Using an In-Line Slit-Die Viscometer to Study the Effects of Extrusion Parameters on Corn Melt Rheology

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ABSTRACT

Cereal Chem. 81(1):70–76

An in-line slit-die viscometer (SDV) was used to measure the viscosity of a melt extrudate independently of the extruder operating conditions. The melt produced by extrusion of the corn grits followed a power law rheological model. The viscosity of the melt and extrusion parameters such as specific mechanical energy (SME), torque, and die pressure decreased with increasing moisture content. The degree of starch gelatinization increased when barrel temperature increased from 90 to 130°C. At temperatures higher than 130°C, most of the starch had gelatinized. The increase in barrel temperature, however, resulted in small changes in the apparent viscosity of the melt, until a maximum of ≈130°C. At a constant feed rate, SME increased and torque decreased when screw speed increased due to the shear thinning behavior of the melt. At a constant screw speed, the torque increased and SME decreased with increasing feed rate. This was due to a decrease in apparent viscosity of the melt at higher feed rates. SME is not an independent extrusion variable and should be used with caution either when predicting the effect of thermomechanical treatment of the product or as the key and only variable for controlling the food extrusion process.

One of the important parameters defining the food extrusion process is the viscosity of the melt in the melting zone. Melt viscosity controls extrudate properties and influences the transport of material in the extruder and the buildup of melt pressure (Bruin et al 1978; Lai and Kokini 1990; van Lengerich 1990).

Degree of starch gelatinization greatly influences melt viscosity. It is thought that an increase in the degree of starch gelatinization results in a more viscous melt. For example, higher die and barrel temperatures increase starch gelatinization, resulting in products with a higher viscosity (Lawton et al 1972; Owusu-Ansah et al 1983). The interaction between barrel temperature and moisture content is the most important factor affecting starch transformation during extrusion (Chiang and Johnson 1977).

van Lengerich (1990) observed that the viscosity of starch melts composed of smaller average molecular weights was the result of dextrinization of starch. This usually occurs at very high extrusion temperatures (>160°C) (Chiang and Johnson 1977; Colonna et al 1984; Davidson et al 1984a,b; Chinnaswamy and Hanna 1987; Senouci and Smith 1988a; Lai and Kokini 1990; Padmanabhan and Bhattacharya 1993a,b; Vergnes et al 1993) or by increasing specific mechanical energy (SME) (Senouci and Smith 1988a; Chang et al 1999). Large SME values can be achieved by decreasing feed rate or increasing screw speed (extrusion at a low degree of fill) (Senouci and Smith 1988a; van Lengerich 1990; Chang et al 1999).

The amount of water present during food extrusion also affects the degree of starch gelatinization and the viscosity of the melt (Lawton et al 1972; Fletcher et al 1985; van Lengerich 1990). Usually melt viscosity decreases with increasing moisture content (Cervone and Harper 1978; Senouci and Smith 1988a; Padmanabhan and Bhattacharya 1989, 1993a,b; Lai and Kokini 1990; Altomare et al 1992; Vergnes et al 1993). The addition of water provides lubrication and results in a less viscous melt, providing less mechanical energy to the material and lowering SME input (van Lengerich 1990). Screw torque also decreases.

To study the relationships among extrusion operating parameters and melt viscosity it is necessary to accurately determine the viscosity of the melt, which can be described by a power law model. The power law model is characterized by two parameters, K and n, using the equation

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

where K is the consistency, n the index, η the viscosity, and $\dot{\gamma}$ the shear rate. Because the rheological properties of extrudate melts are very sensitive to thermomechanical history and the measurement of viscosity is only valid when the extrudate is in a molten state under conditions of high temperature and pressure and in a high shear environment, in-line determination is the only way to measure melt viscosity in food extrusion (Altomare et al 1992; Bhattacharya and Padmanabhan 1992, 1994).

Specially developed capillary die viscometers (CDV) or tube viscometers have been used to measure melt viscosity during extrusion (Jasberg et al 1981; Lai and Kokini 1990, 1992; Moore et al 1990; Wang et al 1990, 1993; Bouzaza et al 1996). Although these studies provided useful information on melt viscosity, the entrance effects of capillary viscometer on non-Newtonian fluids could not be avoided without great efforts. However, an alternative way to eliminate entrance effects has been suggested. Slit-die viscometers (SDV) with flush-mounted pressure transducers have been developed to directly measure the pressure profile along the extrudate flow to obtain the rheological properties of melts in-line (Senouci and Smith 1988a,b; Lai and Kokini 1990, 1992; van Lengerich 1990; Padmanabhan and Bhattacharya 1991, 1993a,b; Altomare et al 1992; Vergnes et al 1993; Bhattacharya and Padmanabhan 1994; Seethamraju et al 1994; Tomas et al 1997).

In the classical approach, using either a capillary or a slit system, the measuring block is mounted at the exit of the extruder. The throughput of the extruder, which goes directly into the measuring block, is modified by altering the screw speed or the feed rate to obtain different shear rates (Cervone and Harper 1978; Jao et al 1978; Bhattacharya and Milford 1986; Senouci and Smith 1988a,b; Lai and Kokini 1990, 1992; Padmanabhan and Bhattacharya 1991; Altomare et al 1992; Tomas et al 1997). The extruded material is subjected to different thermomechanical treatments at each shear rate setting, and the flow curves obtained may not represent the flow behavior of a single product. Thus, the resulting flow curves generated by measurements recorded using the classical in-line approach should be interpreted with caution. Jasberg et al (1981), Lai and Kokini (1990), and Altomare et al (1992) have confirmed that the operation of the in-line viscometer had little effect on the viscosity of plastic, low density polyethylene (LDPE), but had a considerable effect on the rheological properties of foods.

Several designs to reduce or eliminate the interference between the CDV/SDV measurements and the extruder operation have been investigated recently. For example, the idea of using a side-

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Publication no. C-2003-1215-01R.

stream valve to vary the flow rate at the SDV was introduced by Padmanabhan and Bhattacharya (1993a) and used in the work of Padmanabhan and Bhattacharya (1993b), Bhattacharya and Padmanabhan (1994), Seethamraju and Bhattacharya (1994) and Seethamraju et al (1994). In this design, a side-stream valve was placed at the last section of a single screw extruder that was flood fed at fixed screw speeds. By adjusting the opening of the side-stream valve, the flow rate through the slit die was controlled. The flow curves obtained using this technique were significantly different (power law index $n = 0.3–0.44$) from those obtained by varying the screw speed and the throughput, which for some conditions yielded values of $n < 0$. Padmanabhan and Bhattacharya (1993a) claimed that this design reduced the interference between the SDV and the extruder. However, it seemed that the total flow restriction, which is determined by the side stream valve and the SDV, was not maintained at a constant value. When the opening of the side stream valve was increased, there was no way of decreasing the opening of the SDV channel (i.e., to increase the flow restriction leading to the SDV). This could result in pressure changes in both the extruder and SDV and to changes in extruder operating conditions.

Springer et al (1975) presented a novel SDV to measure in-line rheological properties of polystyrene. The design was based on a dual-slit geometry with a double valve. Based on this principle, a new SDV for food extrusion called Rheopac was described by Vergnes et al (1993) and used by Della Valle et al (1996, 1997). Through a balanced diversion of the feed rate between the two channels, the flow rate and shear rate in one of the channels could be modified without changing the flow conditions in the extruder. Each channel was provided, at its entrance, with a piston valve that could be moved up and down to partially obstruct the flow section. Because the die pressure was not monitored, the relationship between the two valve openings had to be calculated before the experiment to maintain the same operating conditions. The relationship between the two valve openings was dependent on the power law index. Vergnes et al (1993) showed that if a proper ratio between the valve and slit lengths was chosen and the power law index of the melt was $n > 0.4$, the valve opening was weakly dependent on n.

Using a twin-screw extruder, van Lengerich (1990) suggested that if the specific throughput, defined as the ratio between the extruder throughput and the screw speed, was kept constant, the degree of fill in the extruder also remained constant and therefore the product underwent the same thermomechanical history. Hence, it is possible to vary the throughput to obtain different flow rates at the SDV without modifying the thermomechanical treatment of the product. The method, however, may not be used with some single-screw extruders.

The objectives of this study are to develop an in-line SDV that can be operated independently of the extrusion process, and to use this SDV to study the relationship between the viscosity of the melt and extrusion operating parameters.

MATERIALS AND METHODS

Corn grits from a single batch milled from a Pioneer brand corn hybrid, P3515, were obtained from Seedbank Ltd NZ with a moisture content of 14.1% wb and an oil content of <0.9%. The density of the grits was 1,430 kg/m^3. A twin screw co-rotating extruder (Clextral BC21) equipped with four barrel segments (100 mm each) was used. The SDV described by Li et al (1997a,b) was used in this study (Fig. 1). It consists of an adapter and a slit-die block that is used to measure the shear rate and stress. The slit used in this research was 2 × 30 × 250 mm. Five combined pressure and temperature transducers (Dynisco TPT463) were flush mounted on one side of the slit far from the entrance and exit. The pressure profile inside the slit along the longitude axis was linear. Therefore, both entrance and exit effects can be neglected.

Wall shear stress, apparent shear rate and shear rate were calculated.

Wall shear stress

$$\tau_w = \frac{H}{2}\left(\frac{\partial P}{\partial x}\right) \cong \frac{H}{2}\frac{\Delta P}{L}$$

Apparent shear rate

$$\dot{\gamma}_{app} = 6Q/WH^2$$

Shear rate

$$\dot{\gamma} = [(2n+1)/3n](6Q/WH^2)$$

τ_w is the shear stress at the slit wall, $\partial P/\partial x$ is the pressure gradient along the flow direction, H is the height of the slit, W is the width of the slit, L is the length between two pressure transducers, Q is the volume flow rate, and n is the power law index.

The calculation of corrected shear rate requires the value of n, which is determined by the slope of a plot of

$$\log(\partial P/\partial x) \text{ vs. } \log(6Q/W\times H^2)$$

Between the slit viscometer and the extruder, an adapter was fitted to allow the diversion of flow. By carefully adjusting the openings of valves A and B (indicated in Fig. 1), the flow rate in the SDV was varied to achieve different shear rates. At the same time, the die pressure monitored by a pressure transducer (Dynisco PT415) and the resulting SME were maintained at constant levels to ensure that the operating conditions remained unchanged. Compared with the design of Vergnes et al (1993), this design had the advantage that the operation of valves A and B were independent of the power law index, n.

The degree of starch gelatinization was measured as the ratio of gelatinized starch to total starch in the sample using the method described by Wootton et al (1971) and modified by Owusu-Ansah et al (1984). Dried samples of the collected extrudates were ground into fine powder (<200 µm) using a cyclone mill (Cyclotech 1092 sample mill). Two samples (0.1 g) were weighed and put into labeled, screw-capped test tubes. A solution of 0.25*M* KOH (5 mL) was added to the first sample test tube to solubilize the gelatinized starch. To the second sample, 5 mL of 0.7*M* KOH solution was added to obtain a solution of the total starch. The mixtures were shaken for 15 min and centrifuged at 3,000 × *g* for 15 min. Each supernatant (1 mL) was neutralized with 1 mL of HCL of the appropriate molarity (0.25 or 0.7*M*). The neutralized supernatants were diluted 20× using distilled water. To 0.5 mL of the diluted starch solution, 4.5 mL of distilled water was added, followed by 50 µL of iodine solution. The concentrations of the starch-iodine complex formed in the two aqueous suspensions were determined using a spectrophotometer (model 240, Gilford Instrument, Oberlin, OH) measuring the absorbances at 600 nm, which is a linear function of the concentration of the starch-iodine complex in the solution. The absorbance of the gelatinized sample (A_1) and that

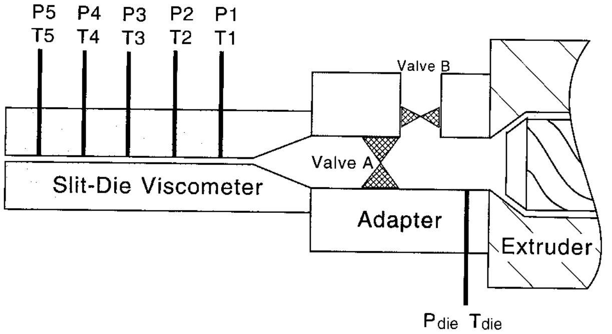

Fig. 1. New in-line slit-die viscometer (SDV) and adapter.

of the total soluble starch sample (A_2) were used to calculate the degree of starch gelatinization from the equation

$$\text{Degree of starch gelatinization } \% = (A_1/A_2) \times 100\%$$

A computerized data acquisition and control system was used to measure extrusion and SDV parameters. The temperature of the SDV was kept constant by eight evenly distributed built-in heating elements controlled by this system. Each measurement was taken only when the extruder was stable for >20 min. Each measurement was the mean of continuous data logging for 2–3 min at a rate of >1 raw data point per parameter per second. During the experiments, one extrusion parameter was changed at a time to investigate its effect on melt viscosity.

For the first experiment, the temperatures in each of the barrel segments were kept constant at 60, 90, 120, and 120°C for barrel sections 1 to 4 respectively. The temperature of the SDV was constant at 120°C. Screw speed was set at 400 rpm. Feed rate was constant at 7.5 kg/hr. The moisture contents of the extrudate melt were adjusted to 40.0, 35.0, and 31.7%.

In the second experiment, the feed rate was constant at 7.5 kg/hr. Screw speed was set at 450 rpm and the moisture content of the melt at 35% wb. The temperature of the last two barrels was varied from 90 to 160°C at 10°C intervals.

In the third experiment, the feed rate and moisture content were kept constant at 9.5 kg/hr and 35% wb while the screw speed was varied from 300 to 400 to 500 rpm. The temperature of the last two barrels and the SDV were constant at 120°C.

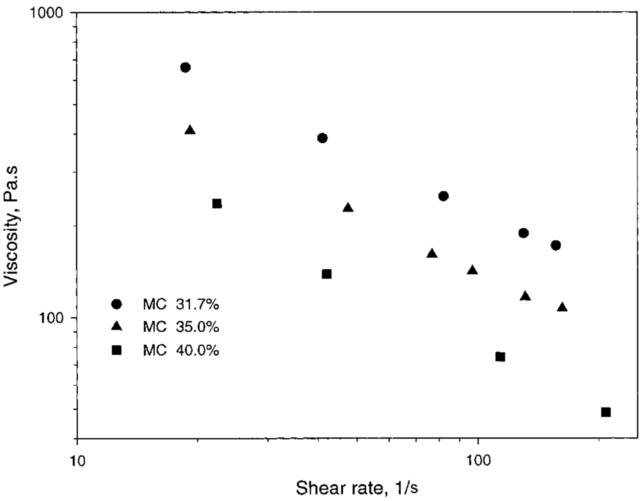

Fig. 2. Viscosity vs. shear rate for melts produced at three different moisture levels (MC).

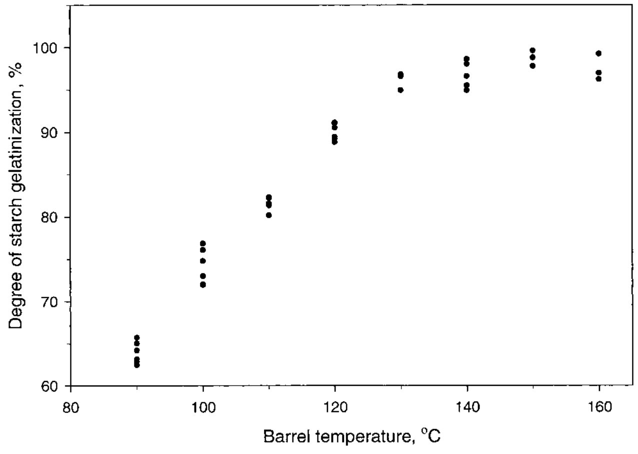

Fig. 3. Effect of extruder barrel temperature (last two barrel sections) on degree of starch gelatinization.

In the fourth experiment, the moisture content was kept constant at 35% wb while the screw speed was 450 rpm. The temperature of the last two barrels and the SDV were constant at 120°C. The feed rate of the extruder was varied from 7.1 to 9.8 to 12.1 kg/hr.

In the fifth experiment, the moisture content was kept constant at 35% wb. The temperature of the last two barrels and the SDV were constant at 120°C. Table I summarizes the experimental conditions used to verify the procedures suggested by van Lengerich (1990). The experiment consisted of two steps. In the first step, the viscosity was measured using van Lengerich's approach with the valve A of the SDV fully open and *B* fully shut. Each feed rate determined a different shear rate in the SDV. Thus, the combination of four different feed rates and screw speeds yielded four different shear rates. In the second step, the viscosity of the melt was measured using the SDV and the procedures developed in this study. For each feed rate and its corresponding screw speed, the shear stress was measured at various shear rates by adjusting the openings of valves A and B.

RESULTS AND DISCUSSION

Effect of Moisture Content

Figure 2 shows the flow curves in logarithmic coordinates for melts obtained at the three different moisture contents. The melts followed a power law model. The slope of the plots for each moisture content in Fig. 2 are similar, indicating that the power law index *n* did not change significantly with moisture content. Values of the flow index were 0.30, 0.37, and 0.36 for moisture contents of 40.0, 35.0, and 31.7%, respectively.

As moisture content decreased from 40 to 35 to 31.7%, the power law consistency *K* increased from 2,377 to 3,106 to 4,963, indicating that moisture content has a very large effect on the melt viscosity. This result is consistent with those obtained by van Lengerich (1990), Padmanabhan and Bhattacharya (1993a,b), and Vergnes et al (1993), who reported that viscosity increases with decreasing moisture content. At high moisture content, the melt had a lower viscosity, providing less resistance for the extruder screw rotation and flow through the extruder die. Thus, the torque, the screw thrust pressure, and die pressure decreased (Table II). SME applied to the material during the extrusion process also decreased when the moisture content of the melt increased from 31.7 to 40.0%. This was due to the fact that the torque on the screw decreased, whereas the screw speed and extruder throughput remained constant.

TABLE I
Screw Speeds and Feed Rates Used to Keep a Constant Degree of Fill in Extruder

	Screw Speed (rpm)	Set Corn Grit Feed Rate (kg/hr)	Set Water Feed Rate (L/hr)	Measured Throughput (kg/hr)
1	200	3.5	1.0	4.68
2	300	5.4	1.5	7.16
3	400	7.2	2.0	9.58
4	500	9.3	2.5	12.24

TABLE II
Effect of Moisture Content on Extruder Operating Conditions[a]

Moisture Content (%, wb)	SME (Whr/kg)	Torque (Nm)	P_{thrust} (kPa)	P_{die} (kPa)	Degree of Starch Gelatinization (%)
31.7	50.9	18.2	7,340	8,520	80.1
35.0	29.7	13.7	4,820	5,673	91.2
40.0	12.4	10.1	2,650	3,249	86.2

[a] Specific mechanical energy (SME), torque, screw thrust pressure (P_{thrust}), and die pressure (P_{die}).

However, the degree of starch gelatinization did not follow the expected trend where increased mechanical energy input at low moisture content increases the degree of starch gelatinization. The degree of starch gelatinization in the sample obtained from the 31.7% moisture content experiment was abnormally low. This could have been caused by errors, including sample contamination during measurement of the degree of starch gelatinization. The measured degree of starch gelatinization for the other two samples is as expected.

Effect of Barrel Temperature

Increasing the barrel temperature increased the degree of gelatinization (Fig. 3). When the temperature was set to 90°C, only 64% of starch gelatinized, whereas at temperatures above 130°C, >95% of the starch gelatinized. Starch gelatinization increased with increasing temperature; the rate of increase decreased until approximately constant gelatinization occurred at temperatures >130°C.

Figure 4 shows that changes in barrel temperature at 90–160°C resulted in small changes in the apparent viscosity of the melt. As barrel temperature increased from 90 to 160°C, the melt became slightly less shear thinning as the power index n increased from 0.40 to 0.49. A similar result was also observed by Vergnes and Villemaire (1987) using corn starch, Senouci and Smith (1988a) using maize grits, Lai and Kokini (1990) using corn starch, and Padmanabhan and Bhattacharya (1993a, 1993b) using corn meal. This has been attributed to a decrease in the size of the starch molecules due to degradation at high temperatures (Vergnes et al 1993).

The barrel temperature and the consistency index K were not linearly correlated, but a maximum value of K occurred at 120–140°C. Because the power law parameters K and n cannot vary independently (Schowalter 1978), it is more appropriate, for comparison purposes, to calculate the apparent viscosity at different shear rates. Values of apparent viscosity, calculated using the measured rheological parameters and shear rates that can exist in the extruder, are plotted in Fig. 5 as a function of the barrel temperature. These plots show that the maximum apparent viscosity occurs at 120–140°C for all shear rates.

The increase in melt viscosity at ≤130°C is due to the increase in the degree of starch gelatinization, whereas the decrease in the melt viscosity >130°C indicates that starch dextrinization occurred. This phenomenon has been reported by Colonna et al (1984) and Davidson et al (1984a) during extrusion of corn and wheat starch at >120°C. In these two reports, the average macromolecular weight of starch was substantially reduced during extrusion at >120°C.

As illustrated in Fig. 6, plots of SME, torque, die pressure, and screw thrust pressure as a function of temperature, all had peak values at barrel temperatures of ≈120°C and followed the same trend as that followed by the apparent melt viscosity. The variations in torque and SME were caused by changes in the viscosity of the melt. When the barrel temperature was <120°C, the melt had a lower viscosity. Therefore, the resistance to the rotation of the screw was smaller, resulting in lower torque. When the viscosity of the melt decreased at >150°C, torque, SME, die, and thrust pressure all decreased.

Effect of Screw Speed at Constant Feed Rate

When the screw speed was increased from 300 to 500 rpm, there was a 6.8% increase in the degree of starch gelatinization (Table III). This increase in starch gelatinization had a small effect on the rheological properties of the melt. However, the small difference in viscosity and the shear thinning behavior of the melt ($n < 1$) explains the noticeable change in SME and torque shown in Table III. The mean shear rate produced by the screw rotation in the extruder barrel can be estimated by

$$\dot{\gamma} = \frac{\pi \times \mathit{Screw\ Speed} \times \mathit{Screw\ Diameter} \times \cos(\mathit{ScrewFlightAngle})}{60 \times \mathit{ScrewFlightChannelDepth}}$$

Thus, the apparent viscosity of the melt at the three screw speeds can be calculated using the rheological parameters in Table III, and the shear rates calculated by the above equation. Results of these calculations are illustrated in Fig. 7 where a decrease in the apparent viscosity with increasing screw speed is evident. Values of the shear rate for each screw speed calculated by the above equation are included in the figure.

The viscosity of the melt in the extruder barrel becomes smaller at higher screw rotating speeds, which results in decreased torque. However, this change in viscosity caused by screw speed is not proportional to the increase in screw speed. The changing rate of apparent viscosity with screw speeds from 400 to 500 rpm (0.35 Pa.s/rpm on average) is smaller than that obtained when the screw speed increased from 300 to 400 rpm (0.6 Pa.s/rpm on average). Given the relationship of SME to torque and screw speed at a constant feed rate

$$\text{SME} = \text{torque} \times \text{screw speed/feed rate}$$

the small change observed in SME when the screw speed increased from 300 to 400 rpm was due to the large decrease in viscosity and, consequently, torque. When the screw speed was increased to 500 rpm, viscosity decreased to a lesser extent, resulting in a smaller decrease in torque. Thus, the increase in screw speed from 400 to 500 rpm resulted in a large increase in SME.

TABLE III
Rheological Properties and Degree of Starch Gelatinization of Melts at Different Screw Speeds at a Constant Feed Rate of 9.5 kg/hr

			Viscosity[a]		
Screw Speed (rpm)	**SME (Whr/kg)**	**Torque (Nm)**	***n***	***K***	**Degree of Starch Gelatinization (%)**
500	35.8	6.51	0.35	3,326.6	93.1
400	29.7	6.77	0.37	3,106.0	91.2
300	28.0	8.48	0.39	3,005.9	86.3

[a] Power law index n; power law consistency K.

TABLE IV
Effect of Feed Rate on Rheological Properties and Degree of Starch Gelatinization at a Constant Screw Speed of 450 rpm

			Viscosity[a]			
Feed Rate (kg/hr)	**SME (Whr/kg)**	**Torque (Nm)**	***n***	***K***	**Die Pressure (MPa)**	**Degree of Starch Gelatinization (%)**
7.1	33.8	5.2	0.42	2,683.5	5.20	86.6
9.8	34.3	7.3	0.45	2,324.4	6.23	90.0
12.1	30.5	8.1	0.40	2,780.6	6.31	89.8

[a] Power law index n; power law consistency K.

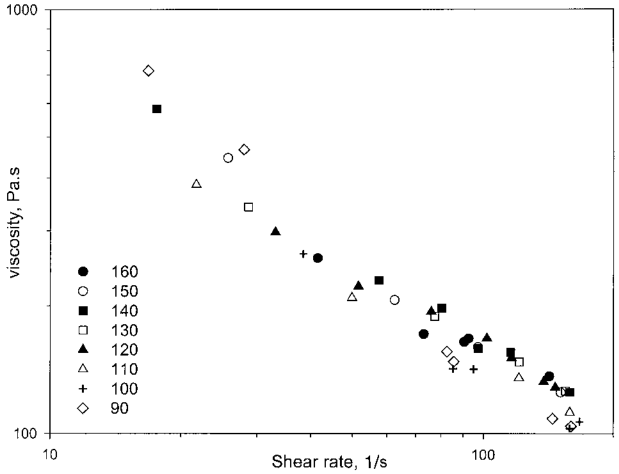

Fig. 4. Effect of barrel temperatures (last two sections) on melt viscosity measured at several temperatures (°C). Normal corn grits were used and fed at a constant feed rate of 7.5 kg/hr. Screw speed 450 rpm; moisture content of the melt 35% wb.

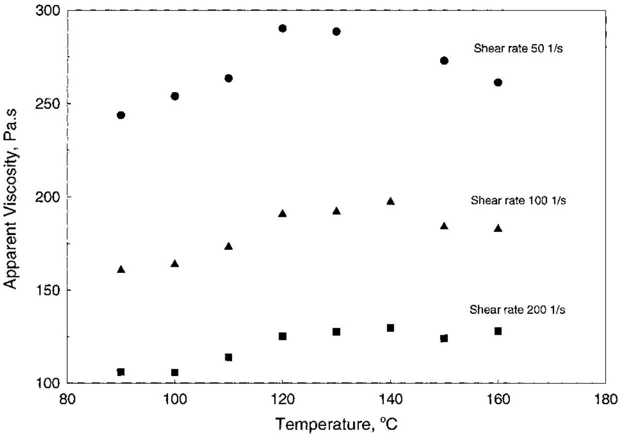

Fig. 5. Effect of barrel temperature on apparent viscosity calculated at different shear rates.

The above discussion clearly illustrates that the magnitude of SME is related to the rheological properties of the melt. The torque can also be considered a function of melt viscosity and screw speed. Thus, SME could not be well defined because it contains variables that are not truly independent.

The increase in the degree of starch gelatinization with the increase in SME is consistent with data reported by Senouci and Smith (1988a) and van Lengerich (1990). Increasing screw speed increases the shear and friction in the extruder, resulting in a higher rate of mechanical energy transfer. However, an increase in screw speed also reduces the residence time and the degree of fill if feed rate is kept constant. A lower degree of fill also contributed to a smaller torque. In other words, the molecular degradation of starch caused by the increase in the input of mechanical energy due to the increase in screw speed is, in part, compensated for by the shorter residence time.

Effect of Feed Rate at Constant Screw Speed

The effect of feed rate on extrusion and the resulting melt viscosity is less noticeable than the effect of moisture content, temperature, and screw speed. The degree of starch gelatinization increased marginally as feed rate increased from 7.1 to 9.8 kg/hr, but no change in gelatinization was observed from 9.8 to 12.1 kg/hr (Table IV).

However, values of die pressure and torque (Table IV) increased with increasing feed rate. SME was similar when the feed rate increased from 7.1 to 9.8 kg/hr and decreased as the feed rate increased to 12.1 kg/hr. At high feed rates, these results are in agreement with those of van Lengerich (1990), who found that low SME values are associated with a higher degree of fill.

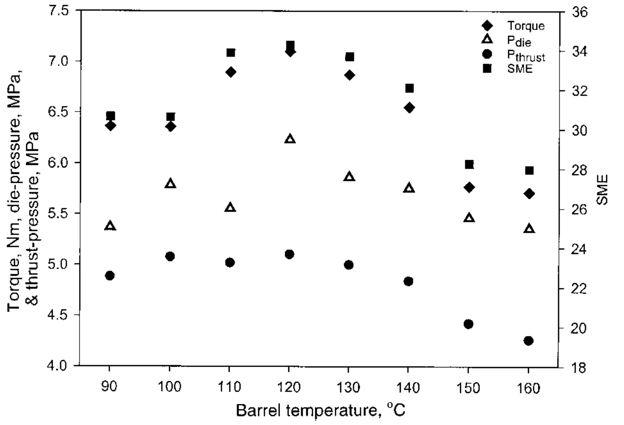

Fig. 6. Effect of barrel temperature on SME, torque, die pressure (P_{die}) and thrust pressure (P_{thrust}).

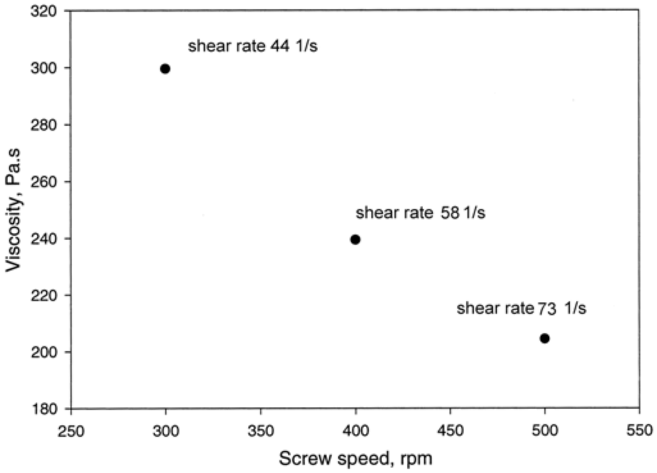

Fig. 7. Viscosity of the melt in the extruder barrel calculated at three screw speeds (300, 400, and 500 rpm).

The changes in torque and SME can be linked to small changes in melt viscosity. To explain this, it is assumed that screw torque is a function of degree of fill (in this instance, feed rate) and melt viscosity. In this experiment, the screw speed was kept constant at 450 rpm. Therefore, the apparent shear rate in the extruder did not change when the feed rate increased. The apparent shear rate was ≈66 1/s. At this shear rate, the melt obtained from the condition of highest feed rate had the lowest viscosity. The viscosities for the other two were similar. The rate of change in viscosity when feed rate increased from 7.1 to 9.8 kg/hr was smaller (1.5 Pa.s/kg/hr) than that when feed rate increased from 9.8 to 12.1 kg/hr (3.0 Pa.s/kg/hr). This explains why, when feed rate increased from 7.1 to 9.8 kg/hr, the torque increased at a higher rate, resulting in a very small change in SME. However, when the feed rate was increased from 9.8 to 12.1 kg/hr, there was a larger decrease in melt viscosity, resulting in a smaller increase in torque and therefore a larger decrease in SME. These effects could be much larger in industrial extruders, where energy introduced into the melt could be significantly greater. The above discussion clearly shows that at constant screw speed, torque is related to feed rate, and the values of SME do not follow a simple relationship when the feed rate is varied.

Effect of Degree of Fill

The measured viscosities of the melt plotted as a function of shear rate are shown in Fig. 8. There is a close agreement between the results obtained using the SDV and those obtained from van

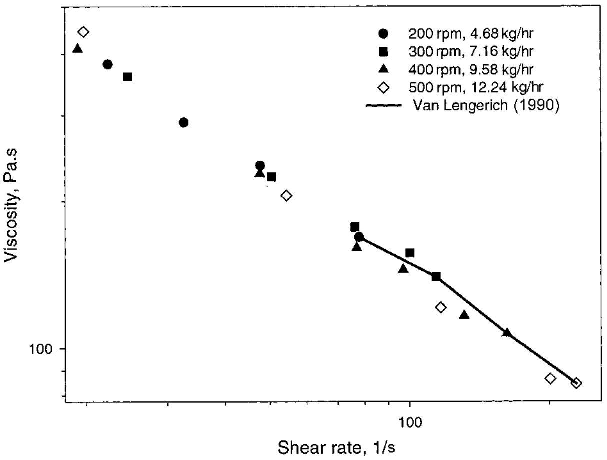

Fig. 8. Effect of constant degree of fill on the melt viscosity measured by in-line slit-die viscometer (SDV) using approach of van Lengerich (1990).

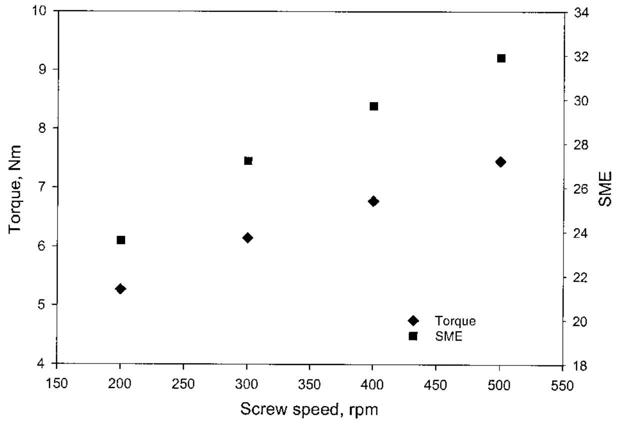

Fig. 9. Effect of screw speed on torque and SME at constant degree of fill.

Lengerich's approach. It took ≈2 hr to complete four viscosity measurements using van Lengerich's approach. However, it took <150 min to obtain four sets of measurement with an extended shear rate range using the SDV. Thus, the SDV developed in this study was a more efficient measuring instrument.

This experiment also showed that the degree of starch gelatinization, and the melt viscosity remained unchanged whereas torque and SME increased with increases in screw speed at a constant degree of fill (Fig. 9). This increase in SME, however, is accompanied by a decrease in the thermal energy input because residence time decreases with increasing screw speed. As a consequence of the shortened residence time, the extrudate receives less thermal energy at a constant barrel temperature.

SME has been used by many researchers (Kirby et al 1988; Senouci and Smith 1988a; van Lengerich 1990; Sokhey et al 1994) as an indication of the thermomechanical treatment undergone by the material during extrusion. However, the results obtained in this research clearly show that SME alone should not be used to predict the degree of thermomechanical modification of the extrudate melt. The thermal energy input should also be considered, especially when the residence time distribution varies. Caution must be exercised when using SME as the key and only parameter to control the extrusion process.

CONCLUSIONS

The SDV was useful for measuring the viscosity of the melt in-line. Its operation is independent of the extrusion process. Results showed that the melt produced by extrusion of corn grits follows a power law model. The viscosity of the melt, SME, torque, and die pressure decreased with increasing moisture content. The degree of starch gelatinization increased when the barrel temperature increased from 90 to 130°C. For temperatures higher than 130°C, most of the starch was gelatinized. The increase in barrel temperature, however, resulted in small changes in the apparent viscosity of the melt with a maximum at ≈130°C. Constant feed rate, SME increased, and torque decreased when screw speed increased due to the shear thinning behavior of the melt. At constant screw speed, the torque increased and SME decreased with increasing feed rate. The decrease in SME was due to the change in rheological properties of the melt, resulting in a decrease in apparent viscosity at the high feed rate.

Melt viscosity measured using the SDV agreed with the results obtained using the van Lengerich's approach, which uses a conventional SDV and relies on a constant ratio between the feed rate and screw speed.

SME should be used with caution either to predict the effect of thermomechanical treatment of the product or as the key and only variable for process control because its value is related to the rheological properties of the melt, which, in turn, are influenced by almost all extrusion operating parameters, so it is not an independent variable.

ACKNOWLEDGMENTS

Funding is acknowledged from the Foundation for Research, Science and Technology, Bluebird Foods Ltd. and from Seedbank Ltd. I wish to thank Ken J. Kirkpatrick for his involvement and support in this study, and Byron McKillop, head technician of the Institute of Food, Nutrition, and Human Health, Massey University, for his effort in machining the die blocks of the Slit-Die-Viscometer.

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[Received February 28, 2003. Accepted June 24, 2003.]