

Determination of gas length for gas-assisted extrusion forming of polymer melt

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Abstract. To determine the optimal gas length for the gas-assisted extrusion forming of melt, numerical investigations about the gas length on the extrudate swell of melt were performed by using the finite element method. Meanwhile, the geometric model of gas-assisted extrusion forming was established. The full slip boundary condition was used as the gas-assisted condition. Numerical results show that the gas length should be shortened with increasing of the inlet volume flow rate of melt. In addition, under the given inlet volume flow rate of melt, the extrudate swell ratio, X velocity and shear stress of melt greatly decreases with increasing the gas length. According to the numerical results and experiences reported past time, under the inlet volume flow rate of $0.5\text{cm}^3/\text{s}$, the optimal gas length of gas-assisted extrusion forming is about 10mm.

1. Introduction

In the process of the plastic extrusion forming, the products of plastic easily occur some problems, such as extrudate swell [1], melt fracture [2], and extrudate distortion [3] due to the high elasticity and high shear rate. To eliminate these extrudate problems, there are some methods have been studied and applied, such as, the polymer additive [4], mechanical vibration extrusion [5], ultrasonic-assisted extrusion [6], and gas-assisted extrusion. The gas-assisted extrusion is a most-promising and well-established extrusion method due to the advantages of convenient, environmental protection, and high efficiency. The gas-assisted extrusion method has been validated by many experimental and numerical studies. Brzskowski [7] firstly proposed the gas-assisted extrusion technique. Liang [8] firstly applied the gas-assisted extrusion technique into the polymer melt extrusion. Laterly, Huang [9] successfully achieved the gas-assisted extrusion of the rob plastics. Huang[10] successfully studied the gas-assisted coextrusion of the polymer melt. Deng [11] successfully performed the studies of the gas-assisted coextrusion of the L cross-typed profile plastics. Liu et al. [12] numerically studied the gas-assisted extrusion of the melts by using the finite element method. These studied all validated that the gas-assisted extrusion method is an efficient way of eliminating the extrudate swell, melt fracture, and extrudate distortion. However, it was also demonstrated that the reasonable controlling of the gas parameters and gas length are important to form the stable gas-assisted layer. In this paper, the determination of the optimal gas length for the gas-assisted extrusion of melt was studied by using the numerical method.



2. Numerical simulations

2.1 Numerical model

Figure 1(a) is the geometric model of gas assisted extrusion for the melt. In Figure 1(a), the ABCD-EFGH is the part of no gas-assisted die, its length is 10mm. EFGH-IJKL is the part of gas-assisted die, its length is 30mm. IJKL-MNOP is the part of free surface outside of die, its length is 10mm. Figure 1(b) is the finite element mesh of the geometric model (Figure 1(a)). The meshes were appropriately reinforced near the inlet and outlet surface of die, and the exit surface of melt. The mesh number was 3200.

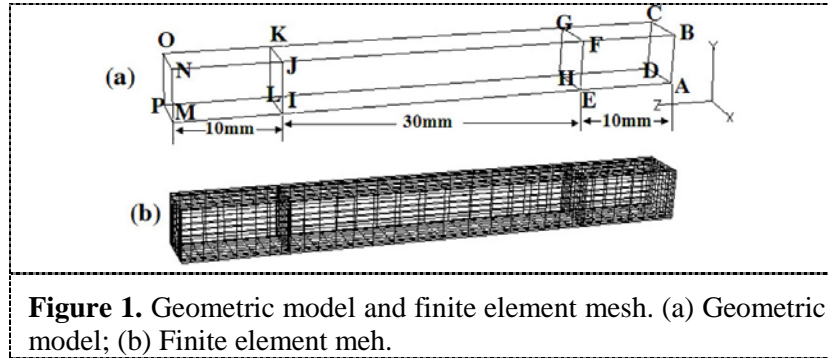


Figure 1. Geometric model and finite element mesh. (a) Geometric model; (b) Finite element mesh.

2.2 Governing equations

In the numerical simulations, the melt was regarded as non-compressible, iso-thermal, steady, laminar and visco-elastic Non-Newtonian fluid. The inertia, gravity force, viscous dissipation, and surface tension effects were neglected.

The mass and momentum conservation equations are given as follows:

$$\nabla v = 0 \quad (1)$$

$$-\nabla p + \nabla \tau = 0 \quad (2)$$

where ∇ is Hamilton operator, v is velocity of melt, p is pressure drop, τ is extra stress tension.

In simulations, Phan-Thien-Tanner (PTT) constitutive model [13] was used, which is given as follows:

$$\exp\left[\frac{\varepsilon\lambda}{(1-\eta_r)\eta} \text{tr}(\tau_1)\right] \tau_1 + \lambda \left[\left(1 - \frac{\xi}{2}\right) \overset{\nabla}{\tau}_1 + \frac{\xi}{2} \overset{\Delta}{\tau}_1 \right] = 2(1-\eta_r)\eta D \quad (3)$$

where $\eta_r = \eta_2 / \eta$ is viscosity ratio, η is the total viscosity of melt, η_2 is Newtonian viscosity component of melt, λ is the relaxation time, ε and ξ are the parameters of melt correlated with material tensile and shear characteristics, respectively. $\overset{\nabla}{\tau}_1$ is the upper convected derivative of the extra stress tensor τ_1 , η_1 is the Non-Newtonian component viscosity of melt, D is the strain-rate of tensor.

2.3 Material parameters

In the simulations, the material parameters are given in Table 1.

Table 1 The parameters of PTT construction equation

Parameters	η (Pa.s)	λ (s)	ε	ξ	η_r
Values	2700	0.2	0.18	0.23	0.12

2.4 Boundary conditions

(1) inlet boundary: ABCD is the inlet surface of melt. Supposed that the flow of melt is full-developed, steady and laminar flow, the dynamic and kinematics conditions are given as follows:

$$\partial v_z / \partial z = 0, v_x = v_y = 0 \quad (4)$$

(2) wall boundary: ABFE, and BCGF are the wall boundary, i.e., the no gas-assisted boundary. The following relationship should be satisfied, i.e.,

$$v_n = v_s = 0 \quad (5)$$

(3) gas-assisted boundary: EFJI, and FGKJ are the gas-assisted boundary. The following relationship should be satisfied, i.e.,

$$v_n = 0, f_s = 0 \quad (6)$$

(4) Free boundary: IJNM, and JKON are the free boundary. The following relationship should be satisfied, i.e.,

$$v \cdot n = 0, f_n = 0, \text{ and } f_s = 0 \quad (7)$$

(5) Exit boundary: Supposing that no tranc force and entangle velocity are imposed. $f_n = f_s = 0$

3. Numerical results and discussion

3.1 Effect of inlet volume flow rate on the pressure of melt

To determine the gas length in the gas-assisted extrusion of melt, in the range of the inlet volume flow rates from 0 to 1cm³/s, four different inlet volume flow rates(0.1, 0.2, 0.5, and 1 cm³/s) were imposed on the inlet surface of the die. The pressure distribution of melt under four different inlet volume flow rates were shown in Figure 2.

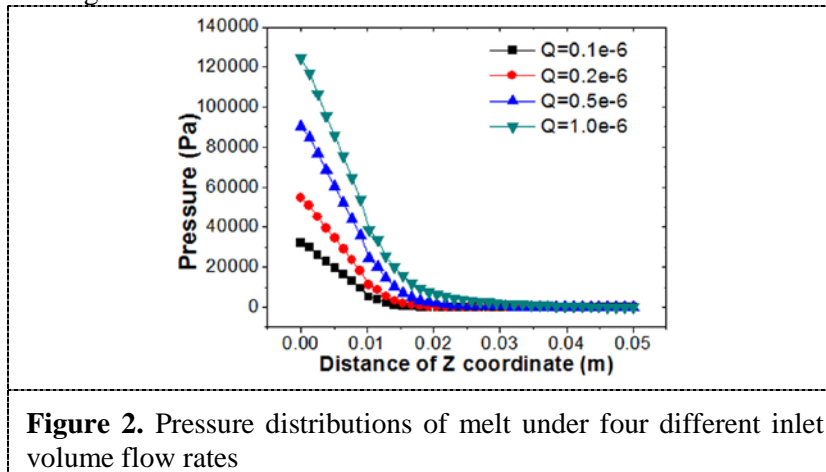


Figure 2. Pressure distributions of melt under four different inlet volume flow rates

From Figure 2, it can be seen that, for the inlet volume flow rate of 0.1 cm³/s, the pressure decreases to zero when the distance of Z coordinate is about 15mm, i.e., the gas length is about 5mm. When the inlet volume flow rate of melt is increased, it can be seen that the pressure of melt increase, and the gas length when the pressure of melt decreased to zero is longer. When the inlet volume flow rate of melt increases to 1cm³/s, the gas length is about 30mm, which demonstrates that the gas length should be lengthened in the gas-assisted extrusion forming.

3.2 Effect of gas-length on the extrudate swell

To study the effect of the gas length on the extrudate forming of the melt, three different gas lengths were used, i.e., 5mm, 10mm, and 15mm. the same inlet volume flow rate and same boundary conditions were imposed on the corresponding boundaries. In this simulation, the inlet volume flow rate was 0.5 cm³/s. The extrudate swell ratio change for the gas-assisted melt extrusion under three different gas lengths are shown in Figure 3.

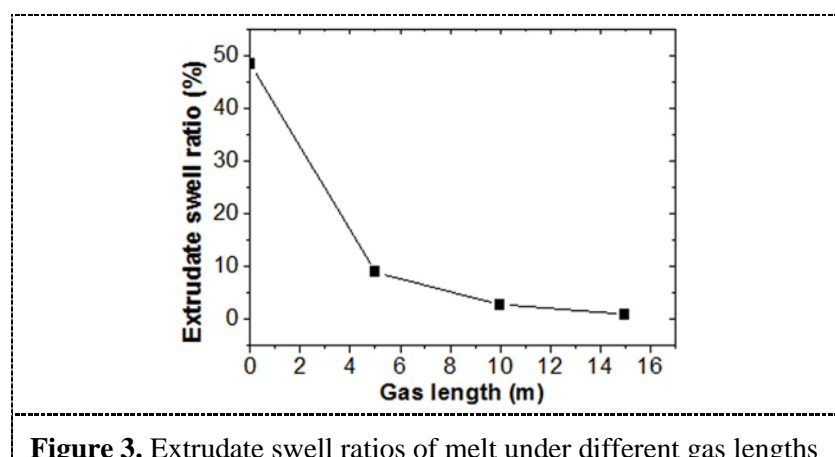


Figure 3. Extrudate swell ratios of melt under different gas lengths

From Figure 3, it can be seen that the extrudate swell ratio of melt decreases with increasing the gas length. Moreover, when the gas length is about 10mm, the extrudate swell ratio is nearly equal to zero.

3.3 Effect of gas-length on the flow velocity

Figure 4 is the X flow velocity of melt under four different gas lengths.

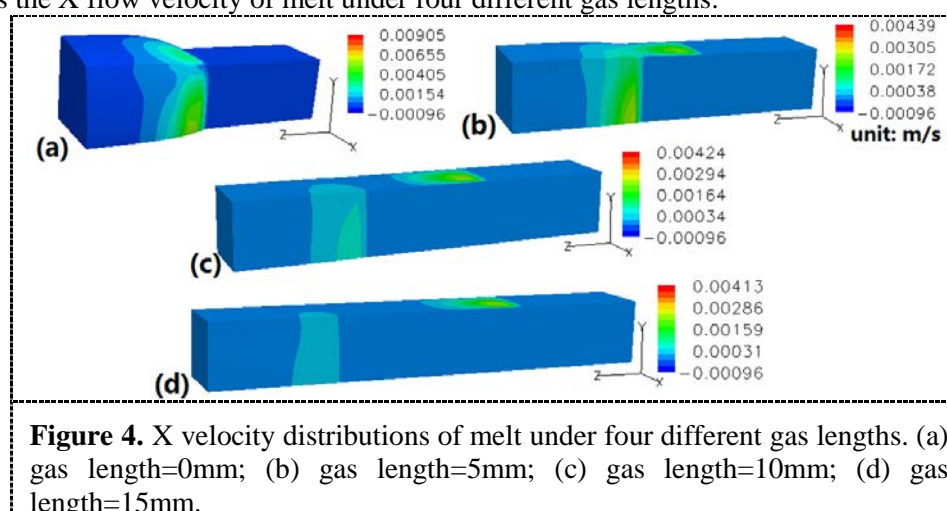
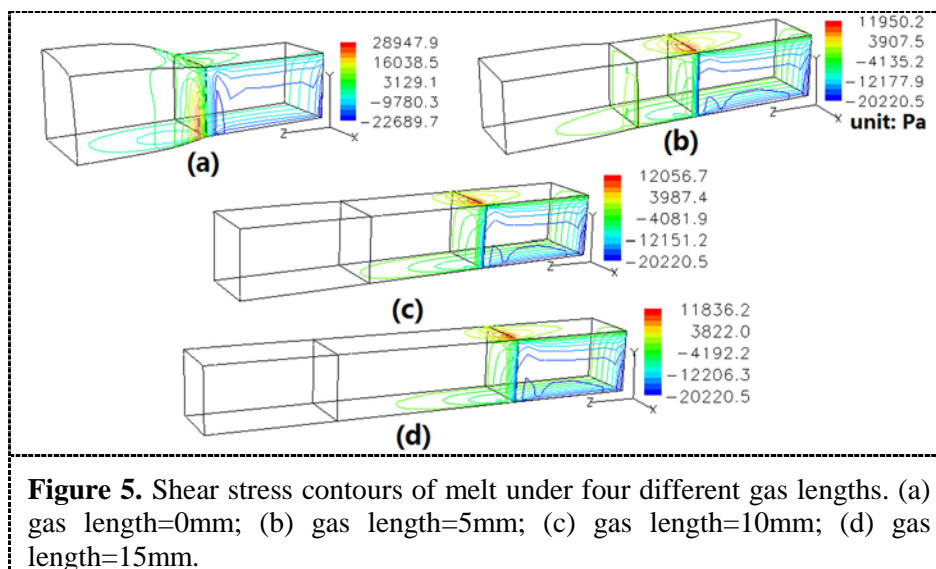


Figure 4. X velocity distributions of melt under four different gas lengths. (a) gas length=0mm; (b) gas length=5mm; (c) gas length=10mm; (d) gas length=15mm.

From Figure 4, it can be seen that the X velocity is largest for the no gas-assisted extrusion mode, which results in the largest extrudate swell phenomenon. With the increasing of the gas length, the X velocity distribution of melt at the outlet of the die was greatly decreased. When the gas length is increased to about 10mm, the X velocity of melt at the outlet of die nearly equals to zero. However, when the gas length is continuous to increase, the X velocity of melt at the outlet of die nearly does not change.

3.4 Effect of gas-length on the shear stress

Figure 5 is the shear stress contours of melt under four different gas lengths.



From Figure 5, it can be seen that the shear stress of melt at the outlet of the die is largest for the no gas-assisted extrusion mode. With the increasing of the gas length, the shear stress of melt was greatly decreased. When the gas length is increased to about 10mm, the shear stress at the outlet of die nearly equals to zero. Then, when the gas length is continuous to increase, the shear stress of melt at the outlet of die does not change, i.e., nearly equals to zero, which demonstrates that the extrudate swell effect of melt nearly removed when the gas length is about 10mm. According to the results in the past reports [9-12], under the condition of removed extrudate problems, e.g., extrudate swell, the gas length should be short because the gas length is longer the gas flow is more unstable. Therefore, the reasonable gas length should be chosen about 10mm for the inlet volume flow rate of $0.5\text{cm}^3/\text{s}$.

4. Conclusions

In this paper, the gas-assisted extrusion method was used into the extrusion forming of melt to remove the extrudate swell phenomenon. Among the process parameters of gas-assisted extrusion forming, the gas length is one of most important factors of impacting the effect of gas-assisted extrusion forming. To determine the optimal gas length of the gas-assisted extrusion forming, the square cross-typed model of gas-assisted extrusion forming was established, and the numerical simulations about the effect of gas length on the extrusion forming were performed by using the finite element method. Numerical results showed that the extrudate swell decreased with increasing gas length, which also verified from the viewpoints of X flow velocity and shear stress of melt at the outlet of the die. The optimal gas length was determined based on the numerical simulation results and the practical experiences.

Acknowledgements

This work is supported by the Natural Science Foundation of Jiangxi Province (20151BAB202011), the Science and Technology Pillar Program of Jiangxi Province (20132BBG70103), Top-notch talent foundation project of JXSTNU (2014QNBjRC004), the Scientific Research Foundation of Jiangxi Provincial Education Bureau (No. GJJ150814), and 2011 Cooperative Innovation Center Project of Jiangxi Province (2014XTCX005).

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