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To cite this article: Z Ren et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 479 012099

View the article online for updates and enhancements.
Numerical comparison on the influence of geometric size on melt viscosity for conventional and gas-assisted extrusion of plastic micro-tube

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Abstract. We studied the effects of the geometric size on the viscosity of melt for plastic micro-tubes with different radius or L/D ratios by using the finite element method in this paper. Meanwhile, the Bird-Carreau constitutive model was used to describe the rheological properties of non-Newtonian melt. Two of geometric models were used in this study. For the geometric model with same L/D ratio but different radius, the same inlet pressure value was imposed on the inlet face of geometric model. For the geometric model with the same radius but different L/D ratios, the same inlet volume flow rate of melt were imposed on the inlet face of geometric model. Numerical results show that, for the conventional extrusion of plastic micro-tubes with same L/D ratio but different radius, the apparent viscosity of melt decreases with the decreasing of the radius. For the plastic micro-tubes with same radius but different L/D ratios, the apparent viscosity of melt is nearly not changed with the decreasing of the L/D ratio. However, for the gas-assisted extrusion of plastic micro-tube, the geometric size doesn’t seem to affect the melt viscosity.

1. Introduction

Due to the properties of small size, high precision, good quality, the plastic micro-tube has already been widely used in a lot of fields, such as medical diagnosis, optic communication, automatic oil-pipe, and precision instruments. The plastic micro-tube is usually manufactured by using the extrusion forming technique [1, 2]. Since polymer melt is a kind of high viscoelastic non-Newtonian fluid, and the large stresses can be focused on the inner walls and outlet of die channel during the process of extrusion forming, some extrusion problems, such as extrudate swell [3, 4], melt fracture [5] and the extrudate distortion phenomenon will be easily generated. For the polymer melt, the rheological properties of melt includes the viscosity and flow behaviors will be changed with the geometric size, which will finally influence extrusion forming for the plastic micro-tube. Up to now, although the rheological properties of melt in small scale have been studied by some scholars [6, 7], there are different results for the different researches. For example, some scholars claimed that the mesoscopic viscosity of melt increased with the decreasing of geometric size [8, 9]. However, there are some scholars held the opposite views [10, 11]. Some researchers even thought that the viscosity of melt was not change when the geometric size was in the scale range of mesoscopic size, which was the same as the macroscopic size [12]. In order to further ascertain the viscosity change of melt with
geometric size for the plastic micro-tube, the effect of geometric size on the viscosity of melt for the extrusion forming of the plastic micro-tube was numerically investigated in this paper. Moreover, to eliminate the extrusion problems generated by the conventional extrusion method, the gas-assisted extrusion technique [13, 14] was used into the extrusion forming of the plastic micro-tube in this study. At the same time, the effect of the geometric size on the melt’s viscosity for the gas-assisted extrusion forming of the plastic micro-tube is also numerically investigated and compared with that of the conventional extrusion forming. Therefore, there are two purpose in this study. The first one is to numerically investigate the effects of geometric size on the viscosity of melt during the extrusion forming of plastic micro-tube, and obtain the change law for the effects of geometric size on the viscosity of melt. The second one is based on the advantage of eliminating the extrusion problems by using the gas-assisted extrusion, then, to numerically study the effect of geometric size on the viscosity of melt during the gas-assisted extrusion of plastic micro-tube, and to find the difference about the effect of geometric size on the viscosity of melt between the gas-assisted extrusion and the conventional extrusion.

2. Numerical simulations

2.1. Geometric model

In the simulations, two kinds of different effects of geometric size on viscosity of melt were considered, i.e., one effect refers to the plastic micro-tubes with same length-diameter (L/D) ratio but different diameters, another effect refers to the plastic micro-tubes with same diameters but different length-diameter (L/D) ratios. Therefore, two kinds of different geometric models of plastic micro-tube were used, which are shown in Figure 1(a)-(d).

![Figure 1](image)

Figure 1. The geometric models of plastic micro-tubes. (a) the plastic micro-tube with L/D ratio of 4 but the inner radius of 0.5mm; (b) the plastic micro-tube with L/D ratio of 4 but the inner radius of 0.25mm; (c) the plastic micro-tube with inner radius of 0.25mm but the L/D ratio of 4; (d) the plastic micro-tube with inner radius of 0.25mm but the L/D ratio of 2.

Figure 1(a) and (b) are the models of plastic micro-tubes with same length-diameter (L/D) ratio but different diameters. The L/D ratio of the plastic micro-tube in the Figure 1(a) and (b) are all equal to 4. In Figure 1(a) and (b), the inner radiuses of two plastic micro-tubes are 0.5mm and 0.25mm, respectively. The outer radiuses of two plastic micro-tubes are 0.7mm and 0.35mm. In Figure 1(a), the lengths of the inner die and outer die are 4mm and 2mm. In Figure 1(b), the lengths of the inner die and outer die are 2mm and 1mm. Figure 1(c) and (d) the models of plastic micro-tube with same diameters and wall thicknesses but different L/D ratios. In Figure 1(c) and (d), the inner and outer radiuses of plastic micro-tubes are 0.5mm and 0.6mm, respectively. However, the L/D ratios of plastic
micro-tubes in Figure 1(c) and (d) are 4 and 2. In Figure 1(c), the lengths of the inner die and outer die are 2mm and 1mm. In Figure 1(d), the lengths of the inner die and outer die are 1mm and 2mm.

2.2. Governing equations

The following hypotheses should be satisfied, i.e., the melt of plastic micro-tube is regarded as the isothermal, steady, laminar and non-Newtonian fluid. Moreover, the gravity and inertia forces of melt were neglected due to the high viscosity properties and low flow velocity. Based on these above mentioned hypotheses, the governing equations [15] are shown as follows,

\[ \nabla \cdot v = 0 \]  
\[ \nabla p - \nabla \cdot \tau = 0 \]

where, \( \nabla \) is Hamilton operator, \( v \) is the velocity vector, \( p \) is pressure vector, \( \tau \) is the extra stress tensor.

In the simulations, a kind of constitution model of non-Newtonian fluid, i.e., Bird-Carreau model [16] was used to describe the rheological properties of melt, which is shown as follows,

\[ \frac{\eta - \eta_{\infty}}{\eta_0 - \eta_{\infty}} = \frac{1}{\left[ 1 + (\lambda \cdot \dot{\gamma})^2 \right]^{n-1/2}} \]

where, \( \eta \) is the viscosity of melt, \( \eta_0 \) is the shear viscosity of melt at the zero shear rate, \( \eta_{\infty} \) is the shear viscosity of melt at the infinite shear rate, which is usually equal to 0. \( \lambda \) is the relaxation time of melt, \( \dot{\gamma} \) is the shear rate of melt, \( n \) is the flow index.

2.3. Boundary conditions

Based on the Figure 1(a), the boundary conditions of models are shown in Table 1.

| Boundary       | Boundary conditions              |
|----------------|----------------------------------|
| Inlet face (ABCD) | \( \partial v/\partial z = 0 \), \( v_x = v_y = 0^* \) |
| Wall (BCGF and ADHE) | conventional extrusion \( v_n = v_s = 0^{**} \) |
| Gas-assisted extrusion | \( v_n = f_s = 0 \) |
| Free faces (FGKJ and EHLI) | \( f_n = f_s = 0 \) |
| Symmetric faces (ABJI and CDLK) | \( v_n = 0, f_s = 0 \) |
| Exit face (IJKL) | \( v = f_n = 0 \) |

* \( v_x, v_y, \) and \( v_z \) are the flow velocities of melt at x, y, and z direction; 
** \( v_n \) and \( v_s \) are the normal and tangential velocities of melt, respectively. \( f_n \) and \( f_s \) are the normal and tangential stress of melt, respectively.

2.4. Material parameters

In the simulations, the material parameters of Bird-Carreau model are shown in Table 2.

| Parameters (Unit) | \( \eta_0 \) (Pa.s) | \( \lambda \) (s) | \( n \) |
|-------------------|---------------------|-----------------|--------|
| Values            | 853.82              | 0.2             | 0.5    |

2.5. Schematic diagram of gas-assisted extrusion

To eliminate the extrusion problems of plastic micro-tube, the gas-assisted extrusion method was used in this paper. At the same time, the effect of geometric size on the viscosity of melt for the gas-assisted
extrusion of plastic micro-tube was also numerically investigated and compared with that of the conventional extrusion of plastic micro-tube. The schematic diagrams of conventional extrusion and gas-assisted extrusion for plastic micro-tube is shown in Figure 2.

Figure 2. Schematic diagrams of conventional extrusion (a) and gas-assisted extrusion (b) for plastic micro-tube.

From Figure 2, it can be seen that, for the conventional extrusion, the extrudate swell phenomenon will be generated since the adhesion flow of melt on the surface of die’s channel wall will produce the larger shear stress to store elastic energy. However, since there are two layers of assisted gases are formed between the die’s channel inner wall and the annular melt, as well as between the mandrel’s outer wall and the annular melt. The flow behaviour of melt becomes the full slip and plug flow, which will eliminate the shear stress of melt on the surface of walls to reduce the elastic energy storage. Therefore, the extrusion problems, such as extrudate swell, melt fracture and extrudate distortion can be overcome by using the gas-assisted extrusion.

3. Numerical results and analyses

3.1. Numerical results of plastic micro-tubes with same L/D ratio but different radiiuses

The numerical simulations in this study were performed by using the commercial finite element software package Polyflow. Firstly, the effects of geometric size on the melt viscosity for the conventional and gas-assisted extrusion of plastic micro-tubes with same L/D ratio of 4 but different radiiuses were numerically investigated. For the plastic micro-tubes with same L/D ratio, the shear stresses of melt are not changed when the same pressure is imposed on the inlet face of flow channel. Therefore, the same input pressure value, i.e., 0.04MPa was imposed on the inlet face of plastic micro-tube. The numerical results of viscosity change of melt at the radial direction of die channel are shown in Figure 3(a) and (b), respectively. Since the diameters and wall thicknesses in Figure 1(a) and (b) are different, in order to conveniently compare the viscosity changes of melt, the normalized thicknesses of micro-tube are used in the Figure 3(a) and (b). The normalized radial size was defined as follows,

\[ x' = \frac{x}{W} \]
where $x'$ is the normalized size of micro-tube at the radial direction, $x$ is the original size of micro-tube at the radial direction, $W$ is the wall thickness of each micro-tube.

![Figure 3](image.png)

**Figure 3.** Viscosity changes of plastic micro-tube's melt for the conventional extrusion and the gas-assisted extrusion. (a) numerical results of the conventional extrusion; (b) numerical results of the gas-assisted extrusion.

From Figure 3(a), it can be seen that, for the conventional extrusion of plastic micro-tubes with the same L/D ratio, the viscosities of melt near the walls are less than that in the middle of micro-tubes, and the viscosity of melt linearly decreases from the middle places to the walls of micro-tubes. In the middle of micro-tubes, the viscosities of melt are nearly constant. Moreover, it can be found that the viscosity amplitude of melt decreases with the decreasing of geometric size. However, for the gas-assisted extrusion of plastic micro-tube with the same L/D ratio, from Figure 3(b), it can be found that the viscosities of melt are not changed at all regions of die channel.

3.2. **Numerical results of plastic micro-tubes with same radius but different L/D ratios**

Then, for the conventional extrusion and the gas-assisted extrusion, the effects of geometric size on the viscosity of melt for plastic micro-tubes with same radius but different L/D ratios were also numerically investigated. For the micro-tubes with same radius, the shear rates of melt are not changed when the same inlet flow volume rate is imposed on the inlet face. Therefore, the same inlet volume flow rate ($0.02\text{mm}^3/\text{s}$) was imposed on the inlet face of plastic micro-tube. The numerical results of viscosity change of melt at the radial direction of die channel are shown in Figure 4(a) and (b), respectively.

![Figure 4](image.png)

**Figure 4.** Viscosity changes of plastic micro-tube's melt for the conventional extrusion and the gas-assisted extrusion. (a) numerical results of the conventional extrusion; (b) numerical results of the gas-assisted extrusion.
From Figure 4, as same as the Figure 3, it can be seen that, for the conventional extrusion of plastic micro-tube with same radius, the viscosities of melt near the walls are also less than that in the middle of micro-tube. At the places near the inner and outer walls, the viscosity of melt linearly decreases with the distance. In the middle of micro-tube, the viscosities of melt are nearly constant. But unlike Figure 3, the viscosity of melt is not nearly changed with the decreasing of the L/D ratio, especially at the inner and outer walls. For the gas-assisted extrusion of plastic micro-tube, from Figure 4(b), it can be seen that, as same as Figure 3(b), with the decreasing of the L/D ratio, the viscosity of melt is also not any changed at the all regions of die channel.

3.3. Shear rate distributions
For the plastic micro-tubes with same L/D ratio but different radiuses, to ascertain the mechanism on the effect of geometric size on the viscosity of melt, the shear rate distributions of melt at the radial direction of micro-tubes were obtained, which are shown in Figure 5.

![Figure 5. Shear rate distributions of melt for plastic micro-tubes with same L/D ratio but different radiuses. (a) conventional extrusion; (b) gas-assisted extrusion.](image_url)

Since the same pressure value was imposed on the inlet face of the plastic micro-tubes with the same L/D ratio, the shear stress can be gotten from the following equation,

$$\tau = \frac{\Delta P \cdot R}{2L}$$  \hspace{1cm} (5)

where $\tau$ is the shear stress of melt. $\Delta P$ is the pressure value. $R$ is the radius of plastic micro-tube. $L$ is the length of plastic micro-tube.

Based on the Eq.(5), it can be known that the shear stress of melt is constant due to the unchanged inlet pressure value and the L/D ratio. However, from Figure 5, it can be seen that the shear rate of melt near the inner and outer walls are larger than that in the middle of micro-tube. Moreover, near the walls, the shear rates linearly decrease from walls to middle of micro-tube. In the middle of micro-tube, the shear rate is nearly constant. Then, according to the relationship between the viscosity and the shear rate, i.e.,

$$\eta = \frac{\tau}{\dot{\gamma}}$$  \hspace{1cm} (6)

where $\eta$ is the viscosity, $\dot{\gamma}$ is the shear rate. From Eq.(6), it can be found that the viscosity of melt is inversely proportional to the shear rate at the constant shear stress. Therefore, for the conventional extrusion of plastic micro-tube, the numerical results are in agreement with the results shown in Figure 3(a). However, from Figure 5(b), it can be seen that, for the gas-assisted extrusion of plastic micro-tubes with the same L/D ratio but different radiuses, the shear rates of melt are all equal to 0 due to the assistance of gases, which result in the unchanged viscosity of melt (See Figure 3(b)). The result is in agreement with the result computed from Eq.(3).
3.4. Shear stress distributions

Then, for the plastic micro-tubes with the same radius but different L/D ratios, when the same inlet volume flow rate was imposed on the inlet face, the shear stress distributions of melt at the radial direction of micro-tubes were obtained, which are shown in Figure 6.

![Figure 6. Shear stress distributions of melt for plastic micro-tubes with same radius but different L/D ratios. (a) conventional extrusion; (b) gas-assisted extrusion.](image)

As we know, the shear rates of melt will not change when the same inlet volume flow rates are imposed on the inlet face of plastic micro-tubes with the same radius based on the following equation,

$$\gamma = \frac{4Q}{\pi R^3}$$  \hspace{1cm} (7)

where $Q$ is the inlet volume flow rate of melt.

From Figure 6(a), it can be seen that, for the conventional extrusion of plastic micro-tubes with the same radius but different L/D ratios, with the decreasing of the L/D ratios, the shear stresses of melt are nearly not changed. Therefore, according to the Eq. (7) and Figure 6(a), it can be known that the L/D ratio doesn’t impact the viscosity of melt for the plastic micro-tubes with the same radius, which is in agreement with the numerical results shown in Figure 4(a). However, for the gas-assisted extrusion of plastic micro-tube, from Figure 5(b), it can be seen that, for the plastic micro-tubes with the same radius but different L/D ratios, the shear stresses of melt are all equal to 0 due to the assistance of the gases. That is, the effect of geometric size on the viscosity of melt for the gas-assisted extrusion forming of plastic micro-tube does not work, which result in the unchanged viscosity of melt (See Figure 4(b)).

4. Conclusions

In this paper, the effects of geometric size on the viscosity of melt for plastic micro-tube based on the conventional extrusion and the gas-assisted extrusion were numerically investigated. Two kinds of different geometric models of plastic micro-tubes were established. For each model, under the same inlet pressure value or the inlet volume flow rate of melt, the viscosity changes of melt were obtained with the decreasing of the geometric size. Numerical results show that, for the conventional extrusion of the plastic micro-tube with the same L/D ratio, the viscosity of melt decreases with the decreasing of the radius. For the plastic micro-tubes with the same radius but different L/D ratios, the effect of geometric size on the viscosity of melt is not obvious. However, for the gas-assisted extrusion of plastic micro-tube, the geometric size doesn’t impact the viscosity of melt. Therefore, in the numerical simulations of gas-assisted extrusion in the micro-scale, the micro-scale effect of viscosity can be neglected.
Acknowledgments
This work was supported by the National Natural Science Foundation of China (51763011), 2018 Natural Science Outstanding Youth Foundation Project of Jiangxi Province (2018ACB21006), and Doctor Start-up Foundation Project of JXSTNU (2017BSQD021).

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