Experimental Studies on Extrudate Swell Behavior of PS and LLDPE Melts in Single and Dual Capillary Dies

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ABSTRACT: Extrudate swell behavior of polystyrene (PS) and linear low-density polyethylene (LLDPE) melts was investigated using a constant shear rate capillary rheometer. Two capillary dies with different design configurations were used, one being a single flow channel and the other being a dual flow channel. A number of extrudate swell related parameters were examined, and used to explain the discrepancies in the extrudate swell results obtained from the single and dual flow channel dies, the parameters including output rate and output rate ratio, power law index, wall shear rate, wall shear stress, melt residence time, pressure drop induced temperature rise, flow channel position relative to the barrel centerline, and the flow patterns. It was found in this work that the power law index (n value) was the main parameter to determine the output rate ratio and the extrudate swell between the large and small holes for the dual flow channel die: the greater the n value the lower the output rate ratio and thus decreased extrudate swell ratio. The differences in the extrudate swell ratio and flow properties for PS and LLDPE melts resulted from the output rate ratio and the molecular chain structure, respectively. The extrudate swell was observed to increase with wall shear rate. The discrepancies in the extrudate swell results from single and dual dies for a given shear rate were caused by differences in the flow patterns in the barrel and die, and the change in the melt velocities flowing from the barrel and in the die to the die exit. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 87: 1713–1722, 2003

Key words: swelling; rheology; extrusion; processing; polymer melts; thermoplastics

INTRODUCTION

It has been accepted that die swell or extrudate swell is an important parameter determining the size and the quality of the extruded-polymer products. In polymer extrusion, the final shapes of the polymeric extrudate are not easily determined because of the swell phenomenon occurring while the melt is being forced out of the shaping die. The mechanism and degree of swelling of the extrudate are usually explained in terms of elastic recovery and/or residence time upon the applied stresses.[1]

The extrudate swell of polymer melts has been widely studied, mostly being performed in capillary rheometers. The swelling of a polymer melt during the flow is affected by many parameters such as shear rate, temperature, fillers, and die size and design. Among these parameters, die design has still gained interests from many researchers[2–8] due to the fact that the extrudate swell is closely associated with the behavior of the polymer melt flow, which is in turn very complex and three-dimensional.[2] The components and complexity of the flow include shear (both convergent and divergent), elongation, reversal, and the rapid velocity gradient near the die exit,[3] these being believed to be influenced by the design of the die being used, especially dies with irregular shapes. Kiriakidis and Mitsoulis[4] performed studies on extrudate swell of a high-density polyethylene melt by using slit and capillary dies with respect to the effect of die-length/diameter (gap) using the finite element method (FEM) and an integral constitutive equation. They found that for any given shear rate, the swelling was greater with the capillary die than the slit ones, and the extrudate swell decreased drastically as the die-length/diameter (gap) ratio were increased. Liang[5] investigated the influence of the die entry angle on the flow behavior for rubber compounds. They found that the shear stress and the melt viscosity reduced with increasing die entry angle to a certain value and then increased. He also found that the swelling of the extrudate decreased linearly with a length/diameter (L/D) ratio due to an increase in the

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melt residence time in the die. Lee and Ho[6] studied the effects of melting temperature and die length on the die swell behavior of a polystyrene melt to design a profile die, the experimental results being compared to the theoretical ones. It was found that the die swell became smaller as the melting temperature and die length were increased, the results from the experiment being in good agreement with those from the theory. Recently, Sombatsompop and Dangtugee[7] examined the effect of using two dies located along a barrel on the extrudate swell and flow patterns of natural rubber in the barrel of a capillary rheometer using a colored tracer method. They found that the change in extrudate swell was associated with the degree of flow complexities occurring in the barrel, residence flow time, elastic characteristic, and the temperature rise during the flow. The flows with more complexity tended to reduce the degree of extrudate swell of the rubber. Sombatsompop and Dantugee[8] also found that the change in the extrudate swell was linearly influenced by the entrance pressure drop at low actual barrel/die diameters (D_B/D_D from 20/4 to 30/7 mm/mm), and was then associated with the change in material viscosity at high barrel/die diameters (D_B/D_D from 35/7 to 40/8 mm/mm). For a constant barrel diameter, the smaller the die diameter the greater the extrudate swell due to the increases in the extensional deformation and wall shear rate coupled with a reduction in the melt residence time.

This article is part of an ongoing research program on investigations into the extrudate swell of polymer melts during the flow in rheometer. It is continued from a series of published work[7,8] aiming to study the extrudate swell and flow properties of polystyrene (PS) and a linear low-density polyethylene (LLDPE) melts in a rheometer using capillary dies with single and dual flow channels, the differences in the extrudate swell results due to the die designs used being of our main interest. The work covered the measurements and discussion on extrudate swell ratio, output rate and output rate ratio, power law index, wall shear stress and wall shear rate, material residence time and pressure drop induced temperature rise, the flow patterns in the barrel and die of the rheometer as well as the effect of flow channel position relative to the barrel centerline.

EXPERIMENTAL

Raw materials

The two thermoplastic melts used in this article were a polystyrene (Styron 656D 267) supplied in granular form by Siam Polystyrene Co., Ltd (Thailand), and a LLDPE (El-Lene L2009F) supplied in granular form By Thai Polyethylene Co., Ltd. (Thailand).

Experimental apparatus

The constant shear rate rheometer was used as employed in previous work.[7] The barrel, having 30 mm diameter and 150 mm long, was designed so that the die system could be easily changed. In this work, two circular dies with different flow channels were used, one being a single flow channel having L/D of 65.0/4.48 and the other being a dual flow channel having L/D of 65/4 and 65/2, the dies and their dimensions being shown in Figure 1. For the dual flow channel die, the channel L/D of 65/4 was referred to as *large hole* whereas that of 65/2 was referred to as *small hole*. In this work, the diameters of the two dies were intentionally designed to obtain the same cross-sectional area for comparison purposes, the sum of the cross-sectional area of the small and large holes in the dual channel die being equal to that of the single channel die. These two dies were also made of the same material (mild steel). A small pressure hole was located between the two die locations to detect the entrance pressure drop occurring, the entrance pressure being taken using the Pin-Spring pressure sensor.[9] The apparatus temperature was controlled using a Eurotherm 018 temperature controller, the apparatus temperature being of 180°C throughout this work.

Measurements and Calculations

Calculations of output rate (Q) and wall shear rate (γ_w)

Since the size of flow channels was varied depending on the design of the dies used, the output rate and wall shear rate for each flow channel at a given piston speed would be different, and they had to be calculated individually. For the single flow channel die, the total output rate was directly determined using the piston velocity and the barrel cross-section. In the case of dual flow channel die, the output rate of the melt through each flow channel (large and small holes) was determined based on the power law equations [eqs. (1) and (2)] and the fact that for a given piston speed the entrance pressure drop at small hole (ΔP_S) was equal to the entrance pressure drop at large hole (ΔP_L) as shown in eq. (3):

$$\tau = K\gamma^n \tag{1}$$

$$\Delta P = \frac{2KL}{R}\left(\frac{4Q}{\pi R^3}\right)^n \tag{2}$$

$$\Delta P_S = \Delta P_L \tag{3}$$

This gives

$$\frac{2KL_S}{R_S}\left(\frac{4Q_S}{\pi R_S^3}\right)^n = \frac{2KL_L}{R_L}\left(\frac{4Q_L}{\pi R_L^3}\right)^n \tag{4}$$

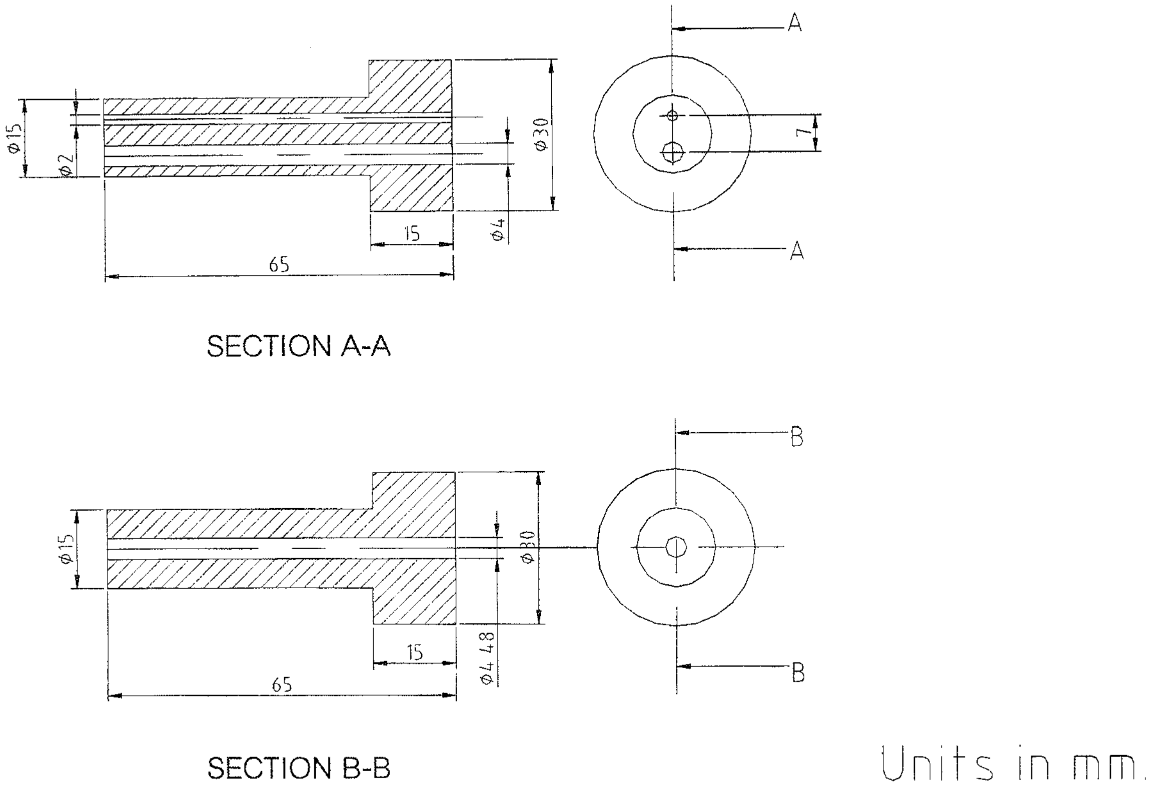

Figure 1 Die design and their dimensions (units in mm).

where K is the power law constant, n is the power law index, L and R are the length and radius of the die, respectively, and the subscripts S and L indicate small and large holes in dual flow channel die, respectively.

Equation (4) was reduced to give eqs. (5) and (6):

$$\frac{Q_S^n}{R_S^{3n+1}} = \frac{Q_L^n}{R_L^{3n+1}} \tag{5}$$

$$\frac{V_S^n}{R_S^{n+1}} = \frac{V_L^n}{R_L^{n+1}} \tag{6}$$

It should be noted that the power law index (n) was experimentally determined using the single channel die and the n values of PS and LLDPE melts were found to be 0.39 and 0.46, respectively. In this work, the power law index values of the melts in the dual flow channel die were assumed to be the same as those obtained in the single flow channel die, the assumption being based on the work of Drozdex and Faller,[10] who suggested that the n values between single and dual flow channel dies were very similar. As a result, the average melt velocities in the dual die for PS and LLDPE melts are calculated and shown in eqs. (7) and (8), respectively.

$$\text{For PS melt} \quad V_L = 12.02V_S \tag{7}$$

$$\text{For LLDPE melt} \quad V_L = 8.89V_S \tag{8}$$

By determining the average melt velocity in the small hole (V_S) and (V_L), the output rates at each channel (Q_S and Q_L) could be then determined, the sum of these two parameters equaling the total output rate (Q_t). The values of Q_t, Q_S, and Q_L were then used to determine the wall shear rate in single flow channel, small and large holes of dual flow channels respectively, by using eq. (9). Rabinowitsch corrections were applied to the shear rate data due to the use of different polymer melts.

$$\gamma_w = \frac{(3n+1)}{4n}\frac{4Q}{\pi R^3} \tag{9}$$

Extrudate swell measurement

In this work, the extrudate swell ratio (B) of the polymer melts was directly measured by calculating the ratio of diameter of the extrudate to that of the die, the extrudate diameter being based on the size of the extrudate diameter in the fully swollen (approximately 2 inches away from the die exit).[7] The test temperature was 180°C. By trial-and-error experiment, the critical shear rates for the onset of extrudate distortions (melt fractures) during extrusion were found to

TABLE I
The Output Rate and Wall Shear Rate of the Single and Dual Flow Channel Die for PS and LLDPE Melts

Total output rate (Q_i) in single die (10^{-9} m^3/s)	Wall shear rate in single die (s^{-1})		Output rate in dual die (10^{-9} m^3/s)				Wall shear rate in dual die (s^{-1})			
			PS		LLDPE		PS		LLDPE	
	PS	LLDPE	Small (Q_S)	Large (Q_L)	Small (Q_S)	Large (Q_L)	Small (γ_S)	Large (γ_L)	Small (γ_S)	Large (γ_L)
58.6	9.3	8.6	1.2	57.4	1.6	57.1	1.5	9.1	2.1	9.1
117.8	18.6	17.3	2.4	115.5	3.2	114.7	3.1	18.4	4.1	18.3
235.2	37.1	34.4	4.8	230.5	6.5	228.2	6.1	36.7	8.2	36.3
588.5	92.7	86.0	11.9	576.6	16.2	572.3	15.2	91.8	20.6	91.1
1177.7	185.6	172.2	23.9	1153.8	32.4	1145.4	30.5	183.6	41.2	182.3

be about 200 s^{-1} for both polymer melts used. In order to accurately measure the extrudate swell the wall shear rate used in this work ranged from 1 to 185 s^{-1} (corresponding to the piston speeds of 5–100 mm/min).

Entrance pressure drop (δP_{ent}) and wall shear stress (τ_{w})

The entrance pressure drop was measured under the test conditions at which the extrudate swell measurements were taken. The wall shear stress (τ_{w}) of the polymer melt was calculated from the measured entrance pressure drop (ΔP_{ent}) using eq. (10).[8] In this work, Bagley's corrections were not applied to the shear stress data generated, the shear stress data solely being used for comparative reasons to illustrate the magnitude of the changes observed in the flow characteristics of the materials as a function of the design of the dies used.

$$\tau_W = \frac{R\Delta P_{\text{ent}}}{2L} \tag{10}$$

Melt residence time

It is widely accepted that the residence time (t_r) of the melt flowing in the die, being related to the relaxation of the polymer molecules, is one of the major factors that influences the extrudate swell. The residence time can be readily determined based on the die dimensions (L/D) and the wall shear rate (γ_{w}), this being expressed as[11]

$$t_r = 8\,\frac{(L/D)}{\gamma_w} \tag{11}$$

Pressure drop induced melt temperature rise

For a simple melt flow, the temperature increase (ΔT) of a polymer melt can be easily calculated using the entrance pressure drop (ΔP_{ent}) obtained under the conditions at which the extrudate swell was measured and the material characteristics are as shown in eq. (12)[12]:

$$\Delta T = \frac{\Delta P_{\text{ent}}}{\rho \cdot C_p} \tag{12}$$

where ρ is the melt density (1.03 g/cm^3 for PS and 0.92 g/cm^3 for LLDPE) and C_p is the specific heat of the melt (1970 J/kg K for PS and 3206 J/kg K for LLDPE).

It should be noted in this work that the melt temperature rise due to the viscous heating of the melt was not taken into account since the work was conducted under low shear rates. Previous work[13] on measuring true temperature rise of polymer melts resulting from shear heating effect has clearly suggested that at low shear rates (less than 200 s^{-1}) the temperature rise difference of the melt due to shear heating effect was very small, this being about 0–2°C. Besides, the determinations of ΔT value proposed in this work were only used to explain the differences in the extrudate swell between two different die systems (single channel and large hole in dual channel die) which had very similar (and low) shear rates. Therefore, the melt temperature rise caused by shear heating effect in this particular case could be neglected.

RESULTS AND DISCUSSION

Determinations of output rate, output rate ratio, and wall shear rate

Table I shows the output rate and wall shear rate of the single and dual flow channel dies for PS and LLDPE melts. It can be seen that the wall shear rates for PS and LLDPE melts in the single flow channel die were not the same, this being due to different n values as shown earlier. The wall shear rates for the single flow channel die was similar to that for the large hole in the dual flow channel die. In the dual flow channel die, the output rate and wall shear rate for the large hole was much greater than those for the small hole. In general, one may expect to obtain the opposite results due to the dimensions of the flow channel, the smaller

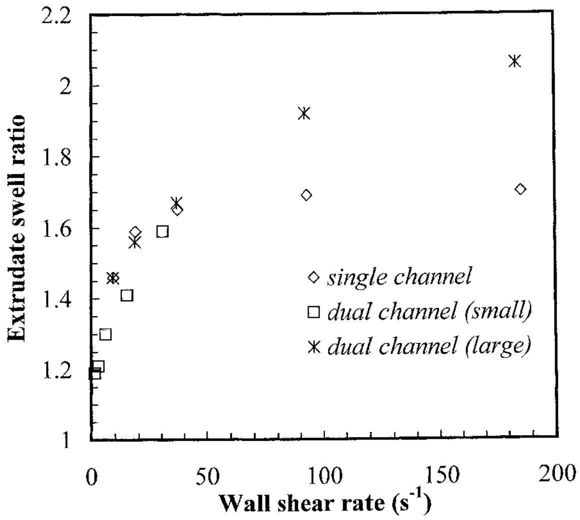

Figure 2 Extrudate swell of PS melt for single and dual flow channels.

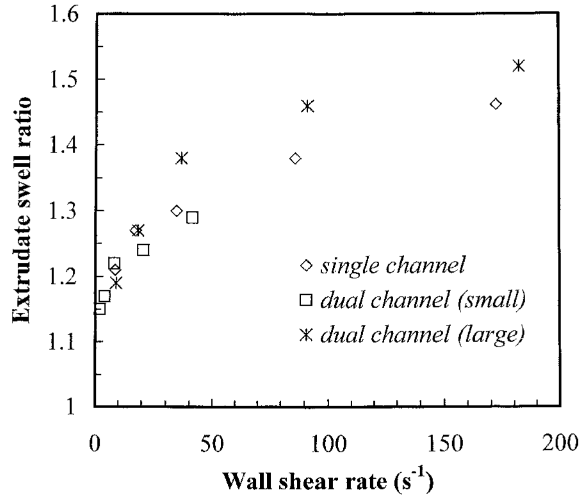

Figure 3 Extrudate swell of LLDPE melt for single and dual flow channels.

the flow channel diameter the greater the wall shear rate.[10] In this case, the output in the large hole of the dual channel die seemed to be the dominant factor to control and determine the wall shear rate. It was also interesting to note that the average output rate ratio (Q_L/Q_S) for PS and LLDPE melts were different, the Q_L/Q_S value in all output rates being 48.4 for PS and 35.3 for LLDPE, due to the fact that, according to eqs. (7) and (8), the output rate ratio was associated with the pseudoplastic characters (power law indexes) of these two fluids: the greater the power law index the lower the output rate ratio. This was in good agreement with the results reported by Drozdex and Faller.[10] In this work, we also found that the output rate ratio was linked with the extrudate well ratio of the melt, which is discussed later.

Extrudate swell behavior

Figures 2 and 3 show the relationship of extrudate swell changes against wall shear rate for the PS and LLDPE melts, respectively, using the single and dual flow channel dies. Generally, it can be seen that the extrudate swell increased with shear rate for both polymer melts and for all dies used. When comparing these two polymer melts, the PS melt had a greater swelling ratio than the LLDPE melt for both dies used. It was postulated for the dual flow channel die that this was linked with the output rate ratio as mentioned earlier: the greater the output rate ratio the higher the swelling in the dual channel die. In this case, the output rate ratio of the PS melt was greater than that of the LLDPE. When considering the extrudate swell in single and dual channel dies, it was found that the extrudate swell ratio for all dies was very similar at low shear rates (less than 40 s^{-1}, whereas the greater difference in the swelling ratio was observed at high shear rates (from ~40 to 185 s^{-1}). In the case of a small hole in the dual flow channel die, the shear rate to be reached was limited due to the operable range of the system. Possible explanations for the discrepancies in the extrudate swell results from single and dual (large) channel dies at higher shear rates are discussed as follows.

Differences in the flow properties

It has been known that variations of the extrudate swell are directly related to the change in the flow properties. In this work, the relationships between wall shear stress and wall shear rate of the two polymer melts were constructed under the conditions under which the extrudate swell was measured, the re-

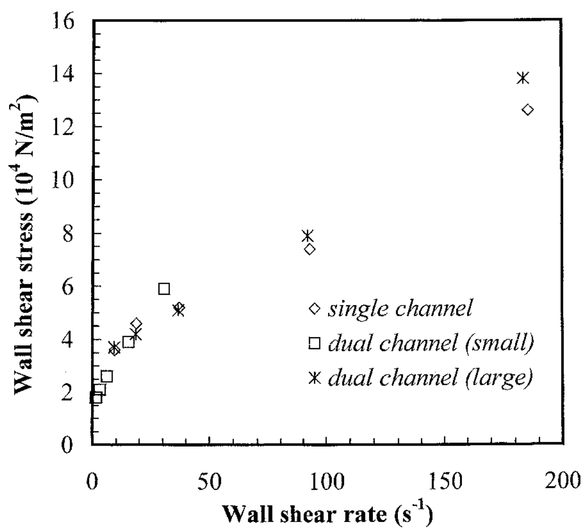

Figure 4 Flow properties of PS melt for single and dual flow channels.

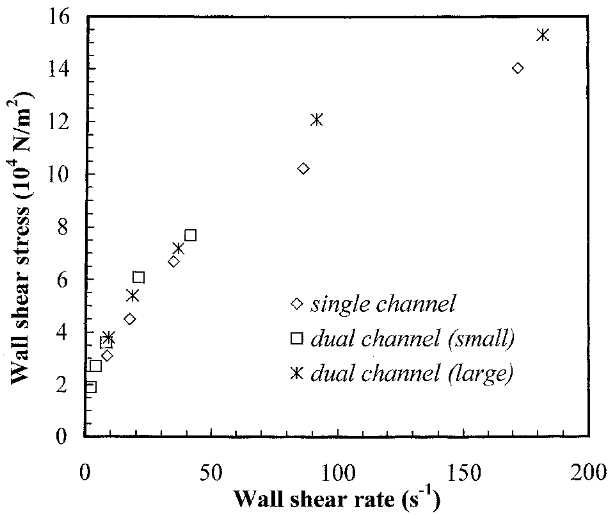

Figure 5 Flow properties of LLDPE melt for single and dual flow channels.

sults being shown in Figures 4 and 5 for PS and LLDPE melts, respectively. It can be seen that both polymer melts exhibited the pseudoplastic non-Newtonian behavior. The differences in the flow properties between PS and LLDPE melts for any given shear rates were due to differences in molecular chain structure. For both polymer melts, the differences in the flow properties between the single and dual channel dies were not as much as those found in the extrudate swell results (in Figs. 2 and 3). Therefore, the discrepancies in the extrudate swell results between single and dual channel dies in this case were not caused by the changes in the flow properties of the melts.

Entrance corrections

One would expect that the differences in the extrudate swell results might be caused by the entrance losses since different die sizes were used. In the general case, Bagley's methods were applied to correct the die entrance pressure drop, and the flow curves produced with different die sizes would then be superimposed, the true shear stress values for a given true shear rate from various die sizes used being less different.[2] In relation to the results in this work, if Bagley's corrections were applied, the flow data from the single and dual channel dies would be even more similar. Therefore, the entrance losses did not cause the extrudate swell differences.

Differences in melt residence time

It may be expected that if the melt has more time to flow in the die the degree of extrudate swell would reduce due to the stress relaxation.[7] In relation to the results in Figures 2 and 3, the residence times of the materials flowing in the single die should be greater than those in the large hole of the dual die due to less swelling of the extrudate. The residence time results are listed in Table II. The residence times of the PS and LLDPE melts were very similar for the two dies used except for the results from the small hole of the dual flow channel die. These results suggested that the discrepancies in the extrudate swells of the melts in the single and dual channel dies did not result from the differences in the residence time of the melts. Another interesting point to prove this explanation to be true was that, at low shear rate tests the differences in the residence time of the materials were very large (comparing between small and large holes), but the extrudate swell ratios were very similar.

It should also be noted that the differences in the residence times between PS and LLDPE melts were due to the differences in the n value (or flow properties of the two polymers) that were used to calculate the wall shear rates in eq. (11). In these particular circumstances, the power law indexes of PS and LLDPE, calculated from the flow curves in Figures 3 and 4, were found to be 0.39 and 0.46, respectively.

Pressure drop induced temperature changes

From previous work,[14,15] the melt temperature was usually expected to increase due to the shear heating and the development of the flow patterns of the material during the flow. The increase in the melt temperature would then result in the reduction of the elastic characters of the melt and thus reduced swell-

TABLE II
The Calculated Residence Times of PS and LLDPE Melts for Single and Dual Flow Channels

Total output rate (10^{-9} m^3/s)	Single channel die		Dual channel die			
			PS		LLDPE	
	PS	LLDPE	Small	Large	Small	Large
58.6	12.5	13.5	173.3	14.2	123.8	14.3
117.8	6.2	6.7	83.8	7.1	63.4	7.1
235.2	3.1	3.4	42.6	3.5	31.5	3.6
588.5	1.3	1.4	17.1	1.4	12.6	1.4
1177.7	0.6	0.7	8.5	0.7	6.3	0.7

TABLE III
The Calculated Temperature Rise of PS and LLDPE Melts for Single and Dual Flow Channels

Total output rate (10^{-9} m^3/s)	Temperature rise (°C)			
	Single channel die		Dual channel die	
	PS	LLDPE	PS	LLDPE
58.6	1.0	0.6	1.2	0.8
117.8	1.3	0.8	1.4	1.2
235.2	1.5	1.3	1.6	1.6
588.5	2.1	1.7	2.6	2.7
1177.7	3.6	2.7	4.5	3.4

ing of the extrudate. In this article, the temperature rises of the PS and LLDPE melts were determined using the entrance pressure drop, which were experimentally measured under the conditions used for the extrudate swell measurement, and the temperature results are shown in Table III. It can be seen that the maximum melt temperature rise ranged from 0.6 to 4.5°C, the differences in the melt temperature rise between the single and dual channel dies being very small (being less than 1°C in all cases). As a result, the melt temperature change was not the reason for the discrepancies in the extrudate swell due to the die designs being discussed.

The flow channel position relative to the barrel centerline

An independent investigation on the effect of flow channel position of dies relative to the barrel centerline on the flow properties and extrudate swell of the melts was conducted using a series of dies having the same size (L/D = 30/1.5) with a die temperature of 190°C. Each flow channel of dies was positioned at different points across the barrel diameter, the centerlines of the each die being 0.0, 0.75, 1.5, and 2.25 mm away from those of the barrel, and the flow properties and extrudate swell ratio being produced. The results are shown in Table IV. It can be seen that the flow properties and the extrudate swell of both LDPE and PS melts for the same shear rates did not change significantly with the flow channel position, the differences in the obtained results for each flow channel position being within the experimental errors (±2%). Therefore, it was suggested that the position of the die channel across the barrel diameter was not the cause of the differences in the extrudate swell results produced by dual and single flow channels. It should be noted that due to the limitation of the experiment regarding the size of the die flow channel and barrel diameter in the rheometer, the same L/D (i.e., 65/4.8) ratio of dies as in single flow channel die could not be used. The flow property results reported in this section aim only to explain the discrepancies of the extrudate swell results due to the single and dual flow channels qualitatively.

Proposed possible causes to the discrepancies in the extrudate swell from single and dual (large hole) flow channel dies

In this section, we offer some possible explanations for the discrepancies of the extrudate swell results due to

TABLE IV
Flow Properties and Extrudate Swell of PS and LLDPE Melts at Various Die Positions Across the Barrel Diameter: (a) PS Melt and (b) LLDPE Melt

(a) PS melt

Wall shear rate (s^{-1})	Wall shear stress (10^5 N/m^2)				Extrudate swell ratio			
	Die position away from the centre (mm)				Die position away from the centre (mm)			
	0.0	0.75	1.5	2.25	0.0	0.75	1.5	2.25
18	1.1	1.0	1.0	0.9	1.3	1.4	1.4	1.5
36	1.2	1.2	1.2	1.1	1.5	1.5	1.5	1.6
179	1.8	1.7	1.8	1.7	1.9	1.6	1.8	1.9
360	2.2	2.1	2.2	2.1	2.0	1.8	1.9	2.1
719	2.7	2.6	2.7	2.6	2.2	2.1	2.2	2.2
1078	2.9	2.9	2.9	2.9	2.3	2.2	2.2	2.3

(b) LLDPE melt

Wall shear rate (s^{-1})	Wall shear stress (10^5 N/m^2)				Extrudate swell ratio			
	Die position away from the centre (mm)				Die position away from the centre (mm)			
	0.0	0.75	1.5	2.25	0.0	0.75	1.5	2.25
18	0.9	0.8	1.5	1.2	1.3	1.3	1.3	1.3
36	1.4	1.5	1.9	1.7	1.4	1.4	1.4	1.4
179	2.7	2.9	3.0	2.9	1.5	1.5	1.5	1.5
360	3.5	3.7	3.8	3.7	1.5	1.5	1.6	1.5
719	4.4	4.5	4.3	4.4	1.7	1.7	1.7	1.7
1078	4.5	4.7	4.6	4.6	1.8	1.8	1.8	1.8

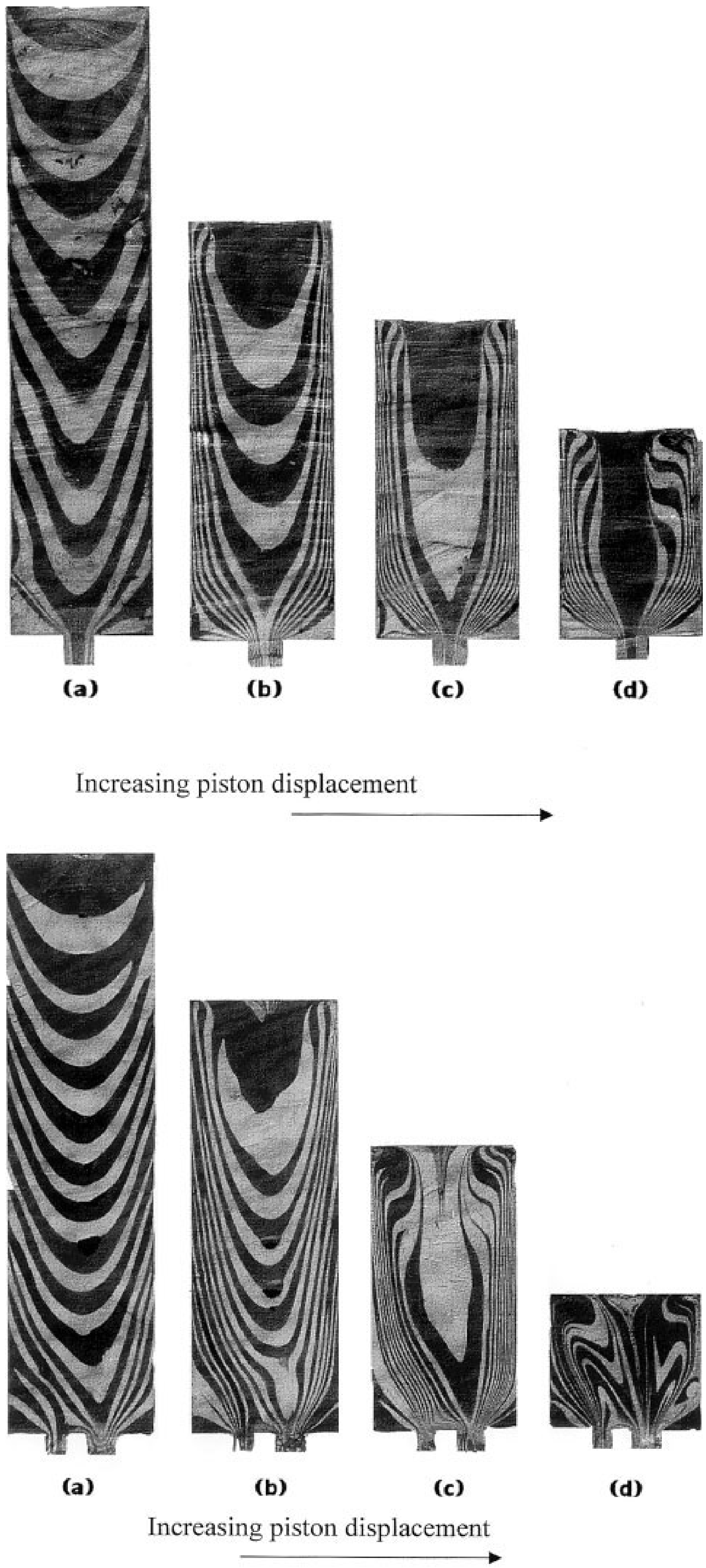

Figure 6 The flow patterns for NR compound in the barrel of capillary rheometer at different displacements down the barrel. [Piston displacements for (a)–(d): 10, 40, 70, and 100 mm.] Top: single flow channel; bottom: dual flow channel

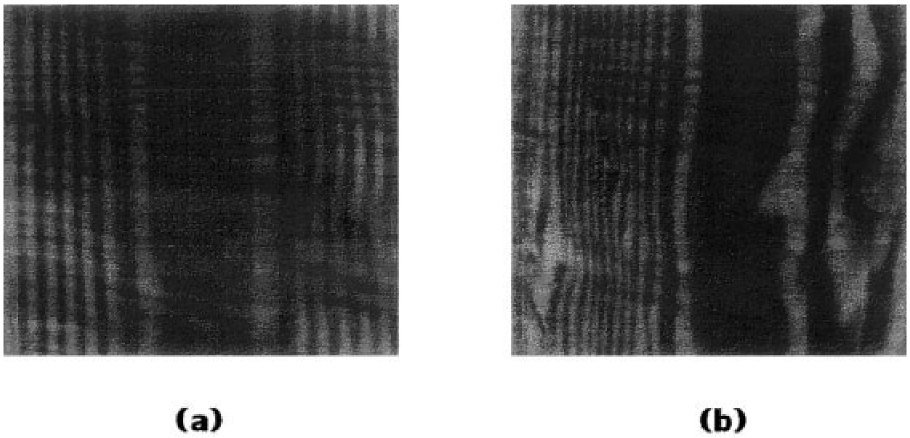

Figure 7 The flow patterns for rubber compound in the die at a piston displacement of 100 mm. (a) Single flow channel and (b) large hole of dual flow channel.

the single and dual flow channels at high shear rates (from 40 to 185 s^{-1}), this being carried out through the flow visualization. An independent experiment was then carried out using the colored tracer technique[7] to reveal the flow patterns in the capillary rheometer, especially at the die entrance. It should be noted that, in this case, we used a natural rubber (NR) compound for the flow pattern studies instead of either PS or LLDPE melt due to some limitations in the visualization technique used. Previous work[16] has indicated that the flow patterns for the NR and thermoplastic melts like LDPE, PS, and PP melts in the capillary rheometer were very similar in terms of qualitative consideration. The details of the experimental procedure including the preparation of the rubber compound can be found elsewhere.[1,7]

The flow pattern results for the rubber compound *in the barrel* at different piston displacements using single and dual flow channels are shown in Figure 6, which clearly indicates that the general style of the flow patterns in the barrel for the two die systems were very similar, the flows changing with piston displacement. This was supported by previous work,[1,7] which suggested that the flow pattern development in the barrel occurred due to the moving action of piston along the barrel.[1] In the dual flow channel (Fig. 6, bottom), the amount of the material flowing in the large hole was greater than that in the small hole, this being also confirmed by the output rate results as given in Table I. At a 100 mm piston displacement, the flow in the dual flow channel became very complex compared to the single flow channel (Fig. 6, top). It was interesting to observe that in all cases, the central velocity of the material flowing in the barrel in the dual flow channel die appeared to be higher than that in the single flow channel die, especially at high piston displacements. These complex and fast flows *in the barrel* of dual flow channel then resulted in a nonsymmetric flow patterns of the material *in the die* (at 100 mm piston displacement) as shown in Figure 7, the flow patterns in the single flow channel [Fig. 7(a)] being symmetric and stable whereas that in the large hole of dual flow channel [Fig. 7(b)] was not. Nonsymmetric and unstable flows in the dual flow channel die may be caused by the fast central flow of the melt in the barrel (Fig. 6, bottom) when entering the die, the velocity profiles of the melt in this die being then rearranged. In relation to the extrudate swell results, it was postulated that the material around the center of the barrel would also continue such high velocities along the die length (thus causing the flow complexity in the die), and would then decelerate as the melt exited from the die in order to equalize the velocity of the extrudate on the die exit. This sudden change in the melt velocities would then cause an increase in the cross-sectional area and thus greater extrudate swell, this phenomenon being the case for the large hole of dual flow channel. This explanation was supported by Chirstodoulou et al.[17]

Beyond the scope of this paper, the present work should be continued to quantitatively measure the exit pressure in order to calculate normal stress differences, recoverable shear strain as well as the velocity profiles along the die, which can be used to explain the extrudate swell behavior of the material for these particular die systems.

CONCLUSION

This article investigated the effect of flow channel characteristics of capillary dies on the extrudate swell of PS and LLDPE melts in a constant shear rate capillary rheometer. It was found that the power law index was the main parameter to determine the output rate ratio between the large and small holes in the dual flow channel die, the greater the power law index the lower the output rate ratio, and the lower extrudate swell ratio. The differences in the extrudate swell ratios and flow properties for polymer melts were caused by the output rate ratio and the molecular chain structure, respectively. The extrudate swell of the melts increased with wall shear rate. The discrepancies in the extrudate swell results from single and dual dies for a given shear rate were caused by differences in the flow patterns in the barrel and die, and the sudden change in the melt velocities flowing from the barrel and in the die to the die exit.

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