Numerical study on the effect of gas layer width on the gas-assisted extrusion forming of plastic pipes

Zhong Ren¹ *, Xingyuan Huang², Zihua Xiong¹
¹Key Laboratory of Optic-electronics and Communication, Jiangxi Science and Technology Normal University, 330038 Nanchang, China
²School of Mechanical and Electrical Engineering, Nanchang University, 330031 Nanchang, China
*Corresponding author: renzhong0921@163.com

Abstract. To study the effect of the gas layer width on the gas-assisted extrusion forming of plastic pipes, we established 2D models of gas-assisted extrusion forming of plastic pipes based on two phase fluid model. In the geometric models, four different widths of gas layers were used. Under the same boundary conditions and material parameters, the numerical results about the effect of gas layer width on the extrusion forming of plastic pipes were obtained by the finite element software Polyflow. In the numerical simulations, the non-isothermal effect and gas compression effect were also considered. Numerical results show that the gas layer width has great impact for the gas-assisted extrusion forming of plastic pipes, the flow velocities of melt at X and Y direction, first normal stress difference increase with the gas width. It is demonstrated that the flow behaviours and stresses of melt can be greatly influenced by the gas layer. Therefore, in practice, the reasonable controlling of the gas layer width is one of most important factors of impacting the stability and quality of gas-assisted extrusion forming of plastic pipes.

1. Introduction
Plastic pipes [1] are usually used as a kind of transmission tool for liquids or gases, which has been widely applied in the many fields, such as medical diagnosis [2], architectural engineering [3], optical communication [4], water supply and drainage system. The plastic pipes are usually produced by using the extrusion process of molten polymers [5]. By means of the extruder, the polymers, e.g., polyethylene, polypropylene, etc, are melted by the heater into the molten polymer. Under the stirring and driving of the screw in the extruder, the molten polymers are transmitted into the metal die, then extruded from the outlet of die with certain of annual or square cross section, finally cooled by the water to form the plastic pipes. For the traditional extrusion form of plastic pipes, the extrude swell and fracture phenomenon will occur due to the elastic storage energy recovery effect of polymer molecular, shear stress concentration effect, velocity rearrangements effect, normal stress effect, etc. To overcome the drawbacks of the traditional extrusion of plastic pipes, some researches have used some methods in practice, for example, lengthen the stereotype section of die to delay the elastic storage energy recovery time of melts[6], fluoridization on the wall surface of metal die[7], polymer modification[8], ultrasound-aided extrusion forming[9], etc. However, the gas-assisted extrusion is an effective, convenient, environment friendly, and well-promising extrusion forming method of polymer melt[10-12]. Up to now, the gas-assisted extrusion forming of polymer melt has been studied by many researches. Great deal of experimental results have fully verified that the gas-assisted extrusion
method can greatly overcome the extrudate swell, extrudate fracture and extrusion distortion phenomenon of polymer melt. In the process of gas-assisted extrusion, the properties of gas layer are directly impact the stability and quality of extruded polymer. In this paper, the effect of gas width on the gas-assisted extrusion forming of the plastic pipes was numerically studied by using the finite element software Polyflow. The geometric models of plastic pipes with different widths of gas layer were established. Under the same inlet conditions, the numerical results of extrudate swell ratio were obtained. At the same time, to ascertain the reason for the effect of gas width on the extrudate swell and fracture of plastic pipes, the several physical field distributions of melts under the impact of gas with different widths were also presented and analysed.

2. Numerical simulation

2.1 Geometric models

The geometric model of the gas-assisted extrusion forming of plastic pipes at the stereotype section of die based on two phase flow is shown in Figure 1(a). where, OO’ is the symmetric axis, the inner radius OA and outer radius OB are 3mm and 5.5mm, respectively. The wall thickness AB of plastic pipes is 2.5mm, the length of the melt in the die and outer die are all 20mm. The width of the gas layer can be changed according to the actual situation. Figure 1(b) is the finite element mesh of the Figure 1(a), the meshes are refined near the boundaries and interfaces to improve the numerical precision.

![Figure 1. Geometric model (a) and finite element mesh (b)](image)

2.2 Governing equations

The governing equations are given as follows,

\[ \nabla \cdot (\rho_k \mathbf{v}_k) = 0 \]  \hspace{1cm} \text{(1)}

\[ \rho_k \mathbf{v}_k \cdot \nabla \mathbf{v}_k + \nabla p_k - \nabla \cdot \mathbf{\tau}_k = 0 \]  \hspace{1cm} \text{(2)}

\[ \rho_k C_p \mathbf{v}_k \cdot \nabla T_k - k \nabla^2 T_k = \mathbf{\tau}_k : \nabla \mathbf{v} \]  \hspace{1cm} \text{(3)}

where \( \nabla \) is Hamilton operator, \( \mathbf{v}_k \) is the velocity, \( p_k \) is the pressure, \( \mathbf{\tau}_k \) is the extra stress tension. \( \rho_k \) is the density, \( k \) is the heat transfer coefficient, \( C_{pk} \) is the specific heat capacity, \( T_k \) is the temperature, \( k = \text{I, II} \) denotes the melt and gas phase, respectively.

In the numerical simulations, PTT constitutive model [13] was used to describe the viscous-elastic properties of plastic pipe’s melt, i.e.,

\[ \tau_1 = \tau_{11} + \tau_{12} \]  \hspace{1cm} \text{(4)}

\[ \begin{align*}
\exp \left[ \frac{\varepsilon A}{(1-\eta) \eta} \right] & = \left[ 1 - \frac{\varepsilon^2}{2} \right] \eta_1 + \left[ 1 + \frac{\varepsilon}{2} \right] \eta_2 = 2(1-\eta) \eta D_1 \\
\tau_{12} & = 2\eta_2 D_1 
\end{align*} \]  \hspace{1cm} \text{(5)}

where, \( \tau_{11} \) is the elastic component of extra stress tensor for the melt, \( \tau_{12} \) is the viscous component of extra stress tensor for the melt. \( \eta_1 = \eta_{12} / \eta_1 \) is the viscosity ratio, \( \eta_{11} \) is the Non-Newtonian component viscosity of the melt, \( \eta_{12} \) is the Newtonian viscosity component of the melt; \( \eta_1 \) is the
total viscosity of the melt. $\lambda$ is the relaxation time, $\epsilon$ and $\xi$ are the parameters of the melt correlated with the material tensile and the shear characteristics, respectively. $\tau$ is the upper convected derivative of the extra stress tensor $\tau$. $D$ is the strain-rate of the tensor.

For the gas layer, the constitutive equation is the same as the Eq.(5), the strain-rate of the tensor of the gas phase is given as,

$$D_\text{II} = \frac{1}{2}(\nabla u_\text{II} + \nabla^\tau u_\text{II}) - \frac{1}{3}\nabla u_\text{II}\delta_\text{II}$$

(7)

In order to obtain the numerical solution, the gas state equation is given as follows,

$$p_\text{II} = \rho_\text{II}RT_\text{II}$$

(8)

where, $R$ is the gas constant, which is equal to $287\text{J/kg} \cdot ^\circ\text{C}$.

### 2.3 Boundary conditions

Based on the Figure 1(a), the boundary conditions are given as follows,

1. Inlet: AB is the inlet of the melt, AA’ and BB’ are the inlets of the gas. Supposed that the flow of the melt and gas are all full-developed when the melt and gas enter into the stereotype section of die, the following relationships are satisfied, i.e., $\frac{\partial v_y}{\partial x} = 0, v_y = 0$. where $v_x$ and $v_y$ are the flow velocities of melt and gas at the $x$ and $y$ direction, respectively. In this numerical studies, the flow volume flow rate is set to $-7.31\times10^{-3} \text{m}^3/\text{s}$. The pressures of gas imposed on the inlets are about $0.1014\text{MPa}$. The temperatures of melt and gas at the inlet boundaries are all set to $463.16\text{K}$.

2. Wall: The no slip wall condition was used, i.e., $v_n = v_s = 0$. The temperature of wall was also set to $463.16\text{K}$.

3. Gas/melt interface: AD and BC are the interfaces between the gas and the melt. The effect of slip between the gas and melt on the flow of melt was neglected. The kinetic and dynamic conditions are satisfied as follows, $f_\text{II}^I = f_\text{II}^\text{m}, f_\text{II}^I = f_\text{II}^\text{g}$, and $v_\text{II}^I = v_\text{II}^\text{m}, \vec{v} \cdot \vec{n} = 0$, where superscript I,II denotes melt and gas, respectively. $\vec{n}$ is the normal unit vector.

4. Free boundaries: EC and FD are the free boundaries of melt. The following relationship should be satisfied, i.e., $f_n = 0$, $f_s = 0$ and $v_s = 0$. Since the thermal convection exchange exists between the free boundary and external environment, the temperature condition of the heat flux was used. At the same time, the heat radiation effect of melt was neglected. The heat flux condition is given as follows: $q = -k \nabla T = h(T - T_{\text{air}})$, where $q$ is the heat flux, $k$ is the heat conduction coefficient, $h$ is the natural convection coefficient of air, which can be equal to $5\text{W/m} \cdot ^\circ\text{C}$, $T$ is the temperature of melt, $T_{\text{air}}$ is the temperature of outside air, which was set to $300\text{K}$.

5. Exit: EF, CC’, and DD’ are the melt and gas exits, respectively. Supposed that no any traction forces were imposed on the exits, i.e., $f_n = 0$ and $v_s = 0$. At the same time, the outflow temperature condition was imposed on the exit because the temperatures on the exits are unknown.

### 2.4 Material parameters

The material parameters of the melt and gas are shown in Table 1.

| Parameters       | Melt      | Air       |
|------------------|-----------|-----------|
| $\eta/(Pa \cdot s)$ | 8823      | 2.6×10^5  |
| $\lambda/(s)$    | 0.1       | 0         |
| $\epsilon$       | 0.15      | 0         |
3. Numerical results and analyses

3.1 Influence of flow velocities

To study the effect of gas layer’s width on the extrusion forming of plastic pipes, we set the width of gas layer to 0.125mm, 0.25mm, 0.5mm, and 1mm, respectively. Under the same inlet pressure of gas, the flow velocity of melt at the X direction on the inlet interface between the melt and gas layers were obtained, which are shown in Figure 2.

![Figure 2. Effect of gas width on the flow velocity of melt at X direction](image)

From Figure 2, it can be seen that the radial flow of melt was generated under the impact of the gas flow. Moreover, the flow velocity at X direction increases with the increasing of gas width. At the same time, it can be found that the flow velocity of melt at the X direction near outer gas layer is greatly larger than that of melt near the inner gas layer, which demonstrates that the force of outer gas layer imposed on the melt is larger than that of inner gas layer. Therefore, at the interfaces between the gas and melt in the stereotype section of die, the radial second flow phenomenon of melt can easily generated under the impact of gas layer with larger pressure, which finally impact the stability of melt flow behavior and the surface quality of extruded plastic pipes.

The flow velocities of melt at Y direction are also obtained, which are shown in Figure 3.

![Figure 3. Effect of gas width on the flow velocity of melt at Y direction](image)
From Figure 3, it can be seen that the flow velocity of melt at Y direction gradually increases along the channel of die. At the same time, it can be seen that the flow velocity amplitude increases with the increasing of the gas width, which demonstrates that gas flow has the traction effect for the melt.

3.2 Influence of first normal stress difference

The effect of different gas widths on the first normal stress difference of melt was also investigated, which are shown in Figure 4.

![Figure 4. Effect of gas width on the first normal stress difference of melt. (a) gas width=0.125mm, (b) gas width=0.25mm, (c) gas width=0.5mm, (d) gas width=1mm.](image)

From Figure 4, it can be seen that the first normal stress difference of melt at the inlet interface of gas/melt increases with the width of gas layer, which demonstrates that the melt will suffer from the impact of gas flow near the inlet point of gas layer. That is, the reason of the flow velocity of melt at the X direction (See Figure 2) is just resulted from the first normal stress difference of gas layer imposed to the melt. When the first normal stress difference of melt is larger, the stability of melt flow will be destroyed and finally impact the surface quality of extruded plastic pipes. Therefore, in practice of gas-assisted extrusion forming of plastic pipes, the width of gas layer can be less than 0.5mm.

4. Conclusion

In this paper, the effect of gas width on the gas-assisted extrusion forming of plastic pipes was numerically investigated. The geometric models of gas-assisted extrusion forming of plastic pipes with different widths of gas layer based on two-phase fluid were established. Under the same inlet pressure of gas layer, boundary conditions and material parameters, the numerical results for the effect of gas layer width on the flow velocities and first normal stress difference of melt were obtained. Numerical results show that the flow velocities of melt at X and Y directions all increase with the increasing of the gas layer’s width. The stability and surface quality of gas-assisted extrusion forming of plastic pipes are easily influenced by the gas layer with larger width. Therefore, the reasonable width of the gas layer is an important factor of impacting the gas-assisted extrusion forming of plastic pipes.
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