Numerical simulation of the gas-assisted forming of double-lumen plastic catheter

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Abstract. The numerical simulations of the gas-assisted extrusion (GAE) of double-lumen plastic catheter (DLPC) were performed by using the software Polyflow. The extruded profiles, swell ratios, flow velocities, pressures, stresses of melt based on gas-assisted method were gotten and compared with those of traditional method. Results show that the gas-assisted method can well eliminate the extrusion swell and deformation phenomena of DLPC. The reasons are that, by means of gas-assisted method, the radial velocity of melt is zero, axial velocity distributions are uniform, pressure and stresses are greatly less than the traditional extrusion. Therefore, the gas-assisted method has great value used in the extrusion forming of DLPC.

1. Introduction
Among the medical catheters, DLPC is one of most important catheter used in the interventional diagnosis and treatment, such as double-lumen central venous catheter, double-lumen deep intravenous integrated catheter, double-lumen thrombus catheter, double-lumen drainage catheter. For the double-lumen catheters, the salient feature is that there are two cavities existed in the plastic catheters. As same as the single-lumen plastic catheter, the DLPC is also produced by the continuous extrusion forming for the polymer melt. As we know, for the polymer melt with high visco-elasticity, the plastic catheter will generate some extrusion problems including the extrudate swell [1, 2], melt fracture [3, 4] and extrudate deformation [5], etc. Except for the processes of produce, the extrusion problems are also impacted by the geometric structure of plastic catheter. Compared with the single-lumen plastic catheter, the DLPC is more complicated in the structure of product and the structure of extrusion die. Moreover, the extrusion problems of DLPC will also be more complex and changeable. In this paper, to overcome the extrusion problems of DLPC, the GAE technique [6-9] was used. The numerical simulation of the extrusion forming of the DLPC was performed, and compared with the numerical results of GAE forming of the DLPC. The effects of inlet volume flow rate on the traditional extrusion and GAE of DLPC were all performed and compared with each other. Numerical results show that the GAE technique can better overcome the extrusion problems of DLPC.
2. Simulation

2.1. Model
In the simulation, since only the melt inside die was studied, the melt part in the water cooling procedure were ignored. The geometric models of 3D DLPC are shown in Figure 1, where Figure 1(a) is the cross-section model. The outer diameter is 4mm, the inner diameters of double cavities are all equal to 1.2mm, the widths between the cavity and the outer wall of plastic catheter are all 0.5mm. The width between the two cavities is 0.6mm. Figure 1(b) is the 3D numerical model used in the simulations, the 1/2 part of geometric model was used due to the axis-symmetric characteristic. The lengths of model inside die and outside die are all equal to 10mm. Figure 1(c) is the finite element mesh of Figure 1(b). The mesh number is 2560. In addition, in the numerical, the gas-assisted model was simply replaced by the wall condition. Therefore, the single-phase flow mode was used in this paper.

![Figure 1](image)

Figure 1. Geometric model: (a) cross-section; (b) 1/2 part of numerical model; (c) finite element mesh.

2.2. Equations
In the numerical simulations, the melt was looked as the iso-thermal, steady, non-Newtonian, and laminar fluid in the die because the temperature change of melt is little before it enters into the water cooling system. The gravity force and inertia force of melt were all neglected. The continuum and momentum equations are given as follows,

\[ \nabla \cdot (\rho \vec{v}) = 0 \]  
\[ \rho \vec{v} \cdot \nabla \vec{v} = -\nabla p + \nabla \cdot \tau \]  

where \( \nabla \) is the Hamilton operator. \( \vec{v} = (\vec{v}_x, \vec{v}_y, \vec{v}_z) \) is the flow velocities of melt at x, y, and z coordinates, respectively. \( p \) is the pressure. \( \tau \) is the extra stress tensor. \( \rho \) is the density.

In the simulation, Phan-Thien-Tanner (PTT) constitutive model [10] was used to describe the visco-elastic characteristic, which is given as follows,

\[ \tau = \tau_1 + \tau_2 \]  
\[ \exp \left( \frac{\nu^2}{(1-\eta_s)\eta} \right) \]  
\[ = 2(1-\eta_s)\eta D \]  

where \( \tau_1 \) and \( \tau_2 \) are the viscoelastic component and viscous component of \( \tau \), respectively. \( \eta \) is the total viscosity of melt, \( \eta_1 \) and \( \eta_2 \) are respectively the Non-Newtonian viscosity component and the
Newtonian viscosity component of the melt, $\eta_r = \eta_2 / \eta$ is the viscosity ratio. $\lambda$ is the relaxation time of melt. $\varepsilon$ and $\xi$ are the parameters controlling the shear viscosity and elongational behavior of melt, respectively. $D$ is the melt rate-of-deformation tensor. $\tau_v$ and $\tau_\Lambda$ are the upper convected derivative and below convected derivative of viscoelastic extra stress tensor component ($\tau_1$).

2.3. Boundary conditions
(1) inlet face: In Figure 1(b), ABCC’B’A’ is the inlet face of the DLPC. Supposed that the melt has been already full-developed before the melt flows into the setting section of die, the kinetic equation is given as follows, $\partial v_x / \partial z = 0$, $v_x = v_y = 0$. Additionally, since the gas-assisted forming was replaced by wall condition, the inlet of assisted gases were ignored.
(2) walls: AA’DD’ is the outer wall of plastic catheter, BCEF and C’B’F’E’ are the inner walls of DLPC. For the traditional extrusion, the no-slip boundary condition was used, i.e., $v_n = v_s = 0$. For the GAE, the full-slip boundary condition was used, i.e., $v_n = f_s = 0$.
(3) free boundaries: DD’GG’ is the outer free face of DLPC. EFHI and E’F’H’I’ are the inner free faces of DLPC, $f_n = f_s = 0$.
(4) symmetric faces: ABHG, CC’T’I’, and A’B’H’G’ are the symmetric faces. The following equations should be satisfied, $f_n = v_n = 0$.
(5) exit face: GHII’H’G’ is the exit face of DLPC. Supposed that there are no any normal forces and tangential velocities imposed on the exit face, i.e., $f_n = v_s = 0$.

2.4. Material parameters
In the simulations, the material parameters of melt are shown in Table 1.

| $\eta$ (Pa.s) | $\lambda$ (s) | $\varepsilon$ | $\xi$ | $\rho$ (kg/m$^3$) |
|--------------|---------------|---------------|------|------------------|
| 2700         | 0.2           | 0.23          | 0.18 | 900              |

Figure 2. Numerical results of DLPC for different extrusion methods: (a) inlet and exit faces for traditional extrusion; (b) 3D profile for traditional extrusion; (c) inlet and exit faces for GAE; (d) 3D profile for GAE.

3. Numerical results and analyses

3.1. Results of traditional extrusion and GAE
In simulations, the inlet flow rate of 4mm$^3$/s was imposed. The numerical results of DLPC for the traditional extrusion and the GAE were obtained, which are shown in Figure 2. Figure 2(a) gives the cross-sections of inlet face and the exit faces of DLPC by using the traditional extrusion. Figure 2(b) is
the 3D profile for the DLPC based on the traditional extrusion. Figure 2(c) is the cross-sections of inlet face and the exit faces of DLPC by using the GAE. Figure 2(d) is the 3D profile for the DLPC based on the GAE.

From Figure 2(a) and 2(b), the extrusion swell and deformation of DLPC by using the traditional method are very obvious, especially for double cavities. However, for the GAE, from Figure 2(c) and 2(d), the extrusion swell and deformation don’t occur.

3.2. Swell ratio analysis
The swell ratio of DLPC prepared by two different extrusion methods are gotten, and several variants of the swell ratio were used, i.e., outer diameter at horizontal and vertical directions, width of AB (See Figure 1(a)) ($W_1$), width of BC ($W_2$), width fo CC’ ($W_3$), and the diameter of inner cavity ($W_4$), which are shown in Figure 3(a)-3(c). From Figure 3, with the increase of inlet flow rate of melt, the horizontal and vertical diameters, $W_2$, $W_3$, $W_4$ of the traditional extrusion for DLPC are larger and larger, but $W_1$ decreases, which demonstrates that the extrusion swell and deformation become more and more serious. However, for the gas-assisted extrusion, the swell ratios of all size are equal to zero, which demonstrates that the extrusion swell and deformation are all eliminated.

![Figure 3. Swell ratios of DLPC: (a) outer diameter at horizontal and vertical directions; (b) $W_1$, $W_2$, $W_3$,and $W_4$ of traditional extrusion; (c) $W_1$, $W_2$, $W_3$,and $W_4$ of GAE.](image)

3.3. Flow velocity distributions
(1) radial velocity
Figure 4(a) and 4(b) show the radial velocities of melt for the traditional extrusion and the GAE for the DLPC. For the traditional extrusion, the radial velocity of melt was produced. However, there are no any radial velocity in the melt. Figure 4(c) gives the radial velocities of melt along the axial direction for two different extrusions. From Figure 4(c), the melt extruded by the traditional method has large radial velocities on the outer wall and two inner wall, especially at the outlet of die. However, for the melt extruded by gas-assisted method, the radial velocities can not be found. Figure 4(d) shows the radial velocities of melt for the two different extrusions at the horizontal direction of cross-section face.
of outlet of die. From Figure 4(d), the radial velocity distribution is the cosine function, i.e., the melt near the middle of DLPC has negative radial velocity, but the melt near the outer wall has the positive radial velocity, which demonstrates the radial velocity of melt for the traditional extrusion isn’t uniform, and results in the generation of large deformation. However, the radial velocity of melt for the GAE is equal to 0, the extrusion deformation can be well eliminated.

Figure 4. X velocity distributions of melt for DLPC: (a) traditional extrusion; (b) GAE; (c) axial distribution; (d) radial distribution.

(2) axial velocity
Figure 5(a) and 5(b) gives the axial velocity distributions of melt for the two different extrusions. For the traditional extrusion, the axial velocity distribution is not uniform at each cross-section face along the axial direction of melt, i.e., the axial velocity of melt near the walls has zero velocity, the large axial velocity is mainly focused at the middle of the DLPC. For the GAE, the axial velocity of melt is same. The axial velocities of melt along the axial direction of outer wall and two inner walls for the two different extrusions are shown in Figure 5(c).

Figure 5. Axial velocity distributions of melt for the DLPC: (a) traditional extrusion; (b) GAE; (c) axial velocity along the axial direction of outer wall and inner walls; (d) axial velocity at the horizontal direction of the cross-section for the outlet face of die.
From Figure 5(c), the axial velocity of melt for the traditional extrusion has the obvious jump change at the outlet of die, which will easily lead to produce the melt fracture problems at the surface of DLPC. However, the axial velocity of melt for the GAE is not changed along the axial direction. The axial velocities of melt for two different extrusions at the horizontal direction of cross-section face for the outlet of die are shown in Figure 5(d). From Figure 5(d), we can see that the gas-assisted method overcomes the uniform problems of melt produced by the traditional method.

3.4. Pressure distribution
The pressure distributions of melt for DLPC based on two different extrusions are shown in Figure 6(a), and 6(b). From Figure 6, it is obviously seen that the pressure value of melt is greatly reduced by the gas-assisted method compared with that of the traditional method.

![Figure 6](a) Pressure distribution of melt for traditional extrusion; (b) pressure distribution of melt for GAE.

3.5. Stress distribution
The shear stress distributions of melt for the DLPC by using the traditional and GAEs are given in Figure 7(a), and 7(b). For the traditional extrusion, the larger shear stresses focus on the outer walls and two inner walls, and the shear stress distributions are not uniform at each cross-section face, which results in the different distributions of shear stress, and finally lead to produce the different degrees of extrusion swells and deformations for the extruded DLPC. However, for the GAE, the shear stress values are very little due to the help of the assisted gases.

![Figure 7](a) Stress distribution of melt: (a) shear stress of traditional extrusion; (b) shear stress of GAE; (c) first normal stress difference of traditional extrusion; (d) first normal stress difference of GAE.

Then, the first normal stress difference of melt for two different extrusions are presented in Figure 7(c), and 7(d). As same as shear stress distributions, the first normal stress difference of melt is also greatly reduced by the gas-assisted extrusion method.

4. Conclusions
The GAE forming of the DLPC was numerically simulated in this paper. Compared with the traditional extrusion, the extrusion swell and deformation problems were well eliminated by using the gas-assisted method. To analysis the reasons, the radial velocity, axial velocity, pressure, stresses distributions of melt for two different extrusions were obtained and compared. Results show for the gas-assisted method, the radial velocity of melt is nearly equal to 0, the axial velocity of melt is uniform, and the pressure, stresses of melt are all less than those of traditional extrusion. From the
simulation results, it can be seen that the gas-assisted forming can overcome the extrudate swell, deformation problems of DLPC by the full-slip effect between the gas layers and the walls.

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