

Influence of Particle Size on the Twin-Screw Extrusion of Corn Meal¹

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ABSTRACT

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Effects of particle size (50–1,622 μm), screw speed (200–400 rpm), and feed moisture content (19–22%) on twin-screw extrusion of corn meal were investigated using a full-factorial design. Torque, specific mechanical energy, and product temperature generally showed no change within the commonly used particle-size range (100–1,000 μm), but each value dropped significantly as the particle size increased >1,000 μm . Die

pressure was influenced by the three-way interaction of particle size, screw speed, and feed moisture content. The highest moisture level (22%), largest particle size (1,622 μm), and two lowest screw speeds (200 and 300 rpm) were the only conditions where the starch was <97.5% of transformation (gelatinization). Consequently, these two conditions also showed the least expansion and hardest product.

Over the last several decades the twin-screw extrusion of corn snacks and ready-to-eat cereals have increased due to favorable economics and improved product qualities from the high-temperature short-time (HTST) process. Throughout these years, extrusion has evolved from an art into a science with the aid of empirical models that divide the extrusion process into independent (controlled) and dependent parameters. These empirical models have made it possible to predict the properties of the extrudate based on the controllable system parameters, thus showing producers how the influence of process parameters and raw materials can lead to new and better products or processes.

Many journal publications and textbooks have briefly reported the importance of the feed granulation or particle size in HTST extrusion. Observations from preliminary runs are frequently the basis of these findings. Textbooks on food extrusion seem to give more detail about why feed particle size is important but generally do not base their reasoning on a designed research experiment. Due to the lack of models and many generalized statements, conflicting comments about the influence of particle size have been reported.

Matz (1993) and Williams et al (1977) suggested the particle size of raw ingredients is important when extruding puffed snacks, but did not discuss it in any more detail. General observations have led to conflicting statements about the influence of particle size. Huber and Rokey (1990) reported that a soft texture resulted from a fine granulation and a coarser meal led to a more crunchy product, but Harper (1982) suggested a finer granulation gave a harder, more dense collet. When extruding different granulations of soybean meal, the bulk density of the raw material decreased with particle size, which changed the feed rate of the table top feeder used, thus changing operating conditions (Hayakawa et al 1992). Mohamed (1990) found that when extruding corn grits varying in size from 402 to 618 μm in a Brabender laboratory extruder, pressure increased with increased particle size but expansion and hardness decreased. Unfortunately, there was no mention of statistical significance in the Mohamed report. Yeh et al (1992) showed that the time needed for water diffusing into the rice particles decreased with decreasing particle size and increasing water temperature. Since water was needed to diffuse into the rice particles for gelatinization to proceed, the degree of gelatinization of rice extrudate decreased with increasing particle size.

Extruder conditions can be used to predict the final product properties (Bhattacharya and Hanna 1987, Lue et al 1994). According to past observations, product quality is influenced by the particle size of feeding ingredient. Therefore it was hypothesized that the particle size of feeding ingredient will influence processing conditions during twin-screw extrusion. The objective of this project was to investigate the effects of particle size (50–1,622 μm), screw speed (200–400 rpm), and feed moisture content (19–22%) on twin-screw extrusion of corn meal using a full-factorial design.

MATERIALS AND METHODS

Raw Materials

Degermed yellow corn that had been dry milled into different granulations was obtained from the Illinois Cereal Mill Company (Paris, IL). Five commercially available sizes were chosen, giving a broad spectrum ranging from an ultra-fine corn flour to a coarse corn grit. The approximate composition of each sized corn sample is shown in Table I. Table II shows the particle-size distribution and average particle size for each corn sample based on the ASAE Standard (1993).

Experimental Design

A full-factorial design was used consisting of five average feed granulations (50, 94, 594, 988, and 1,622 μm), three screw speeds (200, 300, and 400 rpm) and three processing moisture contents (19, 20.5, and 22%). All treatments were duplicated. The analysis of variance was a random complete block split-plot design in which the linear statistical model contained the main effects of replication and granulation. The subplot contained screw speed, moisture, screw speed \times moisture, and all possible interactions with feed granulation. The main effect of feed granulation was tested using replicate \times granulation as the denominator in the *F*-test. Mean differences were ascertained using Fisher's least significant difference. Polynomial regression equations also were generated and surface response plots were produced to illustrate how the conditions or properties were affected.

Extrusion Conditions

Extrusion experiments were performed with an APV Baker 50/25, 28.0 kW, co-rotating and intermeshing twin-screw extruder (APV Baker, Inc., Grand Rapid, MI). The rated speed of the machine was 500 rpm. The diameter of the screw was 50 mm, and a length-to-diameter ratio of 15:1 was used. The screw configuration and barrel temperature profile can be seen in Fig. 1. The product temperature was measured with thermocouples (Type K) immediately before the die. The die plate had two circular die inserts, each with one hole. The diameter of each hole was 27.5 mm

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initially, tapered to 3.18 mm downstream in a distance of 15.5 mm, and then was a constant 3.18 mm in diameter for 3.08 mm further downstream. A pressure transducer (Dynisco, Inc., Norwood, MA) measured the die pressure at the die plate. An adjustable four-blade die-face cutter was operated at 325 rpm.

The corn was fed directly into the extruder with a loss-in-weight feeder (AccurRate, Whitewater, WI) at 45.4 kg/hr. The processing moisture content of the feed was controlled by injecting water at ambient temperature into the extruder 10.8 cm downstream of the feed port by a variable stroke, positive displacement pump with an 8-mm head (model B-P 33, Bran & Lubbe, Chicago, IL).

Data Collection of Extrusion Parameters

Measurements of temperature (°C), pressure (kPa), torque (%), screw speed (rpm), and cutter speed (rpm) were collected using a MACS PL-1000 data acquisition system (Elexor Assoc., Morris Plains, NJ) on a PC-AT/XT computer (Northgate, Plymouth, MN) and recorded to the hard disk every 15 sec. The percent torque recorded was the ratio of the torque necessary for maintaining the set screw speed to the torque required for the rated screw speed. The specific mechanical energy (SME) was calculated as:

$$SME = \frac{\dot{\omega}}{\dot{\omega}_r} \times \frac{\tau}{100} \times \frac{Z_r}{Q} \quad (1)$$

where $\dot{\omega}$ represents screw speed, $\dot{\omega}_r$ is the rated screw speed, τ is percent torque, Z_r represents rated power, and Q represents the feed rate (Hsieh et al 1990).

TABLE I
Proximate Compositions (%) of Each Corn Sample^a

Component	Fine Flour (50 μm)	Flour (94 μm)	Meal (594 μm)	Grits (988 μm)	Coarse Grits (1,622 μm)
Moisture	8.0	12.0	13.0	13.0	13.0
Fat	2.0	1.3	0.65	0.7	0.3
Ash	0.7	0.4	0.3	0.25	0.2
Protein	6.7	6.5	6.75	7.0	8.0

^a Supplier's data.

Water Absorption Capacity of Raw Corn

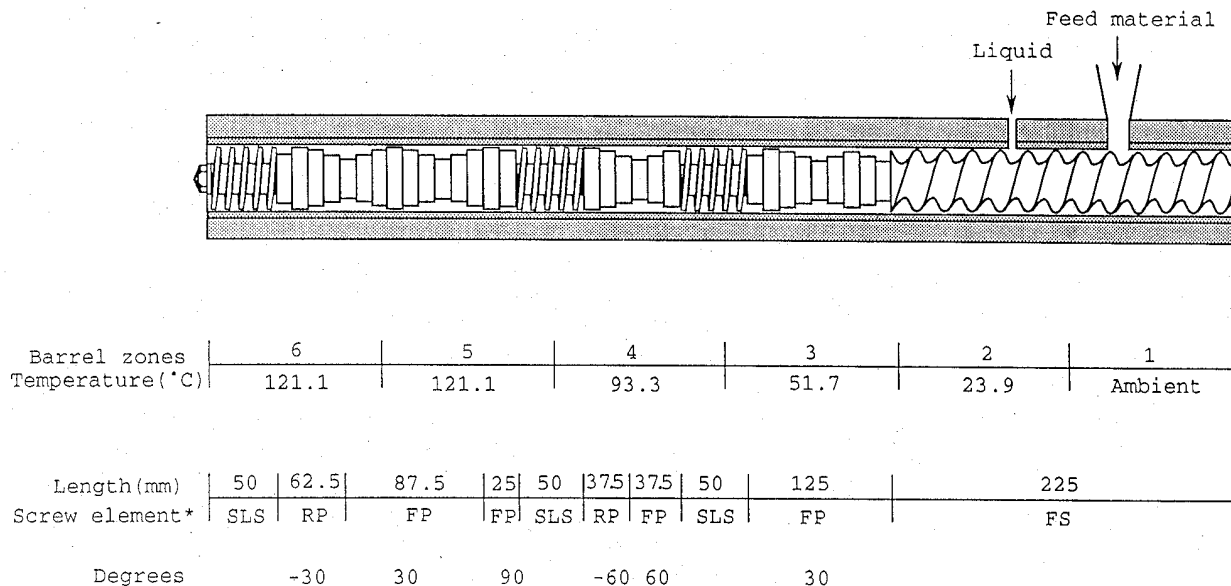
AACC Approved Method 56-20 (hydration capacity of pregelatinized cereal products) (AACC 1995) was used to determine the effect of raw corn meal particle size on water absorption capacity.

TABLE II
Particle-Size Distributions for Each Corn Sample^a

Particle Size ^b , μm	Distribution, %
Fine Flour	
>180	1
125-180	3
75-125	6
53-75	9
49-53	8
38-49	73
<38	trace
Flour	
>180	6
125-180	25
75-125	42
53-75	9
49-53	7
38-49	11
<38	trace
Meal	
>850	trace
710-850	14
600-710	41
425-600	44
<425	1
Grits	
>1,400	3
1,180-1,400	18
850-1,180	59
600-850	19
<600	1
Coarse grits	
>2,000	1
1,400-2,000	90
1,000-1,400	8
<1,000	1

^a Based on sieving method (S319.2, ASAE standard).

^b Average particle sizes: fine flour = 50 μm, flour = 94 μm, meal = 594 μm, grits = 988 μm, coarse grits = 1,622 μm.



* FS=Feed Screw; FP=Forward Paddles
RP=Reverse Paddles; SLS=Single Lead Screw

Fig. 1. Screw profile. FS = feed screw, FP = forward paddles, RP = reverse paddles, SLS = single lead screw.

Product Properties

Samples of each treatment were collected when stable extrusion conditions were achieved, based on achieving a stable torque and die pressure. The samples were then dried to $\approx 7\%$ moisture (wb) and stored in polyethylene bags.

The expansion ratio was calculated as the diameter of the collet divided by the die hole diameter. The specific length was defined as the length of the extrudate per unit mass. The specific volume was determined by the rapeseed displacement test (Hsieh et al 1991). Apparent bulk density was determined by weighing the collets required to fill a 1-L container.

The degree of starch gelatinization was defined as the weight ratio of gelatinized starch to total starch of sample. The total starch content and digestible starch content of the extrudate samples were determined by the modified method of Chiang and Johnson (1977). For total starch content measurement, the sample was solubilized in alkali and digested with glucoamylase to form glucose. The released glucose reacted with *o*-toluidine to form a green chromophore, which was quantified by measuring the absorbance at 630 nm. The amount of digestible or gelatinized starch was determined using a similar procedure; however, no alkali treatment was applied before enzymatic incubation. The degree of gelatinization is calculated as:

$$DG = \frac{(GS - K) \times 100}{TS - K} \quad (2)$$

where DG is the degree of gelatinization (%); GS is the gelatinized starch content (% db); TS is the total starch content (% db); and *K* is the percentage of native starch in corn meal attacked by enzyme (Shetty et al 1974, Chiang and Johnson 1977). The *K* value of corn meal was determined by incubating various amounts of raw and alkali-treated corn meal with glucoamylase and

establishing regression lines of released glucose with corn meal weight. *K* value was calculated by dividing the slope of the raw corn meal regression line by that of the alkali-treated regression line.

Breaking strength was defined as the force necessary to shear the collet divided by the cross-sectional area of the collet. The force was determined by the Instron universal testing machine (model 1132, Instron Corp., Canton, MA). The cross-sectional area was calculated with an average diameter assuming a perfectly circular puff.

RESULTS AND DISCUSSION

Torque

Torque indicates the resistive load on the motor. Harper et al (1971) used the following equation to represent torque:

$$\tau = G_1 \omega N \bar{\mu}_a + \frac{G_2 V \bar{\mu}_d}{R_d} \quad (3)$$

where τ represents torque; ω is screw speed; μ_a and μ_d are the average viscosity of the dough in the screw and die, respectively; V is the volumetric flow rate; G_1 and G_2 are geometrical constants of the screw; N is the number of filled flights in the screw; and R_d is the resistive coefficient of the die. Neglecting the second term, which represents the torque due to the pressure generated (the pressure readings were relatively low), and recognizing that the screw speed and number of filled flights cancel each other out due to their inverse relationship (Booy 1978, Hsieh et al 1991), leads to torque being represented as a function of viscosity:

$$\tau = G \bar{\mu}_a \quad (4)$$

Statistically the torque was not affected by changing the granulation within the commonly used ranges (94.2–988.3 μm) as Fig. 2a and c clearly show, but a sharp decrease occurred at $\approx 1,000 \mu\text{m}$.

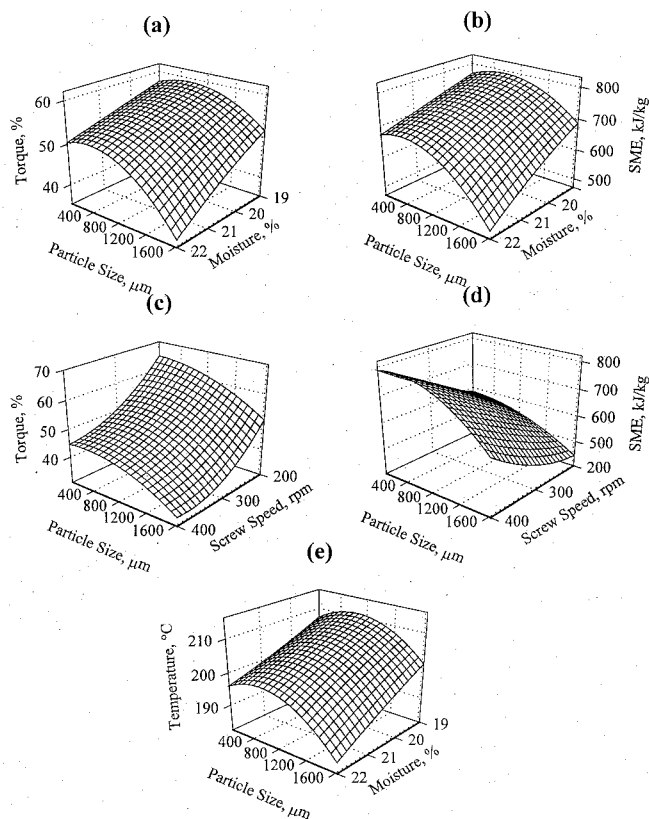


Fig. 2. Effect of particle size and moisture (wb) on torque (a) and specific mechanical energy (SME) (b) at 300 rpm; and the effect of particle size and screw speed on torque (c) and SME (d) at 22% moisture; and the effect of particle size and moisture on product temperature ($^{\circ}\text{C}$) (e).

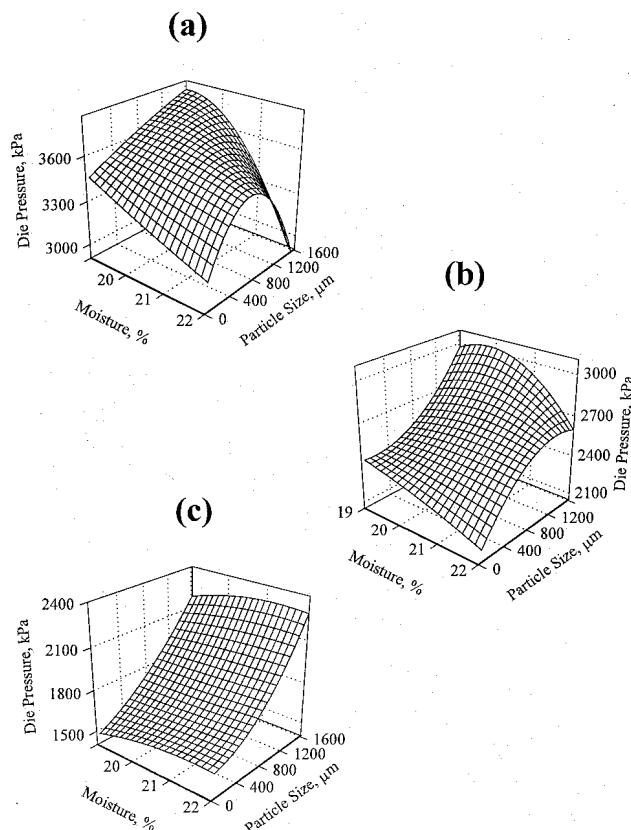


Fig. 3. Effect of moisture and particle size on die pressure (kPa) at constant screw speed: 200 rpm (a), 300 rpm (b), 400 rpm (c).

The dough viscosity of the largest grit must have been drastically less than that of the other particle sizes, thus causing a decrease in torque. Coarse grits contain a higher percentage of the outer endosperm than flours and meals (Pomeranz 1987). This harder, more dense endosperm does not absorb water like the soft, mealy endosperm (Pomeranz 1987). The large size of the grits also will reduce the total water uptake due to a low surface-to-volume ratio (Hsu 1983, Yeh et al 1992). The water absorption of the largest grit (1,622 μm) was 1.83, which was significantly less than the others (2.65, 2.71, 2.60, and 2.51 for particle sizes 50.2, 94.2, 593.0, and 988.3 μm , respectively). The smaller four were not significantly different from each other. Therefore, the dough of the largest grit never forms a thick paste but rather a nonhomogenous mixture of grit and water. This was observed visually during processing as the extrudate strand of the largest grit contained hard pieces of corn.

A significant decrease in torque occurred due to each moisture increase, which agrees with Eq. 3 because increases in moisture will decrease viscosity. Figure 2a shows a linear reduction of torque occurred due to increases in moisture.

Figure 2c shows screw speed significantly affected torque. The effect of screw speed on viscosity can be expressed as a power function because of the pseudoplastic behavior of the dough (Harper et al 1971, Bhattacharya and Hanna 1987) and the linear relationship between shear rate and screw speed (Harper 1981, Martelli 1983, Levine 1989):

$$\bar{\mu}_a = m\dot{\gamma}^{n-1} \quad (5)$$

$$\tau \propto \bar{\mu}_a \propto \dot{\omega}^{n-1} \quad (6)$$

where m is the consistency coefficient, n is the flow index behavior, and $\dot{\gamma}$ is the shear rate.

The flow behavior index, calculated by regression analysis and by using the ratio of screw speeds (Hsieh et al 1993), were within

the 0.27–0.74 range, which agreed with previous research (Harper et al 1971, Bhattacharya and Hanna 1987). The pseudoplastic behavior caused torque to decrease as screw speed increased. Another reason for the decrease of torque with increasing screw speed was that the filled length of the screw channels decreased with increasing screw speed (Martelli 1983, Liang et al 1994).

Specific Mechanical Energy

Martelli (1983) showed SME could be expressed as:

$$\text{SME} = \tau\dot{\omega} \propto \bar{\mu}_a \dot{\omega} \quad (7)$$

If screw speed is held constant, viscosity controls SME. Thus it will be affected in a manner similar to torque (Fig. 2a and b), but the effect of changing screw speed is drastically different for torque and SME (Fig. 2c and d). Increasing screw speed decreased torque but increased SME (Fig. 2c and d). Similar results have been reported elsewhere (Fletcher et al 1985, Hsieh 1989). The effect of screw speed on viscosity leads to expressing SME as a function of screw speed raised to the n th power, as

TABLE III
Influence of Particle Size on the Expansion Properties^a

Particle Size, μm	Expansion Ratio	Specific Length (mm/g)	Specific Volume (mL/g)	Apparent Bulk Density (g/L)
50.2	4.69a	98.54a	9.68a,b	47.92d
94.2	4.51a,b	100.23a	11.39a	50.01d
593.0	4.45b	89.55b	7.94b	61.74b
988.3	4.47a,b	92.70b	8.97b	56.88c
1,622.1	3.99c	65.67c	4.61c	111.74a

^a Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

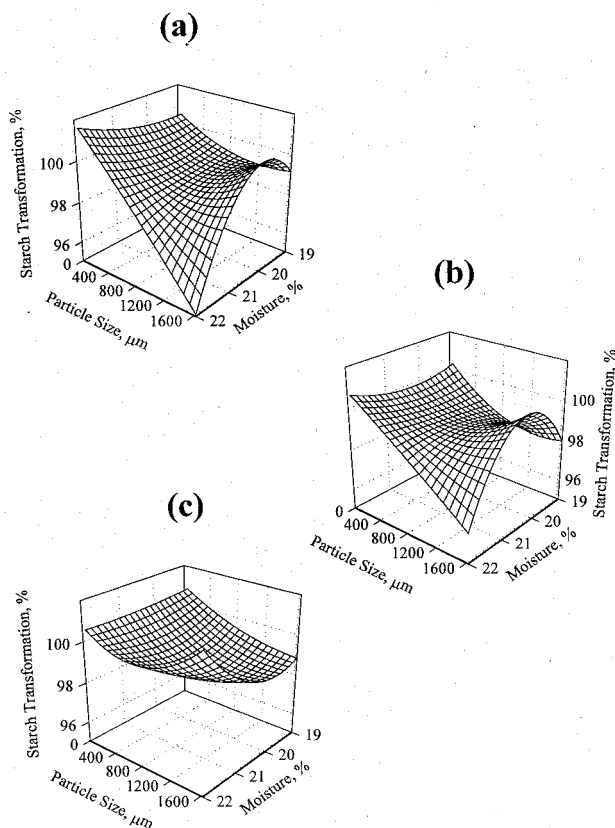


Fig. 4. Effects of particle size and moisture on starch transformation (%): 200 rpm (a), 300 rpm (b), 400 rpm (c).

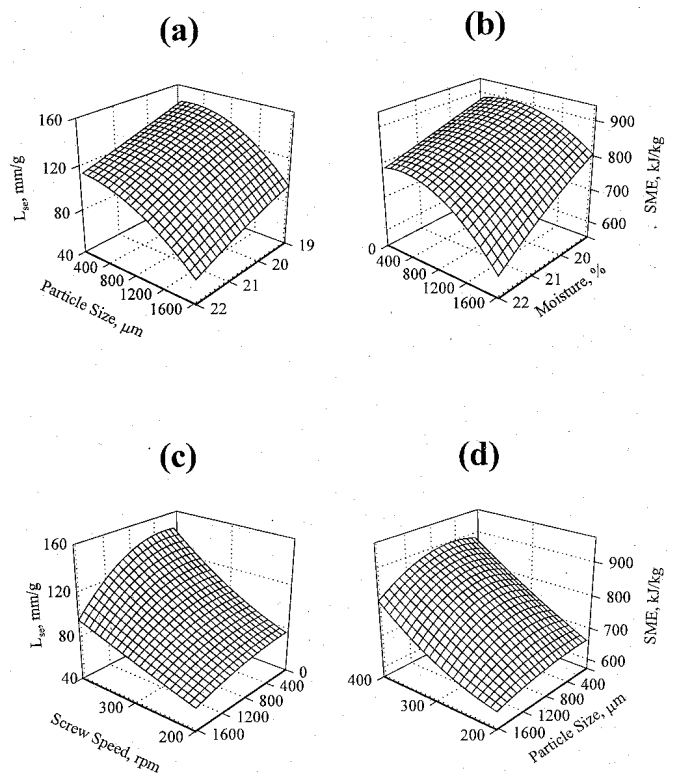


Fig. 5. Comparison of the effects of particle size, moisture, and screw speed on longitudinal expansion and specific mechanical energy (SME): specific length at 400 rpm (a), SME at 400 rpm (b), specific length at 19% moisture (wb) (c), SME at 19% moisture (wb) (d).

shown by combining Eq. 6 and 7, rather than the n^{-1} power as in torque (Eq. 6).

$$\text{SME} = \dot{\omega}^n \quad (8)$$

Because the flow behavior index (n) was <1 , as mentioned in the previous section, torque decreased and SME increased with increasing screw speed (Eq. 6 and 8). In addition, Fig. 2c also shows that increasing screw speed 100% (200–400 rpm) only decreased torque ≈ 30 –40%. Since the increase in screw speed was not fully compensated by the concomitant decrease in torque, the increase in SME was not unexpected, according to Eq. 7 (Hsieh et al 1989).

Product Temperature

Figures 2b and e show the product temperature was affected in a manner similar to SME. An energy balance equation derived by Janssen (1989) shows why both SME and product temperature were similarly affected:

$$T_p = T_o + \frac{\text{SME} - E_g}{C_p} \quad (9)$$

where T_p and T_o are the final and initial temperature, respectively, E_g is the gelatinization energy, and C_p is the specific heat of the dough. The energy balance was derived by neglecting the heat from the barrel because in high-shear extrusion most of the heat is generated by frictional energy from the screw (Janssen 1989). In this study, the only variable affecting product temperature was SME, because the heat capacity and the energy for gelatinization were similar for all granulations, either before or after starch gelatinization, due to their similar compositions.

Die Pressure

Figure 3 shows that the three-way interaction, particle size \times moisture \times screw speed, influenced die pressure. The surface

response plots for the three different screw speeds were drastically different from each other. In addition, die pressure became lower as screw speed increased. The range of pressure change for each screw speed was $\approx 1,000$ kPa.

Die pressure decreasing with increasing screw speed has been reported (Bhattacharya and Hanna 1987; Hsieh et al 1991, 1993; Liang et al 1994). The filled length of the screw channels decreased with increasing screw speed and thus less dough mass was accumulated behind the die (Hu et al 1993). In addition, a high screw speed required more SME input (Fig. 2d), which led to a higher product temperature and, hence, a lower viscosity. This also would have resulted in a lower die pressure (Harper 1981, Janssen 1989, Hu et al 1993).

It is interesting to note that the lowest pressure at 200 rpm occurred at the maximum size and moisture (Fig. 3a). But the maximum size and moisture produced the highest pressure reading at 400 rpm (Fig. 3c), although the magnitude of pressure at 200 rpm was still higher due to increased viscosity from the decreased shear rate and also a high degree of fill in the screw channels. The reason the pressure of the largest grit (1,622 μm) and moisture (22%) dropped rapidly at 200 rpm as compared to the other speeds (Fig. 3) was probably because of the influence screw speed had on viscosity. The nonhomogenous dough at the maximum size and moisture obviously had a lower viscosity than at lower moisture or finer granulations. This decrease in viscosity is clearly seen in Fig. 3a, but it was slightly less evident in Fig. 3b, and not evident at all in Fig. 3c, because at higher screw speeds, the reduction in viscosity due to increased shear rates overshadowed the reduction in viscosity due to moisture increases.

Starch Transformation

Figure 4 shows that all the starch transformation values exceeded 97.5% except two, (1,622 μm , 200 rpm, 22% moisture) and (1,622 μm , 300 rpm, 22% moisture). These two processing

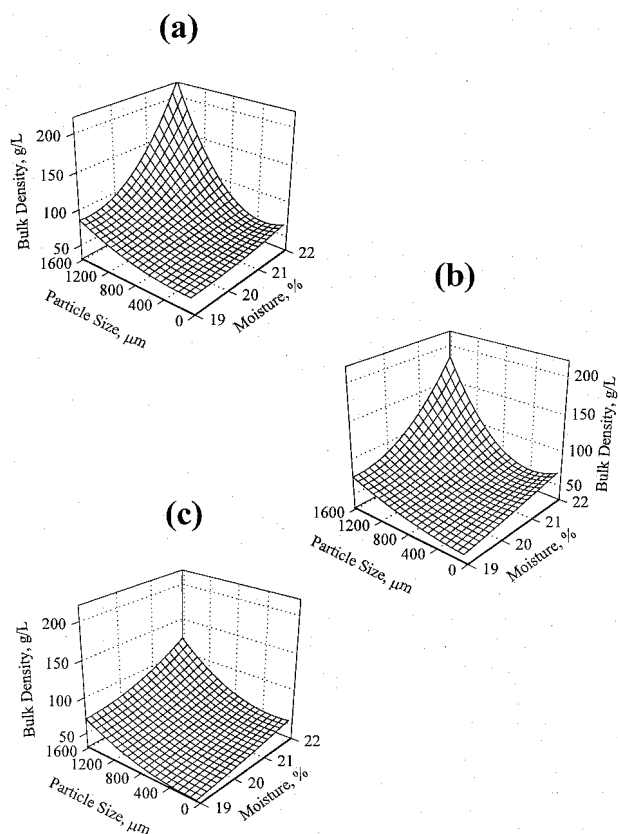


Fig. 6. Effects of particle size and moisture on apparent bulk density (g/L) at constant screw speed: 200 rpm (a), 300 rpm (b), 400 rpm (c).

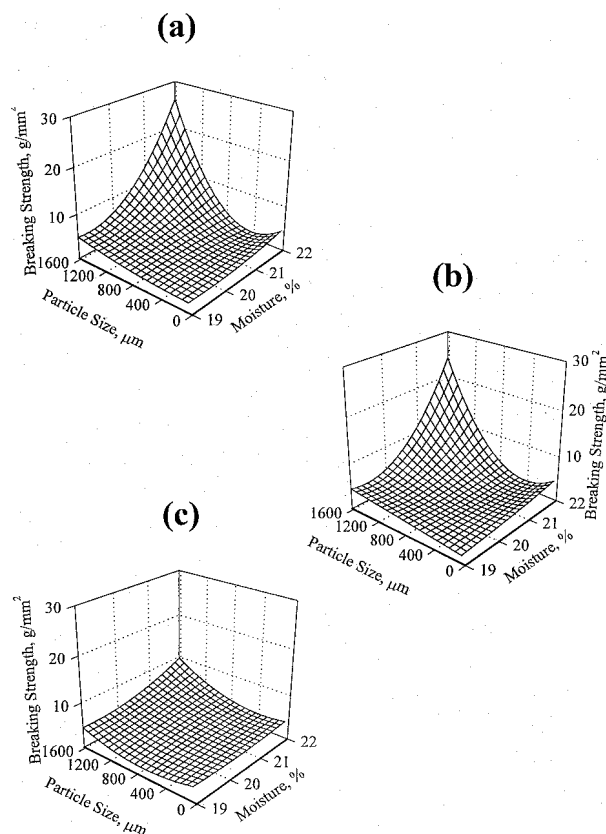


Fig. 7. Effects of particle size and moisture on breaking strength (g/mm^2) at constant screw speed: 200 rpm (a), 300 rpm (b), 400 rpm (c).

conditions also produced the lowest product temperature (Fig. 2e) and highest bulk density. The temperature readings at these conditions were 150.8 and 154.4°C. The next lowest temperature was 158°C. These results indicate that 158°C was a sufficient temperature for complete transformation at the extrusion conditions used but 154.4°C was not. This data agrees with Lin (1994), whose data showed complete transformation at temperatures >155°C.

Expansion

Table III shows that as the particle size increased, generally the overall expansion of the collet decreased. The difference between the flours, meals, and grits were significantly different from each other, but no difference was made among the two flours (50.2 and 94.2 μm) or among the two meals (593.0 and 988.3 μm) ($P > 0.05$). The flour produced the greatest radial, longitudinal, and overall expansion; the meals reduced expansion slightly; and expansion was drastically reduced for the largest grit due to incomplete gelatinization (Fig. 4).

The amount of energy transferred from the screw to the dough seemed to control the amount of longitudinal expansion (Fig. 2b, Fig. 5a and b, Fig. 2d, Fig. 5c and d). Harper and Tribelhorn (1992) found product temperature was a more significant factor in longitudinal expansion than moisture. As previously shown, changes in SME seemed to drive the changes in product temperature (Fig. 2b and e). SME was compared to expansion (Fig. 5) because it is a parameter that is often used in scale-up procedures and best describes the process. A lower SME resulted in a lower product temperature, which, in turn, caused less expansion. A lower product temperature also resulted in less gelatinization, which reduced expansion.

Figure 6 shows that a significant increase in apparent bulk density occurred at the highest moisture (22%) and largest particle size (1,622 μm) during the lowest two screw speeds (200 and 300 rpm). These were the same two operating conditions that caused the lowest degree of starch transformation. The lower temperatures and excess water in the dough caused less expansion with high density collets at these conditions. By comparing Figs. 6 and 7, it is obvious the density of the collet dictated the hardness of the product, as suggested by Halek and Chang (1992).

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