The effect of gas assisted length on polymer melt extrusion based on the gas-assisted extrusion technique

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Abstract. In this study, the gas-assisted technique was used into the process of polymer melt extrusion to overcome the extrudate swell problem. The gas length is an important factors in the gas-assisted extrusion technique. To ascertain the mechanism of the gas-assisted extrusion technique, and to determine the optimal gas length, the effect of gas length on the extrudate swell ratio of melt was numerically investigated. In finite element numerical simulation, PTT constitutive model and full slip boundary condition were used to achieve the gas-assisted mode. Compared with the traditional no gas-assisted extrusion, numerical results showed that the extrudate swell problem was well eliminated by the gas-assisted method. Moreover, the extrudate swell of melt decreased with the increasing of the gas length because the pressure and shear stress of melt were greatly decreased. Moreover, the flow velocity of melt is uniform at the die outlet.

1. Introduction

In the process of polymer processing, the extrudate swell and sharkskin phenomena usually occur due to some factors, such as high elasticity of polymer melt, high shear stress and tensile stress. Many methods have been proposed to eliminate these extrusion problems, for example, fluoropolymer coating [1], fluoro polymer additive [2], lubrication oil coating [3], vibration extrusion [4] and gas assisted extrusion [5], etc. The gas-assisted extrusion (GAE) is a promising and environmental method. Brzoskowski [6] firstly proposed the GAE technique. Liang [7] firstly applied the GAE technique into the polymer melt extrusion. Then, the GAE technique was studied by Arda [8], Huang [9], and Liu [10], etc. Experimental and numerical researches have fully demonstrated that the GAE can well overcome the extrudate swell of melt, melt fracture and extrusion distortion phenomena. However, in GAE, the gas layer length is one of the most important factors of impacting the extrusion effect of GAE. Huang [11], Huang [12], and Deng [13] thought that, if the gas length was short, the extrudate problems were not eliminated because the elastic energy effect of melt was not completely diminished, whereas the extrusion of melt was also influenced by gas flow if the gas length was too long. Therefore, the gas length is a key factor in the designing of the gas extrusion die of polymer melt. In order to determine
the optimal gas length, the influence of the gas length on the flow behavior and extrudate effect of polymer melt was studied in this paper.

2. Numerical model and method

2.1 Numerical model

The geometric model and finite element mesh of GAE are shown in Fig.1(a) and (b), respectively. In Fig.1(a), OA is the inlet, DG is the exit, AB is wall boundary, BC is gas layer, CD is free boundary, OG is the symmetry axis, where the length of inlet OA and exit DG are 5mm, the length of AB is 5mm, as well as the CD, the length of BC can be changeable from the range of 1 to 20mm.

![Figure 1. Numerical model. (a) geometric model; (b) finite element mesh](image)

2.2 Governing equations

In the simulations, the polymer melt is regarded as the non-compressible, iso-thermal, steady, laminar and viscoelastic Non-Newtonian fluid. The inertia, gravity force, viscous dissipation effects are neglected. The mass and momentum equations are given as follows:

\[ \nabla \cdot \mathbf{v} = 0 \]
\[ -\nabla p + \nabla \cdot \mathbf{\tau} = 0 \]  \( (1) \)
\( (2) \)

where \( \nabla \) is Hamilton operator, \( \mathbf{v} \) is velocity of melt, \( p \) is the pressure drop, \( \mathbf{\tau} \) is the extra stress tension.

In this study, Phan-Thien-Tanner (PTT) constitutive model [14] was used because it not only describe the characteristic of shear-thinning, but also represent the elastic properties of viscoelastic fluid, PTT constitutive equation is given as follows:

\[
\exp \left[ \frac{\varepsilon \dot{\lambda}}{1 - \eta_r} \right] \tau_1 + \lambda \left[ \left( 1 - \frac{\xi}{2} \right) \frac{\dot{\xi}}{2} + \frac{\dot{\lambda}}{2} \right] = 2 \left( 1 - \eta_r \right) \eta D
\]

where \( \eta_r = \eta_2 / \eta \) is viscosity ratio, \( \eta \) is the total viscosity of melt, \( \eta_2 \) is Newtonian viscosity component of melt, \( \dot{\lambda} \) is the relaxation time, \( \varepsilon \) and \( \xi \) are the parameters of melt correlated with material tensile and shear characteristics, respectively. \( \tau_1 \) is the upper convected derivative of the extra stress tensor \( \tau \), \( \eta_r \) is the Non-Newtonian component viscosity of melt, \( D \) is the strain-rate of tensor.

In this simulations, for PTT construction equation, its parameters are given in Table 1.

| Table 1 The parameters of PTT construction equation |
|-----------------------------------------------|
| Parameter | \( \eta \) (Pa.s) | \( \lambda \) (s) | \( \varepsilon \) | \( \xi \) | \( \eta_r \) |
| Values    | 2700              | 0.2              | 0.18             | 0.23      | 0.12      |
2.3 Boundary conditions
(1) For the inlet face, the flow of melt is full-developed, steady and laminar flow. The following equations should be satisfied, i.e., $\frac{\partial v_x}{\partial x} = 0, v_y = 0$ ;
(2) For no gas-assisted wall, no slip wall is suitable for the traditional no gas-assisted wall, the following equation is satisfied, i.e., $v_n = v_s = 0$ ;
(3) For the gas-assisted wall, the full-slip boundary condition is used, i.e., $v_n = 0, f_s = 0$ ;
(4) For the free surface, no normal stress and entangle velocity are imposed. $v \cdot n = 0, f_n = 0$ ;
(5) For the symmetric axis, the following equations are satisfied, i.e., $v_n = f_s = 0$ ;
(6) For the exit of melt, no trance force and entangle velocity are imposed. $f_n = f_s = 0$.

3. Numerical results and discussion
3.1 Effect of gas length on the swell ratio
To investigate the effect of gas length on extrudate swell ratio of melt, the different gas length from 0 to 20mm were test, and the extrudate swell ratio were obtained, which are shown in Figure 2. From Figure 2, it can be seen that the extrudate swell ratio was decreased with increasing gas length. However, the extrudate swell ratio is nearly equal to zero when the gas length is about 15mm, and the change of extrudate swell ratio is not obvious when the gas length is larger than 15mm, which demonstrates that the gas length of 15mm is the optimal length.

![Figure 2](image)

**Figure 2.** The extrudate swell ratios of polymer melt under different gas lengths

3.2 Effect of gas length on the flow velocity of melt
Figure 3 (a) and (b) are the X velocity distributions of polymer melt at the axial and radial direction, respectively. From Figure 3, it can be seen that the change of X velocity at the axial direction is not obvious for the different gas lengths, but for the X velocity at the radial direction, the X velocity amplitude of melt decreases with increasing the gas length, which demonstrates that the extrudate swell effect is decreased with the gas length.
3.3 Effect of gas length on the pressure drop of melt

Figure 4 is the pressure drop of polymer melt at the axial direction under the different gas lengths. In general, the pressure drop of melt increases with increasing the change of flow channel. However, from Figure 4, it can be seen that the change pressure drop of melt is not large with increasing the gas length or flow channel, which demonstrates that the increasing of gas layer decreases the pressure drop of melt.

3.4 Effect of gas length on the shear stress of melt

Figure 5 is the shear stress of melt under the different gas lengths. From Figure 5, it can be seen that the shear stress of melt decrease with the gas length at the outlet of die, which demonstrates that the extrudate swell effect and the melt fracture phenomena can be well eliminated with increasing the gas length.
4. Conclusions

The gas length is an important factor in the gas-assisted extrusion process because it can impact the effect of overcoming extrudate swell of plastic products extrusion. To ascertain the mechanics of gas-assisted extrusion technique, and to determine the optimal gas-length, the effect of gas length on the extrudate swell of plastic products was numerically studied by using the finite element computation method. In the numerical simulation, the gas-assisted extrusion model based on the full slip boundary condition was used, and PTT constitutive model was used to characterize the viscoelastic properties of plastics. Numerical results showed that the gas-assisted technique well eliminated the extrudate swell problem. Moreover, the extrudate swell decreased with the increasing of the gas length. The reason was that the flow velocity of melt became uniform when the melt was extruded out the die, the pressure and the shear stress of melt was greatly decreased due to the gas-assisted mode. Therefore, the gas-assisted extrusion technique has the good prospect in the field of plastics extrusion process.

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