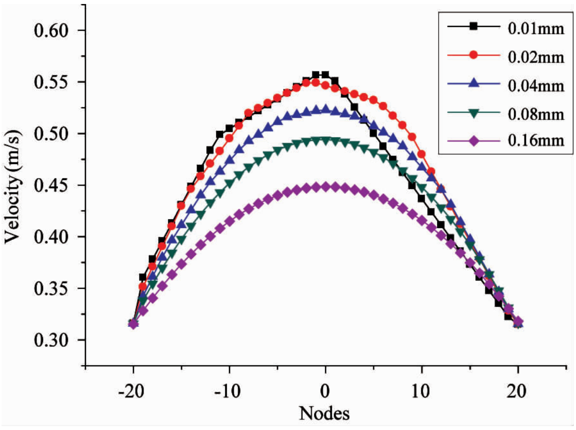


Fig. 5 Velocity distribution along the direction of ink thickness

Fig. 6 shows the relation curve between maximum pressure and feature size in extrusion zone under no slip condition. As can be seen from Fig. 6, the pressure at the inlet of the extrusion zone increases with the decrease of the channel feature size.

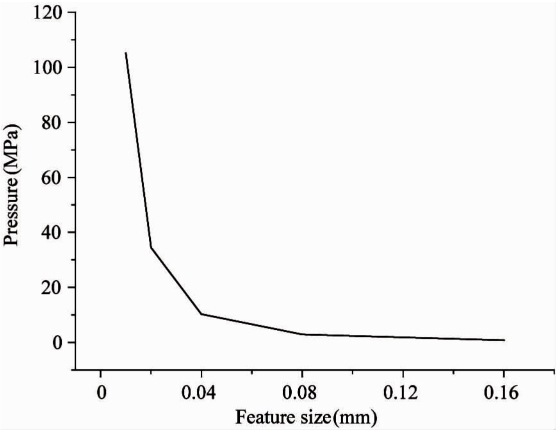


Fig. 6 Relation curve between maximum pressure and feature sizes

Fig. 7 shows the relation curve between maximum velocity and feature size in extrusion zone under no slip condition. As shown in Fig. 7, the maximum velocity of the ink in extrusion zone increases with the decrease of feature size.

As shown in Fig. 5, Fig. 6 and Fig. 7, as the feature size of the channel decreases, the ink is accumulated when it passes to the inlet of the extrusion zone. The pressure at the inlet of the extrusion zone also increases slowly. When the channel feature size is reduced to 0.04mm, the inlet pressure of the extrusion zone increases more sharply. At this point, the flow pattern of the ink in the extrusion zone can be recognized as pressure drive. As the channel size decreases, both the inlet pressure and the outlet tension increases. That is to say, the pressure difference between the inlet and the outlet of the extrusion zone increases, thus the ink velocity increases.

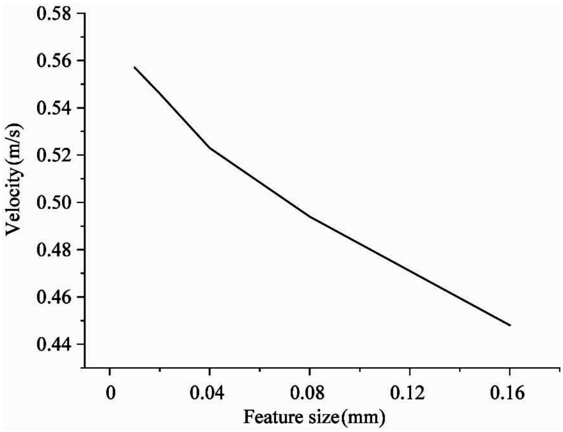


Fig. 7 Relation curve between maximum velocity and feature sizes

As seen from Fig. 8, it depicts wall shear stress in the extrusion zone of different feature sizes under no slip condition.

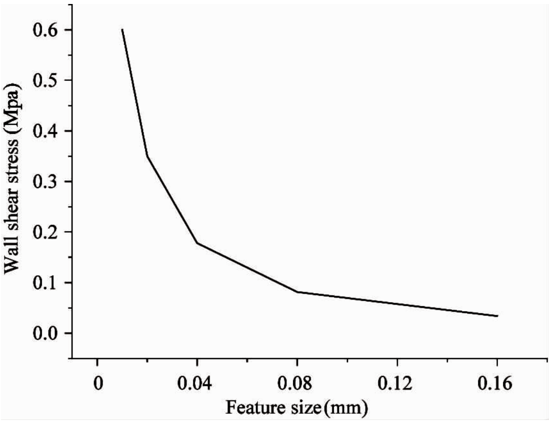


Fig. 8 Relation curve between wall shear stress and feature sizes

Fig. 8 shows that with the decrease of the feature size of the ink flow channel, the wall shear stress of the extrusion zone increases. And when the channel size is reduced to 0.04mm, the wall shear stress increases more and more. Because the channel feature size decreases and the pressure difference between the inlet and outlet of the extrusion zone increases, the ink velocity increases and the wall is set under no slip condition, the ink velocity gradient in the thickness direction of the ink layer is larger and the shear stress $\tau_{\text{fluid}} = \mu \frac{\mathrm{d}u}{\mathrm{d}y}\Big|_{\text{wall}}$ between the ink layers near the wall is larger. From the point of force balance, a larger wall shear force is needed to balance the shear force between the micro layers of the ink at the wall. Therefore, the wall shear force increases with the decrease of channel size.

3 Numerical analysis of the influence of feature size on ink flow characteristics under slip condition

3.1 Setting of boundary conditions and ink physical parameters

In consideration of the slip, the selection of calculation model, the coupling method of velocity and pressure, the setting of inlet and outlet boundary conditions, the velocity of upper and lower walls, the setting of axial end surfaces and ink physical parameters are the same as subsection 2.2.

Two wall surfaces of the extrusion zone are set as slip wall with fixed shear force. And the shear force values are determined according to the wall shear stress under no slip condition. Because the wall shear stress under slip condition is smaller than that without slip[10], this paper sets the former as 3/4 of the latter. The values of former are shown in Table 3.

Table 3 The wall shear stress of extrusion zone under slip condition

Number of models	Channel feature size (mm)	Wall shear stress (MPa)
1	0.01	0.450
2	0.02	0.263
3	0.04	0.134
4	0.08	0.061
5	0.16	0.025

3.2 Analysis of simulation results

Fig. 9 shows the velocity distribution in the middle of the ink flow channel along the direction of ink layer thickness under slip condition.

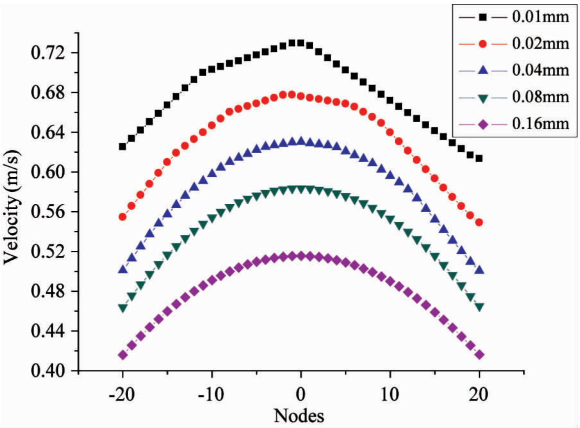


Fig. 9 Velocity distribution along the direction of ink thickness

As seen from Fig. 9, when considering velocity slip, the velocity gradient along the ink thickness direction is smaller than it without slip. And the ink velocity in the extrusion zone increases with the decrease of channel feature size. Compared with no slip condition, the ink velocity at the same channel feature size increases, because the ink velocity is no longer limited by the no slip boundary condition.

Extracting the characteristic data of the flow models under slip condition, the result is shown in Table 4.

Table 4 The characteristic data of the models under slip condition

Number of models	Feature size (mm)	Max velocity (m/s)	Max pressure (MPa)	Slip velocity (m/s)
1	0.01	0.73	105.03	0.31
2	0.02	0.68	34.51	0.24
3	0.04	0.63	10.30	0.19
4	0.08	0.58	1.93	0.15
5	0.16	0.52	0.81	0.10

Fig. 10 shows the relation curve between slip velocity in micro-scale channel and channel feature sizes.

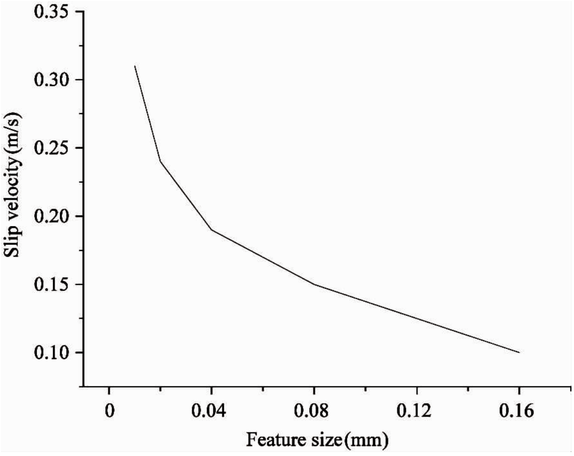


Fig. 10 Relation curve between slip velocity and feature sizes under slip condition

Fig. 10 shows that slip velocity increases continually with the decrease of channel feature size. And when the channel size is reduced to 0.04mm, the slip velocity increases faster and faster. According to the law of Fig. 10, it can be inferred that when the channel size increases to 1mm or larger, the slip velocity decreases gradually and infinitely approaches to 0. Therefore, it is easy to explain why it is set as no slip boundary condition in macroscopic scale.

As seen from Table 4, under slip condition, the ink pressure at the inlet of the micro-scale channel decreases with the increase of feature size. And the ink maximum velocity has the same change rules with pressure. The larger the feature size is, the weaker the ink accumulation degree at the inlet of the extrusion zone is. Thus the smaller the pressure at inlet is, the smaller the driving force of the ink in the extrusion zone is, and the smaller the ink velocity is.

4 Comparison of the influence of feature size on ink flow characteristics under conditions of slip and no slip

Fig. 11 and Fig. 12 show the curves between the maximum pressure or maximum velocity and feature sizes under conditions of slip and no slip respectively.

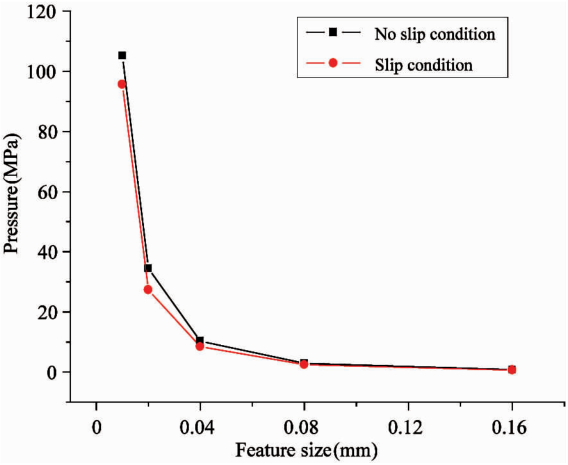


Fig. 11 Relation curves between maximum pressure and feature sizes under conditions of slip and no slip

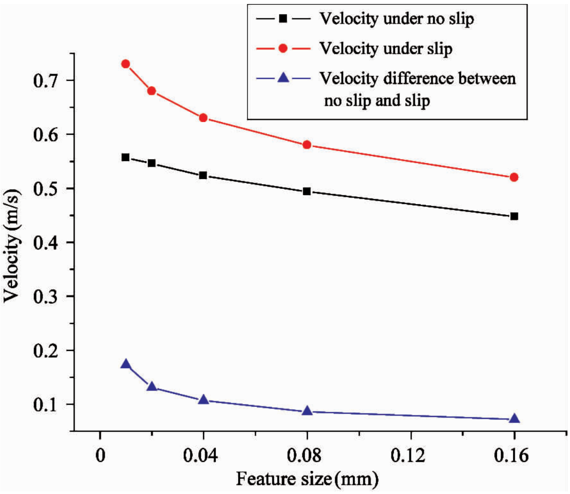


Fig. 12 Relation curves between velocity or velocity difference and feature sizes

As seen from Fig. 11 and Fig. 12, the ink maximum pressure under slip condition is less than that under no slip condition. The ink maximum velocity under slip condition is larger than that under no slip condition.

Setting variable named slip differential factor ζ:

$$\zeta = \frac{\text{max velocity in slip} - \text{max velocity in no slip}}{\text{max velocity in slip}}$$

Fig. 13 shows relation curve between slip differential factor ζ and feature sizes.

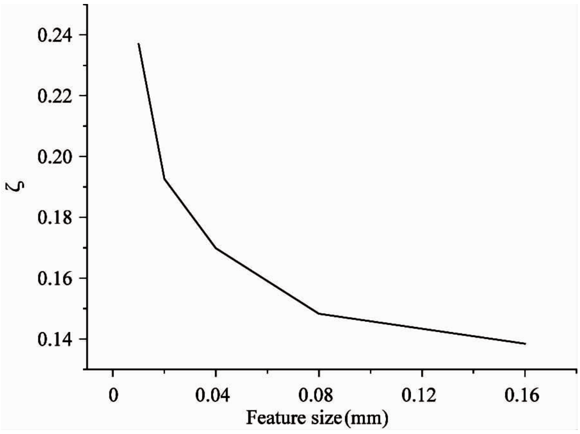


Fig. 13 Relation curve between ζ and feature sizes

Fig. 13 shows that ζ decreases gradually with the feature size increases. When the feature size is small, the slip differential factor ζ is large, so it is necessary to consider slip. It can be speculated that when the feature size increases to a certain degree, ζ approaches to 0. At this moment, whether considering slip has little effect on the analysis results, so there is no need to consider slip condition.

5 Conclusion

(1) Under conditions of slip and no slip, with the decrease of ink flow feature size, ink velocity increases gradually, the pressure at the inlet of the extrusion zone increases slowly. When the feature size is reduced to 0.04mm, the ink pressure increases sharply.

(2) At same feature size, the ink maximum velocity under slip condition is larger than that under no slip condition. And at same feature size, the ink maximum pressure under slip condition is smaller than that under no slip condition.

(3) With the decrease of channel feature size, slip velocity increases gradually. And when the feature size is less than 0.4mm, slip velocity increases faster and faster.

(4) When the feature size is small, the slip differential factor ζ is large, so it is necessary to consider slip in simulation analysis. With the feature size increases, ζ decreases gradually and finally approaches to 0. Therefore, when the feature size increases to a certain degree, it is not necessary to consider slip.

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