Effects of the Actual Diameters and Diameter Ratios of Barrels and Dies on the Elastic Swell and Entrance Pressure Drop of Natural Rubber in Capillary Die Flow

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ABSTRACT: The effects of the actual diameters and diameter ratios of barrels and dies on the elastic swell and entrance pressure drop of natural rubber compounds in an extrusion capillary rheometer were investigated. Either the barrel diameter or the die diameter was altered so that different barrel-diameter/die-diameter (D_B/D_D) ratios were obtained, both the barrel and die diameters also being varied simultaneously. The extrudate swell and entrance pressure drop were dependent not only on D_B/D_D but also on the actual diameters used. For fixed D_B/D_D ratios, the change in the extrudate swell was linearly influenced by the entrance pressure drop at low actual barrel and die diameters (D_B/D_D = 20/4–30/7 mm/mm) but was associated with a change in the material viscosity at high barrel and die diameters (D_B/D_D = 35/7–40/8 mm/mm). When the die diameter was fixed, the relationship between the entrance pressure drop and the extrudate swell was linear up to a certain value of the barrel diameter greater than 30 mm. Beyond this critical barrel value, the relationship became nonlinear and associated with the shearing stress generated by the formation of semipluglike flow patterns and the residence time of the material. For a constant barrel diameter, the smaller the die diameter was, the greater the extrudate swell was because of the increases in the extensional deformation and wall shear rate coupled with a reduction in the material residence time. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 86: 1762–1772, 2002

Key words: rheology; swelling; extrusion; processing; rubber

INTRODUCTION

The properties of end products are very much dependent not only on the types of materials used but also on the design of the processing equipment, such as the dies and screws used in the extrusion process. Unstable flows occurring during processing can result in low-quality products. It has been shown[1] that the complex flows occurring are due to the design of the equipment, the characteristics of the material, and the pressure and temperature. The most common technique used for the determination of the flow properties of polymer melts is capillary rheometry. It has been observed that the flow property results produced in a capillary rheometer depend on the design of the apparatus, the same die giving different results when used in different apparatus designs. The differences in the results are associated with the flow patterns occurring.[2] As the polymer melt is forced from the barrel through a capillary die, the extrudate size is not equal to the die size. The ratio between the extrudate and the die sizes is known as the die swell or extrudate swell. It has been widely found that the extrudate swell is a function of many parameters, such as the die wall temperature, melt temperature, shear rate, and molecular characteristics of the polymer melt.[3] However, the effects of these parameters on the flow properties and extrudate swell vary with the die design.[4]

The fundamental flow properties and the phenomenon of elastic swell of the polymer melt (extrudate) in the extrusion process must be taken into consideration when dies are designed. Liang et al.[5] investigated the influence of the die entry angle on the flow behavior for rubber compounds. They found that the shear stress and melt viscosity decreased with an increasing die entry angle to a certain value and then increased when the die entry angle was increased beyond this value. The given explanation was related to the stability of the flows inside the barrel. A study on the effect of the length/diameter (L/D) ratio of the die on the extrudate swell in a capillary rheometer was also carried out by Liang.[6] The swelling of the extrudate decreased linearly with the L/D ratio because of a decrease in the melt residence time (t_r) in the die. He proposed studies on the effect of the diameter ratio of

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the barrel to the die ($D_R/D \lesssim 20$) on the entry pressure drop and the die swell in capillary extrusion, and he found that the pressure drop and die swell increased with an increasing diameter ratio.[7] The explanation was based on the increases of the extensional deformation and the elastic energy stored in the melt as the diameter ratio was increased. Sombatsompop and coworkers[1,8] investigated the flow patterns of natural rubber (NR) compounds developed in the barrel and capillary die of a rheometer by the use of pigmented rubber compounds with various die sizes and die entry angles. They found that the die size and entry angle did not affect the general style of the flow patterns but did have an effect on the actual melt velocities across the duct. Although the die design did not affect the general style of the flow patterns in the barrel, it did influence the flow patterns in the die. Ma et al.[9] studied the flow patterns of various elastomers in the entrance region of a circular die with a wide range of geometries (converging and diverging entrance dies and 180° entrance angle dies with off-center and double holes). The results indicated that in all cases the elastomers exhibited streamline flow into the entrance, with the exception of degraded rubber, which gave evidence of vortices in the die corners. Song et al.[10] conducted flow marker experiments of various rubber compounds, including NR, styrene-butadiene rubber (SBR), and ethylene-propylene copolymer (EPDM), in the barrel of a capillary rheometer with a wide range of die designs. They found that the flow radially moved inward to the capillary die as the ram moved down the barrel, with no secondary flows occurring. Shin et al.[11] determined the extrudate swell of SBR with different carbon black grades and die L/D ratios. They found that the extrudate swell decreased as the carbon black loading and the L/D ratio of the die increased. Sombatsompop and Dantangee[12] recently established the relationship between the flow patterns and the elastic swell of the NR extrudate in a capillary rheometer with respect to the die designs. In their work, two dies located along the barrel were used, this type of system being novel in its rheometer design. The flow of the rubber in the upper barrel was dependent on the piston/barrel action and changed with the piston displacement, whereas the complexity of the flow in the lower barrel was dependent not only on the piston displacement but also on the geometry of the upper die design. The flow patterns that developed in the whole barrel were independent of the die located at the bottom of the barrel. The change in the extrudate swell was associated with the flow occurring in the barrel, t_r, the elastic characteristic, and the temperature rise during the flow. The more complex the flow was inside the barrel and the die, the lower the extrudate swell was.

In this work, effects of the barrel-diameter/die-diameter (D_B/D_D) ratio and the actual values of the barrel and die diameters on the elastic swell of NR and the entrance pressure drop in a capillary rheometer, which was specially designed and built, were studied. This work was part of ongoing investigations into the effects of rheometer design on the extrudate swell and flow-related properties of polymer melts.[12,13] Unlike the work of Liang[7] mentioned earlier, our aim was not only to investigate the effects of the D_B/D_D ratio but also to examine those of the actual diameters of the barrels and dies used on the extrudate swell, entrance pressure drop, and flow patterns of the rubber in the rheometer, some plausible explanations being given to establish the relationship between these three parameters. In addition, either the barrel or die diameters, including simultaneous alternations of the barrel and die diameters, were varied in this work so that different D_B/D_D ratios were obtained, whereas in Liang's work, the diameter ratio was varied only with a fixed barrel diameter.

EXPERIMENTAL

Raw material

The flow behavior and extrudate swell in the capillary rheometer were studied with NR (STR-20CV) supplied by Tech Bee Hang Co., Ltd. (Bangkok, Thailand), with a Mooney viscosity of 62.

Rubber compounding and sample preparation

The formulation of the rubber compound, in parts by weight, was 100 NR, 3 zinc oxide (ZnO), 2.5 stearic acid, 1 N-cyclohexyl-benzothiazole-2-sulfenamide (CBS) (accelerator), 1 sulfur, and 1 pigment master batch (TiO_2). The materials were compounded in accordance with the experimental procedure of Sombatsompop and Dangtagee.[12] The rubber compound was loaded into the capillary rheometer in the form of circular discs (5 mm thick), the diameters of which were produced corresponding to the barrel diameters being used to ensure good and uniform packing of the material. The rubber discs were prepared by the rubber compound being pressed between layers of polyester film with a hydraulic press for 60 min at room temperature; this produced a sheet 5 mm thick. A cork punch was used to cut the resulting rubber sheet into discs, the discs still being kept between the polyester film to prevent elastic contraction of the rubber before further use.

Experimental apparatus

In this work, a shear-rate-controlled rheometer was specially designed and built, consisting of a barrel, a die, a die holder, a piston, and temperature- and pressure-sensing systems; details can be found elsewhere.[12] All the components were fitted into an AGS-500D (Shimadzu, Japan) tensile testing machine, which allowed an extrusion process to proceed. A number of barrels and circular dies with different diameters were specially designed and manufactured so that various D_B/D_D ratios were obtained, the size (diameter) of the piston also being altered to correspond to that of the barrel. The barrel and die lengths were fixed at 145 and 65 mm, respectively. A small pressure hole was located between the two die locations for the detection of a die entrance pressure drop, the pressure drop being taken with the a pin-spring pressure sensor.[14] The apparatus temperature was controlled with a Eurotherm 018 (UK) temperature controller.

Experimental design

In this work, the extrudate swell, entrance pressure drop, and the flow patterns of NR compounds were examined with respect to the effects of D_B/D_D ratios and the actual diameters of the barrels and dies. The investigations were carried out for three different cases:

1. Effect of the actual diameters of the barrels and dies with a fixed D_B/D_D ratio. Various dimensions of the barrels and dies (D_B/D_D = 20/4, 25/5, 30/6, 35/7, and 40/8), with a constant D_B/D_D ratio of 5, were used.
2. Effect of the D_B/D_D ratio with a fixed die diameter. A die 6 mm in diameter with various barrel diameters (20, 25, 30, 35, and 40 mm) was used.
3. Effect of the D_B/D_D ratio with a fixed barrel diameter. A barrel diameter of 30 mm was used with two different die diameters (4.7 and 6 mm).

Experimental procedure

The experimental procedures for the extrudate swell, entrance pressure drop, and flow patterns of NR compounds in the rheometer were as follows.

Elastic (extrudate) swell measurements

The elastic swell ratio (B) of the polymer extrudate was directly measured by the calculation of the ratio of the 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 sample (ca. 2 in. away from the die exit).[15] The test temperature during the extrudate swell measurement was 80°C, and the shear rate ranged from 2 to 50 s^{-1}. Because the t_r value of the material flowing in the die is related to the relaxation of the polymer molecules, it is regarded as one of the major factors influencing the extrudate swell t_r can be determined with the die dimensions (L/D) and wall shear rate (γ_w):[16]

$$t_r = 8\,\frac{(L/D)}{\gamma_w} \tag{1}$$

Entrance pressure drop measurements

The entrance pressure drop was measured under the test conditions at which the extrudate swell measurements were taken. The wall shear stress (τ_w), γ_w, and shear viscosity (η) of the rubber were also considered, the calculations of which can be obtained elsewhere.[13] For material comparison, no corrections to the shear stress and shear rate were applied in this work.[1]

Flow pattern investigations

A colored tracer technique was employed.[8] In this part of the work, during compounding, the rubber was divided into two separate parts, one being pigmented with TiO_2 to give a white compound. Previous research[1,8] has indicated that pigmentation by TiO_2 does not affect the rheological properties of rubber compounds. The experimental procedure was begun with the loading of alternating unpigmented and pigmented discs of the rubber compound (with an unpigmented disc first) into the barrel before the extrusion was started. The rubber was partially extruded at a temperature below that at which vulcanization would occur (80°C). The residual material in the barrel and die was then vulcanized for 30 min, and the temperature of the apparatus was raised to 160°C. A rod of the vulcanized compound was removed from the barrel, cooled, sectioned, and polished, and the flow patterns were investigated. The flow patterns were investigated under the same test conditions at which the extrudate swell measurements were taken.

RESULTS AND DISCUSSION

Effect of the actual diameters of the barrels and dies with a fixed D_B/D_D ratio

Figure 1 shows the percentage of the extrudate swell as a function of piston displacement for the NR compound at a constant D_B/D_D ratio of 5 with five different barrel and die diameters. In all cases, the extrudate swell progressively decreased with piston displacement, this behavior and its explanations being found in previous research.[12] Although D_B/D_D was the same, the percentage swell of the rubber varied with the actual diameters of the barrels and dies used. Figure 2 shows the relationship between the extrudate

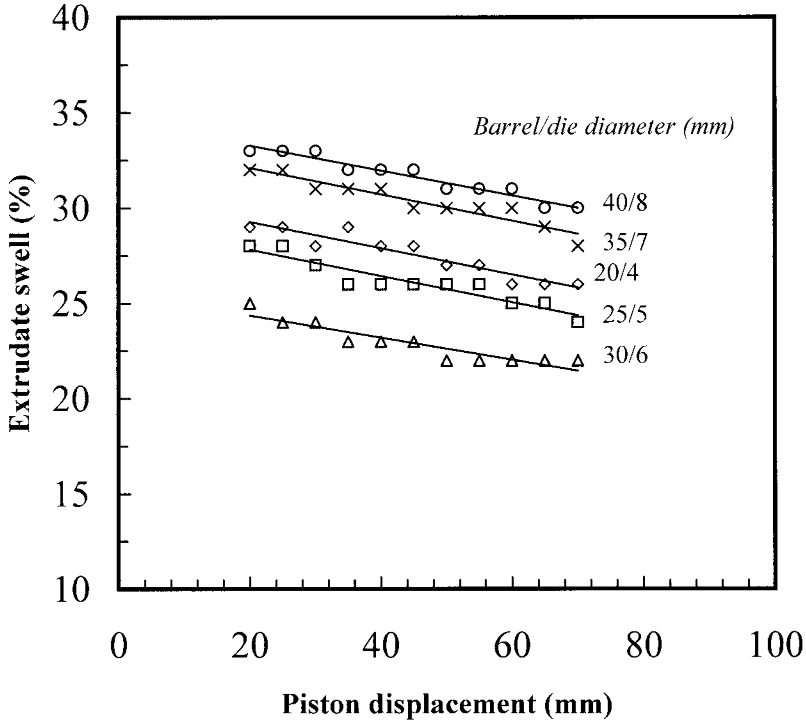

Figure 1 Percentage of the extrudate swell for NR at different piston displacements with a constant D_B/D_D ratio of 5 and a piston speed of 10 mm/min.

swell and wall shear rate. The results showed that the extrudate swell increased with the shear rate as expected. In Figures 1 and 2, we can see that the extrudate swell decreased as the actual barrel/die diameters increased from 20/4 to 30/6 and then sharply increased for greater barrel/die diameters (35/7 and

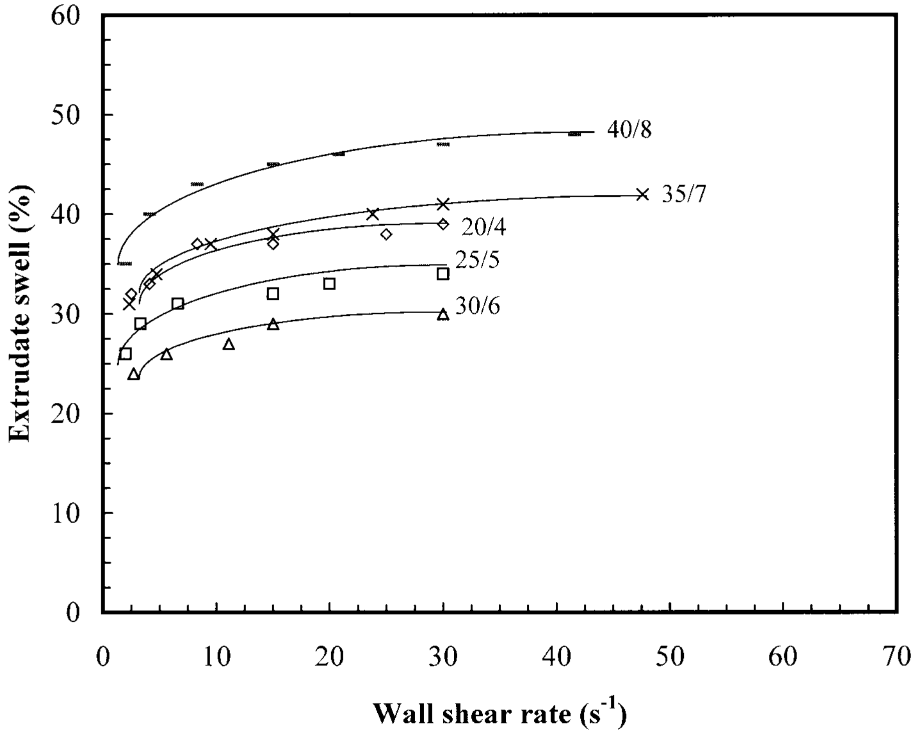

Figure 2 Percentage of the extrudate swell as a function of the shear rate for different barrel and die diameters ($D_B/D_D = 5$).

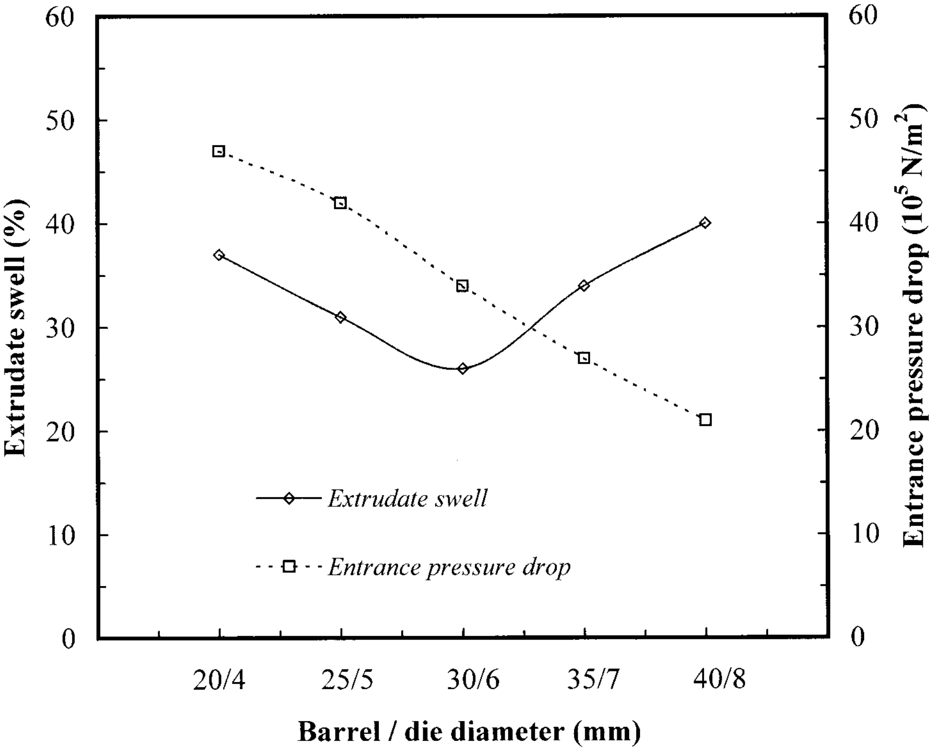

Figure 3 Percentage of the extrudate swell, entrance pressure drop, and actual D_B/D_D ratio for rubber at a piston speed of 10 mm/min.

40/8). This clearly implied that the actual diameters of the barrel and die used had an effect on the extrudate swell behavior of the polymer melt. These findings could lead to significant practical benefits because one would usually obtain rheological results from a testing machine, which is usually smaller than real processing machinery. In this respect, one should consider whether the results are dependent on the size of the testing machines used.

In light of the t_r effect, the differences in the extrudate swell of the material with various actual barrel and die diameters at a fixed contraction ratio in this case were not caused by the t_r value of the material in the die because all cases had the same calculated value of t_r, about 15.6 s. The changes in the extrudate swell, as reported in Figures 1 and 2, were explained with the results of the entrance pressure drop, as shown in Figure 3. Similar results were obtained. From barrel/die diameters of 20/4 to 30/6, the extrudate swell was reduced by the decrease in the pressure drop, but as the actual barrel/die diameters were increased (>30/6), the extrudate swell increased, although the pressure drop continued to decrease. These results suggested that the entrance pressure drop was not the only main factor influencing the extrudate swell.

A possible reason for the increased extrudate swell at actual barrel/die diameters greater than 30/6 was associated with a change in the material viscosity. Table I lists the values of γ_w, τ_w, and η for different actual barrel and die diameters at a piston speed of 10 mm/min. γ_w and τ_w decreased with the increasing actual diameters of the barrel and die, the reverse being found for η. Although the pressure drop (or shear stress) decreased, as the actual barrel and die diameters increased, the viscosity appeared to increase. This happened because the magnitude of the decrease in the pressure drop (or shear stress) was not directly proportional to that of the decrease in γ_w as the actual barrel and die diameters were increased, the shear stress decreasing with a lesser magnitude than the shear rate, and this resulted in the increase in material viscosity. It was clearly observed that the

TABLE I
γ_w, τ_w and η of the NR for a 10 mm/min Piston Speed Using Different Actual Barrel/Die Diameters, a Test Temperature of 80°C, and L = 65

Actual barrel/ die diameters (mm/mm)	Material property		
	γ_w (s^{-1})	τ_w (kN/m^2)	η (10^3 Ns/m^2)
20/4	8.3	35.6	4.2
25/5	6.7	34.1	5.1
30/6	5.5	32.2	5.8
35/7	4.7	31.3	6.7
40/8	4.1	30.7	7.4

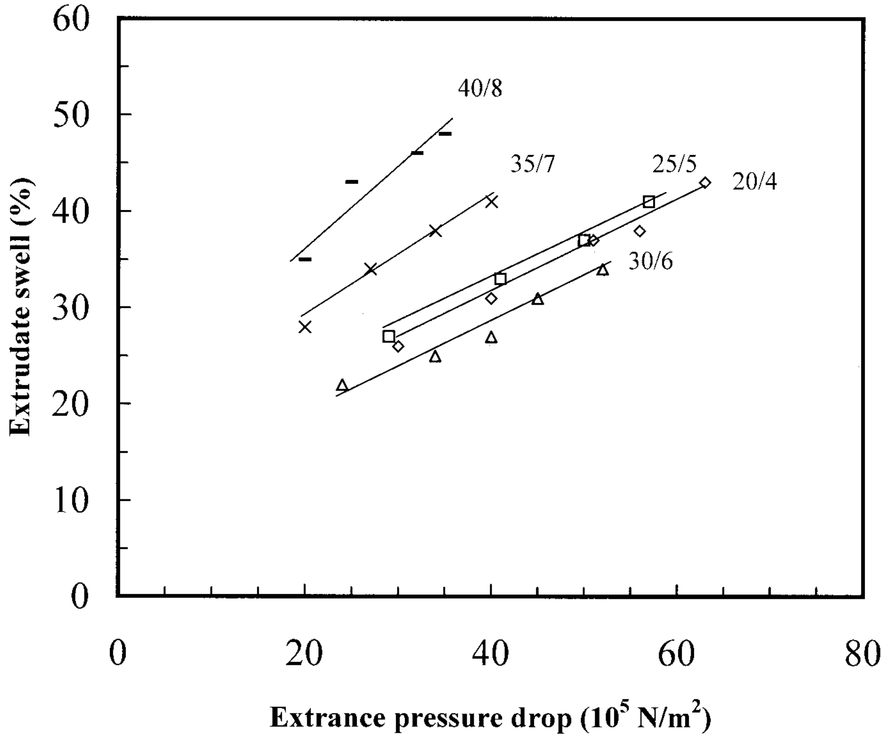

Figure 4 Percentage of the extrudate swell and entrance pressure drop for different barrel and die diameters at a piston speed of 10 mm/min.

increasing magnitude of the viscosity was more pronounced at barrel/die diameters of 35/7 and 40/8 (see Table I), and this gave rise to the increased extrudate swell.

For a more in-depth analysis, a plot of the extrudate swell and entrance pressure drop was established, as shown in Figure 4. The relationship was linear: the extrudate swell increased with the pressure drop increasing. This was in good agreement with the work of Liang.[7] From the results in Figure 4, two constants related to this linear relationship were produced, these being the slope and intercept listed in Table II. The slope represents the sensitivity of the extrudate swell change due to the entrance pressure drop, whereas the intercept represents the extrudate swell at a zero pressure drop. The slope did not change at D_B/D_D = 20/4–30/6 but considerably increased with barrel/die diameters of 35/7 and 40/8. This was also the case for the intercept value. This means that at actual barrel/die diameters of 35/7 and 40/8, there were some other factors, apart from the pressure drop, taking part in the change in the extrudate swell. One of the possible factors being proposed in this article is the change in material viscosity, as discussed earlier.

TABLE II
Constant Values from the Relationship of Percentage Extrudate Swell and Pressure Drop for Various Barrel/Die Sizes (with a Constant Ratio of 5)

	Constant values	
D_B/D_D ratio	Slope	Intercept
20/4	0.49	10.93
25/5	0.49	11.96
30/6	0.45	10.69
35/7	0.64	15.70
40/8	0.81	20.40

Effect of the D_B/D_D ratio with a fixed die diameter

Figure 5 shows the percentage of the extrudate swell as a function of the piston displacement of the NR compound for different D_B/D_D ratios with variations in the barrel diameter. In all cases, the extrudate swell decreased with piston displacement. Figure 6 illustrates the relationship between the extrudate swell, entrance pressure drop, and barrel diameters with a 6-mm die diameter at a piston speed of 10 mm/min. The percentage swell of the extrudate increased with increasing barrel diameter, this being due to the increase in the entrance pressure drop caused by the increasing contraction ratio (increasing D_B/D_D ratio). The increase in the pressure drop was due to the increased shear rate as well as the enhanced extensional deformation and elastic energy stored in the melt as the contraction ratio was increased. At very high barrel diameters (especially for a barrel diameter

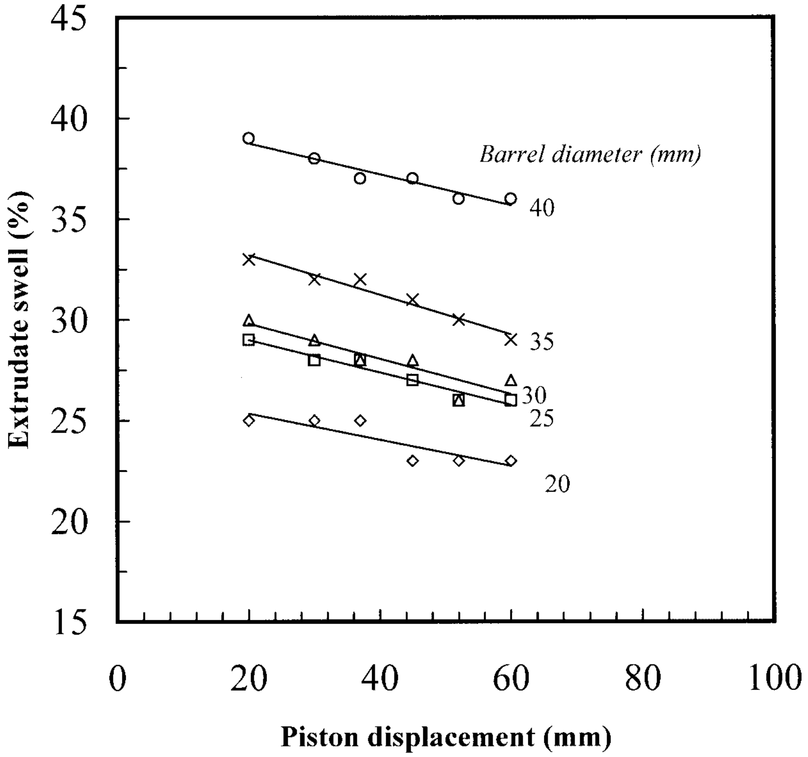

Figure 5 Percentage of the extrudate swell for NR at different piston displacements and barrel diameters (with a die diameter of 6 mm and a piston speed of 10 mm/min).

of 40 mm), a sharp increase in the extrudate swell was marked, although the pressure drop did not show such a rapid change. This again implied that the pressure drop (from the contraction ratio effect) was not the only factor for the extrudate swell. It was postulated that the sharp increase in the extrudate swell with a 40-mm barrel diameter might be explained by the flow patterns that developed in the rheometer. This speculation was also drawn from previous work[12] indicating that the change in the extrudate swell was closely related to the development of the flow patterns in the barrel of the rheometer with respect to the flow complexities and the t_r value of the material. The flow pattern results for the NR compound with different barrel diameters are shown in Figure 7. Generally, the flow patterns for each barrel size were different, especially near the die entrance. At the die entrance, the converging angles of the flows for each barrel varied with the barrel diameter, the angles decreasing as the barrel diameter was decreased. Moreover, the overall flow patterns for the barrel diameter of 40 mm were not fully developed (showing a semipluglike pattern and no obvious convergent streamline), this being due to the relatively large diameter of the barrel with respect to its length (the barrel was not long). It was thought that the semipluglike (wide-entry-angle) flows probably generated some local shearing stresses near the die entrance at a certain degree of the extensional deformation. The local shearing stresses were then stored during the flow and resulted in the increased extrudate swell at the die exit. However, if such deformation had occurred, one would expect to observe an increase in the entry pressure drop, this not being the case for the results in this work. This can be explained by the work of Laing et al.,[5] who investigated the relationship of the die entry angle and pressure drop at the die entrance. They indicated that the dies giving convergent flow patterns tended to produce a greater entry effect (high pressure drop). In this work, with a 40-mm barrel diameter, the convergent flow was not clearly seen but instead was suppressed by the semipluglike flows, and so the pressure drop did not show an obvious change.

The rapid change in the extrudate swell was not caused by the material property change with the barrel diameter. This was confirmed by the flow curve results produced with different barrel diameters (with the 6-mm die diameter) and shown in Figure 8, the flow curves for all barrel diameters used being very similar within experimental error (±2.5%). At this stage, we should note that the flow properties measured by a capillary rheometer are widely known to vary with die size but have been now found to be unaffected by barrel size. Another factor that caused the increase in the extrudate swell with increasing

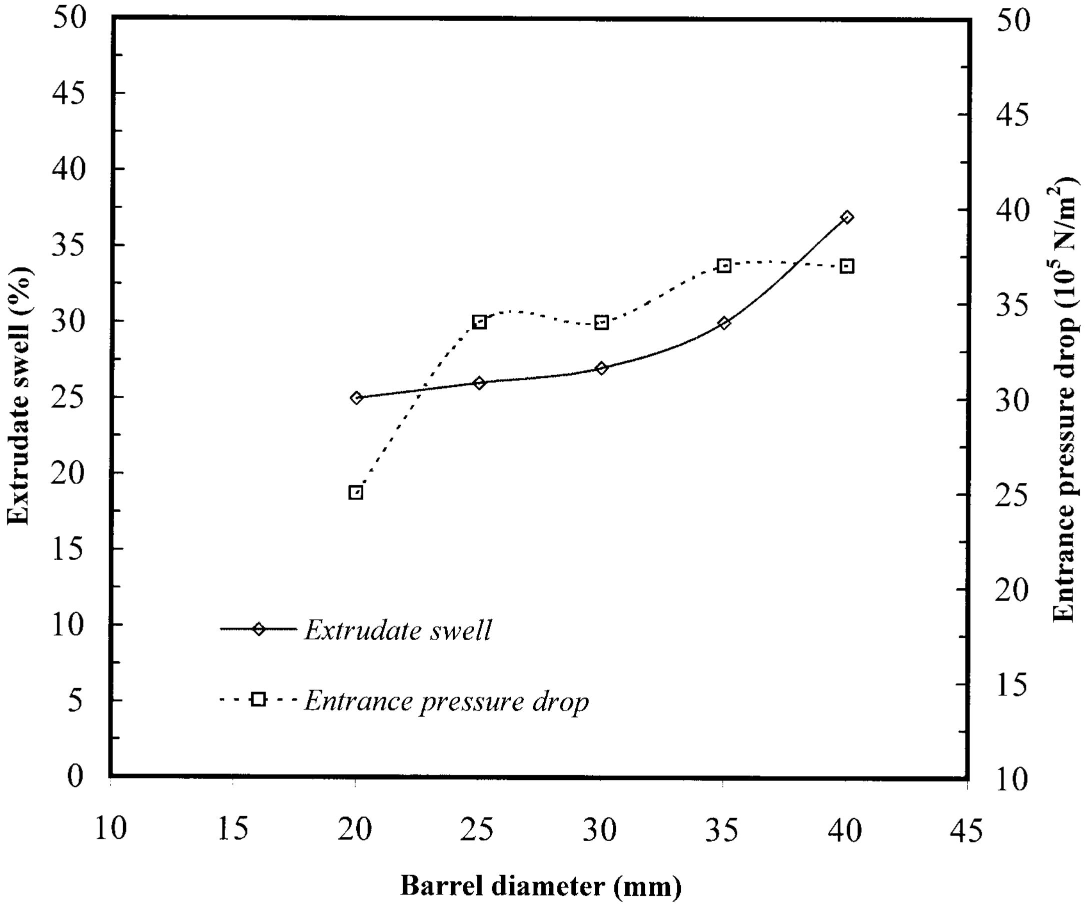

Figure 6 Percentage of the extrudate swell, entrance pressure drop, and barrel diameter with a die diameter of 6 mm for NR at a piston speed of 10 mm/min.

barrel diameter (at a fixed die diameter) was the t_r value of the material. Table III shows that t_r decreased with the barrel diameter, as expected, as a result of the increase in γ_w [see eq. (1)].

A plot of the extrudate swell and the entrance pressure drop is shown in Figure 9; the relationship is nonlinear, especially for barrel diameters of 35 and 40 mm. Work by Liang[7] suggested that the relationship between the extrudate swell and entrance pressure drop was linear. However, this was not the case in this work. The differences in these two findings arose because the barrel diameter used in Liang's work was small (19 mm), whereas that used in this work was much larger (up to 40 mm). It can be concluded that the relationship between the entrance pressure drop and the extrudate swell was linear up to a certain value of the barrel diameter (>30 mm in this work), with the relationship being nonlinear beyond this value.

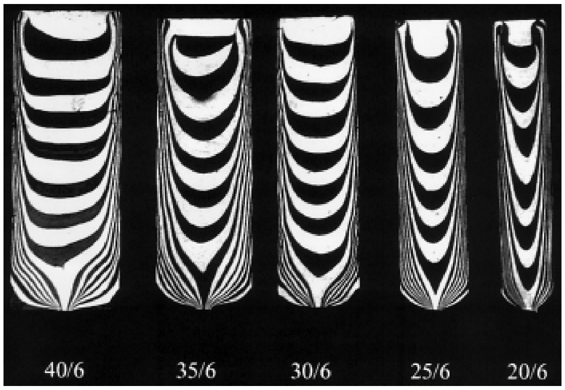

Figure 7 Flow patterns of NR compounds for different barrel diameters (with a die diameter of 6 mm) at a 40-mm piston displacement and a piston speed of 10 mm/min.

Effect of the D_B/D_D ratio with a fixed barrel diameter

Figure 10 shows the relationship between the extrudate swell and entrance pressure drop of the NR compound for two different die diameters with a 30-mm barrel diameter. The extrudate swell increased with the entrance pressure drop, the relationship being relatively linear as one would expect because the barrel

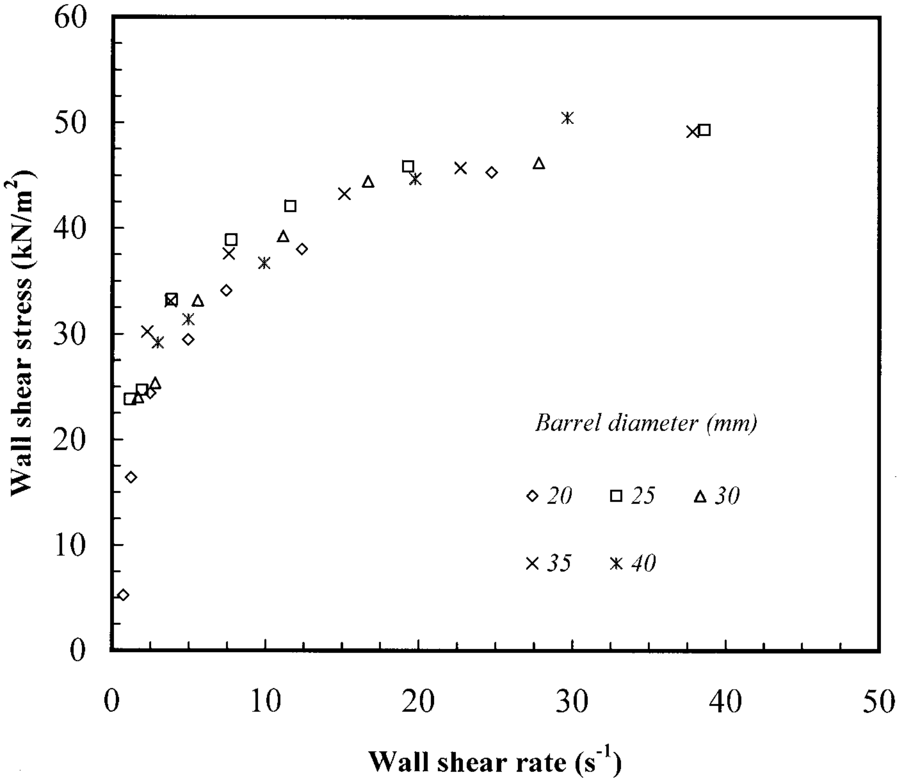

Figure 8 Flow curves of rubber compounds with different barrel diameters at 80°C.

diameter did not exceed the critical value (30 mm) mentioned earlier. Generally, it was concluded that the smaller the die diameter was, the higher the extrudate swell ratio was. The extrudate swell results in this work were best explained by three contributing factors:

- Contraction ratio: Because the barrel diameter was fixed, the decrease in the die diameter resulted in an increase in the contraction ratio of the barrel to the die, which then gave rise to increases in the extensional deformation and shearing stresses and, therefore, the increased extrudate swell.
- γ_w: Because the die diameter was varied, it would be appropriate to explain the changes in the die swell by the shear rate result, the shear rate being directly proportional to the piston speed. Table IV shows the values of γ_w and t_r for the three different piston speeds of the two dies used. The smaller die generated a higher shear rate than the other, resulting in the greater extrudate swell.
- t_r: t_r was calculated with eq. (1), and the results are listed in Table IV. The t_r value for the smaller die was smaller, so the polymer had less time to relax, and this caused the higher swell of the extrudate.

Because the effects of the die diameter on the extrudate swell have been widely studied by many researchers,[6,11,17] no further attempts are made in this article to discuss the effects of the die diameter on the extrudate swell behavior.

TABLE III
γ_w and t_r of the Rubber for Different Barrel Diameters (Using a Die *L/D* of 65/6)

Barrel diameter (mm)	Parameter	
	γ_w (s^{-1})	t_r (s)
20	2.5	34.6
25	3.9	22.2
30	5.6	15.5
35	7.6	11.4
40	9.9	8.7

CONCLUSIONS

An investigation into the effects of the barrel and die diameters and the D_B/D_D ratio on the elastic swell and entrance pressure drop of NR compounds in a capillary rheometer was carried out. The following findings were noted:

- A fixed D_B/D_D ratio: At low actual barrel and die diameters (D_B/D_D = 20/4–30/7 mm/mm), the change in the extrudate swell was linearly influ-

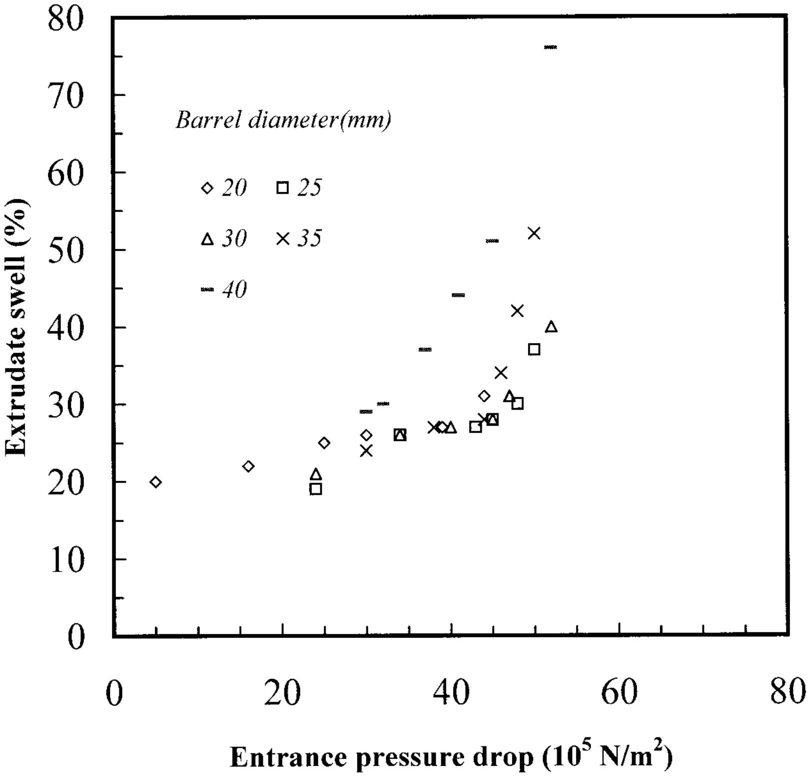

Figure 9 Percentage of the extrudate swell and entrance pressure drop for different barrel diameters with a die diameter of 6 mm.

enced by the entrance pressure drop, extrudate swell, and pressure drop decreasing with increasing actual barrel and die diameters, the effect being reversed at actual high barrel and die diameters (D_B/D_D = 35/7–40/8 mm/mm). At the high barrel and die diameters, the increase in the

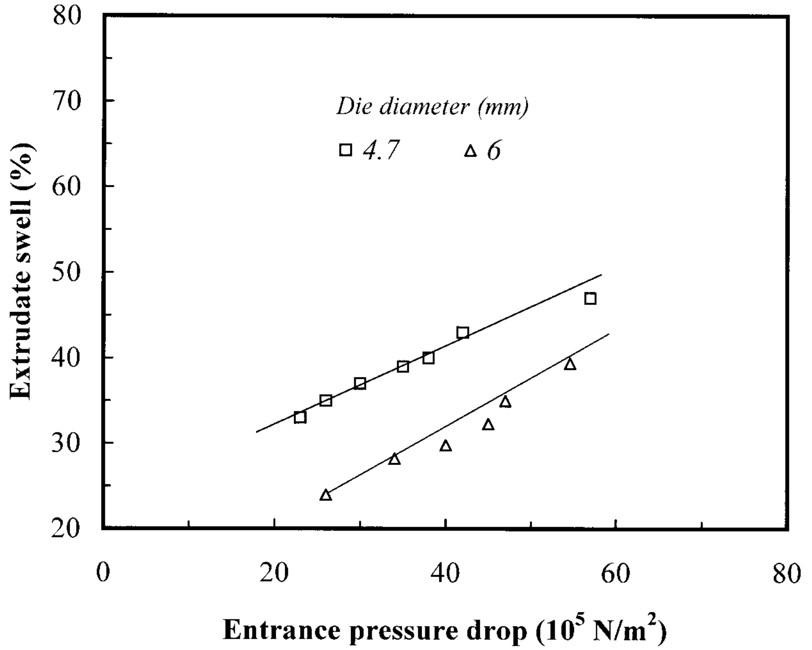

Figure 10 Percentage of the extrudate swell and entrance pressure drop for different die diameters with a barrel diameter of 30 mm.

TABLE IV
Piston Speed, γ_w and t_r of the Rubber for Two Different Die Diameters (L = 65mm)

Piston speed (mm/min)	γ_w (s^{-1})		t_r (s)	
	Die diameter		Die diameter	
	4.7 mm	6.0 mm	4.7 mm	6.0 mm
10	11.5	5.6	9.6	15.5
20	23.1	11.1	4.7	7.8
30	34.7	16.7	3.2	5.2

extrudate swell with the actual barrel and die diameters was linked with the increased material viscosity. t_r did not cause the change in the extrudate swell in this case.

- A fixed die diameter: The extrudate swell and entrance pressure drop were greatly influenced by the contraction ratio of the barrel diameter to the die diameter. The relationship between the entrance pressure drop and the extrudate swell was linear up to a certain value of the barrel diameter (>30 mm under the experimental conditions in this work). Beyond this critical barrel diameter, the relationship became nonlinear and was associated with the shearing stress generated by the semipluglike flows and t_r value of the material in the die.
- A fixed barrel diameter: The smaller die diameter tended to give a higher percentage of the swell of the extrudate because of the increases in the extensional deformation and γ_w accompanied by a decrease in the t_r value of the material.

In summary, the extrudate swell and entrance pressure drop in the capillary rheometer were, in this work, dependent not only on D_B/D_D but also on the actual diameters of the barrels and dies used.

References

1. Sombatsompop, N.; Tan, M. C.; Wood, A. K. Polym Eng Sci 1997, 37, 270.
2. Wood, A. K.; Read, A. G. G.; Lovegrove, J. G. A. Plast Rubber Process Appl 1989, 12, 15.
3. Yang, B.; Lee, L. J. Polym Eng Sci 1987, 27, 1088.
4. Cogswell, F. N. Polymer Melt Rheology; George Godwin: London, 1981.
5. Liang, J. Z.; Huang, Y. Q.; Tang, G. J. Plast Rubber Compos Process Appl 1992, 18, 311.
6. Liang, J.-Z. J Appl Polym Sci 2000, 78, 759.
7. Liang, J.-Z. Plast Rubber Compos Process Appl 1993, 19, 311.
8. Sombatsompop, N.; Wood, A. K. Polym Eng Sci 1997, 37, 281.
9. Ma, C.-Y.; White, J. L.; Weissert, F. C.; Isayev, A. I.; Nakajima, N.; Min, K. Rubber Chem Technol 1985, 58, 815.
10. Song, H. J.; White, J. L.; Min, K.; Nakajima, N.; Weissert, F. C. Adv Polym Technol 1988, 8, 431.
11. Shin, K. C.; White, J. L.; Nakajima, N. J Non-Newtonian Fluid Mech 1990, 37, 95.
12. Sombatsompop, N.; Dangtugee, R. J Appl Polym Sci 2001, 82, 2525.
13. Sombatsompop, N. J Appl Polym Sci, to appear.
14. Sombatsompop, N.; Intawong, N.-S.; Intawong, N.-T. Polym Testing 2000, 19, 579.
15. Dealy, J. M.; Saucier, P. C. Rheology in Plastics Quality Control; Hanser: Munich, 2000.
16. Anand, J. S.; Bhardwaj, I. S. Rheol Acta 1980, 8, 318.
17. Eggen, S.; Hinrichsen, E. L. Polym Eng Sci 1996, 36, 410.