Fiber Diameter of Polybutylene Terephthalate Melt-Blown Nonwovens

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ABSTRACT: A polymer air-drawing model of Polybutylene Terephthalate (PBT) melt-blown nonwovens has been established. The predicted fiber diameter coincides with the experimental data. The effects of the processing parameters on the fiber diameter have been investigated. A lower polymer flow rate, a higher initial air velocity, and a larger die-to-collector distance can all produce finer fibers, whereas too high an initial air velocity and too large a die-to-collector distance contribute little to the polymer drawing of PBT melt-blown nonwovens. The results show the great potential of this research for the computer-assisted design of melt-blowing technology. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 97: 1750–1752, 2005

Key words: computer modeling; fibers; drawing

INTRODUCTION

Our previous work has shown that the predicted fiber diameter of melt-blown nonwoven fabrics coincides with the measured data quite well with the use of a polymer air-drawing model that we have established with special reference to polypropylene.[1,2] The polymer flow behavior is, however, not quite the same for different kinds of polymers because of their different shear viscosity and constitutive equations. To determine whether the model can be used for predicting the fiber diameter of other polymers, such as polyesters, work similar to that mentioned previously has been done especially for the polybutylene terephthalate (PBT) polymer in this study. Meanwhile, in comparison with ordinary polyester, the methylene segment of the PBT macromolecular chain is longer, and the melting point and glass temperature of PBT are lower; this consequently makes PBT more suitable for melt-blowing processing, and its products are characterized by high porosity, tiny pore diameters, and ultrafine fibers. All these features mean that PBT melt-blown nonwoven fabrics can serve the function of filter materials well, and they also push us to further investigate how fine a fiber diameter can be reached in the melt-blowing process and what factors influence the fiber diameter formed.

POLYMER AIR-DRAWING MODEL WITH REFERENCE TO PBT

The polymer air-drawing model consists of a continuity equation, a momentum equation, an energy equation, and a constitutive equation. The air velocity and air temperature are obtained by the numerical solution of the air-jet flow field of a dual-slot die.[1]

Continuity equation

$$G = \frac{\pi}{4} D^2 u \rho \tag{1}$$

where G is the polymer flow rate, D is the fiber diameter, u is the fiber velocity, and ρ is the polymer density. ρ of PBT is 1.35 g/cm^3.[3]

Momentum equation

$$\frac{dF_r}{dx} = G\frac{du}{dx} + \frac{1}{2} j\pi D C_f\, \rho_a (u_a - u)^2 - \frac{\pi}{4} D^2 \rho g \tag{2}$$

where F_r is the rheological force, ρ_a is the air density, x is the axial position, u_a is the x component of the air velocity, C_f is the air-drawing coefficient, and g is the gravitational acceleration. The j factor is a sign flag; that is, j is -1 when u_a is greater than u, and j is 1 when u_a is less than u. This means that, near the spinneret, the air flow acts a positive (downward) force on the polymer, but on the far side of the spinneret, the force is negative.

F_r is

$$F_r = \frac{\pi}{4} D^2 (\tau_{xx} - \tau_{yy}) \tag{3}$$

where τ_{xx} is the axial tensile stress of the polymer and τ_{yy} is the transversal tensile stress of the polymer.

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TABLE I
Experimental Program and Results

Parameter	Testing number 1	2	3	4	5	6	7
Polymer flow rate (g/s)	0.049	0.049	0.049	0.079	0.098	0.049	0.049
Initial polymer temperature (°C)	280	280	280	280	280	280	280
Initial air velocity (m/s)	311	91	194	311	311	311	311
Initial air temperature (°C)	320	320	320	320	320	320	320
Die-to-collector distance (cm)	10	10	10	10	10	12	14
Measured fiber diameter (μm)	4.87	8.58	5.24	6.15	6.75	4.52	4.24
Predicted fiber diameter (μm)	4.53	8.14	4.96	5.61	6.04	4.11	3.85
Error (%)	6.98	5.13	5.34	8.78	10.52	9.07	8.77

C_f was given by Matsui[4] with the following correlation:

$$C_f = \beta Re^{-n} \tag{4}$$

where β and n are the constants of Matsui's correlation and Re is the Reynolds number.

Re is defined by

$$Re = \frac{D|u_a - u|}{\upsilon_a} \tag{5}$$

where υ_a is the air kinematic viscosity. Majumdar and Shambaugh[5] found that $\beta = 0.78$ and $n = 0.61$ are appropriate values for eq. (4). These values have been used in our computations.

Energy equation

$$\frac{d\theta}{dx} = -\frac{\pi D h_p(\theta - \theta_a)}{G C_p} \tag{6}$$

where C_p is the specific heat capacity at a constant pressure of the polymer, h_p is the heat-transfer coefficient, and θ_a is the air temperature. C_p of PBT is 0.3 cal/(g °C).[3]

A value for h_p can be calculated from the following relation:

$$Nu = \gamma Re^k \tag{7}$$

where Nu is the Nusselt number and γ and k are constants of this correlation. The assumed values of γ and k are 0.42 and 0.334, respectively.[6]

Constitutive equation

Because the polymer melt of PBT is a kind of non-Newtonian fluid, the constitutive equation of the power-law fluid is introduced in our model:

$$\tau_{xx} = 2\eta\left(\frac{du}{dx}\right)^m \tag{8}$$

$$\tau_{yy} = -\eta\left(\frac{du}{dx}\right)^m \tag{9}$$

where η is the shear viscosity and m is the power-law exponent.

According to Wei,[3] m of PBT is 0.34, which is different from the m value of 0.78 in our previous study for a polypropylene melt-blown nonwoven.[2]

The freezing-point boundary condition is defined as the point at which the rheological force equals the sum of the gravitational force and air-drawing force acting on the frozen part of the polymer. Beyond the freezing point, the fiber diameter remains constant until the fiber is laid down on a collection screen.

EXPERIMENTAL

The experiments were carried with the melt-blowing nonwoven equipment at Donghua University.[3] The dual-slot-die parameters were as follows: die width = 0.7 mm, die length = 200 mm, slot width = 0.2 mm, head width = 0.5 mm, angle between the slot and spinneret axis = 30°, and spinneret diameter = 0.3 mm. The initial polymer temperature and the initial air temperature were 280 and 320°C, respectively. The polymer was 62 MFI L1082 PBT. The experimental program and results are shown in Table I.

The parameters of concern are the polymer flow rate, initial air velocity, and die-to-collector distance. To condense the discussions and comparisons, a group of fundamental parameters was assumed during the computations: a polymer flow rate of 0.049 g/s, an initial air velocity of 311 m/s, and a die-to-collector distance of 10 cm. When one processing parameter was varied, the fundamental values of the other two were maintained. The image analysis method was employed to measure the fiber diameter. The images of nonwoven samples were acquired with a Questar three-dimensional video frequency microscope (Questar Corp., New Hope, PA) with an enlargement factor of 600 and a depth of focus of 1 mm and then processed with Image-Pro Plus image analysis software (Media Cybernetics, Inc., Silver Spring, MD) to measure the fiber diameter. The image processing included enhancement, smoothing, binarization, and filtering. The mean value of the diameters of 200 fibers was considered the fiber diameter of a PBT nonwoven sample.

Figure 1 shows the effects of the polymer flow rate on the fiber diameter. As expected, reducing the poly-

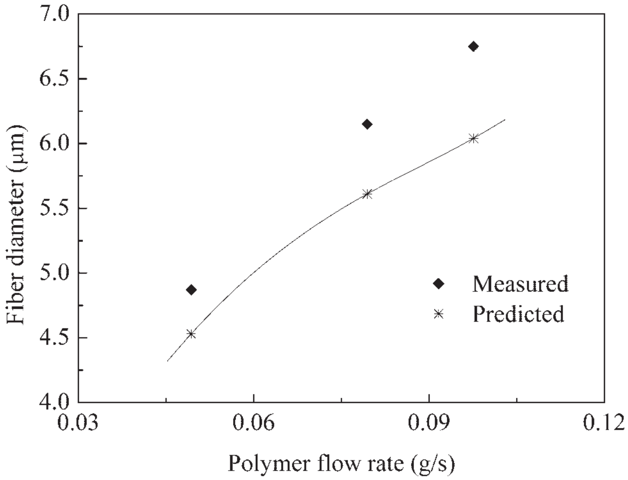

Figure 1 Effects of the polymer flow rate on the fiber diameter.

mer flow rate produces a finer fiber diameter. For the conditions in Figure 1, the final fiber diameter of 4.87 μm for a polymer flow rate of 0.049 g/s is 28% smaller than the final fiber diameter of 6.75 μm for the high polymer flow rate (0.098 g/s).

Figure 2 illustrates how changes in the initial air velocity cause changes in the rate of fiber attenuation. The higher the initial air velocities are, the finer the fibers are. The high initial air velocity (311 m/s) results in a final fiber diameter of 4.87 μm, whereas the low initial air velocity (91 m/s) results in a final fiber diameter of 8.58 μm. The fiber diameter decays less rapidly when the initial air velocity increases over 200 m/s. It can be concluded that too high an initial air velocity contributes little to the polymer drawing as far as the polymer melt of PBT is concerned, and this gives us valuable insight into reducing the energy consumption of the melt-blowing process.

Figure 3 shows the effect of the die-to-collector distance on the fiber diameter. A larger distance causes the fibers to be attenuated much more. When the distance increases to 14 cm, the final fiber diameter is 13% smaller than that when the distance is 10 cm. Moreover, the fiber diameter only decreases slightly when the die-to-collector distance is larger than 12 cm as far as this investigation is concerned. The reason may be that the polymer drawing procedure is completed within a certain distance, after which the fiber diameter does not change even when the die-to-collector distance still increases.

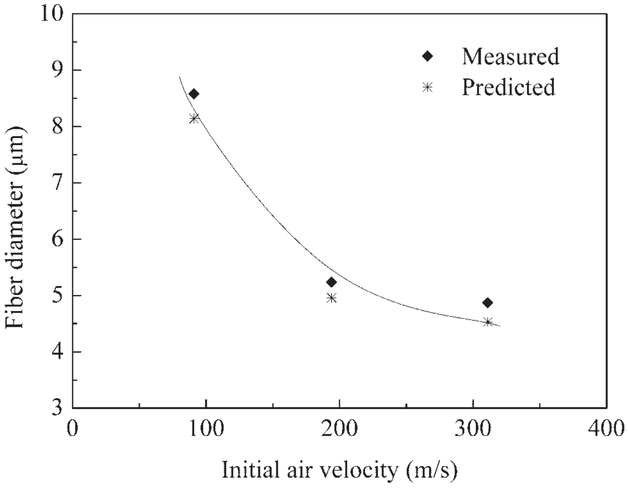

Figure 2 Effects of the initial air velocity on the fiber diameter.

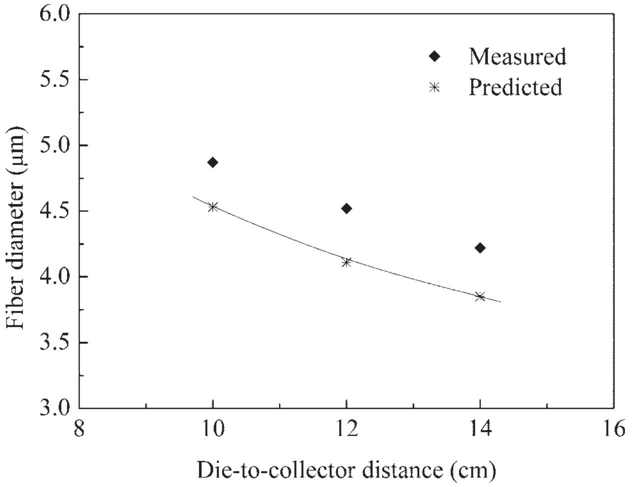

Figure 3 Effects of the die-to-collector distance on the fiber diameter.

The predicted and measured fiber diameters are shown in Figures 1–3. These figures show that the predicted results match the experimental data quite well, and this confirms the effectiveness of the polymer air-drawing model established in this article. However, all the predicted values are lower than the measured values, and this indicates that there is a systematic error and that one of the assumed constants should be corrected later.

CONCLUSIONS

A polymer air-drawing model of PBT melt-blown nonwovens has been established. The predicted fiber diameter coincides with the experimental data. The effects of the processing parameters on the fiber diameter have been investigated. A lower polymer flow rate, a higher initial air velocity, and a larger die-to-collector distance can all produce finer fibers, whereas too high an initial air velocity and too large a die-to-collector distance contribute little to the polymer drawing of PBT melt-blown nonwovens. The results show the great potential of this research for the computer-assisted design of melt-blowing technology.

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