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Studies on the Melt Spinning Process of Hollow Fibers (A Simulation Approach)

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1. Introduction

Most synthetic fibers have a round cross-section. But shaped fibers have a non-circular cross-section similar to a die geometry. Due to the need of new fibers, there has been great developments in the field of a shaped fiber [1, 2]. Hollow fiber is a kind of shaped fiber. There are two types of spinneret design to manufacture the hollow fibers. One is to use an annular die with a system of blowing air into the inner core [3] and the other is to use a die of the segmented arc type [4].

The spinning process of hollow fibers is similar to that of circular cross-sectional fibers. The difference between these two processes is due to an additional dimensional variable, that is, inner radius (R_i), and thus, another information about the inner free surface is needed for hollow fiber spinning. The magnitude of hollow portion is an important factor and it is a controllable variable by changing spinning conditions. Studies on isothermal drawing of hollow tubes were performed using a finite-element method and thin filament equations by Freeman [3] and the dynamics of spinning process of polycarbonatesiloxane hollow fiber using quasi-two-dimensional equations for thin films was studied by Getmanyuk [5].

An application of the finite element procedure to the whole spinline has not been done effectively. This is due to the fact that spinline has a very large length to diameter ratio (L/D) and that some boundary conditions have to be satisfied. Initial profile development near the spinneret for a isothermal low-speed spinning [6] and the radial and axial temperature distribution in a solidifying fiber [7] were analyzed by the finite element method.

In the case of hollow fiber spinning, an application of the thin filament equation is difficult because of the additional variable, and thus, a two-dimensional finite element method can be applied to the analysis of hollow fiber spinning process. This method can generate inner and outer free boundaries.

In this work, the formulation of dynamics of hollow fiber spinning process was carried out using a finite element method by considering an inner free surface, and the change of final dimensions and profile development along the spinline were presented and the effect of spinning parameters and initial die geometry on the process was examined .

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:

$$\nabla \cdot \mathrm{v} = 0 \tag{1}$$

$$\rho \mathrm{v} \cdot \nabla \mathrm{v} = \rho \mathrm{f} + \nabla \cdot \sigma = -\nabla p + \rho \mathrm{f} + \nabla \cdot \tau \tag{2}$$

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.

$$\tau = 2\eta_E \mathrm{D} \tag{3}$$

where D is the rate of strain tensor and η_E is Newtonian viscosity.

The transport of thermal energy in the fluid is described by

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

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. Throughout this work material constants were taken to be those of Poly(ethylene terephthalate).

Galerkin formulation procedure was used to make a weak statement and nonlinear forms of above equations were solved using Newton-Raphson iteration.

The initial velocity as fully developed elongational flow field and the final velocity as take-up velocity are given as boundary conditions. Free boundary conditions are given at inner and outer boundary. To investigate the effect of die gap size, the simulations were performed for the ratio R_i/R_o 0.75, 0.8 and 0.85, respectively. Here, R_i and R_o denotes the inner and the outer radius of die, respectively. Simulation conditions used in this work are presented in Table I.

Table I. Conditions used in the simulation of melt spinning of hollow fibers.

Variables	Conditions
Mass throughput rate (g/min)	0.3, 0.5, 0.7, 0.9
Spinning temperature (°C)	260, 270, 280, 290
Take-up velocity (m/min)	250, 500, 750, 1000
Quench air velocity (cm/sec)	10, 20, 30, 40
Quench air temperature (°C)	10, 15, 20, 25
Inner radius of die (mm)	0.5
Outer radius of die (mm)	0.375, 0.4, 0.425

3. Results and Discussion

Typical profile development of hollow fibers compared with that of circular cross-sectional fibers is shown in Fig. 1. If the initial and the final cross-sectional area of each fiber are equal under the same conditions, the rate of area reduction and the stress along the spinline of hollow fibers are greater than those of circular cross-sectional fibers. Since the hollow fibers have a larger surface area than circular cross-sectional fibers, the heat transfer to ambient air is greater and the length from spinneret to solidification point becomes shorter. The hollow fibers have a shorter deformation zone and greater stress at a solidification point than the circular cross-sectional fibers, which is due to the rapid solidification, and thus, the velocity gradient and the molecular orientation of hollow fibers are greater than those of circular cross-sectional fibers under the same process conditions. From these results, it can be inferred that the physical properties of hollow fibers under the same processing conditions are superior to those of circular cross-sectional fibers.

Fig. 2 shows the radius profile and the ratio A_i/A_t under a typical spinning condition at various positions in the spinline. Here, A_i and A_t denotes the inner and the total cross-sectional area at a take-up point, respectively. The shape of deformation of inner and outer radius is similar and the ratio A_i/A_t decreases along the spinline. If both the radii are deformed at a similar rate along the spinline, the ratio A_i/A_t decreases.

The effect of spinneret geometry on the ratio A_i/A_t for different take-up velocities is plotted in Fig. 3. The same trend is observed irrespective of the initial ratio R_i/R_o at spinneret, but a slight difference is observed at the ratio R_i/R_o of 0.85. At the ratio R_i/R_o of 0.85, the effect of change of process variables is reduced. This may be due to the fact that the change of process variables becomes less effective since a geometric effect is large in the case of the ratio R_i/R_o of 0.85.

To analyze the sensitivity of the ratio A_i/A_t to change in a given process parameter, the computed results are gathered in Fig. 4. The figure shows that the most critical process parameter changing the ratio A_i/A_t is the spinning temperature followed by the mass throughput rate, and then the take-up velocity and quench air velocity. Quench air temperature relatively has a smaller effect than the other process parameters. These results are observed in all cases irrespective of the ratio R_i/R_o. However, the effect of the change of process variables decreases with increasing the ratio R_i/R_o.

4. Conclusions

Profile development of the spinning process of hollow fibers is similar to that of circular cross-sectional fibers. Large rate of area reduction and rapid solidification, as compared with circular cross-sectional fibers, are the characteristics of spinning process of hollow 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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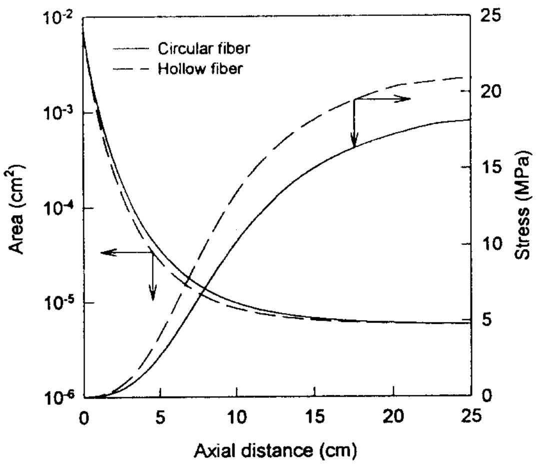

Fig. 1. Comparison of computed area and stress profile of hollow fiber with those of circular cross-sectional fiber.

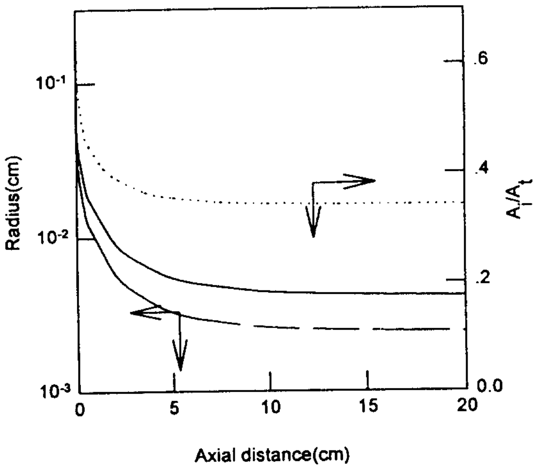

Fig. 2. Computed radius and ratio A_i/A_t profile along the spinline at a typical spinning condition.

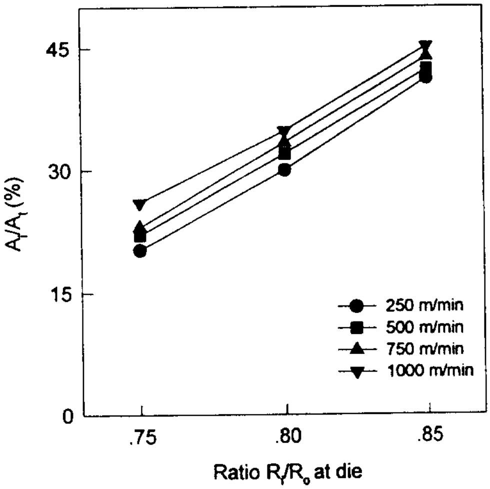

Fig. 3. Computed ratio A_i/A_t as a function of ratio R_i/R_o for different take-up velocities.

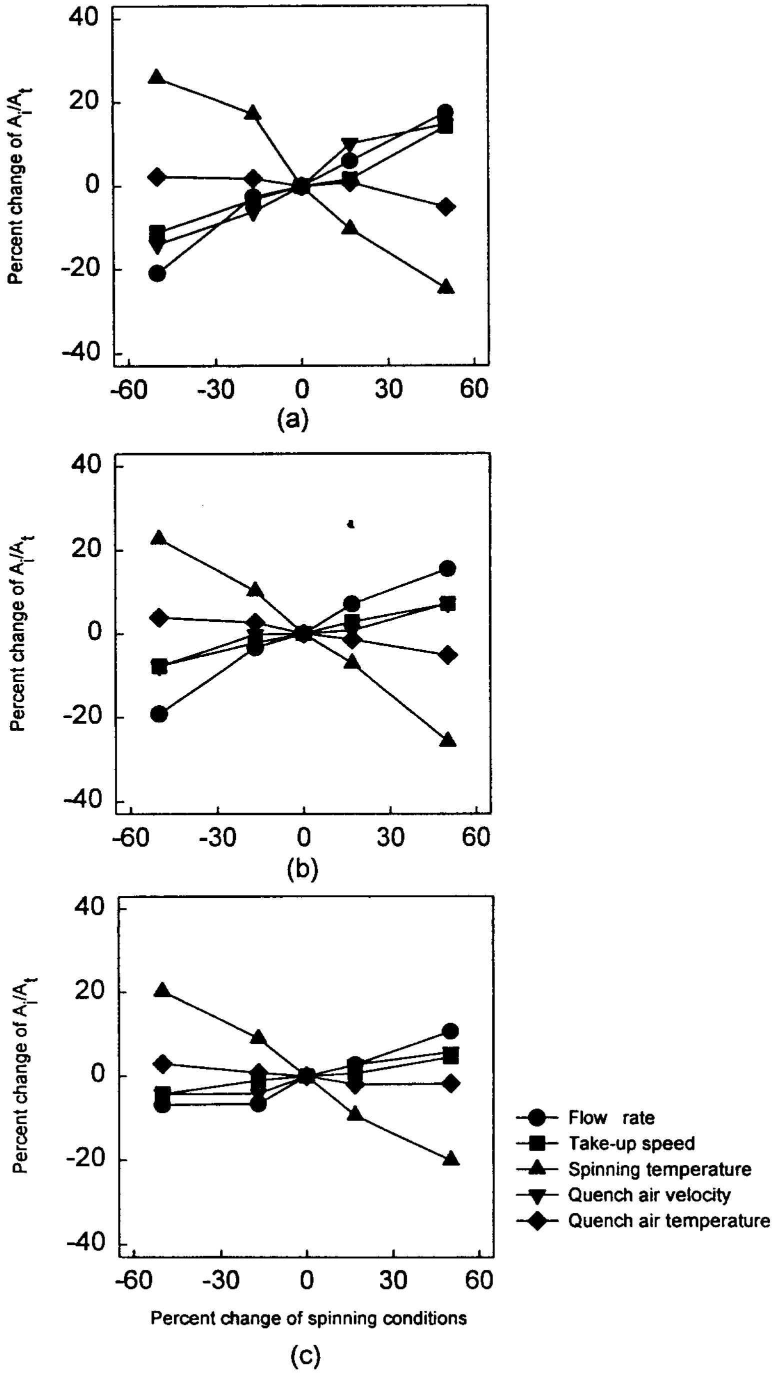

Fig. 4. Sensitivity analysis for A_i/A_t of hollow fiber at different spinning conditions: (a) $R_i/R_o = 0.75$, (b) $R_i/R_o = 0.8$ and (c) $R_i/R_o = 0.85$.