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Numerical investigation of the geometrical effects on UHMWPE flow characteristics in small aperture spinneret orifice

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Abstract. Due to high viscosity of the ultra-high molecular weight polyethylene (UHMWPE), it is difficult for the melt UHMWPE to flow through the small aperture spinneret orifice in the melt spinning forming process. The geometrical parameters of the spinneret orifice become critical to the melt spinning process. Based on the theory of polymer rheology, the finite element model of UHMWPE melt spinning had been developed by using POLYFLOW, and the length-to-diameter ratio and taper angle of the spinneret orifice effects on the UHMWPE melt flow characters were discussed. The results show that suitable length-to-diameter ratio and taper angle are helpful for the compactness and flow stability of the melt.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE), with weight average molecular weights in excess of 2×106 kg kmol-1 [1], is a thermoplastic material with an excellent set of properties, such as good abrasion resistance, the highest impact toughness of any plastic at cryogenic temperature, good corrosion resistance and environmental stress-crack resistance, a low coefficient of surface friction, and noise- and shock-abatement properties. Unfortunately, such high-molecular weight polyethylenes are either difficult or impossible to process in the melt due to their high melt viscosities, and much effort has been directed towards finding suitable processing methods for polyethylenes and, in particular, UHMWPE [2].

At present, the popular preparation method of UHMWPE fiber is gel spinning which use naphthalene, paraffin oil and other hydrocarbons as solvents. In gel spinning process, UHMWPE was prepared into half dilute solution [3], which was extruded through spinneret orifice and drawn to form gel fibers. Then gel fibers were ultra drawn to more than 30 times with a certain temperature after extracting and drying [4]. This gel spinning method is not very strict to the size of molecular weight, and it is an important way to obtain UHMWPE fiber with high strength and high modulus. Smith and Lemstra [5-7] developed the first commercial gel-spinning process. But this process involves significant quantities of solvents requiring removal and recycling, so the environment pollution

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became a big problem for UHMWPE production when using gel spinning.

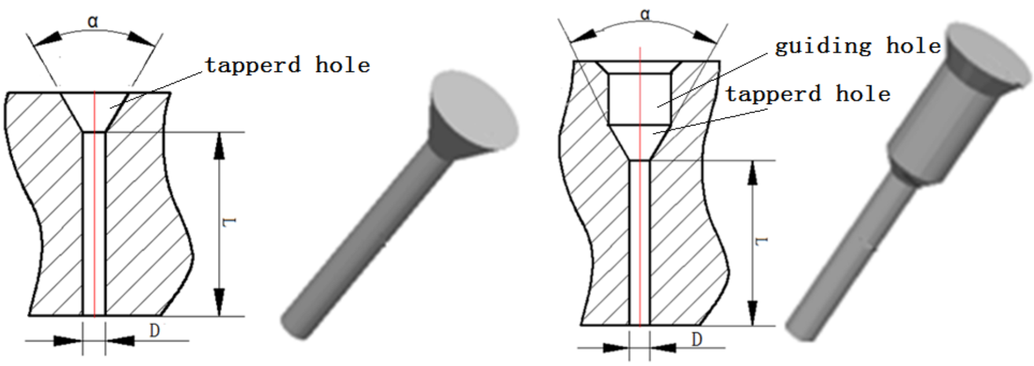
Melt spinning, as a new forming method to product UHMWPE fiber was getting more and more attention in the world. The polymer melt flows through spinneret orifice of the screw extruder quantitatively with metering pump, and shot into the air in the form of trickles, and then cooled into silk in the spinning channel [8]. No solvents and precipitation agent are needed during the forming process. There are many advantages in this forming method such as low cost, energy conservation, environmental protection, high production efficiency etc.

However, the unreasonable design of spinneret hole in the spinning process will lead to the failure of the molding because of large viscosity of UHMWPE. Therefore, reasonable design of spinneret hole is one of the key technologies of UHMWPE melt spinning forming based on the flow field analysis in the spinneret hole. The finite element model of UHMWPE melt spinning was established according to the polymer rheology theory and melt spinning process theory using POLYFLOW software. The spinning forming process of the internal melt was simulated with different structural parameters of spinneret hole, and the distribution of flow field in the hole was studied, which provided the theory basis for reasonable design of spinneret hole.

2. Numerical modelling and conditions

2.1. Geometry and FEM model

Spinneret orifice usually consists of guiding region, tapered region and small aperture orifice region. There D and L represent the diameter and length of the spinneret orifice respectively. In this paper, spinneret orifices with and W/O guiding hole were used as shown in figure 1, and α represents the taper angle. As the geometrical model of the spinneret orifice is axial symmetric, then half of axial cross section was selected for calculating. The ANSYS Polyflow software was used for numerical simulation, which provides advanced fluid dynamics technology for solving tasks in the polymer processing. As the models are axial symmetric, half of axial cross section was selected as the research object, and the finite element models meshed with quad elements are shown in figure 2.



(a) (b)

Figure 1. Geometry model of the spinneret orifices. (a) W/O guiding hole; (b) With guiding hole.

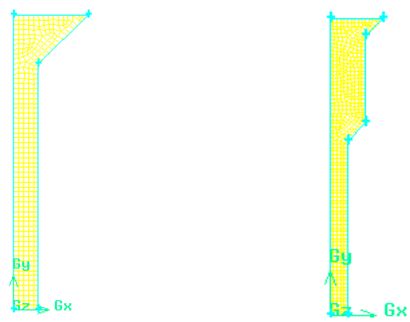


Figure 2. Finite element models.

2.2. Polymer melt rheology

In extrusion molding process of polymer, the melt flow follows the law of mass conservation, the law of momentum conservation and the law of energy conservation, which are described respectively by continuity equation, motion equation and energy equation [9, 10].Melt flow behavior is described by the constitutive equation which reflects the relationship between flow stress and the motion parameters in the process of polymer melt flow. The common constitutive equations of the generalized Newtonian fluid include Bird-Carreau law, Power law, Cross law and so on. Power law [11] fluid is a common material model, the equation is expressed as:

$$\eta = \eta_0 (\lambda \dot{\gamma})^{(n-1)} \tag{1}$$

where η_0 is zero shear viscosity, λ is relaxation time, $\dot{\gamma}$ is the shear rate, n is the non-Newtonian index.

Correlate the continuity equation, energy equation, motion equation and constitutive equation, and impose specific boundary conditions and initial conditions, the flow process of polymer melt can be solved. However, it is difficult to obtain analytic solutions of the above equations as a result of multivariate of high-order nonlinear partial differential equations, and numerical method is adopted usually. The finite element is widely adopted as a numerical method to solve the above equations and the distribution of velocity and pressure can be obtained, which provides the necessary theoretical basis for the polymer molding.

The UHMWPE used in this study was modified by adding nanometer montmorillonoid, and the modified UHMWPE parameters are shown in table 1 [12].

Table 1. Material parameters.

Density	0.97g/cm^3
Zero shear viscosity	13000Pa·s
Coefficient of heat conduction	5×10^{5}W/(m^2·K)
Model index	0.275
Relaxation time	0.1s

3. Results and discussion

3.1. Length-to-diameter ratio effect on flow characters

For investigating the length-to-diameter ratio effect on the UHMWPE flow characters, two different models of spinneret orifices with and without guiding holes, as shown in figure 1, were used. The length-to-diameter ratio changes from 5 to 10. The spinneret orifice geometrical and processes parameters are shown in table 2.

Figure 3 shows flow velocity contours of the two cases as length-to-diameter ratio equals to 5. It can be seen from the figure that the velocity changes obviously in the taper region, especially at the conjunction region of the tapered hole and orifice as the UHMWPE melt is pushed from big space in a small aperture orifice. While the unstable flow phenomenon did not occur in the taper region as the UHMWPE melt has high melt viscosities. Then the flow velocity shows a stable state in the length direction after the melt flows into the orifice. In radius direction, the velocity gradient is obvious at the region closed to the inner wall of the orifice due to the friction between the melt with the orifice, and the flow velocity attached to the inner wall of the orifice is reduced to zero m/s.

Table 2. geometrical and process parameters.

Diameter of orifice	2mm
Taper angle	60°
Length-to-diameter ratio	5,6,7,8,9,10
Inlet melt temperature	473K
Volumetric flow	3.5325×10^{-8}m^3/s.

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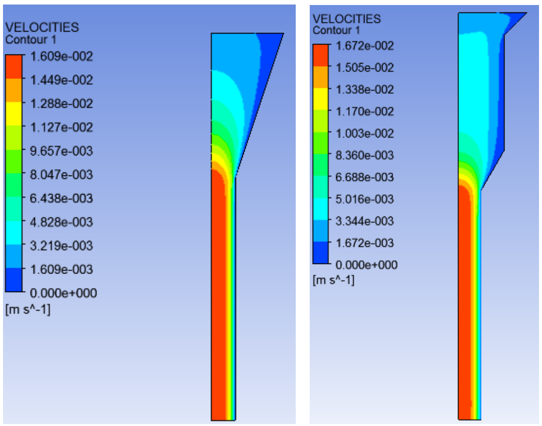
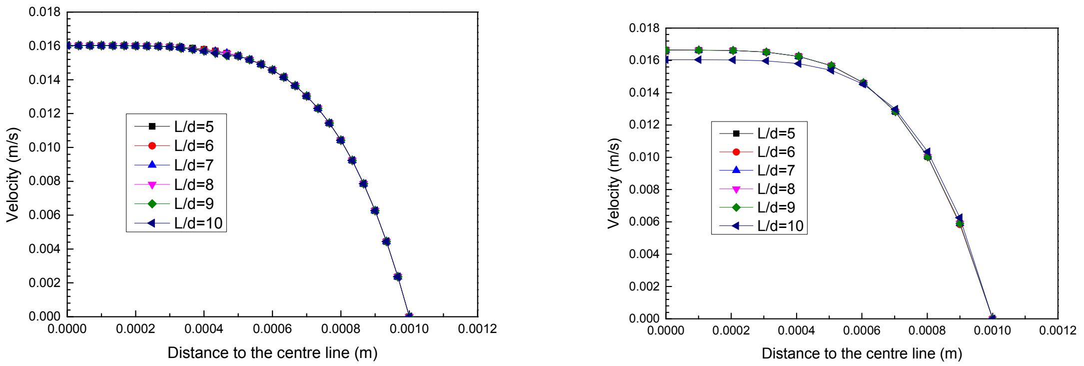


Figure 3. Flow velocity contours with length-to-diameter ratio equals to 5.



(a) (b)

Figure 4. Flow velocity at the exit with different length-diameter ratios. (a) W/o guiding hole; (b) whit guiding hole.

Figure 4 shows flow velocity plot at the mold exit in radius direction with different length-to-diameter ratios. It can be seen that the velocity gradient of the both cases of W/O and with guiding hole become steep from the point about 0.6 mm to the centre line due to the internal friction between the flow layers and the friction between the melt with the orifice. Figure 4(b) shows the flow velocity distribution in the spinneret orifice with guiding-hole have steeper gradient than the w/o guiding-hole cases of length-to-diameter ratios equals 5 to 9. And the velocity gradients are not affected by the length-to-diameter ratio obviously just as the same with the cases without guiding holes. While the velocity gradient could be decreased with larger length-to-diameter ratio as shown in figure 4(b). It may be that enough length of the orifice could make the UHMWPE melt has enough time to fully relax, which guaranteed the stability of the velocity distribution at the exit and orientation of material.

Figure 5 shows the pressure contours with length-diameter ratio equals to 5. It can be seen that the pressure decrease gradually from inlet to exit and the maximum pressure occurs in the region closed to the orifice's wall at inlet. Figure 6 shows the pressure distribution in length direction with different length-to-diameter ratios of the spinneret orifices with and without guiding holes. It can be seen from figure 6 that the curves have same gradient, and higher pressure according to larger length-to-diameter ratio value. Under the condition of constant origin flow rate, higher pressure was generated duo to the higher resistance induced by the high melt viscosities flow in the orifice. The pressure fluctuate more obviously in the guiding hole region as the

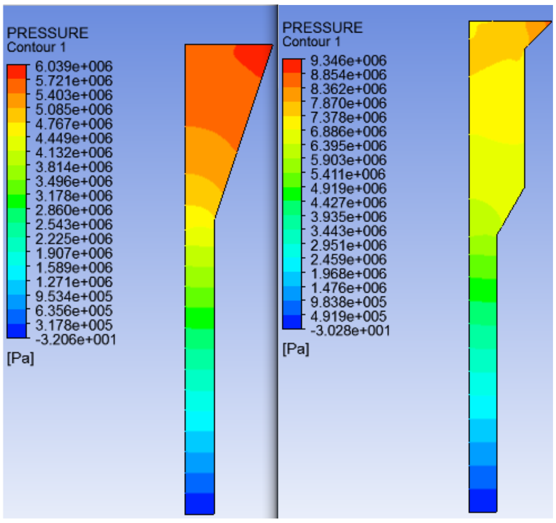


Figure 5. Pressure distribution contours with L/D ratio equals to 5.

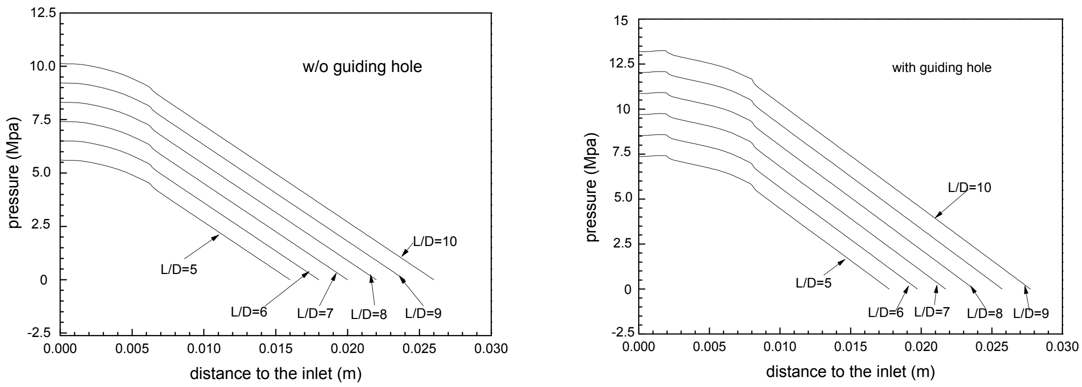


Figure 6. The pressure distribution in length direction with different length-diameter ratios.

Although higher flow pressure in orifice is helpful for improving compactness of the melt and decreasing the end breakage rate of spinning, the bigger length-to-diameter ratio means more difficulty to extrude the melt.

3.2. Taper angles influence on UHMWPE flow characters

From the flow results of the orifices with and w/o guiding hole, it can be seen that the orifice w/o guiding hole has advantages in producing and keeping more stable flow velocity at exit. So the spinneret orifice without guiding hole was used for investigating the taper angle's effect on the flow character. The process parameters are the same with different length-to-diameter ratios cases and the geometrical parameters are shown in table 3.

Figure 7 shows flow velocity distribution at orifice's exit in the radius direction with different taper angles. It can be seen that the velocity decreased gradually from the center to the wall, and the velocity gradient in the wall was larger. Taper angle of guide-hole increased from 60° to 120°, the convergence behavior of the melt flow increased significantly, the tensile deformation and shear deformation increased, which will leaded to instable flow. While in this study, unstable flow phenomenon was not appear in the transitional area of entrance due to the high viscosity and low flow rate of the UHMWPE melt.

Table 3. Geometrical parameters.

orifice diameter (mm)	L/D	Taper angle			
2	10	60°	75°	90°	120°

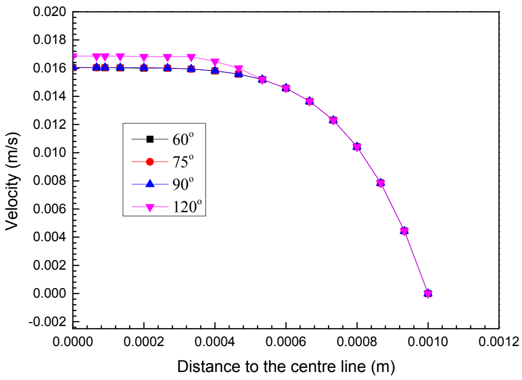


Figure 7. Flow velocity at the exit with different taper angles.

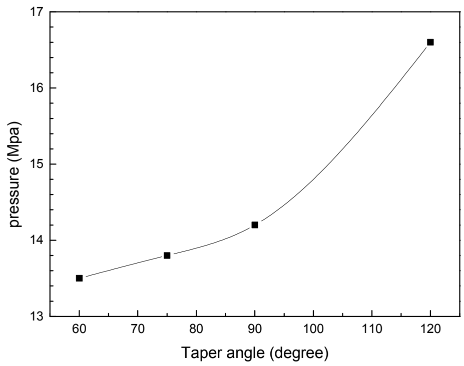


Figure 8. The maximum pressure changes with different taper angles.

Figure 8 shows the maximum pressure with different taper angles. The maximum pressure increases with the taper angle increase due to the convergence behavior induced by the "inlet effect". The pressure increases drastically as the taper angle between 90° and 120° as shown in figure 8. Although higher pressure is helpful to obtain more compactness fiber, too high pressure could induce more unstable flow velocity. Smaller taper angle is helpful to get more stable flow but could make the mold machining harder. So the taper angle should be chosen from 60° to 90°.

4. Conclusions

- The simulation results showed that velocity gradient existed in the radial direction when UHMWPE melt flowed in the spinneret hole, and the velocity decreased gradually from the center to the wall due to the inlet infect. The melt velocity changed obviously in the conjunction region of tapered hole and small aperture orifice. For the orifices with certain diameter, especially in the cases of mold with guiding hole, the melt in longer orifice could get more stable flow velocity in radius direction for the melt has longer relaxation time.
- The maximum pressure and pressure in the orifice were both increased with length-to-diameter ratio and taper angle increase. But too big taper angle may induce the flow velocity unstable, and too big length-to-diameter ratio will make it difficult to extrude the melt. The proper geometrical parameters suggested based the simulation results are that the length-to-diameter ratio should be chosen from 8 to 10, and the taper angle should be chosen from 60° to 90°.

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