Empirical Models for Melt Blowing

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SYNOPSIS

A large data set obtained for melt blowing using a single hole die has been used to develop empirical models which express final average fiber diameter as a function of dimensionless independent variables. The resulting empirical models or equations have been compared to multihole melt-blowing die data. The conclusion of this investigation is that appropriate first-order variables have been identified and the dependence of average final fiber diameter on the independent variables has been established. The resulting model should prove very useful for use in melt-blowing process control and in the design of melt-blowing equipment for polypropylene with an MFR between 500 and 900. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

The complex interaction of polymer characteristics and aeroelasticity associated with the melt-blowing process has not been adequately modeled at this time. The final fiber diameter depends on the initial diameter and the drawing force history. The initial diameter is very dependent on the die swell, which occurs as the polymer is extruded through the orifice. The die swell is dependent on throughput, orifice geometry, polymer characteristics, and processing temperature. The drawing force history is dependent on the local relative velocity between the fiber and the air stream in addition to the local shape of the fiber filament. The flapping behavior of the melt-blown filament results in a continuously varying change in shape.[1]

Some success in theoretically modeling the initial drawndown has been achieved by investigators[2,3] but only with empirical values for die swell, distance to the final diameter, filament shape, and air jet characteristics including drag coefficients and heat transfer coefficients. In view of the lack of modeling capability to guide melt-blowing process changes and design, the current effort was undertaken to develop empirical models. The objective was to develop empirical equations for the common melt-blowing configuration, shown in Figure 1, which could be used to predict the effect of changing process conditions and to guide the design of melt-blowing equipment.

DATA FOR EMPIRICAL MODELS

The data used to develop the empirical models presented in this paper were obtained using the single hole die described in a prior publications.[4] The data covered a range of resin throughput from 0.4 to 1.2 g/min per hole, air temperatures from 250 to 540°F, polymer temperatures from 480 to 550°F, air velocities from 100 to 400 m/s, setbacks from 0 to 2 mm, and airgaps from 0.25 to 2.0 mm. All of the data were for a 60° included angle nosepiece die and for polypropylene with quoted MFR between 650 and 800.

This data set included some 270 different operating conditions covering most normal processing conditions. The data were limited to processing conditions resulting in no "shot" or "fly." Thus the empirical models are valid only for operation with no "shot" or "fly."

DEVELOPMENT OF EMPIRICAL MODELS

Typical results for a fixed geometry from the experimental investigation are shown in Figure 2. Often relationships obtained from experimental data

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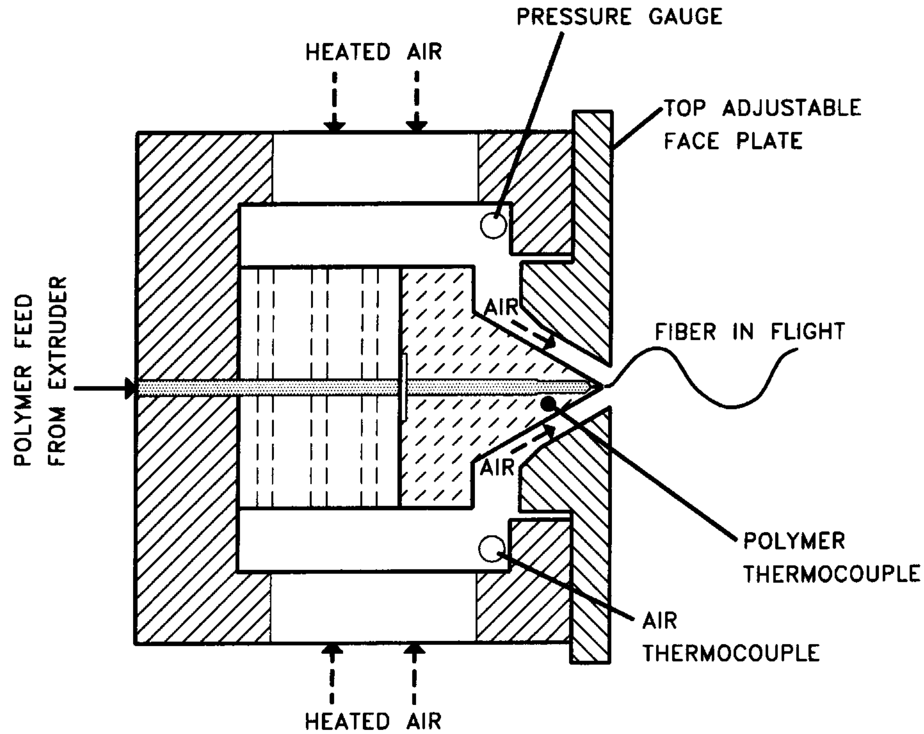

Figure 1 Sectioned view of single hole die.

are initially developed by trial and error or observation. By such observation it was concluded that the data shown in Figure 2 could be collapsed by dividing the air jet velocity by the polymer throughput. Shambaugh[5] presented fiber diameter as a function of mass flow ratio. The mass flow ratio is the ratio of the primary air mass flow rate to the polymer mass flow rate (throughput). The mass flow ratio reported by Shambaugh correlated his data with some success but has little utility for multiple-hole dies with different hole spacing, air gap, etc.

By introducing the air jet and polymer exit areas a mass flow flux ratio, Γ, was developed. Figure 3 shows all of the data presented in Figure 2 using the mass flow flux ratio, Γ, as the correlation parameter. For these fixed geometry data the mass flow flux ratio appears to correlate the data. When variable geometry data were considered the mass flow flux ratio did not correlate the data nearly as well.

By introducing a momentum flux ratio parameter, Ψ, it was possible to obtain a much improved correlation with the data for varying geometries. Using dimensional analysis and observation the following dimensionless parameters were identified as important in describing the melt-blowing process for a given polymer:

Diameter Ratio, δ, defined as the final average fiber diameter divided by the polymer orifice diameter.

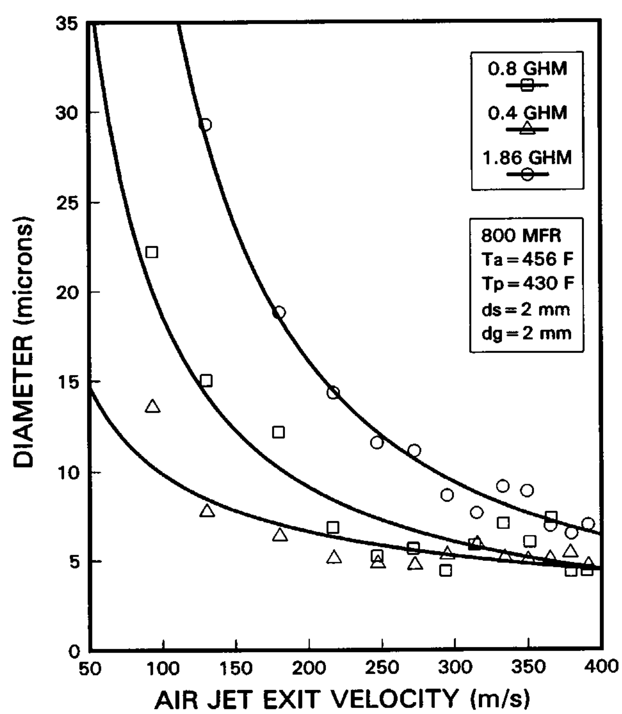

Figure 2 The effect of air jet velocity on average fiber diameter for three throughputs.

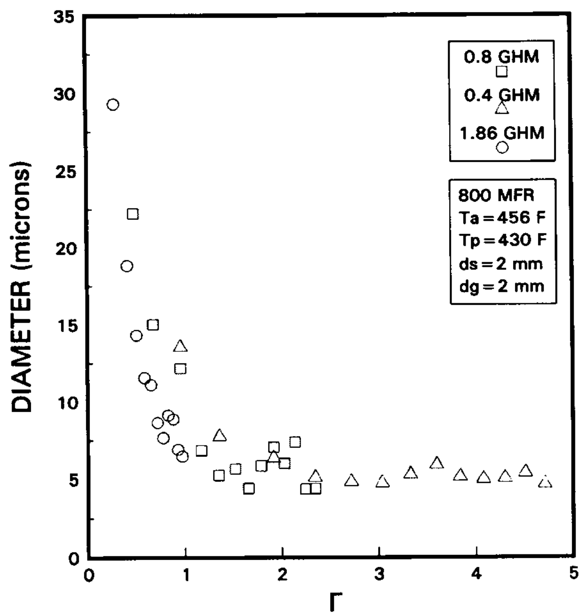

Figure 3 Average fiber diameter versus air to melt mass flux ratio for three throughputs.

Momentum Flux Ratio, Ψ, defined as the air momentum per unit of air exit area divided by the polymer momentum per unit of polymer exit area.

Mass Flux Ratio, Γ, defined as the air mass flow rate per unit of exit air area divided by the polymer mass flow rate per unit of polymer exit area.

Polymer Throughput Ratio, β, defined as the mass flow rate of polymer divided by a reference mass flow rate of polymer, 0.8 g/min hole.

Polymer Temperature Ratio, θ, defined as the polymer temperature divided by a reference polymer temperature, 500°F.

Air Temperature Ratio, ξ, defined as the air stagnation temperature in the die divided by a reference die stagnation temperature, 375°F.

Die Face Width Ratio, ϕ, defined as the die face air width divided by a reference die face air width, 2.67 mm.

Using these variables with the diameter ratio as the dependent variable a statistical computer software package, SAS, was used to perform regression analyses and statistical analyses of the experimental data expressed in terms of the dimensionless parameters defined above.

Two empirical equations have been developed and will be presented along with the corresponding coefficients of multiple determination, γ^2. This coefficient gives an indication of whether the variation in the fit of the empirical equation is due to the regression or due to chance and thus the possibility that important prediction variables have not been considered. For example, $\gamma^2 = 0.8$ means that 80% of the variation is explained by the variation in the independent variables of the empirical equation and the remaining 20% is due to other factors.

Equation (1) is the empirical correlation expressed in terms of mass flux ratio, Γ.

$$\delta = 0.0047 + 0.0149\Gamma^{-1.49}\beta^{-0.65}\phi^{-1.12}\theta^{-3.47}\xi^{-0.92} \quad (1)$$

This correlation for the 270 processing conditions gave a coefficient of multiple determination, γ^2, of 0.92. To express the results in terms of the one independent variable, Γ, eq. (1) was rearranged in the form of eq. (2). Figure 4 is a plot of actual data versus the correlation.

$$\Delta = \frac{\delta - 0.0047}{0.0149\beta^{-0.65}\phi^{-1.12}\theta^{-3.47}\xi^{-0.92}} = \Gamma^{-1.49} \quad (2)$$

In a similar way a correlation in terms of momentum flux ratio, ψ, is given by eq. (3) and is shown in Figure 5.

$$\delta = 0.00646 + 3.373\psi^{-0.81}\beta^{-0.74}\phi^{-1.14}\theta^{-3.78}\xi^{-0.62} \quad (3)$$

Rearranging to a form similar to eq. (2) gives

$$\Delta = \frac{\delta - 0.00646}{3.373\beta^{-0.74}\phi^{-1.14}\theta^{-3.78}\xi^{-0.62}} = \psi^{-0.81} \quad (4)$$

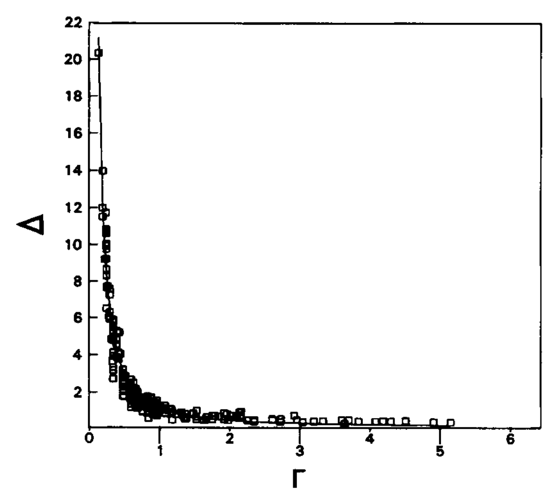

Figure 4 Comparison of single hole data with empirical mass flux ratio correlation.

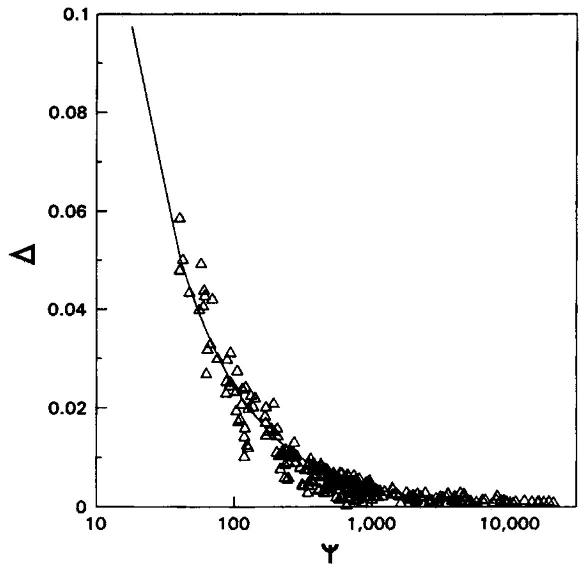

Figure 5 Comparison of single hole data with empirical momentum flux ratio correlation.

This correlational so gave a coefficient of multiple determination, γ^2, of 0.98. Both of these empirical equations provide a good model for these data. Equation (1) is the preferred model since the mass flux ratio, Γ, can be easily determined and when combined with the face width ratio, ϕ, results in an acceptable model. For general use, eq. (3) will give a better correlation since it is more responsive to significant geometry changes, i.e., setback, *ds*, and airgap, *dg*.

MULTIHOLE DATA

To examine the applicability of the empirical correlations given by eqs. (1) and (3) to multihole die, a comparison was made with the multihole data reported by Kahn.[6] These data were obtained on the 6-in. pilot line at the University of Tennessee. The die is of the "Exxon Configuration" with 20 holes per inch. The data are for polypropylene with 650 and 800 MFR. The die geometry covered orifice diameters of 15 and 20 mil, orifice L/Ds of 10 and 15, setbacks of −5 to 39 mil, throughputs of 2.4, 0.8, 1.2, and 1.6 g/min per hole, and air gaps of 30, 60, and 110 mil.

In Figure 6 the correlation of eq. (1) is compared to the 6-in. multihole data and in Figure 7 the correlation of eq. (3) is compared to the 6-in. line data. It is apparent from these figures that the momentum flux model gives a better correlation than the mass flux model. Since the agreement between the data

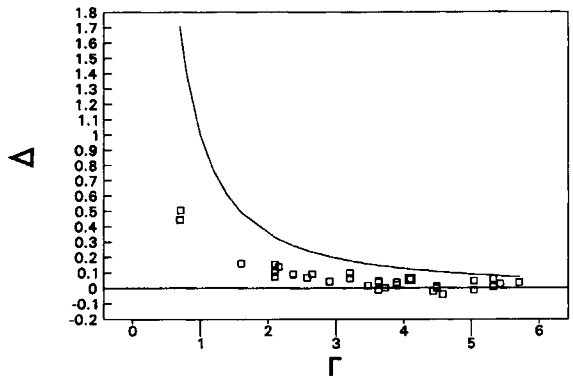

Figure 6 Multihole die data compared with mass flux ratio correlation.

and the empirical models is not as good as desired, an attempt was made to improve the correlations by calculating new constants but retaining the original variation with the independent variables (the exponents on the dimensionless parameters were not changed). Using the data set average value for the two constants in eq. (1) results in eq. (5).

$$\delta = 0.0044 + 0.0053\Gamma^{-1.49}\beta^{-0.65}\phi^{-1.12}\theta^{-3.47}\xi^{-0.92} \quad (5)$$

Figure 8 shows a comparison of this modified correlation with the 6 inch line data. The results is a much improved coefficient of multiple determination or in other words a much improved agreement between the data and empirical model.

Using this same averaging techniques for the constants in eq. (3) gives the following correlation.

$$\delta = 0.0044 + 1.5444\psi^{-0.81}\beta^{-0.74}\phi^{-1.14}\theta^{-3.78}\xi^{-0.62} \quad (6)$$

Figure 9 shows a comparison of this equation with the 6-in. line data. Again the agreement is greatly improved by using average values for the constants.

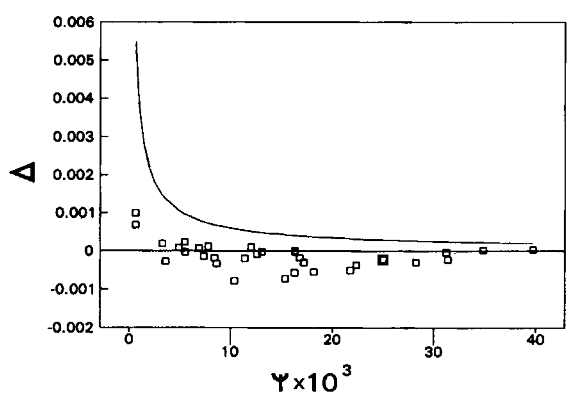

Figure 7 Multihole die data compared with momentum flux ratio correlation.

CONCLUSIONS

The empirical correlations given by eqs. (1) and (3) correctly describe the variation of final fiber diameter with the dimensionless independent variables. It appears the effect of a multihole die can be described by different values of the leading constants with no change in the variation with dependent variables. Since the mass flux parameter is much easier to use and when combined with the face width parameter adequately describes the momentum dependence, it is recommended that the following correlation be used to describe the common melt-blowing process.

$$\delta = C_1 + C_2\Gamma^{-1.49}\beta^{-0.65}\phi^{-1.12}\theta^{-3.47}\xi^{-0.92} \quad (7)$$

The constants C_1 and C_2 would be determined for the particular melt-blowing line and polymer in question by evaluating the constants at two different air flow rates. This technique will allow for variations in geometry and polymer characteristics, which are not described by the constants in the models presented. Since it is the variation of fiber diameter with the processing variables, throughput, polymer temperature, air temperature, and air rate, which is needed for process control, the models provide a much needed tool for melt-blowing processes. In the absence of any experimental data for an existing or proposed melt-blowing line the values for C_1 and C_2 given in eq. (4) should prove adequate for parametric design evaluations and process control when using polypropyline with MFR values between 600 and 900.

At least one first-order variable has not been explored with the empirical model presented in this investigation. The basic viscoelastic nature of the polymer as normally characterized in terms of MFR is a first-order variable which needs investigation. Several second-order variables such as orifice L/D, setback, airgap, air injection angle, collection distance, and collection suction will need to be incorporated into models in order to enhance the sensitivity of such models.

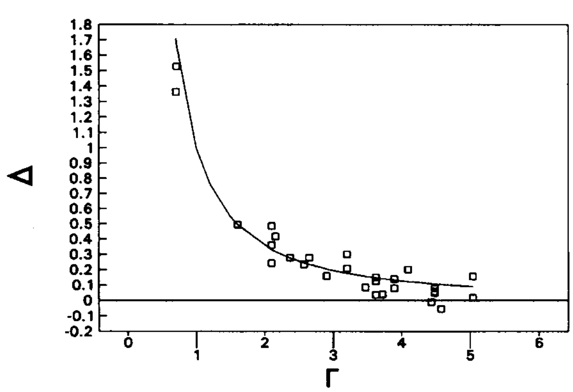

Figure 8 Multihole die data compared with modified mass flux ratio correlation.

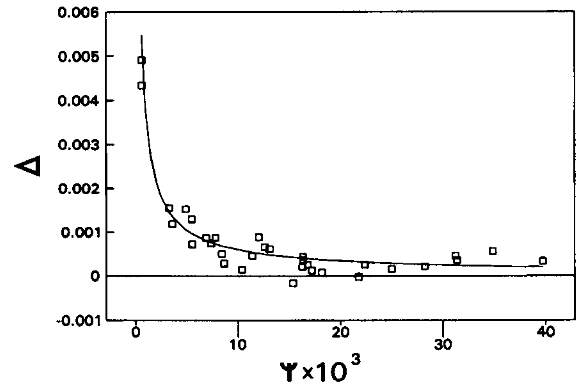

Figure 9 Multihole die data compared with modified momentum flux ratio.

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