Studies on Melt Spinning of PET Hollow Fibers

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1. Introduction

Fiber spinning is a continuous deformation process by which material is converted into a fiber. The melt spinning process was analyzed mainly by employing an asymptotic method of the so-called thin filament equations which formulates dynamics of spinning process by averaging over the cross-section of filament the set of fundamental equations. This method gives the approximate results for commonly used circular fiber spinning. In addition to the asymptotic analysis, other numerical methods such as finite difference and finite element method [1, 2], were applied for the analysis of the spinning process. Finite element method has been often used to study the flow in the region of upstream and an extrudate swell near the spinneret [3, 4]. However, the application of the finite element procedure to the whole spinline has not been achieved effectively. This is due to the fact that spinline has a very large length to diameter ratio (L/D) and some boundary conditions have to be satisfied.

Due to the usefulness of new fibers, there has been great development in the technology of manufacturing [5, 6]. They are in the form of non-circular cross-section. Most of researches [7, 8] were limited to the experimental verification of relations between the die and fiber shapes. Hollow fiber is one of non-circular fibers. It has cylindrical appearance having inner hollow core. The hollow fibers have superior properties in water absorbing, warmth-retentive, bouncy touch, drape, light and bulky hand.

The spinning process of hollow fibers is similar to that of circular fibers. The difference between them is an additional dimensional variable, that is, inner radius (R_i), and thus, the consideration about the inner moving boundary is necessary for the analysis of the hollow fiber spinning.

In this work, the formulation of dynamics of hollow fiber spinning process was carried out using a finite element method by considering the inner and outer moving boundaries, and the change of final dimensions and the profile development along the spinline were presented, and the effect of spinning conditions and initial die geometry on the process was examined. Then, the results were compared with the experiments to prove the usefulness of simulation.

2. Formulation and Numerical method

Throughout this work, a cylindrical coordinate system was employed. For steady flow, the equations for conservation of mass and momentum are as follows:

$$\nabla \cdot \mathrm{v} = 0 \qquad (1)$$

$$\rho \mathrm{v} \cdot \nabla \mathrm{v} = \rho \mathrm{f} + \nabla \cdot \boldsymbol{\sigma} = -\nabla p + \rho \mathrm{f} + \nabla \cdot \boldsymbol{\tau} \qquad (2)$$

where v represents the velocity vector, ρ the density, f the body force, τ deviatoric stress tensor, σ the total stress tensor, and p pressure. Here, the fluid is assumed to be incompressible and Newtonian.

$$\tau = 2\eta \mathbf{D} \qquad (3)$$

where $\mathbf{D}$ is the rate of strain tensor and η is Newtonian viscosity. The transport of thermal energy in the fluid is described by

$$W_p C_p \frac{\partial T}{\partial z} = -\pi D_o h (T - T_\infty) \qquad (4)$$

where W_p is the mass throughput rate, C_p the heat capacity, D_o the outer diameter of filament, h the heat transfer coefficient of the polymer, and T_∞ the temperature of surrounding air. Galerkin formulation procedure was used to make a weak statement and nonlinear forms of above equations were solved using Newton-Raphson iteration.

3. Experimental

The material used in this study is a textile grade PET supplied by SamYang Co. Ltd. The melt spinning extruder MST-I manufactured by SYNTEX Co. was employed to carry out the experiment. Three types of die with different ratios of inner to outer diameter were prepared. All the dies were designed to have the same cross-sectional area, which imposes the equivalent drawdown ratio under fixed mass throughput rate and take-up speed. The dimensions of the segmented arc dies are presented in Table 1. The portable diameter monitor 460D/2 supplied by Zimmer Co. Ltd. was prepared to examine the outer diameter variation along the spinline. The temperature monitor NONTACT Ⅱ-7000 manufactured by Teijin Co. Ltd. was used to measure the fiber temperature. Velocity profile development was observed by LS50M Multiplexed LaserSpeed System manufactured by TSI Inc. In order to estimate the inner diameter and the hollow portion of fibers along the spinline, a fiber capturing device was applied. To measure the dimensions and shape such as inner and outer diameters, hollow portion and roundness, the captured object and the as-spun fiber were carefully cut with a sharp razor or a microtome to produce its cross-section. An electronic imaging program 'Image-Pro Plus' programmed by Media Cybernetics, L. P. was used.

Table 1. Die geometry of segmented arc type.

κ	Outer diameter(mm)	Inner diameter(mm)	Hollow portion, A_i/A_t (%)
0.80	1.0	0.8	64
0.85	1.139	0.9681	72.25
0.90	1.376	1.2384	81

Table 2. Spinning conditions.

Variables	Spinning Conditions
Mass throughput rate (g/min. hole)	1.2, 1.7, 2.2, 2.7
Take-up speed (m/min)	250, 500, 750, 1000
Quench air velocity (m/min)	12, 18, 24, 30
Quench air temperature (oC)	14, 17, 20, 23
Spinning temperature (oC)	275, 280, 285, 290
Spin length(cm)	125

4. Results and Discussion

The mass throughput rate has a strong effect on the profile development and final dimensions because the drawdown ratio varies heavily with mass throughput rate. Fig. 1 exhibits inner and outer diameter variations along the spinline. Here the experimental value of inner diameter was obtained using a capturing device. When the take-up speed is fixed, lower mass throughput rate results in higher drawdown and deformation rate. Deformation patterns of inner and outer diameters are similar to each other and their variation occurs mainly in the position close to the die. The diameter asymptotically approaches the final value near the solidification point. The final cross-sectional area of hollow fibers increases with the increase of mass throughput rate at a fixed take-up speed and thus, both inner and outer diameters increase irrespective of die geometry (Fig. 2). The ratio A_i/A_t of as-spun fiber is determined in terms of the dimensions of inner and outer diameters at solidification point. In the case of circular fiber spinning the final dimension of as-spun fiber is determined only by the drawdown ratio. However, in the hollow fiber spinning the as-spun fibers with the same linear density can have the different inner and outer diameters. The inner and outer diameters of as-spun hollow fiber are thought to be dependent on two process variables such as the drawdown ratio and the position of solidification point. If both inner and outer diameters decrease in a similar fashion, the ratio A_i/A_t decreases. The effect of mass throughput rate on the ratio A_i/A_t is due to the change of final dimensions by change of the drawdown ratio.

4. Conclusions

Profile development of the spinning process of hollow fibers is similar to that of circular cross-sectional fibers. Spinning temperature and mass throughput rate have a strong effect on the ratio A_i/A_t followed by take-up velocity and quench air velocity. Quench air temperature has a relatively smaller effect. The effect of change of process variables decreases as the ratio R_i/R_o increases.

References

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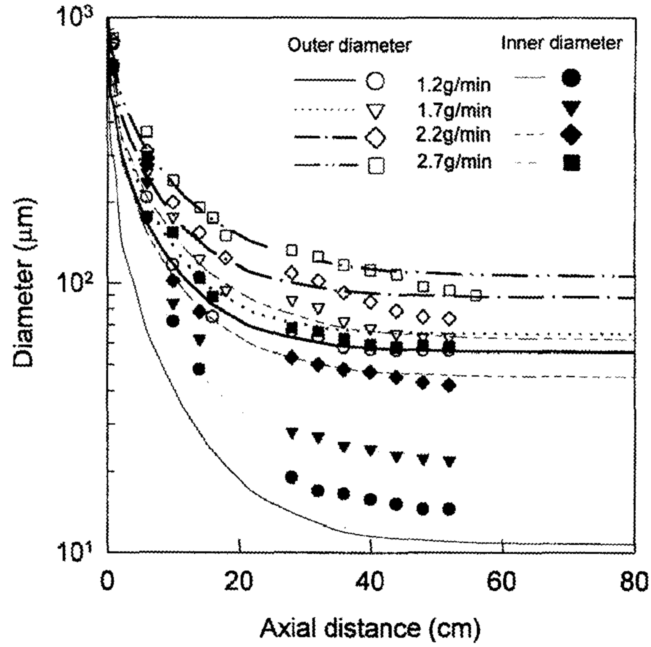

Fig. 1. Diameter profile of hollow fiber at various mass throughput rates : take-up speed; 500 m/min, spinning temperature; 280°C.

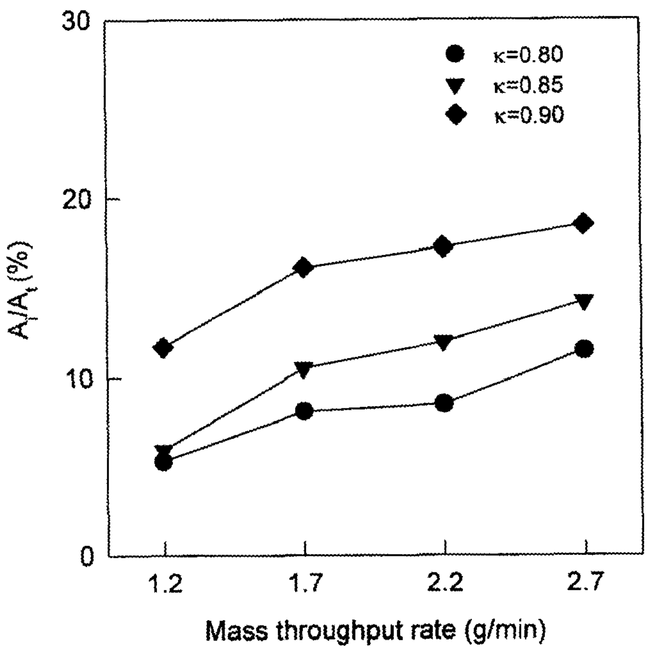

Fig. 2. The ratio A_i/A_t of as-spun hollow fiber as a function of mass throughput rate: take-up speed; 500 m/min, spinning temperature; 280°C.