Twin-Screw Extrusion of Rice Flour with Salt and Sugar[1]

F. HSIEH,[2] K. M. GRENUS,[3] L. HU, and H. E. HUFF

ABSTRACT

Cereal Chem. 70(5):493–498

The effects of screw speed, salt (0–3%), and sugar (0–8%) contents on the extrusion of rice flour using a corotating, fully intermeshing twin-screw extruder were studied. Increasing the screw speed, salt, or sugar generally decreased the torque and die pressure. The screw speed was a more important determinant of the three processing variables (torque, specific mechanical energy, and die pressure) than was the salt or sugar content. The extrudate diameters (radial expansion) were affected only by the sugar content, not by the salt content or screw speed. The extrudate lengths (axial expansion) were higher at a screw speed of 300 rpm than at 200 rpm; they also increased with the salt and sugar. Significant increases in the specific volume were found with the addition of salt and sugar and an increase in screw speed. The breaking strength of extrudates was inversely related to the radial expansion. Raising the screw speed from 200 to 300 rpm resulted in whiter, less green extrudates.

Since its early use for continuous extrusion of pasta products in 1935 (Rossen and Miller 1973), extrusion cooking has become a popular means of preparing snack foods and ready-to-eat breakfast cereals using expandable starch-based raw materials (Sanderude 1969, Harper 1981). These raw materials (corn flour, corn meal, oat flour, rice flour, wheat flour, etc.) can be incorporated into a formulation with many other minor ingredients (such as emulsifiers, fats and oils, sugars, salt, vitamins, and minerals) to change the chemical, physical, sensory, and nutritional properties of a product (Smith 1974, Linko et al 1981, Hsieh et al 1990). Salt and sugars are of particular interest because they are frequently added to the snacks and breakfast cereals. Walker (1989) suggested that sugars contribute to browning and are critical in controlling the texture and mouthfeel. The sugars also act as flavor carriers in breakfast cereals. The levels of addition for salt and sugars are limited either by the product taste (salt) or the capability of maintaining a stable extrusion condition (sugar). Thus, based on field experience, salt is usually extruded at 1%, or less, and rarely exceeds 3%, and sugars are extruded at 5% or less. Some extruded, presweetened breakfast cereals do contain more than 30% sugars (Li and Schuhmann 1980), but these are often added as a glaze or nonglassy coating on cereals after extrusion operation.

Sugars and salt have profound effects on extrusion cooking of starch-based food materials such as wheat flour (Kervinen et al 1981, Vainionpää et al 1984), corn meal (Hsieh et al 1990), and corn starch (Sopade and Le Grys 1991). At a lower temperature range (<160°C), Kervinen et al (1981) found that the degree of starch gelatinization in extruded wheat flour increased to a maximum as sugar content reached 6%, and it decreased with higher sugar contents. Vainionpää et al (1984) reported that 23% sugar and 1.5% salt in a wheat flour-sugar-salt blend resulted in a water activity (a_w) of 0.85 for 25% moisture extrudate. When sugar and salt were mixed with the milled extrudate, 30% sugar and 1.5% salt were needed to reach the same a_w. An increase in salt content (0–3%) in extrusion of corn meal decreased the die pressure, torque, and specific mechanical energy (SME) (Hsieh et al 1990). Similar results were found when adding sugar during extrusion cooking of corn starch. An increase in sugar content (20–50%) decreased the SME, die pressure, and melt temperature and increased the tendency of the extrudate to collapse on cooling (Sopade and Le Grys 1991).

Rice flour is an important ingredient for many ready-to-eat breakfast cereals and snacks. Numerous researches have been conducted on the extrusion of rice-flour-based products (Mottern et al 1969, Spadaro et al 1971, Meister and Schneeweiss 1984, Altomare and Ghossi 1986, Chauhan and Bains 1988, Maga and Kim 1989, Pan et al 1991). In addition, Hsieh and Luh (1991a,b) recently reviewed extrusion in rice snacks and breakfast cereals. However, the effects of salt and sugar on extrusion cooking of rice flour, and the properties of resulting products, have not been well studied.

Starches from different cereals vary greatly in size, shape, and gelatinization properties. For example, the gelatinization temperature range for rice starch is 68–78°C, whereas those for corn starch and wheat starch are 62–72°C and 58–64°C, respectively (Hoseney 1986). Therefore, the effects of salt and sugar on extrusion cooking may vary for different cereals. The objectives of this study were to examine the effects of sugar, salt, and screw speed on extrusion-processing variables, as well as the product properties of rice flour extruded with a corotating, fully intermeshing twin-screw extruder.

MATERIALS AND METHODS

Materials

Long-grain rice flour (RL-100) was supplied by Riceland Foods (Stuttgart, AK) and kept in refrigerated storage in sealed paper bags until use. The proximate composition of the rice flour is given in Table I. Granulated, uniodized salt and powdered sugar (sucrose) were used as additives. The granulation size of salt was: 0.50–0.70 mm (7.5%), 0.25–0.50 mm (91.5%), and <0.25 mm (1.0%). The powdered sugar contained 3% corn starch. Ingredients for each treatment were mixed in 7.5-kg batches using an 18.9-L Hobart mixer (model A-200-F, Hobart Corp., Troy, OH) at 110 rpm. The batches were mixed 5 min to ensure an even distribution of the ingredients. Concentrations of salt and sugar studied were 0–3% (w/w) and 0–8% (w/w), respectively. The extruder was run at 200 and 300 rpm for all levels of salt and sugar additions.

Extrusion Equipment

The extruder used in this study was an APV Baker MPF50/25, 28.0 kW, corotating and intermeshing twin-screw machine (APV Baker, Grand Rapids, MI). A detailed description of the extruder, screw configuration, die, data recording, and volumetric feeder used was as reported by Hsieh et al (1989, 1990). The

TABLE I
Proximate Composition of Rice Flour

Component	Composition (%)
Moisture	12.0
Protein	7.8
Fat	0.4
Ash	0.4
Fiber	0.3–0.7[a]

[a] Supplied by the producer.

---

[1] Contribution from the Missouri Agricultural Experiment Station, Journal Series 11,605.

[2] Author to whom all correspondence should be addressed.

[3] Department of Agricultural Engineering, Purdue University, West Lafayette, IN.

barrel zone temperatures were set at 23.9 (feeding zone), 51.7, 93, and 121.1°C throughout the experiments.

Raw materials were fed into the extruder at a rate of 50 kg/hr. Water was injected 0.108 m downstream from the center of the feed port to the extruder and adjusted to give a moisture content of 21% (wb) in the feed. The die-face cutter, with four blades, was operated at 340 rpm. All these variables were maintained constant for all treatments.

Ten thermocouple sensors were used to monitor the temperatures of barrel and product in different zones. In addition, a Dynisco pressure transducer (Dynisco Inc., Norwood, MA) and extra thermocouples were inserted, from the bottom and the side, into the die plate to measure the product pressure and temperature, respectively, at the die.

All measurements of temperature, die pressure, torque, screw speed, and cutter speed were collected by a MACS PL-1000 data acquisition system (Elexor Assoc., Morris Plains, NJ) through a PC-AT/XT computer (Northgate, Plymouth, MN) and stored in a hard disk through an RS-232C port. Force required to maintain the set screw speed was recorded as percent torque. The SME was calculated as follows (Hsieh et al 1990):

$$\mathrm{SME} = \frac{\omega}{\omega_r} \times \frac{\tau}{100} \times \frac{Z_r}{Q} \qquad (1)$$

where ω = screw speed in rpm; ω_r = rated screw speed (500 rpm); τ = percent torque; Z_r = rated power (28 kW); and Q = feed rate (50 kg/hr).

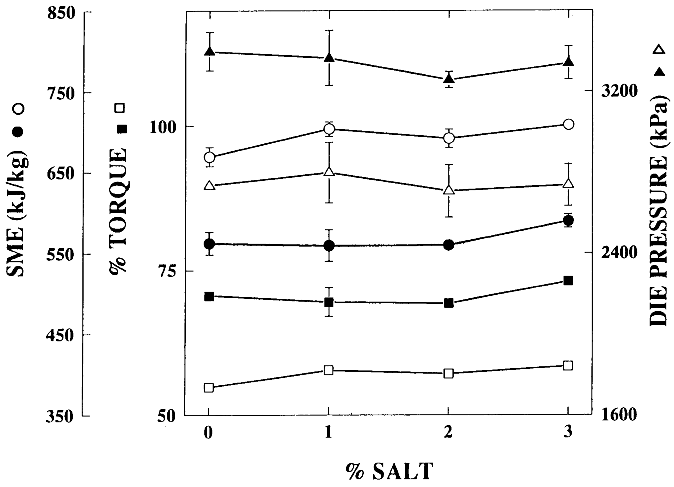

Fig. 1. Effects of salt content and screw speed on torque, specific mechanical energy, and die pressure. Closed symbols = 200 rpm, open symbols = 300 rpm.

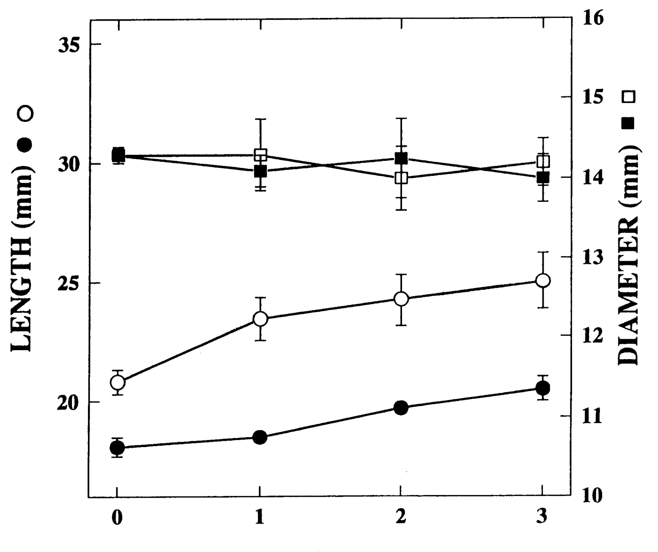

Fig. 2. Effects of salt content and screw speed on extrudate diameter and length. Closed symbols = 200 rpm, open symbols = 300 rpm.

Product Collection and Properties

Sample was collected after a 5-min period of steady die pressure and temperature. A 4-min sampling time was used to ensure a consistent schedule for each sample. The moist extrudates were dried to 7 ± 0.5% moisture (wb) in a fluidized bed dryer at 65°C for about 5 min.

The diameters and lengths of extrudates (50 measurements for each treatment) were taken using electronic calipers (Fletcher et al 1985). Specific volume (three measurements for each treatment) of whole extrudates was measured by the displacement method presented by Park (1976), except that canola seeds were substituted for sand. Breaking strength of 10 extrudates for each treatment was determined using a Warner-Bratzler shear on a model 1132 Instron (Instron Corp., Canton, MA) (Pearson 1963). The breaking strength was reported as the maximum force required to shear the extrudate, divided by the cross-sectional area of the extrudate. The color of ground extrudates (passing through a U.S. standard sieve no. 10) was measured (six measurements for each treatment) using the Hunter D25L colorimeter (Hunter Assoc. Lab, Reston, VA), and the values of *L*, *a*, and *b* were recorded. All measurements were used for data analysis. The means from two replicates were reported.

Experimental Design and Statistical Methods

A full-factorial design consisting of four levels of salt (0, 1, 2, and 3%), five levels of sugars (0, 2, 4, 6, and 8%), and two screw speeds (200 and 300 rpm) was used. The entire experiment was replicated. Analysis of variance was conducted with SAS (1986) using the general linear models procedure. Sources of variation were salt or sugar concentration, screw speed (rpm), and their interactions.

RESULTS

Effects of Salt Concentration and Screw Speed

As shown in Figure 1, the effects of screw speed on all three extrusion-processing variables (torque, SME, and die pressure) were significant ($P < 0.001$). It is also interesting to note that they all exhibited similar trends with increases in the salt content. At 200-rpm screw speed, initially, all three variables decreased when the salt content was raised from 0 to 2%, but the trend was reversed with a further increase in the salt content. At 300-rpm screw speed, they increased with salt content of 0 to 1%, decreased with salt content of 1 to 2%, and then increased again. Thus, there was a significant interaction between the effects of salt content and the screw speed when the salt content was changed from 0 to 1%. In addition, a higher screw speed (300 rpm) resulted in lower torque and die pressure, but a higher SME requirement, than did a lower screw speed (200 rpm). The effects of increasing the screw speed from 200 to 300 rpm on all three processing variables were significantly greater than the effects of increasing the salt content from 0 to 3%.

The effects of salt content and screw speed on some extrudate product properties are shown in Figures 2–4. Figure 2 presents the extrudate expansion in terms of the extrudate length and diameter, which corresponds to axial and radial expansions, respectively. Increasing the salt content (0–3%) and screw speed (200–300 rpm) significantly enhanced extrudate axial expansion ($P < 0.001$). At 300-rpm screw speed, increases of axial expansion, when the salt content was increased, were more rapid than those at 200-rpm screw speed. In contrast, no significant differences were caused by the salt content (0–3%) and screw speed (200–300 rpm) on the radial expansion.

Extrudate specific volume and expansion were positively correlated, and thus, the more the extrudates expanded in either the axial or radial direction, the less dense they became (Fig. 3). A significant increase of specific volume was observed when the salt content was increased from 0 to 3% or when the screw speed was raised from 200 to 300 rpm. This was probably caused mainly by the increases in the extrudate axial expansion, because the increases in the radial expansion were not significant. Figure 3 also shows that neither salt content nor screw speed significantly affected the breaking strength.

The effects of screw speed and salt content on extrudate colors measured by the Hunter lab system are shown in Figure 4. The system provided a measurement of the total lightness (a value of 100) or darkness (a value of 0) of the extrudates as recorded by the *L* value. Greenness and redness were reported as $-a$ and $+a$ values, respectively; $-b$ and $+b$ values were indicative of the blueness and yellowness, respectively. Among the three color parameters of the extrudates, *L* values were not affected by the salt content (0–3%). It was affected by the screw speed; the extrudates were lighter in color at 300 rpm than they were at 200 rpm. Increasing the salt content from 0 to 3% increased $|-a|$ values (more greenness) and reduced *b* values (less yellowness) significantly ($P < 0.001$). Increasing the screw speed from 200 to 300 rpm enhanced overall extrudate lightness (higher *L* value) and reduced greenness (lower $|-a|$ value) at $P < 0.01$ and $P < 0.05$, respectively. Yellowness remained unaffected.

Effects of Sugar Concentration and Screw Speed

Figure 5 shows that the effects of sugar content and screw speed on all three processing variables studied were significant ($P < 0.001$). The effect of changes in sugar content on torque, SME, and die pressure followed the same pattern as that for salt content. At 200-rpm screw speed, all three variables showed, essentially, a declining trend when the sugar content was increased from 0 to 8%. As observed in the effects of salt, measurements for torque, SME, and die pressure were elevated initially as the sugar content was raised from 0 to 2% at 300 rpm and then decreased with further increases in the sugar content. The highest values for all three processing variables occurred at 0 and 2% sugar content and 200 and 300 rpm, respectively, whereas the lowest values were at 8% sugar content for both screw speeds. A higher screw speed, as observed for the effects of salt content and screw speed, also resulted in lower torque and die pressure, but a higher SME requirement, than a lower screw speed. Additionally, the increase of screw speed from 200 to 300 rpm affected all three processing variables more significantly than did raising the sugar content from 0 to 8%.

The extrudate length (axial expansion) and diameter (radial expansion) showed a general increase ($P < 0.001$) with an increase in the sugar content from 0 to 8% (Fig. 6). At the 300-rpm screw speed, the axial expansions were significantly higher ($P < 0.001$) than they were at 200 rpm; the radial expansions were not affected. Both specific volume and breaking strength were affected by the sugar content and screw speed (Fig. 7). A higher screw speed or higher sugar content yielded a higher specific volume but a lower breaking strength. The screw speed had a less pronounced effect on the breaking strength than did the sugar content, however. A noticeable interaction between the screw speed and sugar content was observed. Either the breaking strength decreased or the specific volume increased more rapidly at 300 rpm than at 200 rpm when the sugar content was raised from 0 to 8%.

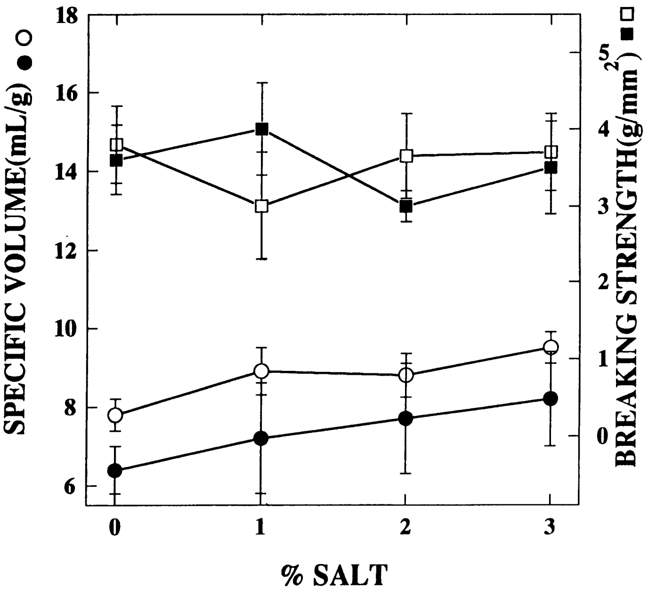

Fig. 3. Effects of salt content and screw speed on extrudate specific volume and breaking strength. Closed symbols = 200 rpm, open symbols = 300 rpm.

All three extrudate color parameters were influenced significantly by the sugar content ($P < 0.001$) (Fig. 8). The redness and yellowness of extrudates was reduced when the sugar content was raised. The lightness of extrudates also declined with the sugar content (0–6%), but the trend was reversed when the sugar content increased from 6 to 8%. No statistically significant difference in the yellowness of extrudates was noted when the screw speed increased from 200 to 300 rpm, but a higher screw speed was associated with whiter (higher *L* value) and less green (lower $|-a|$ value) extrudates.

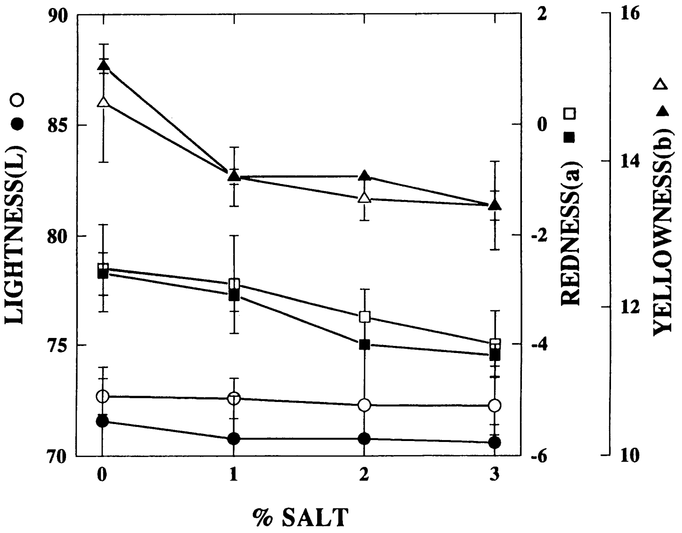

Fig. 4. Effects of salt content and screw speed on the color parameters of extrudates. Closed symbols = 200 rpm, open symbols = 300 rpm.

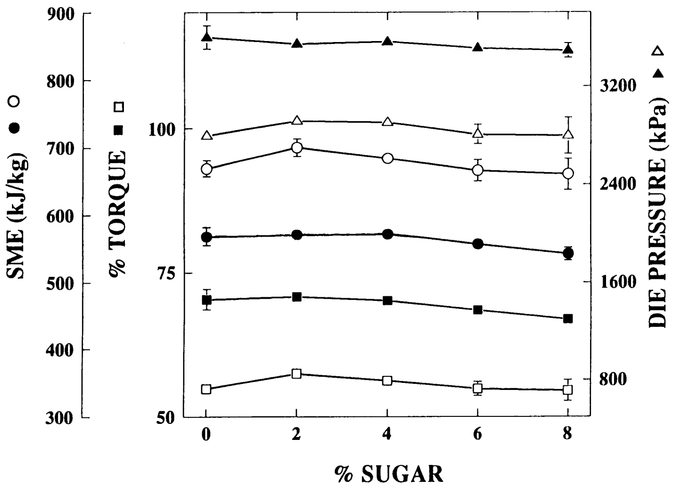

Fig. 5. Effects of sugar content and screw speed on torque, specific mechanical energy, and die pressure. Closed symbols = 200 rpm, open symbols = 300 rpm.

DISCUSSION

According to Martelli (1983), die pressure is related to the feed rate (Q), dough mass viscosity (η), and die conductance (K_f) as follows:

$$P = \frac{Q\eta}{K_f} \qquad (2)$$

In this study, both feed rate (Q_f) and die conductance (K_f) remained unchanged and, thus, die pressure was proportional to the dough mass viscosity. The viscosity of intermediate- and low-moisture dough mass exhibits pseudoplastic behavior and can be described by the power law model (Clark 1978):

$$\eta = m\dot{\gamma}^{\,n-1} \qquad (3)$$

where η = apparent viscosity of power law fluids (Pa·sec), m = consistency index (Pa·sec^n), $\dot{\gamma}$ = shear rate (sec^{-1}), and n = dimensionless flow behavior index. The shear rate is directly proportional to the screw speed. Combining equations 2 and 3 gives:

$$\frac{P_{200rpm}}{P_{300rpm}} = \frac{\eta_{200rpm}}{\eta_{300rpm}} = \left(\frac{200rpm}{300rpm}\right)^{n-1} \qquad (4)$$

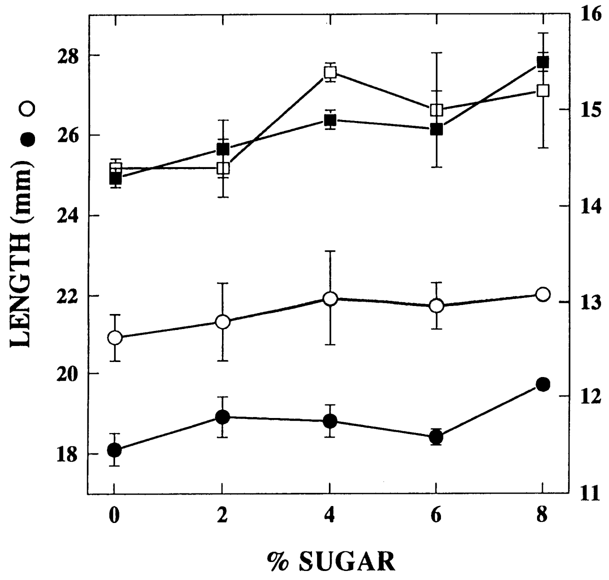

Fig. 6. Effects of sugar content and screw speed on extrudate diameter and length. Closed symbols = 200 rpm, open symbols = 300 rpm.

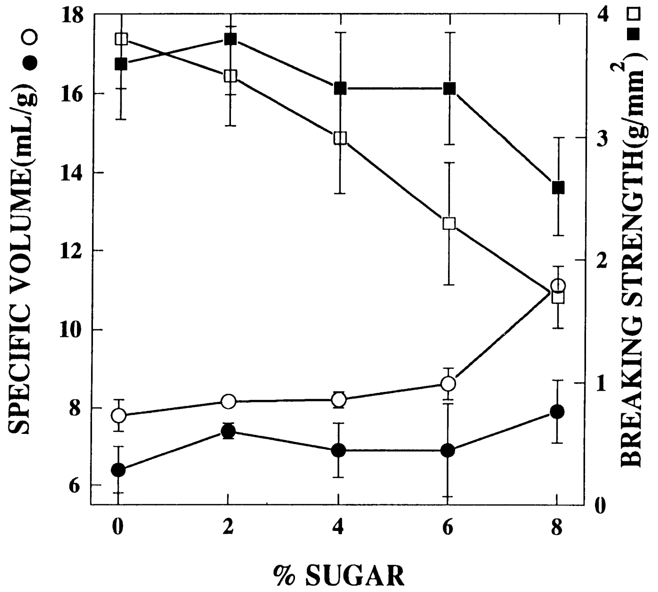

Fig. 7. Effects of sugar content and screw speed on extrudate specific volume and breaking strength. Closed symbols = 200 rpm, open symbols = 300 rpm.

Using the die pressure data shown in Figures 1 and 5, we found that n, the flow behavior index as calculated from equation 4, varied from 0.39 to 0.53. This is similar to the results summarized by Colonna et al (1989) for various starchy materials. Thus, the dough mass viscosity at 300 rpm was lower (~78–82%) than it was at 200 rpm. Physically speaking, die pressure is a result of the constrained flow of the dough mass through the die orifice and its consequent build-up behind the die. It follows that a less viscous dough flows through the orifice more easily, and with a lower die pressure, than does a stiffer dough.

Increases in the screw speed could either increase (Tsao et al 1978; Meuser et al 1982; Fletcher et al 1985; Hsieh et al 1989, 1990) or decrease (Bruin et al 1978, Jao et al 1978, Bhattacharya and Hanna 1987) the SME requirements. This topic has been thoroughly discussed (Hsieh et al 1992). According to Martelli (1983), the total power transmitted from the main motor to the screws is the power dissipated into the material as shear. The power required to create the pressure needed for extrusion is:

$$Z_t = C_1\bar{\eta}N\omega^2 + \frac{Q^2\eta}{K_f} \qquad (5)$$

where C_1 = a constant based on screw geometry, ω = screw speed (1/sec), N = number of filled flights, Q = output rate (m^3/sec), K_f = the conductance (m^3) of the die, and η and $\bar{\eta}$ = melt viscosity and average viscosity (N·sec/m^2) over the filled channels. Because the die pressures were relatively low, it may be assumed that the power needed to create the pressure for extrusion was neligible when compared with that dissipated into the material as shear. Also, the number of filled flights is inversely proportional to the screw speed. Thus:

$$Z_t \approx C_1\bar{\eta}N\omega^2 \qquad (6)$$

and

$$\frac{SME_{300rpm}}{SME_{200rpm}} = \left(\frac{\eta_{300rpm}}{\eta_{200rpm}}\right)\left(\frac{200rpm}{300rpm}\right)\left(\frac{300rpm}{200rpm}\right)^2 \qquad (7)$$

Accordingly, the specific energy at 300 rpm is higher than that at 200 rpm and their ratios were expected to be in the range

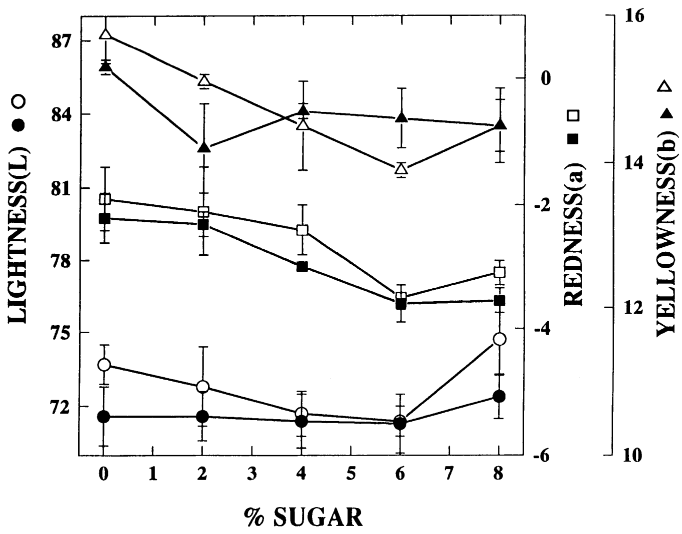

Fig. 8. Effects of sugar content and screw speed on the color parameters of extrudates. Closed symbols = 200 rpm, open symbols = 300 rpm.

of 1.17–1.23, using the range of dough-mass viscosity ratios at 0.78–0.82. Figures 1 and 5 show that the range of specific mechanical energy ratios is 1.17–1.25. A higher SME input to the dough mass at 300 rpm than at 200 rpm was also reflected in the product temperature in the melting zone. At 200-rpm screw speed, the product temperatures in the melting zone were about 170°C, with or without the addition of sugar or salt, but they were 175–182°C at 300 rpm (data not shown).

The torque applied to the extruder shafts is (Martelli 1983):

$$\tau = \frac{Z_t}{\omega} \approx C_1 \bar{\eta} N \omega \tag{8}$$

Therefore:

$$\frac{\tau_{300\text{rpm}}}{\tau_{200\text{rpm}}} = \left(\frac{\eta_{300\text{rpm}}}{\eta_{200\text{rpm}}}\right) \left(\frac{200\text{rpm}}{300\text{rpm}}\right) \left(\frac{300\text{rpm}}{200\text{rpm}}\right) \tag{9}$$

where $\tau_{200\text{rpm}}$ and $\tau_{300\text{rpm}}$ are percent of torque at screw speeds of 200 and 300 rpm, respectively. Thus, percent of torque was lower at a higher screw speed than it was at a lower screw speed, and the ratios of percent of torque should be equivalent to those of the dough-mass viscosity (78–82%). The results shown in Figures 1 and 5 confirmed that the ratios of percent of torque were indeed in the range of 77–81%.

The addition of salt or sugar in the dough mass, in general, decreased torque. Ganz (1965) and Hester et al (1956) found that the swelling of starch was delayed or reduced with the addition of salt or sugar. D'Appolonia (1972) reported that salt caused the starch granule to remain intact for an extended period of time. This resulted in a decrease or delay in the starch gelatinization and reduced the viscosity of dough mass. Whistler and Daniel (1985) and Guy and Horne (1988) also found that high sugar concentrations decreased the rate of starch gelatinization and reduced the dough-mass viscosity. The reduction of dough-mass viscosity could also be explained by the fact that both salt and sugar tended to compete with the starch for water as they were added to the formula. Thus, more water was held outside of the starch granule, in a more mobile and less viscous system, and the gelatinization of starch was delayed. Therefore, torque, SME, and die pressure were lowered with the addition of salt (0–2%) or sugar (0–8%). Similar results were reported by Hsieh et al (1990) for corn meal and Sopade and Le Grys (1991) for maize starch. The slight increases in torque, SME, and die pressure when the salt content was increased from 2 to 3% might be due to the increase in the dough-mass viscosity. Ganz (1965) reported that the peak viscosity of wheat starch increased at 2.5% salt content. However, in the extrusion of corn meal with salt (Hsieh et al 1990), all three processing variables decreased steadily with the increases in salt content.

Figures 1 and 5 also show that, within the ranges of the independent variables studied, the screw speed was a more important determinant of the three processing variables (torque, SME, and die pressure) than the salt or sugar content. The differences in these variables caused by changing the salt content from 0 to 3% or changing the sugar content from 0 to 8% were much less than those caused by raising the screw speed from 200 to 300 rpm. The same was true of corn meal extruded with salt or sugar under similar conditions (Hsieh et al 1990). Inside the extruder, the starch granules lose crystallinity, soften, and compress into a viscous dough mass when the air in the powdery feed system is removed. An increase in the screw speed increases the shearing force and breaks down the starch granular bodies and, perhaps, even the starch molecules. Thus, it is conceivable that a 50% increase in the screw speed (200–300 rpm) played a more important role in torque, SME, and die pressure than did the increase in salt (0–3%) and sugar (0–8%) contents.

The extrudate lengths (axial expansion) were affected by the salt or sugar content and also by the screw speed. However, the extrudate diameters (radial expansion) were affected only by the sugar content, not by the salt content or screw speed (Figs. 2 and 6). The expansion of extrudates is caused when bubbles formed within the dough mass expand until they rupture. In addition, the stored elastic energy within the dough mass is released at right angles to the direction of flow and causes a die swell. Sopade and Le Grys (1991) reported that sugar increased melt or dough-mass extensibility. This explained the observed increases in the radial expansion of extrudates as the sugar content was increased from 0 to 8%, which was also found in the corn meal extrusion (Hsieh et al 1990). Salt did not have a significant effect on the radial expansion of extrudates in this study. This differed from the results reported by Chinnaswamy and Hanna (*unpublished*) for corn starch and Hsieh et al (1990) for corn meal. The addition of salt and sugar might have compensated for the effect of screw speed on the extensibility of the dough mass, thus, the radial expansions of extrudates might not have been affected by the screw speed. This was contrary to results reported by Owusu-Ansah et al (1984) for corn starch, Bhattacharya and Hanna (1988) for corn gluten, and Hsieh et al (1990) for corn meal, where an increase in the screw speed decreased the radial expansion of extrudates.

While the extrudate's radial expansion relies on the cell-wall extensibility of the dough, the axial expansion is inversely related to the dough viscosity (Launay and Lisch 1983, Colonna et al 1989) and the radial expansion. Because of the conservation of mass at the constant feed rate during the radial expansion, a radial bias might cause a longitudinal shortening. This was not observed in this study, however. It appeared that the viscosity of the dough mass played the major role for the axial expansion of extrudate. Because a lower viscosity of dough mass offered less resistance to the axial puffing of extrudates, the extrudate lengths were higher at a screw speed of 300 rpm than they were at 200 rpm, and they also increased with the salt content or sugar content.

The addition of salt or sugar or increase in screw speed (Figs. 3 and 7) caused significant increases in the specific volume as a result of increases in the radial expansion (effect of sugar) or axial expansion (effects of salt and screw speed). Breaking strength of extrudates was affected by decreases in the sugar content and increases in the screw speed in the rice flour-sugar system but was not affected by the salt content and screw speed in rice flour-salt system (Figs. 3 and 7). Different results were reported by Hsieh et al (1990) on the extrusion of corn meal: both axial and radial expansion of extrudates was increased, and breaking strength was decreased with an increase in the salt content. In this study, the breaking strength was also inversely related to the radial expansion. It seemed that a thinner cell wall was formed in extrudates, with a greater radial expansion resulting in a lower breaking strength.

Increasing the salt content from 0 to 3% increased $|-a|$ values (more greenness) and reduced b values (less yellowness) significantly ($P < 0.001$), but it did not affect the lightness of the extrudates (Fig. 4). These observations differed from those in corn meal extrusion. In a study by Hsieh et al (1990), an increase in the salt content enhanced yellowness (higher b value) and lightness (higher L value) but reduced redness (lower a value). Evidently, salt reacted with different pigments contained in the raw materials and interfered with browning reactions, such as caramelization, and Maillard reactions (Hsieh et al 1990) in rice and corn meal differently under similar extrusion conditions.

All three extrudate color parameters were influenced significantly by the sugar content ($P < 0.001$) (Fig. 8). Sugar interfered with browning reactions by producing reducing carbohydrates under mechanical shear (Sahagun and Harper 1980). Therefore, the lightness and yellowness of extrudates was reduced but greenness was enhanced when the sugar content was raised. The trend of lightness was reversed when the sugar content was increased from 6 to 8%, which corresponded to a greater expansion of the extrudates.

For both salt and sugar, raising the screw speed from 200 to 300 rpm resulted in whiter (higher L value) and less green (lower $|-a|$ value) extrudates (Figs. 4 and 8). This corresponded to a higher extrudate-specific volume (Figs. 3 and 7) that tended to spread out the dark pigments, making the products appear lighter

(Maga and Cohen 1978).

In summary, of the three independent variables studied, changes in screw speed had the greatest effect on torque, SME, and die pressure. The alterations in extrudate properties, due to salt or sugar addition and screw speed, varied. Salt and sugar affected the extrudates by altering the functionality of the starch and other components in the rice flour, as opposed to screw speed, which had a physical effect. The interaction patterns of salt or sugar with rice-flour extrusion were more complicated than those with corn meal extrusion. This might be caused by the amount and type of starch, protein, and lipid in the main ingredient (Stevens and Elton 1971, Bhattacharya and Hanna 1988, Falcone and Phillips 1988).

ACKNOWLEDGMENTS

We wish to express our appreciation to Kenneth H. Hsu (RJR Nabisco, E. Hanover, NJ) for his comments and suggestions and to Barry Garber, Kelly Loethen, and Shelly Long for their technical assistance.

LITERATURE CITED

ALTOMARE, R. E., and GHOSSI, P. 1986. An analysis of residence time distribution patterns in a twin screw cooking extruder. Biotechnol. Prog. 2:157-163.

BHATTACHARYA, M., and HANNA, M. A. 1987. Influence of process and product variables on extrusion energy and pressure requirements. J. Food Eng. 6:153-163.

BHATTACHARYA, M., and HANNA, M. A. 1988. Effect of lipids on the properties of extruded products. J. Food Sci. 53:1230-1231.

BRUIN, S., VAN ZUILICHEM, D. J., and STOLP, W. 1978. Fundamental and engineering aspects of biopolymers in a single-screw extruder. J. Food Process Eng. 2:1-37.

CHAUHAN, G. S., and BAINS, G. S. 1988. Effect of some extruder variables on physicochemical properties of extruded rice-legume blends. Food Chem. 27:213-224.

CLARK, J. P. 1978. Dough rheology in extrusion cooking. Food Technol. 32(7):73-82.

COLONNA, P., TAYEB, J., and MERCIER, C. 1989. Extrusion cooking of starch and starchy products. Pages 247-319 in: Extrusion Cooking. C. Mercier, P. Linko, and J. M. Harper, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

D'APPOLONIA, B. L. 1972. Effect of bread ingredients on starch-gelatinization properties as measured by the amylograph. Cereal Chem. 49:533-543.

FALCONE, F. G., and PHILLIPS, R. D. 1988. Effects of feed composition, feed moisture, and barrel temperature of the physical and rheological properties of snack-like products prepared from cowpea and sorghum flour by extrusion. J. Food Sci. 53:1464-1467.

FLETCHER, S. I., RICHMOND, P., and SMITH, A. C. 1985. An experimental study of twin-screw extrusion-cooking of maize grits. J. Food Eng. 4:291-312.

GANZ, A. J. 1965. Effect of sodium chloride on the pasting of wheat starch granules. Cereal Chem. 42:429-431.

GUY, R. C. E., and HORNE, A. W. 1988. Extrusion and co-extrusion of cereals. Pages 331-349 in: Food Structure—Its Creation and Evaluation. J. M. V. Blanshard and J. R. Mitchell, eds. Butterworths: London.

HARPER, J. M. 1981. Extrusion of Foods. Vols. 1 and 2. CRC Press: Boca Raton, FL.

HESTER, E. E., BRIANT, A. M., and PERSONIUS, C. J. 1956. The effect of sucrose on the properties of some starches and flours. Cereal Chem. 33:91-101.

HOSENEY, R. C. 1986. Cereal starch. Pages 33-68 in: Principles of Cereal Science and Technology. Am. Assoc. Cereal Chem.: St. Paul, MN.

HSIEH, F., MULVANEY, S. J., HUFF, H. E., LUE, S., and BRENT, J. 1989. Effect of dietary fiber and screw speed on some extrusion processing and product variables. Lebensm. Wiss. Technol. 22:204-207.

HSIEH, F., PENG, I. C., and HUFF, H. E. 1990. Effects of salt, sugar and screw speed on processing and product variables of corn meal extruded with a twin-screw extruder. J. Food Sci. 55:224-227.

HSIEH, F., and LUH, B. S. 1991a. Breakfast rice cereals and baby foods. Pages 177-194 in: Rice Utilization. B. S. Luh, ed. Van Nostrand Reinhold: New York.

HSIEH, F., and LUH, B. S. 1991b. Rice snack foods. Pages 225-250 in: Rice Utilization. B. S. Luh, ed. Van Nostrand Reinhold: New York.

HSIEH, F., HUFF, H. E., LUE, S., and STRINGER, L. 1992. Twin-screw extrusion of sugar beet fiber and corn meal. Lebensm. Wiss. Technol. 24:495-500.

JAO, Y. C., CHEN, A. H., LEWANDOWSKI, D., and IRWIN, W.E. 1978. Engineering analysis of soy dough rheology in extrusion. J. Food Process Eng. 2:97-112.

KERVINEN, R., LINKO, P., and OLKKU, J. 1981. Extrusion cooking induced changes in functional properties of wheat flour. Page 219 in: Proc. Nordic Cereal Chem Assoc. 21st. Kirjapaino Painorengas Oy: Helsinki.

LAUNAY, B., and LISCH, J. M. 1983. Twin-screw extrusion cooking of starches: Flow behaviour of starch pastes, expansion and mechanical properties of extrudates. J. Food Eng. 2:259-280.

LI, B. W., and SCHUHMANN, P. J. 1980. Gas-liquid chromatographic analysis of sugars in ready-to-eat breakfast cereals. J. Food Sci. 45:138-141.

LINKO, P., COLONNA, P., and MERCIER, C. 1981. High temperature short time extrusion cooking. Pages 145-235 in: Advances in Cereal Chemistry, Vol. 4. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

MAGA, J. A., and COHEN, M. R. 1978. Effect of extrusion parameters on certain sensory, physical and nutritional properties of potato flakes. Lebensm. Wiss. Technol. 11:195-197.

MAGA, J. A., and KIM, C. H. 1989. Co-extrusion of rice flour with dried fruits and fruit juice concentrates. Lebensm. Wiss. Technol. 22:182-187.

MARTELLI, F. G. 1983. Twin-Screw Extruders—A Basic Understanding. Van Nostrand Reinhold: New York.

MEISTER, U., and SCHNEEWEISS, V. 1984. Influence of the extrusion parameters on gelatinization degree and viscosity of rice flour extrudates. Lebensmittelindustrie 31:27-30.

MEUSER, F., VAN LENGERICH, B., and KOHLER, F. 1982. Einfluss der Extrusions Parameter auf funktinnelle Eigenschaften von Weisenstarke. Starch/Staerke 34:366-372.

MOTTERN, J. J., SPADARO, J. J., and GALLO, A. S. 1969. Cooking extrusion-expansion of rice. Food Technol. 23:169-171.

OWUSU-ANSAH, J., VAN DE VOORT, F. R., and STANLEY, D.W. 1984. Textural and microstructural changes in corn starch as a function of extrusion variables. Can. Inst. Food Sci. Technol. J. 17:65-70.

PAN, B. S., KONG, M., and CHEN, H. 1991. Twin-screw extrusion for expanded rice products: Processing parameters and formulation of extrudate properties. Pages 693-710 in: Food Extrusion Science and Technology. J. L. Kokini, C. Ho, and M. V. Karwe, eds. Marcel Dekker: New York.

PARK, K. H. 1976. Elucidation of the extrusion puffing process. Ph.D. thesis. University of Illinois Urbana-Champaign: Urbana, IL.

PEARSON, A. M. 1963. Objective and subjective measurements for meat tenderness. Page 135 in: Proc. Meat Tenderness Symp. Camden, NJ.

ROSSEN, J. L., and MILLER, R. C. 1973. Food extrusion. Food Technol. 27(8):45-63.

SAHAGUN, J. F., and HARPER, J. M. 1980. Effects of screw restrictions on the performance of an autogenous extruder. J. Food Process Eng. 3:199-216.

SANDERUDE, K. G. 1969. Continuous cooking extrusion: Benefits to the snack food industry. Cereal Sci. Today 14(6):209-210.

SAS. 1986. SAS User's Guide: Statistics. SAS Institute, Inc.: Cary, NC.

SMITH, O. B. 1974. Extrusion-cooked snacks in a fast growing market. Cereal Sci. Today 19:312.

SPADARO, J. J., MOTTERN, H. H., and GALLO, A. S. 1971. Extrusion of rice with cottonseed and peanut flours. Cereal Sci. Today 16:238-240.

SOPADE, P. A., and LE GRYS, G. A. 1991. Effect of added sucrose on extrusion cooking of maize starch. Food Control 2(2):103-109.

STEVENS, D. F., and ELTON, G. A. H. 1971. Thermal properties of the starch/water system. I. Measurement of heat of gelatinization by differential scanning calorimetry. Staerke 23:8-12.

TSAO, T. F., HARPER, J. M., and REPHOLZ, K. M. 1978. The effects of screw geometry on extruder operational characteristics. AICHE Symp. Ser. 74:142-147.

VAINIONPÄÄ, J., RAUTALINNA, E.-K., KARRINEN, R., KERVINEN, R., and LINKO, P. 1984. Sugar and salt in extrusion cooking for intermediate moisture products. Pages 267-271 in: Thermal Processing and Quality of Foods. P. Zeuthen et al, eds. Elsevier: London.

WALKER, C. E. 1989. The use of sucrose in ready-to-eat breakfast cereals. Cereal Foods World 34:399-406.

WHISTLER, R. L., and DANIELS, J. R. 1985. Carbohydrates. Pages 69-137 in: Food Chemistry. O. R. Fennema, ed. Marcel Dekker: New York.

[Received August 19, 1992. Accepted January 4, 1993.]