Analysis and Simulation of Non-Newtonian Flow in the Coat-Hanger Die of a Meltblown Process

QIN SUN, DONG ZHANG

TANDEC, The University of Tennessee, Knoxville, Tennessee 37919-1950

Received 28 February 1997; accepted 7 June 1997

ABSTRACT: Meltblown is one of the fastest growing processes for nonwoven production. The design of the coat-hanger geometry of a die is very important for meltblown technology. In this article, melt rheological properties were studied based on capillary rheometry, followed by analysis and simulation of the melt flow in the die and its experimental verification. It is essential for the optimal design of the die and helps to better understand the meltblown process as well. The result of this research showed that the rheological properties of melt flow in the die obey the power-law equation very well in the meltblown process. The coat-hanger die has a good operation feasibility for different resins and various operation conditions from the view of web uniformity. The pressure drop through the orifices is the major contribution to the pressure drop in the die. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci **67:** 193–200, 1998

INTRODUCTION

Meltblown is a one-step process to produce fabrics from thermoplastic polymers. It has become an important industrial technique because of its ability to produce fabrics of microfiber structure, which are ideally suited for filtration media, thermal insulators, battery separators, oil sorbents, and so on. In the meltblown process (Fig. 1), the polymer is heated and fed into the extruder and distributed by a die channel, generally a single or multi-coat-hanger structure to distribute the melt in width in order to obtain the uniformity of the final fabrics (Fig. 2). The coat-hanger geometry directly affects the distribution of melt throughput in width, so its design is very important for meltblown technology. Analysis of the melt non-Newtonian flow in the die is essential for its optimal design. However, reports of the relative research are very limited due to its highly commercial availability and much design work still has to be done, mainly empirically.

The melt flow rate (MFR) or melt flow index (MFI or MI) is widely used in industry to describe the fluidity of a polymer melt. It is a simple flow value of the amount of material extruded at a standardized temperature through a die under pressure from a set mass over a period of 10 min.[1] A high MFR corresponds to a relatively low value of viscosity at very low shear rate. However, the MFR cannot be related directly to any form of shear viscosity useful in design calculations because it cannot reflect the relationship of shear stress to shear rate in the flow. No provision is made in the MFR test to show how fluidity varies with shear rate, temperature, and pressure.

In this article, melt rheological properties were studied based on capillary rheometry, followed by analysis and simulation of the melt flow in the die and its experimental verification. It is essential research for the optimal design of the meltblown die and is very important for the meltblown technology.

RHEOLOGICAL PROPERTIES OF POLYMERS IN THE DIE

Rheological properties of the polymer are the characteristics of the flow behavior concerned

Correspondence to: Q. Sun.

Journal of Applied Polymer Science, Vol. 67, 193–200 (1998)
 CCC 0021-8995/98/020193-08

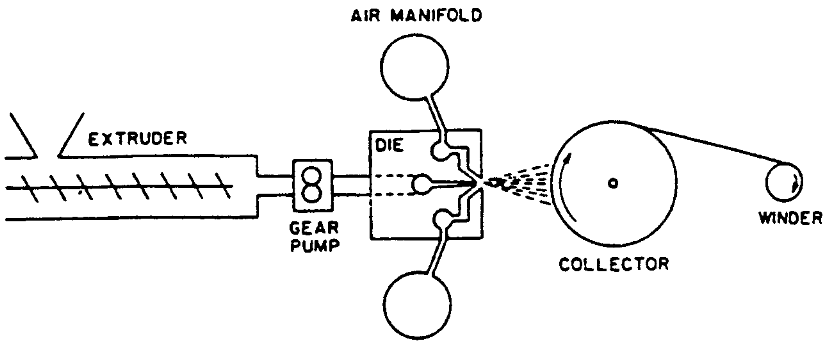

Figure 1 Schematic of a meltblown process.

with almost all aspects of deformation of the polymer melt under the influence of external stresses. Generally speaking, molten polymer is a viscoelastic fluid,[2] i.e., it is of both viscosity and elasticity. In the meltblown process, the behavior of melt flow in the die exhibits mainly viscous properties.

Viscosity is a measure of the relationship of shear stress to shear rate for a fluid, which is dependent not only on the polymer itself, but also on the flow conditions. However, the MFR or MFI or MI is widely used in the polymer industry to describe the fluidity of a polymer melt. It cannot be related directly to any form of shear viscosity useful in design calculations because it cannot reflect the relationship of shear stress to shear rate in the flow. No provision is made in the MFR test to show how fluidity varies with shear rate, temperature, and pressure. So, the rheological properties of polymers in the die should be studied before analysis and simulation of the melt flow.

The power-law model, one of the most widely used principles in polymer rheology, was used to describe the relationship between the shear stress and the shear rate:

$$\eta = K|\dot{\gamma}|^{n-1} \tag{1}$$

K follows the Arrhenius relationship:

$$K = K_0 \exp\left[\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{2}$$

For three-dimensional flow, the shear rate tensor $(\dot{\gamma})$ can be described as

$$\dot{\gamma} = \begin{Bmatrix} \gamma_{xx} & \gamma_{xy} & \gamma_{xz} \\ \gamma_{yx} & \gamma_{yy} & \gamma_{yz} \\ \gamma_{zx} & \gamma_{zy} & \gamma_{zz} \end{Bmatrix} \tag{3}$$

where

$$\gamma_{xx} = \frac{\partial u_x}{\partial x}, \quad \gamma_{yy} = \frac{\partial u_y}{\partial y}, \quad \gamma_{zz} = \frac{\partial u_z}{\partial z},$$

$$\gamma_{xy} = \gamma_{yx} = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right),$$

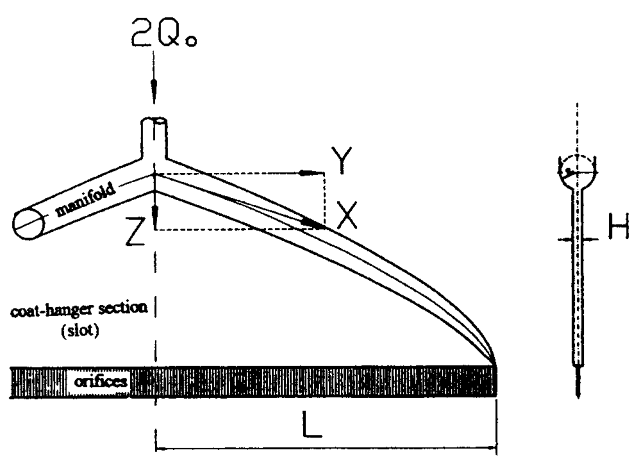

Figure 2 Structure of a coat-hanger die.

$$\gamma_{yz} = \gamma_{zy} = \frac{1}{2}\left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z}\right), \quad \text{and}$$

$$\gamma_{zx} = \gamma_{xz} = \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)$$

According to the properties of the tensor, we get

$$|\dot{\gamma}|^2 = 2\left(\frac{\partial u_x}{\partial x}\right)^2 + 2\left(\frac{\partial u_y}{\partial y}\right)^2 + 2\left(\frac{\partial u_z}{\partial z}\right)^2 + \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right)^2 + \left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)^2 + \left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right)^2 \quad (4)$$

The constitutive equations for common three-dimensional flow are shown as follows, which can be reduced to some simple forms according to differential particular conditions[2–4]:

$$\left.\begin{aligned} \tau_{xy} &= \tau_{yx} = \eta\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) \\ \tau_{yz} &= \tau_{zy} = \eta\left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right) \\ \tau_{zx} &= \tau_{xz} = \eta\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) \end{aligned}\right\} \quad (5)$$

DETERMINATION OF THE RHEOLOGY PARAMETER

For the power-law fluid, the rheological parameters (K and n) are usually obtained by some experimental techniques, such as capillary rheometry, cone-and-plate rheometry, and parallel plate rheometry. In this research, the capillary rheometer Instron Model 3211 was used for rheological measurement of the polypropylenes (PPs) and the values of K and n were obtained based on the principle of capillary rheology. Table I shows the values of K and n for the PP polymers in this study.

Capillary rheometry is a measurement of the flow rate in a tube as a function of the pressure drop, which is the technique that has been most popular for the study of the rheological properties of liquids, because it is the viscometric flow most easily generated in the laboratory. The basic equation for capillary rheometry is

$$\frac{\Delta P \cdot D}{4L} = K\left(\frac{3n + 1}{4n}\right)^n \cdot \left(\frac{4Q}{\pi R^3}\right)^n \quad (6)$$

The values of K and n can be obtained from the slope and intercept of the straight line of

$$\ln \frac{\Delta P \cdot D}{4L} \text{ vs. } \ln\left(\frac{4Q}{\pi R^3}\right)$$

Figures 3 and 4 are the power-law flow curves of the Xindu PP MFR 60 and the Exxon PP MFR60, respectively, which show very good agreement with the power-law relationship.

MELT FLOW IN THE DIE

Assumptions

Basic assumptions in this study include the following:

1. The flow is steady and fully developed.
2. Mass and inertia forces are neglected.
3. There is no slip at the die walls.
4. The melt is purely viscous and incompressible.
5. The melt in the manifold flows only along the X direction and the melt in the coathanger section flows only along the Z direction.
6. Melt flow is laminar and isothermal.
7. Melt obeys the power law.

Flow Equations of Melt Flow in the Die

Melt Flow in the Manifold[5]

$$Q_1 = \left(\frac{\pi n}{3n + 1}\right) \cdot \left(\frac{1}{2K}\right)^{1/n} \times \frac{r^{(3n+1/n)}}{\left[1 + \left(\frac{dY}{dZ}\right)^2\right]} \cdot \left(\frac{dP_1}{dZ}\right)^{1/n} \quad (7)$$

Melt Flow in the Slot[5]

$$Q_2 = \frac{n}{2(2n+1)} \cdot \left(\frac{1}{2K}\right)^{1/n} \cdot H^{(2n+1)/n} \cdot \left(\frac{dP_2}{dZ}\right)^{1/n} \quad (8)$$

According to flow continuity, we have

Table I Power-law Parameters (*K* and *n*) of PP Resins for the Meltblown Process

Resin	Temperature (°C)	K (kg cm^{-2} s)	n	Shear Rate (s^{-1})
Exxon MFR35	282	3.175×10^{-3}	0.67	10^2–10^4
	293	2.593×10^{-3}	0.71	
	304	2.147×10^{-3}	0.73	
	315	1.370×10^{-3}	0.79	
	327	7.665×10^{-4}	0.85	
Exxon MFR800	249	7.072×10^{-4}	0.70	10^2–10^4
	260	7.056×10^{-4}	0.69	
	271	6.303×10^{-4}	0.70	
	282	5.217×10^{-4}	0.72	
	293	2.114×10^{-4}	0.82	
Xindu MFR60	240	2.738×10^{-3}	0.68	10^0–10^4
	260	1.790×10^{-3}	0.68	
	280	1.050×10^{-3}	0.73	10^1–10^4

$$Q_2 = -\frac{dQ_1}{dY} \tag{9}$$

Melt Flow in the Orifices

In the meltblown fiber-forming process, polymer melt has two basic flow fields which are divided by the orifices. One is the melt flow before the orifices and it fundamentally belongs to the shear flow and the other is that after the orifices which essentially belongs to the uniaxial extensional flow. The flow in the orifices belongs mainly to the pressure flow under the effect of the pressure drop, which is often approximately treated as simple shear flow while the entrance and exit effects usually should be considered.

As the fluid approaches the entrance to the capillaries, it starts to undergo a change in velocity distribution, reaching a practically fully developed profile only after moving a small distance down the capillaries. There is a strong convergence of streamlines at the entrance to the capillaries, so there is a high degree of stretching along streamlines. The melt flow through the orifices, quite different from simple shear flow, includes the convergence flow at the entrance, fully devel-

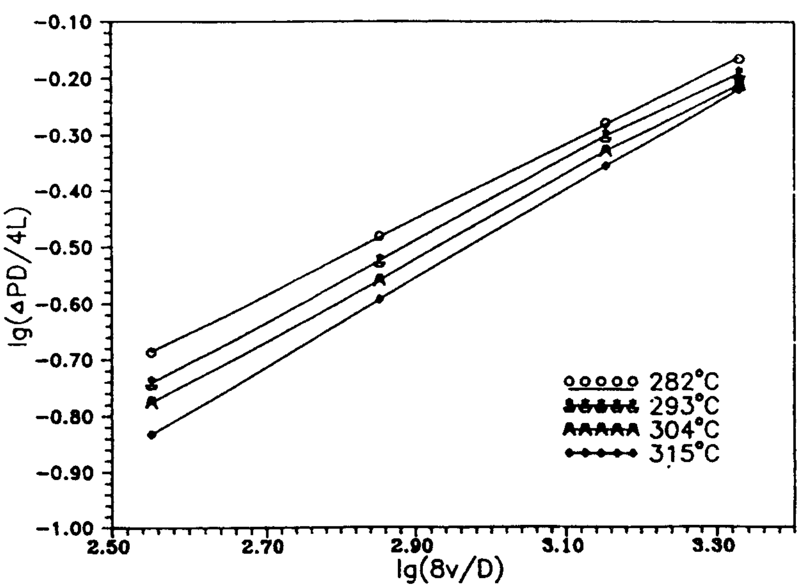

Figure 3 Power-law flow curves of Exxon PP MFR35.

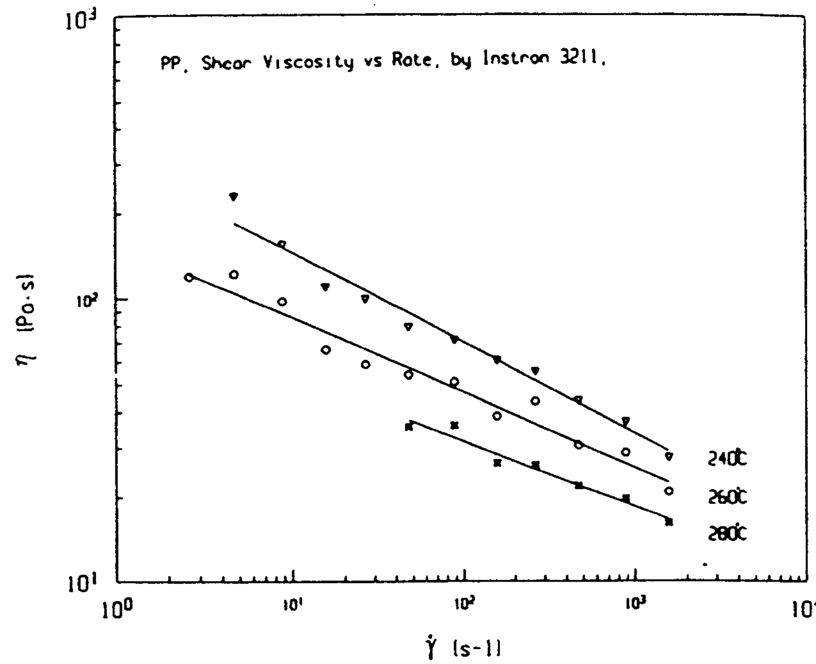

Figure 4 Power-law curves of Xindu PP MFR60.

oped flow in the capillary, and transferring flow to the extensional flow at the exit, which exhibits more viscoelasticity. The entrance pressure drop (ΔP_{ent}), which is especially large in the case of elastic liquid compared to inelastic liquids, generally makes a substantial contribution to the driving pressure. The pressure drop (ΔP) through the orifices consists of three parts, i.e., the entry pressure drop from the converged area of the slot section to the orifices (ΔP_{ent}), the pressure drop caused from the viscous resistance of the flow in the orifices (ΔP_c), and the exit pressure drop at the exit of the orifices (ΔP_{exit}). It can be expressed by

$$\Delta P = \Delta P_{\text{ent}} + \Delta P_c + \Delta P_{\text{exit}} \tag{10}$$

According to the flow equations of the power-law fluid in a tube, we have

$$\Delta P_c = (Aq)^n \cdot L \tag{11}$$

where

$$A = \left[\frac{\pi n}{3n+1} \left(\frac{1}{2K} \right)^{1/n} R^{(3n+1)/n} \right]^{-1}$$

According to flow continuity, we get

$$Q_2 = \sum_{i=1}^{N} q_i \tag{12}$$

where N is the number of the orifices per unit width, and q_i, the volume flow rate of the orifice i.

The entrance pressure ΔP_{ent} was calculated by the Bagley (1954) correction method.[6] It uses a fictitious length of tubing $N_f R$ that is added to the actual length of tube L, such that the measured total ΔP across L is that which would be obtained in a fully developed flow over the length ($L + N_f R$) at the flow rate used in the experiment. The research[7] in spinning rheology showed that N_f is empirically valued as 6 when $L/D = 4-40$.

The exit pressure drop ΔP_{exit} is one of the characteristics of the capillary flow of viscoelastic fluid. It is a measure of the elastic energy of deformation that remains at the exit. For meltblowing, ΔP_{exit} is much smaller than ΔP_{ent} and ΔP_c ($\Delta P_{\text{exit}} \ll \Delta P_{\text{ent}}, \Delta P_c$), so the pressure drop over the orifices can be expressed as

$$\Delta P = \Delta P_{\text{ent}} + \Delta P_c = (Aq)^n (L + N_f R) \tag{13}$$

SIMULATION OF MELT FLOW IN THE DIE

Melt Throughput Distribution

Inserting eq. (9) into eq. (8) gives

$$-\frac{dQ_1}{dY} = \Psi_1 H^{(2n+1)/n} \left(\frac{dP_2}{dZ} \right)^{1/n} \tag{14}$$

where $\Psi_1 = 2(2 + 1/n)/(2K)^{1/n}$. By rearrangement of eq. (14), we have

$$\left(\frac{dP_2}{dZ}\right)^{1/n} = \left(-\frac{dQ_1}{dY}\right)\Psi_1 H^{-(2n+1)/n} \qquad (15)$$

According to assumption 5, $\frac{dP_1}{dZ} = \frac{dP_2}{dZ}$; thus,

$$\left(\frac{dP_1}{dZ}\right)^{1/n} = \left(-\frac{dQ_1}{dY}\right)\Psi_1 H^{-(2n+1)/n} \qquad (16)$$

By inserting eq. (16) in to eq. (7), we get

$$Q_1 = \Psi_1\Psi_2 H^{-(2n+1)/n} r^{(3n+1)/n} \times \left(-\frac{dQ_1}{dY}\right)\cdot\left[1 + \left(\frac{dY}{dZ}\right)^2\right]^{-(1/2n)} \qquad (17)$$

where

$$\Psi_2 = \left(\frac{\pi n}{3n+1}\right)\left(\frac{1}{2K}\right)^{1/n}$$

Here, r and dY/dZ can be described as the functions of Y according the coat-hanger geometry. The coat-hanger geometry of the industrial die in this research obeys[8]

$$\left.\begin{aligned} r &= R_0\left(1 - \frac{Y}{Z}\right)^{1/3} \\ Z &= Z_0\left(1 - \frac{Y}{L}\right)^{2/3} \\ R_0 &= 0.482(BH^2)^{1/3} \\ Z_0 &= 1.474(HB^2)^{1/3} \end{aligned}\right\} \qquad (18)$$

So, eq. (17) can be expressed by

$$Q_1 = f(Y)\,\frac{dQ_1}{dY} \qquad (19)$$

where

$$f(Y) = \Psi_1\Psi_2^{-1} H^{-(2n+1)/n}\cdot r^{(3n+1)/n} \times \left[1 + \left(\frac{dY}{dZ}\right)^2\right]^{-(1/2n)} \qquad (20)$$

By rearrangement of eq. (19), we have

$$\frac{dY}{f(Y)} = \frac{dQ_1}{Q_1} \qquad (21)$$

The following boundary condition was used to solve eq. (21):

$$Y = 0,\ Q_1 = Q_0$$

Integrating eq. (21) gives

$$\int_0^Y \frac{dY}{f(Y)} = \int_{Q_0}^{Q_1} \frac{dQ_1}{Q_1} = \ln\left(\frac{Q_1}{Q_0}\right) \qquad (22)$$

$$Q_1 = Q_0\cdot\exp\left(\int_0^Y \frac{dY}{f(Y)}\right) \qquad (23)$$

Thus, Q_1 can be obtained by differential calculation of eq. (23) and Q_2 can be calculated in the same way by solving $Q_2 = (dQ_1)/(dY)$. To express the uniformity directly, the concept of uniformity was used, which is defined as

$$U = 1 - \sqrt{\frac{1}{N}\sum_{i=1}^{N}\Delta_i^2} \qquad (24)$$

where $\Delta_i = 1 - (q_i/q)$.

The Distribution of Pressure

Pressure Drop of the Slot (ΔP_2)

ΔP_2 is the pressure drop from the center of the manifold over a length of Z_0 along the Z direction (Fig. 2), which is the total pressure drop in the manifold. It can be calculated by the following equation according to eq. (8):

$$\Delta P_2 = \Psi_2^{-1} H^{-(2n+1)/n} Z_0\cdot Q_2 \qquad (25)$$

Pressure Drop Through the Orifices (ΔP_3)

According to eq. (13), ΔP_3 can be expressed as

$$\Delta P_3 = \left(\frac{AQ_0}{N_t}\right)^n (L/D + N_f/2)D \qquad (26)$$

The total pressure drop (ΔP_t) in the die is the sum of ΔP_2 and ΔP_3, i.e.,

$$\Delta P_t = \Delta P_2 + \Delta P_3 \qquad (27)$$

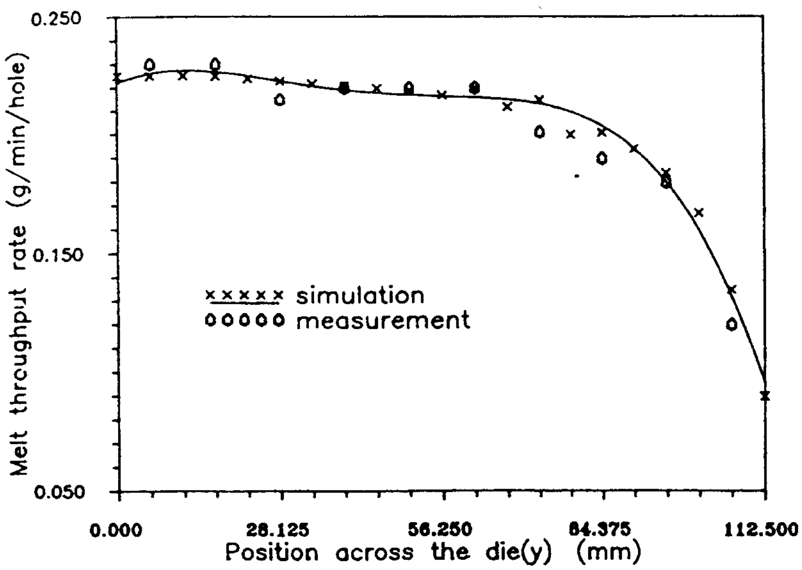

Figure 5 Comparison of simulation results to actual measurement of the MFR.

SIMULATION CASE AND RESULTS DISCUSSION

Given: The die width $2L = 225$ mm; the slot gap $H = 1.6$ mm; the geometry of coat-hanger follows eq. (18); the melt throughput rate was 0.2 g/min/hole; the orifices were arranged in such a way that there is a hole per 0.8 mm width; the orifice diameter was 0.4 mm and the L/D ratio was 15, and Xindu PP was used with $n = 0.73$ and $K = 105.0$ Pa s.

The melt throughput distribution was obtained according to eqs. (22)–(24). Figure 5 is a comparison of simulation results to actual measurement of the MFR. It showed a good agreement between the simulation and the measurement, indicating that the simulation method in this article is valid although some assumptions were made to simplify the problem.

According to eq. (24), the uniformity of melt flow was 85.5% and the actual value was 83.2%. The pressure drop in the slot (ΔP_2) and in the orifices (ΔP_3) were 0.572 and 9.914 kg/cm^2, respectively. It showed that the pressure drop in the orifices is the major part of the pressure drop in the die, which is due to the fact that the manifold and slot have a substantially larger section than has the capillary and so the pressure drop in the manifold and slot is much smaller compared to that resulting from the wall shear stress in the capillary. The pressure drop in the die increases proportionally as the L/D ratio increases.

The above analysis was based on the fact that the rheological parameters (K and n) are constant. Shear rate was considered since they are only constants within a certain shear rate range. The shear rate was calculated according to Ref. 5, which was 13.89, 15.07, and 796.11 s^{-1} in the manifold, slot, and orifices, respectively. As shown in Figure 4, the power-law parameters in this range can be treated as constants although the shear rate in the orifices is much greater than that in the manifold and slot.

Table II shows the effect of different of PP pellets and operation conditions on the uniformity of the MFR using the same die. The uniformities are nearly the same although different resins and processing conditions are used. It indicates that the coat-hanger die has a very good operation feasibility for different raw materials and a reasonable change of processing parameters. In other words, different resins and adjustment of processing parameters usually do not notably affect the web uniformity.

SUMMARY

This article studied the melt rheological properties in the die of the meltblown process according to capillary rheometry and presented a method to simulate its non-Newtonian flow. It is an essential research for the meltblown technology and is very useful for the optimal design of the die geometry.

The results of this research showed that the melt flow in the die obeys power-law behavior very well. The coat-hanger die has a good operation feasibility for different resins and various

Table II Effect of Different Resins and Operation Conditions on the Uniformity

Resins	Temperature (°C)	Melt Throughput Rate (g/min/Hole)	Uniformity (%)
Exxon MFR35	282	0.2–1.2	0.84
	293		0.84
	304		0.85
	315		0.86
	327		0.86
Exxon MFR800	249	0.4–2.0	0.85
	260		0.84
	271		0.84
	282		0.85
	293		0.86
Xindu MFR60	240	0.2–1.2	0.84
	260		0.84
	280		0.85

operation conditions from the view of web uniformity. The pressure drop through the orifices is the major contribution to the pressure drop in the die.

NOMENCLATURE

η	viscosity
K	power-law constant
n	power-law exponent
T	absolute temperature
E	activation energy of flow per mole
R	gas constant per mole
γ	shear rate
u, v	velocity
τ	shear stress
ρ	fluid density
t	time
P	pressure
Q	volume flow rate
Q_1, Q_2	volume flow rate in the manifold, volume flow rate per unit die width in the slot
q, q_i	average volume flow rate per orifice for die width and interval i, respectively
r	manifold radium
U	uniformity
g	gravity acceleration
R, D, L	radium, diameter, and length of the orifice, respectively
x, y, z	Cartesian coordinate system
X, Y, Z	coordinates in the coat-hanger die

REFERENCES

1. J. M. Dealy, *Rheometers for Molten Plastics,* Van Nostrand Reinhold, New York, 1982.
2. J. Ferguson and Z. Kemblowski, *Applied Fluid Rheology,* Elsevier, 1991.
3. K.-Y. Lee and T.-J. Liu, *Polym. Eng. Sci.,* **29,** 1066 (1989).
4. B. Vergnes, P. Saillard, and J. F. Agessant, *Polym. Eng. Sci.,* **24,** 980 (1984).
5. Y. Matsubara, *Polym. Eng. Sci.,* **19,** 169 (1979).
6. N. P. Cheremisinoff, *Product Design and Testing of Polymeric Materials,* Marcel, Dekker, New York, 1990.
7. K. Zhang and Y. Zhang, *Fundamentals of Spinning Rheology,* Textile Industry Press, China, 1993.
8. Z. Huang, *Design of Plastic Modeling Die and Engineering Calculation,* Hydrocarbon Processing Press, China, 1986.