Effects of Feed Rate and Screw Speed on Operating Characteristics and Extrudate Properties During Single-Screw Extrusion Cooking of Rice Flour

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ABSTRACT

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Rice flour (37% moisture content) was used to examine the effects of feed rate and screw speed on the specific energy input during single-screw extrusion cooking. Torque, raised by decreasing screw speed or increasing feed rate, was found to be a power law function of the ratio of feed rate to screw speed (F_r/S_s) with $r^2 > 0.94$. Specific mechanical energy (SME) calculated from torque also was a power law function of F_r/S_s with $r^2 > 0.84$ and negative power law indices. The SME obtained was in the 225–481 kJ/kg range. Thus the extruder can be considered low shear. Increasing SME raised the die temperature and decreased both intrinsic viscosity and water absorption index (WAI). The degree of gelatinization and intrinsic viscosity of extrudates also were power law functions of F_r/S_s. The intrinsic viscosity correlated well with the degree of gelatinization, WAI, and cooking loss, and appeared to be a good index of the extrudate properties. Different screw profiles also affect torque measurement.

With the advantages of versatility and economic benefits, extrusion cooking has been widely used to manufacture a number of food products such as breakfast cereals and snacks, etc. It also is an attractive method, especially single-screw extrusion cooking, due to its low capital investment, for processing some traditional Chinese foods such as rice noodles and rice fettuccine. An extruder provides the functions of conveying, mixing, kneading, heating, and forming in one unit. Extruded food materials undergo various transformations, including starch gelatinization and protein denaturation, which affect the product properties. The thermo-mechanical experiences of the food materials during extrusion plays an important role in the material transformation as well as the product quality.

The energy input to the mass comes mainly from the conversion of mechanical to thermal energy. However, online measurement of energy conversion is not yet available. Most of the applications for process development rely on empirical studies. Response surface methodology is the easiest approach to establishing a mathematical equation in terms of operating conditions. The results are product- and machine-specific and are limited to the scope of the investigation. A system analytical model (Meuser and van Lengerich 1984) has been proposed to establish the relationship between process parameters (including operating conditions and formulas) and the system parameters (such as specific mechanical energy, product temperature, and residence time) or between the system parameters and the target parameters (such as extents of reactions, sensory characteristics of extrudates, etc.). Specific mechanical energy (SME) is the most frequently used system parameter. It is related to the mass transformation leading to variation in expansion, density, and geometric characteristics. SME, product temperature, and residence time have been used to predict the properties of puffed products such as expansion index and sensory characteristics (Meuser et al 1986), solubility (van Lengerich 1984, Pfaller and Meuser 1988). Lue et al (1994) developed a second-order equation using SME, die pressure, temperature, and starch gelatinization to estimate the product characteristics such as diameter, apparent specific volume, breaking strength, and water absorption index (WAI) of extrudates.

SME is calculated from the torque, which can be measured continuously during extrusion. The torque required to turn the extrusion screw is related to speed, fill, and the viscosity of the food material in the screw channel. Increasing the screw speed resulted in a decrease of torque (Grenus et al 1993, Hsieh et al 1993). Torque is negatively related to die temperature (Bhattacharya and Prakash 1994, Singh and Mulvaney 1994). A second-order equation using moisture content, barrel temperature, and die temperature as independent variables has been developed to describe torque for a single-screw extruder (Sheard et al 1985). Kirby et al (1988) pointed out that the screw configuration with low conveying efficiency resulted in increased barrel fill and torque. The feed rate and screw speed are two major variables that affect the barrel fill, operating characteristics, and extrudate properties. However, discussions on the relationship between torque and feed rate or screw speed are limited.

Generally, high moisture content and low shearing are used in the traditional processing for Chinese foods such as rice noodles and rice fettuccine. The performance of a single-screw extruder at these conditions needs to be understood for evaluating process feasibility. The objectives of this study were to investigate the effects of screw speed and feed rate on torque, SME, and their relationship with extrudate properties and the effects of screw profile on the operating characteristics during single-screw extrusion cooking processing of rice flour.

MATERIAL AND METHODS

Polished Indica rice (first crop in 1993) was purchased from Fen-Yuan Agriculture Association in Central Taiwan. The rice was ground using a stamp-mill to pass a 100-mesh screen. The proximate composition was reported by Yeh and Jaw (1998) as water 12.8 ± 0.20%, crude protein 6.66 ± 0.29%, crude lipid 0.46 ± 0.01%, ash 0.42 ± 0.02%, and 79.7 ± 0.58% of total carbohydrate. The total starch content was 89.2 ± 0.68% (db) and amylose content was 27.5 ± 0.3% (based on the dry weight of starch). Preweighed rice flour and a predetermined quantity of distilled water were mixed in a silent cutter to reach a final moisture content of 37% (wb). Rice flour was put in the silent cutter and distilled water was sprayed on the rice flour. The silent cutter not only provided the mixing but also prevented the rice from caking. Therefore, the moisture distribution in rice flour was uniform.

Extrusion

The extrusion cooking was conducted in triplicate using a split-barrel single-screw extruder (Tai-Yu Co., Taipei, Taiwan) as described by Yeh and Jaw (1998). The bore of the profiled barrel had a diameter of 8.5 cm. The L/D ratio was 5.1:1 and the compression ratio was 2.1:1 when a forward element was used. A diaphragm-type pressure transducer and a thermocouple were inserted into the die for measuring die pressure and temperature. A torque transducer (TP-10KMCB, Kyowa Co., Ltd., Tokyo, Japan) was fitted between the motor and gear box to measure the torque. A dynamic strain amplifier (DPM-700B, Kyowa Co., Ltd., Tokyo, Japan) was used to amplify the signal which was recorded by a personal computer.

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The energy losses in bearing and the drive train were assumed negligible as they did not affect the reproducibility of the control system. The screw profile was built up by segmented screw elements. Three different screw profiles (Fig. 1) were used to test the effects of screw element (forward, mixing disk, and nonflight) on the system parameters. The major difference in screw profiles was the screw element (5-cm length) used near the tip of the screw. The forward element had a flight height of 1 cm. Five one-tipped paddle type mixing disks with a unit length of 1 cm were staggered at 60° in the forward direction as illustrated in Fig. 2. The nonflight element was cylindrically shaped with the screw root diameter of 6.3 cm. Eighteen rectangular die orifices (7.5 × 1 mm) were used to form a spaghetti-like product. There were two barrel sections of jacketed and nonjacketed. Water flowed inside the jacket for cooling. A heating tape around the nonjacketed barrel was used for heating. There was a thermocouple attached on the surface of the nonjacketed barrel to measure the barrel temperature. The heating tape and water flow were on-off controlled to keep the nonjacketed barrel at 80 ± 2°C.

From the preliminary tests, three screw speeds (60, 90, and 120 rpm) and three feed rates (6, 9, 12 ± 0.3 kg/hr) were selected. Low screw speed minimized costly wear on the screw. Low feed rate maintains smooth running and avoids blocking of the feed port. In this study, the extruder was run at starved-fed conditions. Preconditioned rice flour was fed into the extruder through a twin-screw feeder that was calibrated before each experiment. During the experiments, the rice flour in the hopper of feeder was controlled manually at a given level (5 cm above the screw). Thus the feeding was maintained at a smooth and consistent rate with a deviation of ±0.3 kg/hr. After stable operations were established (determined by constant torque readings and product output), extrudates were collected and dried in an air oven at 40°C for further analysis of intrinsic viscosity, degree of gelatinization, WAI, and cooking loss.

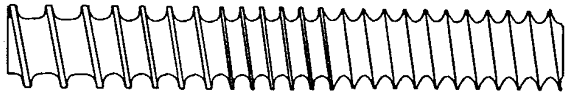
Degree of Fill

Degree of fill was measured after a dead-stop operation. At stable conditions, the extruder was stopped and the barrel was taken apart. The length of the screw channel filled with material was measured. There were no partially filled channels in the screw sections, therefore the degree of fill was calculated as the ratio of the length of fill to the screw length (42.5 cm).

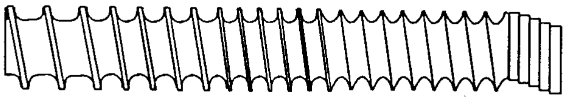
SME

No-load torque was measured while operating with flood feeding of water. The no-load torque was substracted from the operational torque to obtain the corrected torque. The SME was calculated as:

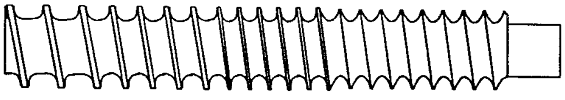
$$\text{SME} = [(2\pi \times \tau \times S_s/60)/F_r] \times 3.6 \text{ [kJ/kg]} \qquad (1)$$



forward screw profile



5 mixing disc 60° screw profile



5 cm non-flight screw profile

Fig. 1. Three screw profiles.

where τ is the corrected torque (N·m), S_s is the screw speed (rpm), F_r is the feed rate (kg/hr) and equivalent to the product output at stable conditions.

Intrinsic Viscosity

According to the methods of Greenwood (1964) and Mahanta and Bhattacharya (1989), extrudates were ground by a rotary speed mill (Pulverisette 14, Fritsch, Germany) to pass an 80-mesh screen. The samples were refluxed with 85% methanol for 24 hr, then dried by an air oven at 40°C. The dried sample (≈0.15 g) was mixed with 25 mL of 0.5N KOH and heated in boiling water while purging with nitrogen gas. The heated sample was cooled first and then centrifuged (9,000 × g) for 10 min. The supernatant was prefiltered using filter paper and filtered through a glass fiber filter (G4). The total polysaccharide in the filtrate was determined by the phenol-sulfuric method (Dubois et al 1956). The intrinsic viscosity was determined at 25 ± 0.1°C with a Cannon-Fenske viscometer using 0.5*N* KOH as the solvent.

Cooking Loss

Weighed extrudates (10 g in 10 mm length) were cooked in boiling distilled water (100 mL) in a covered beaker for 6 min. Distilled water was added to compensate for steam loss, and the mixture was lightly stirred occasionally during cooking. The temperature dropped due to the addition of distilled water, and the cooking time was recounted until the total cooking time at boiling state was 6 min. Then the mixture was filtered through a 20-mesh screen. The filtrate was dried overnight under vacuum at 45°C to a constant weight (w_c). Cooking loss (%) was calculated as the ratio of w_c to sample weight.

Degree of Gelatinization

The degree of gelatinization of the extrudate was determined by an enzymatic method (Chiang and Johnson 1977) with modified sample preparation. The oligosaccharides were removed from the samples before analysis using the method of McCready et al (1950) to increase the accuracy of analysis.

WAI

Following the method of Anderson et al (1969) with some modifications, extrudates were ground by a rotary speed mill (Pulverisette 14, Fritsch, Germany) to pass a 60-mesh screen. The ground powder (2 g) was mixed with 30 mL of distilled water in a centrifuge tube (50 mL) for 2–3 sec using a vortex mixer, then heated for 30 min in a water bath at 30°C. The heated solution was centrifuged (3,000 × *g*) for 10 min. The sediment was weighed to determine the WAI:

$$\text{WAI} = \text{weight of sediment/weight of dry sample solids} \qquad (2)$$

All the experiments were conducted in triplicate and the data were analyzed using Sigmaplot for Windows. Regressed curves and correlation coefficients were obtained. Since the variations in data were <6%, the average values were reported without showing the error bars or standard deviations.

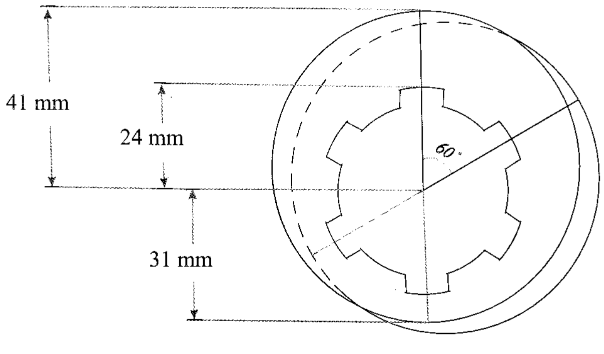


Fig. 2. Two mixing disks (one-tipped paddle type) staggered at 60°.

RESULTS AND DISCUSSION

Under the conditions tested, the measured torque was in the range of 43.1–153.1 N·m (Fig. 3), which was lower than that for extrusion of pasta (70–380 N·m) (Abecassis et al 1994) but higher than that for extrusion of soya flour (11.5–28.6 N·m) (Sheard et al 1985) and for extrusion of blends of rice and chick pea flours (30–80 N·m) (Bhattacharya and Prakash 1994). The differences may have been caused by the difference in feed ingredients and operating conditions. Increasing screw speed resulted in the reduction in torque, and this result was similar to the report for a twin-screw extruder (Grenus et al 1993, Hsieh et al 1993). The increase in feed rate raised the torque, which was in agreement with the report by Fletcher et al (1985). Comparing mixing disk with the forward element, the mixing disk yielded higher torque (63.8–153.1 N·m) than the forward element (49.7–119.4 N·m). This concurred with the report of Kirby et al (1988) that the screw element with low conveying efficiency tended to yield a greater torque. However, the comparison of conveying efficiency alone in determining torque did not seem to fully apply to the nonflight element in this study. The nonflight element had the least conveying efficiency but required torque in 43.1–125.3 N·m range, lower or higher than that of the forward element, depending on the operating conditions. Other factors, such as the degree of fill, may also play a role.

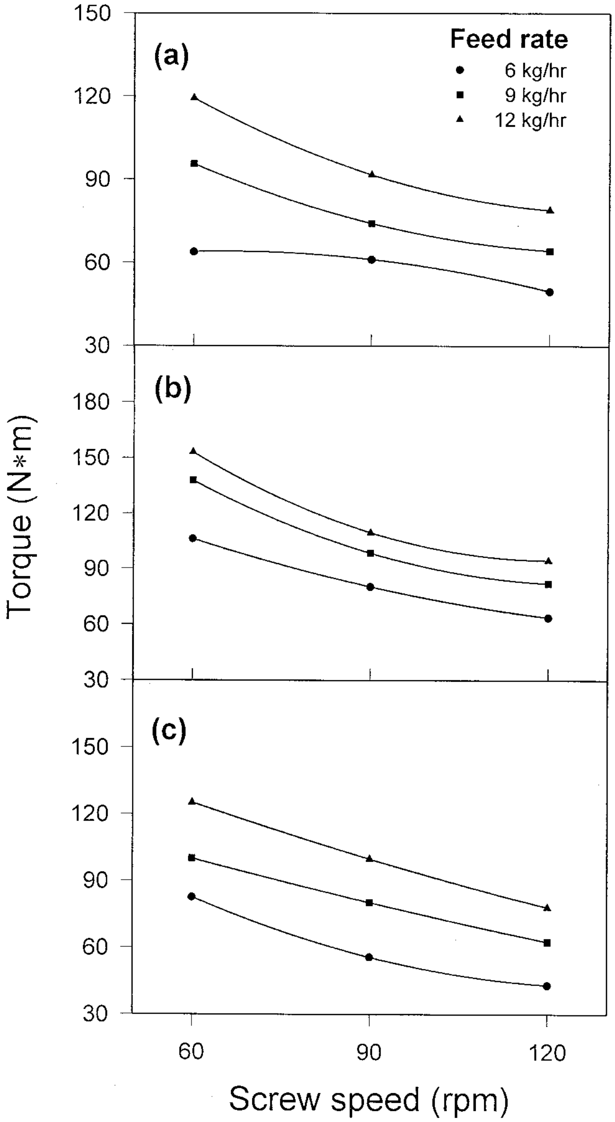


Fig. 3. Torque measured at various screw speeds and feed rates: **a,** forward element; **b,** mixing disk; **c,** nonflight element.

The degree of fill is illustrated in Fig. 4 as a function of the ratio of feed rate to screw speed (F_r/S_s) in log scale. F_r/S_s has the unit of kg/revolution, indicating the mass taken by the screw channels per revolution of screw, which is one of the operating characteristics of an extruder. The increase in screw speed and the decrease in feed rate resulted in a decrease in degree of fill. The regression showed that the degree of fill was a power law function of F_r/S_s instead of a linear relationship as postulated by Della Valle et al (1989). The result provided the experimental evidence that F_r/S_s could be used as an index for the degree of fill in extruders as previously proposed (Della Valle et al 1987, Levine et al 1987, van Zuilichem et al 1989, Yeh et al 1992). The screw profile affected the range of the degree of fill at finite values of F_r/S_s. The forward element yielded a low degree of fill (45–64%) at the operating conditions tested. The mixing disk yielded a higher degree of fill (60–81%) than that of the forward element. The nonflight element with almost no conveying efficiency, however, yielded the widest range of degree of fill (36–99%). When $F_r/S_s > 0.1$, the nonflight yielded the highest degree of fill among the three screw elements tested, but yielded the least degree of fill at $F_r/S_s < 0.1$. The results demonstrate that the degree of fill in the extruder barrel was affected by the screw profile. The physical significance of $F_r/S_s = 0.1$ needs to be determined with further studies.

Torque also was a power law function of F_r/S_s with $r^2 > 0.94$ (Fig. 4). The regressed equations are:

Forward element

$$\tau = 308.76(F_r/S_s)^{0.6135} \qquad (r^2 = 0.94) \qquad (3)$$

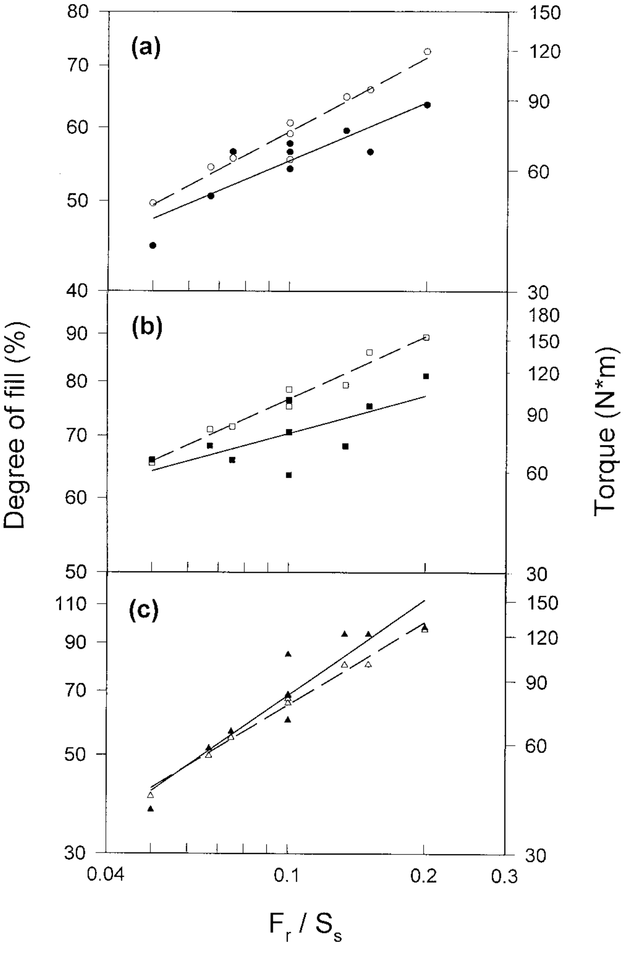


Fig. 4. Degree of fill and torque as functions of the ratio of feed rate to screw speed (F_r/S_s) in log scale: **a,** forward element; **b,** mixing disk; **c,** nonflight element. Closed symbols with solid lines = degree of fill; open symbols with dashed lines = torque.

Mixing disk

$$\tau = 421.28(F_r/S_s)^{0.6263} \quad (r^2 = 0.97) \tag{4}$$

Nonflight element

$$\tau = 449.47(F_r/S_s)^{0.7653} \quad (r^2 = 0.98) \tag{5}$$

As pointed out by Kirby et al (1988), the conveying efficiency of an element was in the decreasing order of forward, mixing disk, and nonflight elements. It appeared that the power law index increased as the conveying efficiency decreased. Further studies need to be conducted to investigate whether formulation affects the coefficients in Eq. 3–5. Such power law relationships indicate that torque is closely related with the degree of fill and further supports that the degree of fill needs to be incorporated with the conveying efficiency to determine torque for different screw profiles. The mixing disk exerted lower conveying efficiency and higher degree of fill than the forward element. Thus, greater torque was required for the mixing disk. At the same operating conditions and $F_r/S_s > 0.1$, the nonflight element required more torque than the forward element due to higher degree of fill. At $F_r/S_s < 0.1$, the nonflight element yielded the least degree of fill, and thus required the least torque among the three screw elements. The results indicated that both the degree of fill and conveying efficiency exerted by the screw element affected the torque, which consequently influenced SME and the product properties.

SME

The SME range was 225–481 kJ/kg, which was higher than that for extrusion of pasta (27–122 kJ/kg) (Abecassis et al 1994). This was because Abecassis et al employed lower screw speeds (15–30 rpm) and higher feed rates (15–36.9 kg/h) than those used in this study. The SME also was higher than that for extrusion of high moisture dough (Tsao et al 1978) but lower than most of the extrusion cooking cited by Colonna et al (1989). The difference indicates that SME is dependent on torque measurement as well as operating conditions and formulation. According to the classification by Harper (1989), the extruder used in this study can be considered a low-shear cooking extruder. Combining Eq. 1 with Eq. 3–5 expresses SME as a power law function of F_r/S_s with a negative power law index. Figure 5 illustrates the fitting of power law equations:

Forward element

$$SME = 116.06(F_r/S_s)^{-0.3879} \quad (r^2 = 0.87) \tag{6}$$

Mixing disk

$$SME = 158.28(F_r/S_s)^{-0.3754} \quad (r^2 = 0.91) \tag{7}$$

Nonflight element

$$SME = 168.74(F_r/S_s)^{-0.2367} \quad (r^2 = 0.84) \tag{8}$$

The significance of Eq. 6–8 is to establish the relationship between system parameters and operating parameters. Increasing screw speed resulted in higher specific energy due to the viscous dissipation in the melt section (Fletcher et al 1985, Della Valle et al 1993). The results are in agreement with the literature (Tsao et al 1978; Meuser et al 1982; Fletcher et al 1985; Hsieh et al 1989, 1993). The mixing disk required the highest SME among the three screw configurations tested. The nonflight element required the lowest SME when $F_r/S_s < 0.1$. It was observed that the screw profile affected the degree of fill and torque, consequently resulting in different extrudate characteristics.

It was surprising to observe that the measured die temperature was much higher than that of the set barrel temperature (80 ± 2°C). Because the experiments were repeated and the instruments were recalibrated at least three times, it was believed that mechanical energy was dissipated as heat (Vainionpää 1991). The die temperature increased with SME (Fig. 6). This was similar to the relationship between die temperature and drive power consumption reported by Fletcher et al (1985). The mixing disk yielded slightly higher die temperature than the forward element. The die pressure range was 6–10 bar and tended to be slightly reduced by increasing SME (Fig. 6). This indicated that the specific energy was mainly dissipated as heat, not for creating pressure.

The increase in SME also resulted in higher degree of gelatinization as illustrated in Fig. 7. At a given level of SME, the nonflight element yielded the highest degree of gelatinization among three screw elements. However, the corresponding value of F_r/S_s for the mixing disk was the highest (Fig. 5). This indicated that same SME was required for different screw profiles at different operating conditions, which result in different extrudate characteristics. For example, at an SME of 300 kJ/kg, the corresponding values of F_r/S_s for the forward, mixing disk, and nonflight element were 0.085, 0.182, and 0.088 kg/revolution, respectively, and the degrees of gelatinization were 93.3, 91.3, and 96%, respectively. The corresponding die temperatures (Fig. 6) were 103.9, 100.5, and 108.2°C, respectively. This indicated that die temperature was a major factor influencing the starch gelatinization (Seibel and Hu 1994). The result was similar to a twin-screw extruder where the nonflight element yielded the highest degree of gelatinization (Yeh and Hwang 1992). Power law models also are applicable to the relationship between SME and degree of gelatinization:

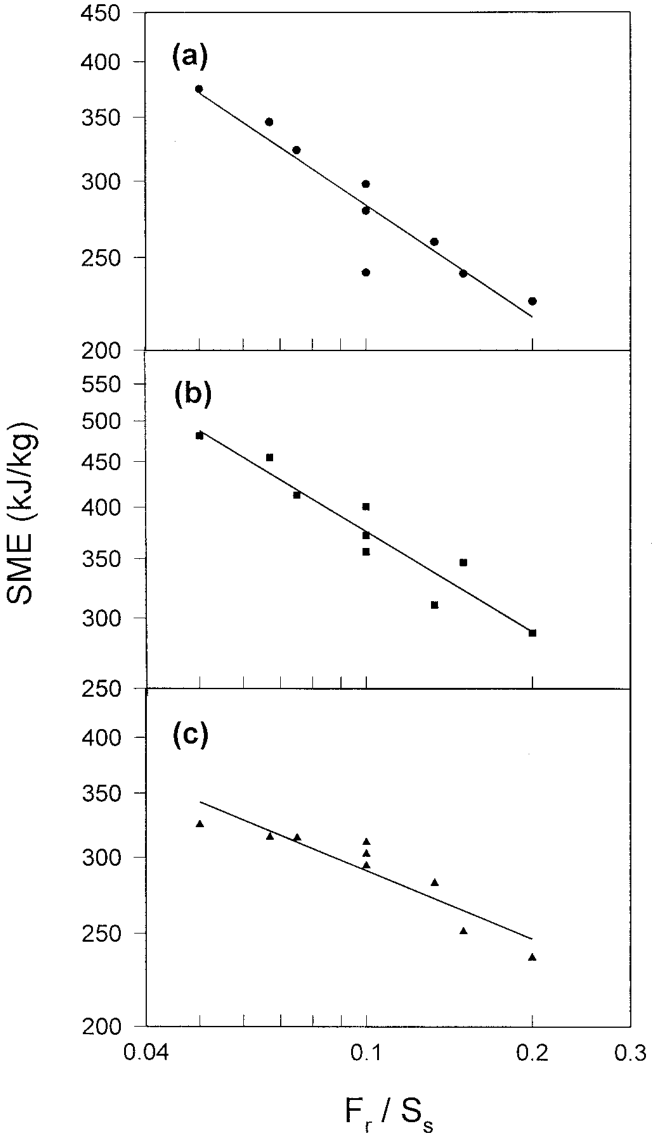


Fig. 5. Specific mechanical energy (SME) as function of the ratio of feed rate to screw speed (F_r/S_s) in log scale: **a,** forward element; **b,** mixing disk; **c,** nonflight element.

Forward element

$$\text{Degree of gelatinization} = 27.967\ \text{SME}^{0.2121} \quad (r^2 = 0.95) \tag{9}$$

Mixing disk

$$\text{Degree of gelatinization} = 39.751\ \text{SME}^{0.1462} \quad (r^2 = 0.83) \tag{10}$$

Nonflight element

$$\text{Degree of gelatinization} = 9.0273\ \text{SME}^{0.4151} \quad (r^2 = 0.83) \tag{11}$$

Combining the Eq. 6–9 with Eq. 9–11 yielded power law equations for degree of gelatinization in terms of F_r/S_s. The regressed equations are:

Forward element

$$\text{Degree of gelatinization} = 76.113(F_r/S_S)^{-0.0855} \quad (r^2 = 0.89) \tag{12}$$

Mixing disk

$$\text{Degree of gelatinization} = 82.83(F_r/S_S)^{-0.0609} \quad (r^2 = 0.92) \tag{13}$$

Nonflight element

$$\text{Degree of gelatinization} = 76.445(F_r/S_S)^{-0.095} \quad (r^2 = 0.65) \tag{14}$$

Both increasing screw speed and decreasing feed rate resulted in the increase in SME and thus the degree of gelatinization.

Increasing SME resulted in a decrease in intrinsic viscosity (Fig. 7), an index of the degradation of the starch molecules. Low intrinsic viscosity indicates high extent of the degradation of starch molecules. Among the three screw profiles, the nonflight element was associated with the highest die temperature and lowest intrinsic viscosity at the same SME. Again, using an SME of 300 kJ/kg as an example, the intrinsic viscosity (obtained from the regressed curve in Fig. 7) of the extrudates for the forward, mixing disk, and nonflight elements were 97.7 , 99.5, and 95.7 mL/g, respectively. It appeared that high die temperature was associated with a high degree of gelatinization and low intrinsic viscosity. This supported that SME alone could not predict the extrudates characteristics. However, it may be used as an index for mechanical energy dissipated when only one screw configuration is used for single-screw extrusion cooking. As illustrated in Fig. 7, the relationship between intrinsic viscosity and SME can be described by the power law equations:

Forward element

$$[\eta] = 184.89\ \text{SME}^{-0.1118} \quad (r^2 = 0.76) \tag{15}$$

Mixing disk

$$[\eta] = 492.73\ \text{SME}^{-0.2798} \quad (r^2 = 0.89) \tag{16}$$

Nonflight element

$$[\eta] = 574.43\ \text{SME}^{-0.3165} \quad (r^2 = 0.72) \tag{17}$$

where $[\eta]$ is the intrinsic viscosity (mL/g). The negative power law index confirms that the increase in the specific energy results in the decrease of intrinsic viscosity as well as the increase in degradation. Combining the Eq. 6–8 with Eq. 15–17, the intrinsic viscosity can be further expressed as a power function of F_r/S_s. Using the regression method, power functions also were obtained:

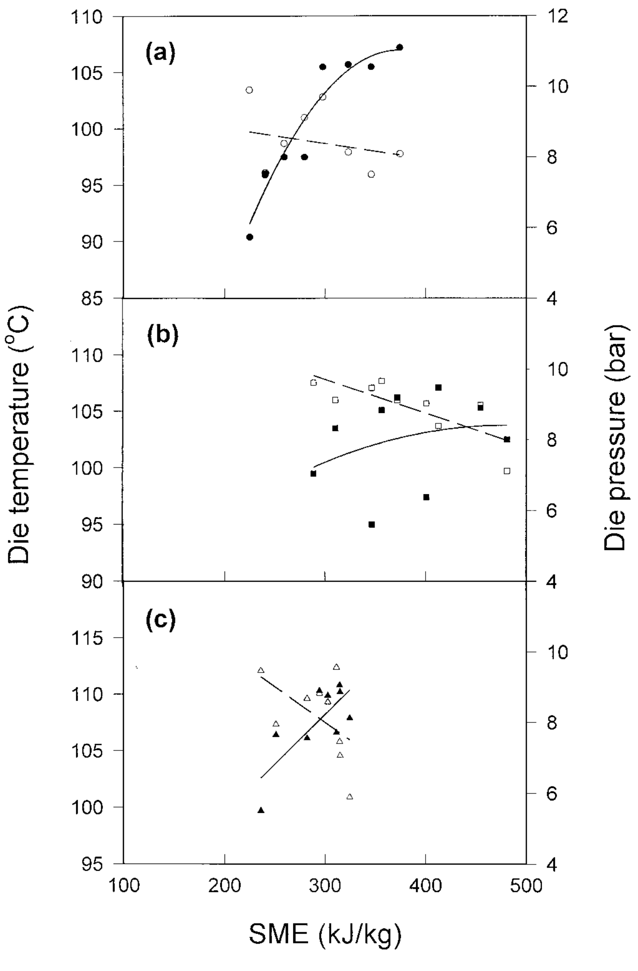


Fig. 6. Die temperature and pressure influenced by SME: **a,** forward element; **b,** mixing disk; **c,** nonflight element. Closed symbols with solid lines = die temperature; open symbols with dashed lines = die pressure.

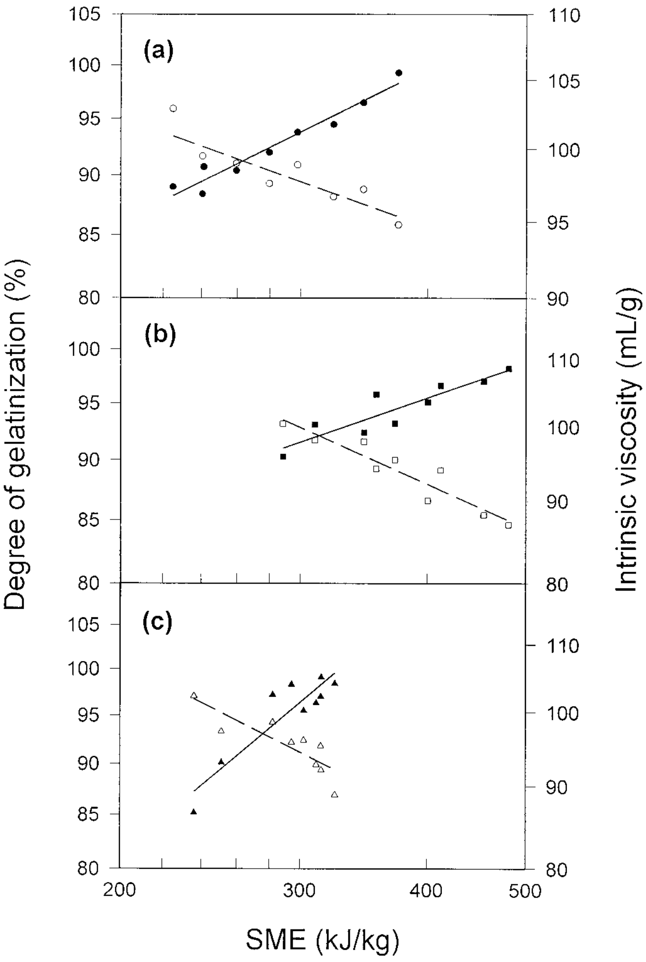


Fig. 7. Degree of gelatinzation and intrinsic viscosity as function of SME in log scale: **a,** forward element; **b,** mixing disk; **c,** nonflight element. Closed symbols with solid lines = degree of gelatinization; open symbols with dashed lines = intrinsic viscosity.

Forward element

$$[\eta] = 110.44(F_r/S_S)^{0.0504} \quad (r^2 = 0.89) \tag{18}$$

Mixing disk

$$[\eta] = 119.7(F_r/S_S)^{0.1059} \quad (r^2 = 0.81) \tag{19}$$

Nonflight element

$$[\eta] = 117.11(F_r/S_S)^{0.0891} \quad (r^2 = 0.86) \tag{20}$$

Either decreasing feed rate or increasing screw speed resulted in greater SME and higher die temperature. Thus the intrinsic viscosity was reduced. The results demonstrate that the degree of gelatinization and intrinsic viscosity can be estimated from the screw speed and feed rate when a specific screw configuration is used.

Correlations for Product Properties

Intrinsic viscosity appeared to be an important index because it was related with other product properties, such as degree of gelatinization, WAI, and cooking loss. Low degree of gelatinization was associated with high intrinsic viscosity for all experimental data (Fig. 8). The degradation of starch molecules enhanced the enzyme digestibility and raised the degree of gelatinization. Extrudates with intrinsic viscosity <90 mL/g exhibited a degree of gelatinization >95%. As reported by Yeh et al (1990), the rice noodles made from traditional method had the degree of gelatinization range of 93–98%, the corresponding intrinsic viscosity from Fig. 8 was <98 mL/g. Most of the data points from mixing disk and nonflight elements were in that region. WAI, found to be a measure of cold paste viscosity (Mercier and Feillet 1975), increased with intrinsic viscosity as illustrated in Fig. 9 with $r^2 = 0.59$. Thus, increasing SME caused the reduction in intrinsic viscosity as well as WAI. Starch molecules with greater molecular weight tended to have a greater capacity to adsorb water. Because intrinsic viscosity was a function of SME, WAI also could be expressed as a function of SME. Therefore, WAI could be estimated from the operating conditions when a specific screw configuration was used. This was similar to the report by Kirby et al (1988).

Figure 10 illustrates the relationships between cooking loss and intrinsic viscosity. In general, the cooking loss decreased with the reduction in intrinsic viscosity. Cooking loss is a surface property and intrinsic viscosity is an index of molecular weight and related with the internal structure. The results indicated that intrinsic viscosity and cooking loss were related. The nonflight element with the lowest dispersion number (Yeh and Jaw 1998) yielded the highest cooking loss among the three screw elements. This indicated that some extents of mixing was required to yield extrudates with low cooking loss. The cooking loss of rice noodles made from traditional method was in the range of 7.5–12.5% (Yeh et al 1990). Thus an extrudate with a cooking loss <12.5% is desirable. All the extrudates made using the forward element fulfilled this requirement. From Fig. 10, the intrinsic viscosity for the mixing disk and nonflight element needed to be lower than 97.2 and 95 mL/g, respectively. Based on the requirements of degree of gelatinization and cooking loss, the mixing disk, even it required the greatest SME among the three screw elements, appeared to have more operating conditions suitable for manufacturing rice noodles.

CONCLUSIONS

Torque was a power law function of F_r/S_s with positive power law index. Both the degree of fill and the conveying efficiency exerted by different screw elements affected the torque requirement. The mixing disk required more torque than the forward element due to its lower conveying efficiency and higher degree of fill. At $F_r/S_s < 0.1$, the nonflight element yielded low degree of fill and required the least torque among the three screw elements tested. SME was a power law function of F_r/S_s with negative power law index and was a good index of mechanical energy dissipated for a specific screw configuration. However, SME alone was not able to predict the extrudates characteristics, such as degree of gelatinization and cooking loss. Further studies are needed to integrate the information on SME, product temperature, and residence time for estimation. The intrinsic viscosity correlated well with other extrudate properties and appeared to be an important index. The extrudate properties, such as WAI and cooking loss, could be estimated from SME or values of F_r/S_s when a specific screw profile was used. Based on the requirements of degree of gelatinization and cooking loss, it appeared that the mixing disk had more operating conditions suitable for manufacturing rice noodles. Because the variation of die pressure was very narrow, torque was more sensitive to the change of operating conditions and appeared to be a good control variable.

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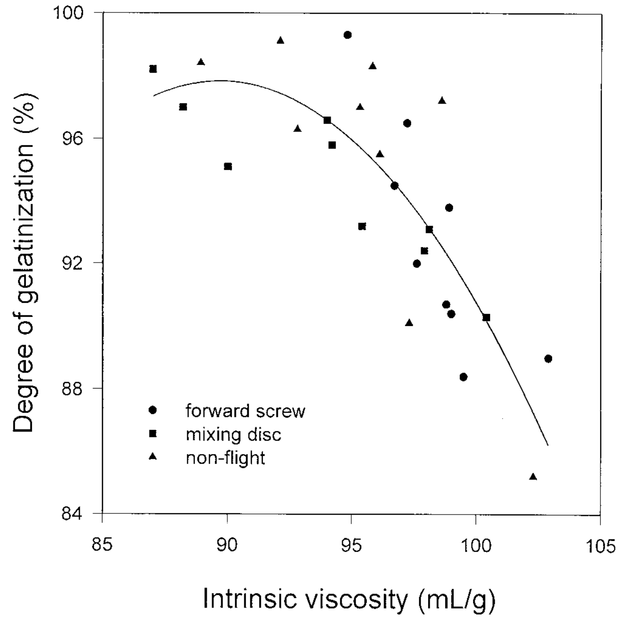

Fig. 8. Decrease in intrinsic viscosity raises the degree of gelatinization.

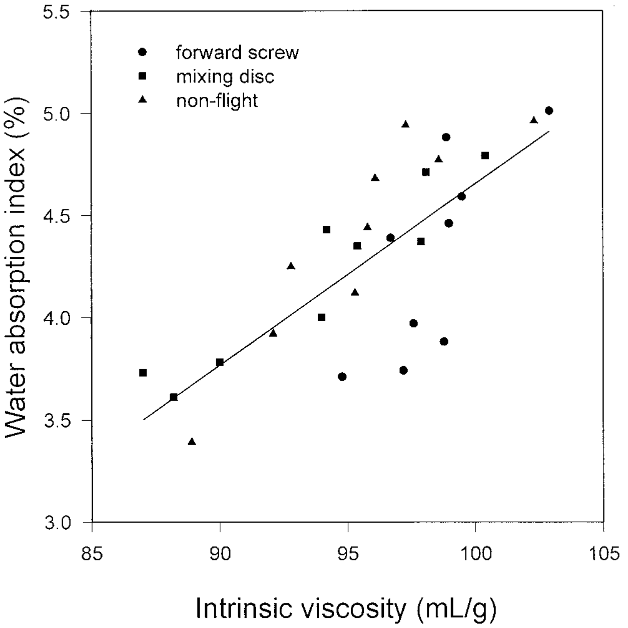

Fig. 9. High water absorption index associated with high intrinsic viscosity.

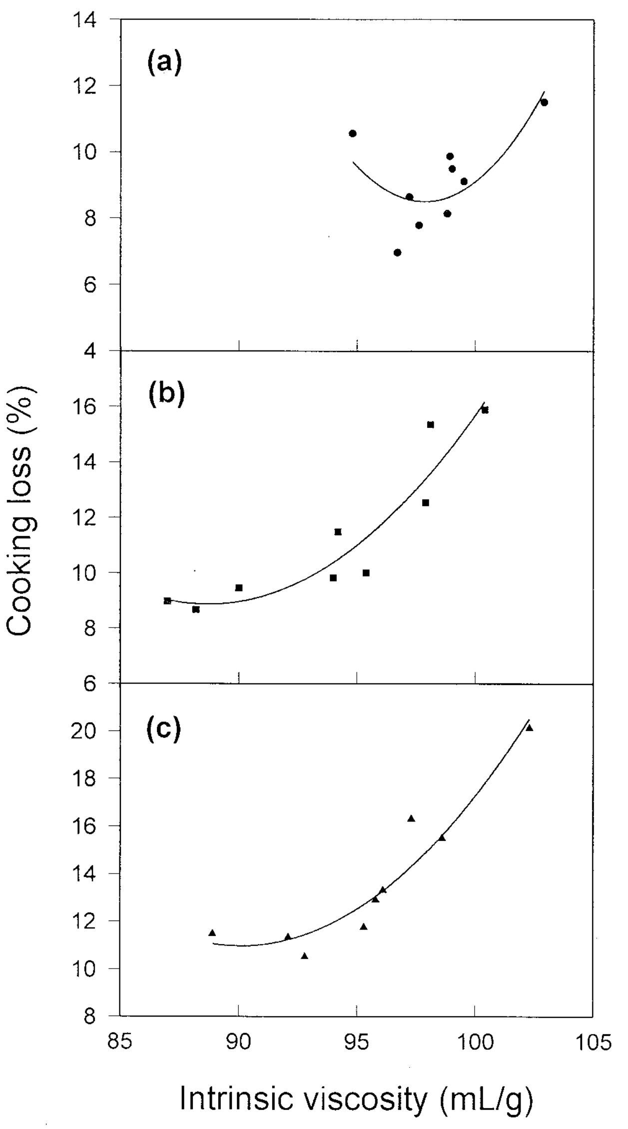

Fig. 10. Cooking loss related to intrinsic viscosity: **a,** forward element; **b,** mixing disk; **c,** nonflight element.

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