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Effect of gas flow rate on the double gas-assisted extrusion forming of plastic pipes

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Abstract. To overcome the extrusion problems of plastic pipes, the double gas-assisted extrusion method was used in this paper. To investigate the effect of gas flow rate on the double gas-assisted extrusion forming of the plastic pipes, the numerical simulations based on the finite element method were performed. Numerical results show that with the increase of the gases flow rate, the inner radius increases and the outer radius decreases, which lead to decrease the wall thickness of plastic pipes. At the same time, the flow velocity changes of melt under the different gases' flow rate were obtained and compared. To ascertain the mechanisms of shrinkage phenomenon of wall thickness, the normal stress and first normal stress difference distribution nephograms of melt under the different gases flow rates were obtained. Results show that the normal stress effect of assisted gases on the melt is the main reason that the wall thickness is decreased by the larger assisted gases flow rates.

1. Introduction

Plastic pipes have already applied into various fields, such as the architectural engineering, engineering mechanics, optical communication, and daily life. In general, the extrusion method [1] is used to produce the plastic pipes. That is, after the plastic materials are molten into the polymer melt in the extruder, the melt is pulled into the die channel under the driving of the screw rotation. The melt flows out the die outlet with a certain cross-section shape under the drawing of the traction machine. Then, the extruded plastic pipes are cooled in the cooling water tank and get the final products. During the extrusion of plastic pipes, the melt not only has the strong viscosity and elastic characteristics, but also suffers from the large shear and tensile stresses in the barrel of extruder and the channel of extrusion die. The strong elastic energy [2] is stored in the molecular of melt. When the melt is extruded from the die outlet, the recovering effect of elastic energy storage, flow velocity rearrangement, and stretching effect will result in the extrudate swell [3, 4], melt fracture [5, 6], and extrudate distortion [7] phenomenon. The qualities of plastic pipes have been limited by these extrusion problems. In order to solve these problems, the double gas-assisted extrusion method [8, 9] was used in this paper. That is, two layers of assisted gases were injected into the interfaces between the melt and the inner wall of die, as well as between the melt and the outer wall of mandrel. This kind of isolation effect will remove the shear and tensile stresses of melt on the wall of die channel. The elastic storage energy and flow velocity change of melt can be greatly eliminated, especially at the outlet of the die. However, the gas-assisted extrusion of engineering plastic pipes is impacted by many factors including the assisted gas flow rate. To ascertain the effect of the gas flow rate on the extrusion forming of the plastic pipes, the numerical simulations of gas-assisted extrusion of plastic pipes were studied by using the finite element method.

2. Numerical simulation

2.1. Model

In order to remove the extrusion problems of plastic pipes, two layers of assisted gases, i.e., inner assisted gas and outer assisted gas, should be formed between the melt and the walls of die channel. Therefore, a kind of three-phases fluid model was established in this paper. The geometric model of the gas-assisted extrusion of plastic pipes is shown in Figure 1.

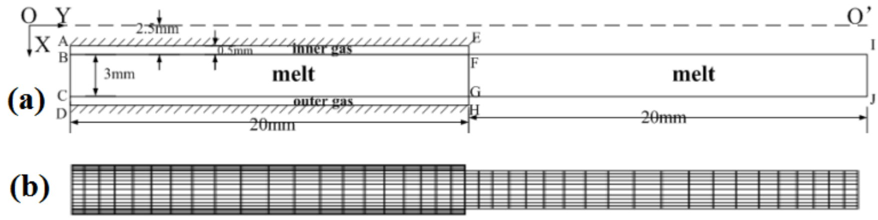

Figure 1. The model of the gas-assisted extrusion of plastic pipes. (a) geometric model; (b)finite element mesh

In Figure 1(a), the melt width of plastic pipe is 3mm, the inner radius is 3mm, the outer radius is 6mm, the length of melt inside die and outside die are all 20mm. The widths of two assisted gas layers are all 0.5mm. Figure 1(b) is the finite element mesh of the plastic pipe. In order to improve the precision of numerical computing, the meshes are refined near the inlet , outlet, exit and interface between the melt and the two layers of assisted gases, and the walls of die. The finite element mesh is about 600.

2.2. Numerical equations

In the numerical simulations, the reasonable hypotheses should be obeyed, i.e., (1) the melt is looked as the iso-thermal, laminar, steady and non-Newtonian fluid; (2) the gravity and inertia forces of melt are ignored due to the properties of strong viscosity and low fluid velocity.

Based on these above mentioned hypotheses, the numerical equations are shown as follows,

$$\nabla \cdot v_k = 0 \tag{1}$$

$$\nabla p_k - \nabla \cdot \tau_k = 0 \tag{2}$$

where, ∇ is Hamilton operator, v_k is the velocity vector, p_k is the pressure vector, τ_k is the extra stress tension. $k = I, II$ are the melt and gases, respectively.

Phan-Thien–Tanner (PTT) constitutive model [10] was used to describe the viscous-elastic properties of plastic pipe's melt, i.e.,

$$\tau_{\mathrm{I}} = \tau_{\mathrm{I1}} + \tau_{\mathrm{I2}} \tag{3}$$

$$\exp\left[\frac{\varepsilon\lambda}{(1-\eta_r)\eta_{\mathrm{I1}}} tr(\tau_{\mathrm{I1}})\right]\tau_{\mathrm{I1}} + \lambda\left[\left(1-\frac{\xi}{2}\right)\overset{\nabla}{\tau}_{\mathrm{I1}} + \frac{\xi}{2}\overset{\Delta}{\tau}_{\mathrm{I1}}\right] = 2(1-\eta_r)\eta_{\mathrm{I1}} D_{\mathrm{I}} \tag{4}$$

$$\tau_{\mathrm{I2}} = 2\eta_{\mathrm{I2}} D_{\mathrm{I}} \tag{5}$$

where, λ is the relaxation time of melt, ε and ξ are the parameters of the melt correlated with the material tensile and the shear characteristics, respectively. $\overset{\nabla}{\tau}_{\mathrm{I1}}$ and $\overset{\Delta}{\tau}_{\mathrm{I1}}$ are the upper and lower convected derivative of the extra stress tensor τ_{I1}. D_{I} is the strain-rate of the tensor of melt.

$\eta_r=\eta_{I2}/\eta_{I1}$ is the viscosity ratio of melt, η_I is the total viscosity of the melt, η_{11} is the Non-Newtonian component viscosity of the melt, η_{I2} is the Newtonian viscosity component of the melt.

For the assisted gases, it can be looked as the Newtonian fluid, the numerical equation is shown as follows,

$$D_{II}=\frac{1}{2}(\nabla v_{II}+\nabla^T v_{II})-\frac{1}{3}\nabla v_{II}\delta_{II} \quad (6)$$

$$\tau_{II}=2\eta_{II}D_{II} \quad (7)$$

where δ_{II} is the second-order unit tensor. D_{II} is the strain-rate of the tensor of gas. η_{II} is the viscosity of gases. τ_{II} is the stress tensor of gases.

2.3. *Boundary conditions setting*

(1) Inlet boundary: In Figure 1(a), BC is the inlet boundary of melt, AB and CD are the inlet boundaries of inner assisted gas and outer assisted gas, respectively. Supposed that the flow behaviors of melt and two layers of assisted gases are all full-developed before the fluids flow into the forming section of die, the following kinetic condition can be satisfied, i.e., $v_x=0$, $\partial v_y/\partial y=0$. where v_x, and v_y are the flow velocities of melt at the direction of *x,* and *y* coordination, respectively. In the simulation, the inlet boundaries of melt and gases were imposed the boundary condition of volume flow rate.

(2) Wall: AE and DG are the wall boundaries. In this simulations, supposed that the flow velocities of gas fluids on the wall surfaces are zero, the no slip condition is used, i.e., $v_n=v_s=0$. where v_n, v_s are the flow velocities of melt at the normal and tangential direction,

(3) Free boundary: FI and GJ are the free boundaries of melt. The following relationship should be satisfied, i.e., $f_n=f_s=0$, and $v_n=0$. where, f_n is the shear stress at the normal direction.

(4) Exit: IJ is the exit boundary of melt. EF and GH are the exit boundaries of inner assisted gases and outer assisted gases, respectively. Supposed that there are no any normal traction forces and tangential velocities are imposed on the exit boundaries, the following relationship should be satisfied, i.e., $f_n=v_s=0$.

2.4. *Material parameters*

In the simulations, material parameters of melt and two gases layers are given in Table 1.

Table 1. The material parameters of melt and gases

Parameters	melt	gas
viscosity/(Pa.s)	2700	2.6×10^{-5}
relaxation time/(s)	0.2	0
ε	0.23	0
ξ	0.18	0
η_r	0.12	0

3. Numerical results and analyses

3.1. *Effect of gases flow rate on the gas-assisted extrusion forming of plastic pipe*

In the simulations, the inlet volume flow rate of melt was set to 1×10^{-7}m^3/s. Four different inlet volume flow rate double assisted gases were used, i.e., 1×10^{-5}, 1×10^{-4}, 5×10^{-4}, and 1×10^{-3} m^3/s. The double gas-assisted extruded profiles of plastic pipes are shown in Figure 2(a-d).

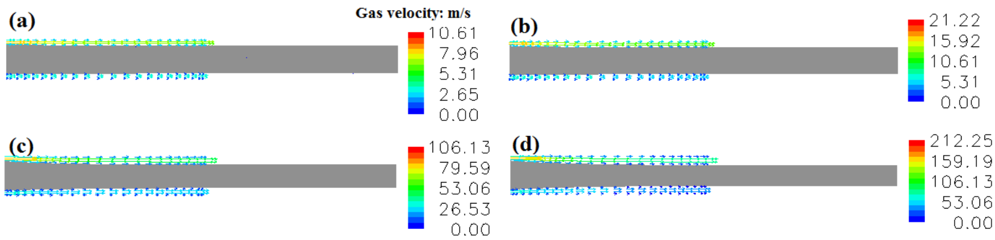

Figure 2. The double gas-assisted extruded profiles of plastic pipes under the different gas inlet volume flow rates. (a) $Q=1\times10^{-5}m^3/s$; (b) $Q=1\times10^{-4}m^3/s$; (c) $Q=5\times10^{-4}m^3/s$; (d)$Q=1\times10^{-3}m^3/s$

From Figure 2, it can be seen that the gas velocity increases with the increasing of the gas inlet volume flow rate. At the same time, the wall thickness of the plastic pipe becomes thinner with the increasing of the gas inlet volume flow rate. Figure 3 shows the size changes of plastic pipes with the increasing of the gas inlet flow volume rate.

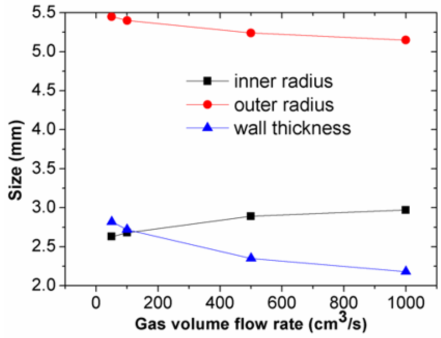

Figure 3. Size changes of plastic pipes with the increasing of the gas inlet flow volume rate

From Figure 3, it can be seen that with the increasing of the gas inlet volume flow rate, the inner radius is increased, the outer radius is decreased, which leads to decrease the wall thickness.

3.2. Effect of gas flow rate on the melt's flow velocities of plastic pipes

To better ascertain the reason that the size change of plastic pipes induced by the gas inlet volume flow rate, the effect of gas flow rate on the melt's flow velocities (X velocity, and Y velocity) of plastic pipe was investigated. The X and Y velocities of melt under the different gas inlet volume flow rates were obtained, which are shown in Figure 4(a), and (b), respectively.

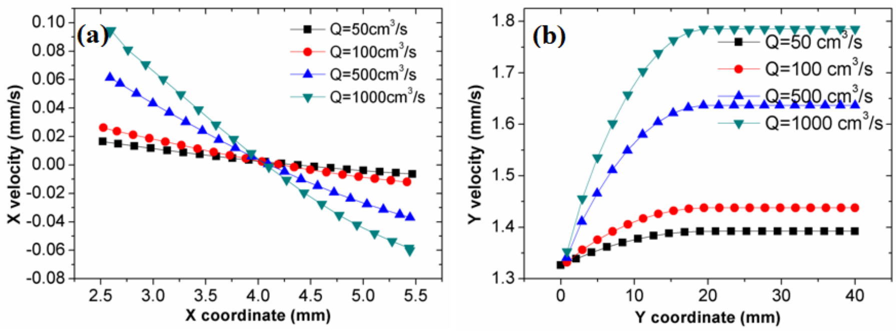

Figure 4. Effect of gas flow rate on the melt's flow velocities of plastic pipes. (a) X velocity; (b) Y velocity.

From Figure 4, it can be seen that with the increasing of the gas inlet volume flow rate, the X and Y velocities of melt all increase. At the same time, from Figure 4(a), it can be seen that under the double gas-assisted extrusion, the X velocity direction of melt near the inner wall and outer wall is just opposite, that is, the melt flows toward the central, which will shrink the wall thickness of plastic pipe. With the increasing of the gas inlet volume flow rate, the shrinkage effect becomes more and more serious, which lead to increase the inner radius, decrease the outer radius and the wall thickness. In addition, from Figure 4(b), it can be found that the flow of melt at the axial direction inside did increase under the assistance of the double gas layers, which demonstrates that the double assisted gases have the drawing effect for the plastic pipe.

3.3. Effect of gas flow rate on the stresses of plastic pipe

To further ascertain the mechanisms of gas flow rate on the extrusion forming of plastic pipe, the normal stresses and first normal stress differences of melt under the different inlet volume flow rates of gases were also obtained, which are given in Figure 5(a-d), respectively.

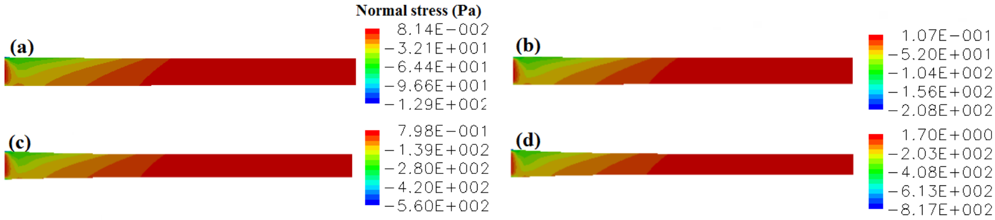

Figure 5. Normal stress nephograms of melt under the different gas inlet volume flow rates. (a) $Q=1\times10^{-5}m^3/s$; (b) $Q=1\times10^{-4}m^3/s$; (c) $Q=5\times10^{-4}m^3/s$; (d)$Q=1\times10^{-3}m^3/s$

From Figure 5, it can be seen that the normal stresses are mainly focused on the near the inlets of gases, and these stresses of melt are generated by the role of the double assisted gases. That is, the normal squeezing effect of double assisted gases on the melt results in the shrinkage flow of melt toward the central, which finally decreases the size of plastic pipe. Moreover, it can be seen that with the increasing of the inlet volume flow rate of gases, the normal stress of melt all increase, which fully verify the reason why the decreasing of wall thickness with the increasing of the inlet volume flow rate of gases.

4. Conclusion

To study the effect of gas flow rate on the double gas-assisted extrusion forming of plastic pipe in this paper, the numerical simulations based on the finite element software Polyflow was performed. Numerical results show that the inner radius becomes bigger, the outer radius becomes smaller, which results in the shrinkage of wall thickness. To ascertain the mechanisms of effect of gas flow rate on the extrusion forming of plastic pipe, the flow velocities, stresses of melt were obtained and compared under the different inlet volume flow rates of gases. Results demonstrate that the normal stress induced by the assisted gases is one of the mainly factors which results in the size change of double gas-assisted extrusion forming of plastic pipe. Therefore, the reasonable controlling of the assisted gases' inlet volume flow rate is one of most important parameters in practice.

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