Effect of Separation and Grinding of Corn Dry-Milled Streams on Physical Properties of Single-Screw Low-Speed Extruded Products[1]

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ABSTRACT

Cereal Chem. 75(6):775–779

Three streams of corn dry-milled products (corn grits, corn cones, and corn flour) were sieved and separated according to average diameter, and some segregated fractions were ground to produce nine streams. Corn grits were separated to produce grits with diameters of 1.19 and 0.841 mm, and selected fractions were ground into grits with average diameters of 0.297 and 0.210 mm. Corn cones were separated into average diameters of 0.595, 0.420, and 0.297 mm. Corn flour was separated into fractions with average diameters of 0.297 and 0.210 mm. The original and the additional streams were extruded at constant speed (50 rpm) and at three different processing extruder barrel temperature profiles: low (LTP, 100–110–120°C), medium (MTP, 110–120–130°C), and high (HTP, 120–130–140°C). The least significant difference ($P < 0.01$) test showed that additional grinding of corn grits affects the expansion ratio of extrudates processed at LTP and HTP. Additional separation of corn flour affects ($P < 0.01$) the bulk density and water solubility index of extrudates at HTP. At HTP, corn cones with diameters of 0.595 mm had significantly ($P < 0.01$) higher torque, specific mechanical energy, and die pressure than did the original corn cone extrudates without separation.

The raw material for finished cereal products requires different particle size ranges. For example, corn grits for corn flakes require a corn endosperm with a size of one-half or one-third of the whole kernel after the germ and the bran are removed. Extruded gun-puffed cereals, on the other hand, require finer products, such as corn flour and corn starch, as the raw materials (Alexander 1987). These different particle size requirements of corn dry-milling products indicate the importance of separation and size reduction processes in the corn dry-milling process. Jamin and Flores (1998) determined that additional separation and grinding of corn dry-milled streams produced changes in distribution of fat, protein, ash, and color. Thus, separation of the streams by a uniform particle size is expected to produce different extruded products, even though the separated and additionally ground streams come from the same "parent" stream. The separation and size reduction processes can affect the characteristics of the extruded products, making some of the corn dry-milling products suitable for extruded breakfast cereals or snack products.

Extruded products are affected by the raw material and processing conditions. Anderson et al (1969) found that corn grits coarser than 14-mesh size were underprocessed and that an increase in particle size caused a decrease in torque, radial, longitudinal, and overall expansion (Garber et al 1997, Mohamed 1990). With five commercial samples that ranged from corn grits to corn flour and using a twin-screw extruder, Garber et al (1997) showed that corn flour has better expansion than corn grits and found no difference between the two flours or two meals with different particle sizes. Besides particle size, moisture content of the raw material, temperature immediately before extrusion, pressure range before expansion, and die diameter also affect the extruded products (Linko et al 1981).

Expansion volume of extruded cereal products mainly depends on starch gelatinization (Linko et al 1981) and increases with an increase in gelatinization, while bulk density (BD) decreases with an increase in gelatinization (Case et al 1992). How much the extruded product expanded is measured using the expansion ratio (ER), the ratio of extruded product diameter over the die diameter (Chinnaswamy and Hanna 1988, Case et al 1992). Likewise, BD is negatively correlated with ER. The higher the ER, the lighter the BD of the extrudates.

As mentioned, starch gelatinization during extrusion has a significant influence on the extruded products' characteristics; therefore, it is important to evaluate the degree of gelatinization of the extruded products. The degree of starch gelatinization is influenced by the specific mechanical energy (SME) of each particular process. SME is the amount of energy input needed to convey the material in the extruder. It depends on the power at the drive shaft and the total throughput ($\dot{m}$) of the extruder. The drive power is the product of torque (T), which is proportional to the current of the drive, and the screw speed (ω). SME increases linearly with screw speed, whereas torque does not increase linearly with screw speed (Martelli 1983). SME is expressed as:

$$SME = T\omega / \dot{m} \tag{1}$$

where SME is in watt hours per kilogram, ($\dot{m}$) is the wet basis throughput rate in kilograms per hour, T is in Newton-meters, and ω is per second.

Garber et al (1997) investigated the influence of particle size on twin-screw extrusion of corn meal from 200 to 400 rpm. They concluded that there were no changes in torque, SME, and product temperature at a particle size range of 100–1,000 μm, but as the particle size increased to >1,000 μm, it influenced the SME significantly.

With the different size requirements of the corn dry-milling streams in the breakfast cereal and snack industry, the separation and size reduction processes of corn dry-milled products influence the characteristics of the finished products of ready-to-eat breakfast cereal or snacks made from corn. Commercial corn dry-milled products have certain ranges of particle size distributions. Each distribution contributes to the whole characteristics of the original stream. However, not all distributions may have extrusion behavior similar to that of the original stream. After segregation, one distribution of the corn stream could produce better or worse extruded products that the "parent" stream. Therefore, the objective of this study was to evaluate the effects of additional separation and grinding of selected corn dry-milled streams on the properties of extruded products using a single-screw extruder at low speed.

MATERIALS AND METHODS

Raw Materials

Commercial corn dry-milled streams consisting of corn grits, corn cones, and corn flour were used for this study. The particle size distribution of each stream was analyzed and the average diameter determined using the ASAE sieving method (ASAE 1989), with a

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[1] Journal paper J-17303 of the Iowa Agriculture and Home Economics Experiment Station, Ames, IA, Project No. 3326. Contribution No. 99-2-J from the Kansas Agricultural Experiment Station, Manhattan, KS.

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Publication no. C-1998-1005-02R.

Ro-tap shaker and sieving screens (W. S. Tyler, Inc., Mentor, OH) that are stacked according to the standard and sieved for 10 min. A detailed particle size distribution of each stream is shown in Table I. Each stream was separated according to the major portion of the particle size distribution of the stream (Table II). The corn grits were additionally ground using a high-speed flour mill (Magic Mill, Salt Lake City, UT). The ground grits were then separated into those with diameters of 0.297 and 0.210 mm, which were the major portions of the ground grits particle size distribution (Table I). After separation and grinding, there were 12 different streams (Table II): original corn grits, corn grits with additional separation (1.19 and 0.841 mm), corn grits with additional grinding (0.297 and 0.210 mm), original corn cones, corn cones with additional separation (0.595, 0.420, and 0.297 mm), original corn flour, corn flour with additional separation (0.297 and 0.210 mm). Figure 1 shows a diagram for the grinding and separation of the material. The chemical properties (ash, crude fat, and protein content) of each stream are shown in Table II. Details of the proximate analysis methods are given in Jamin and Flores (1998).

The samples were conditioned to an average moisture content of 22.7 ± 1.8% (wb) before extrusion. The water was added by manually spraying the sample inside a rotating semihemisphere laboratory mixer (Dayton Electric, Chicago). The preconditioned sample was kept in a polyethylene bag that was stored overnight in a cooler at 4°C. Before extrusion, the preconditioned sample was removed from the cooler to reach room temperature and analyzed for moisture content by using the air-oven method (AACC 1995) at 130°C for 1 hr.

Extrusion Process

After preconditioning, all samples were randomly extruded using a torque rheometer laboratory extruder (PL 2000, Plasti-Corder, C.W. Brabender, South Hackensack, NJ) with two replicates for each processing temperature. The length-to-diameter ratio of the extruder was 20:1, with a screw compression ratio of 3:1. The extruder barrel had eight equally spaced grooves of 3.175 mm width by 0.79 mm depth running the length of the barrel. This study used three different processing profile temperatures: low temperature profile (LTP) at 100–110–120°C, medium temperature profile (MTP) at 110–120–130°C, and high temperature profile (HTP) at 120–130–140°C. Each temperature profile corresponds to the feeding, metering, and die sections of the extruder.

The extruded products (extrudates) were analyzed for moisture content, ER, BD, water absorption index (WAI), and water solubility index (WSI). Extruded product (15 g) was tested for moisture content in at least two dishes for 24 hr at 103°C by the modified moisture air-oven method (Method 44-15A, AACC 1995). The expansion ratio was determined as the extrudates' diameter over the die diameter using a digital micrometer (Digimatic Series No. 293, Mitutoyo, Tokyo, Japan) connected to a 286 personal computer equipped with a data acquisition system and a data collection program. Six to 10 pieces of extrudate 2 cm long were cut and weighed on a digital balance (A-250, Denver Instrument Co., Arvada, CO). With three measurements for each piece of extrudate, there were at least 18 measurements for each sample of extrudate processed at a given temperature profle for each replicate. The BD of the extrudates was calculated as the weight of each piece over its calculated volume, with the assumption that the extrudates had cylindrical shapes. To determine WAI and WSI values, the procedure described by Anderson et al (1969) was followed, as detailed in Jamin (1996). WAI and WSI values were repeated four times for each sample. All results were analyzed for least significant difference (LSD) with $P < 0.01$ except where $P < 0.05$ is mentioned (SAS Institute, Cary, NC).

In the study of SME and die pressure (P_{die}), all streams (12 samples) were extruded at the temperature profile of 120–130–140°C because this temperature profile produced the most gelatinized and expanded products for the extruder used. Each sample was replicated twice. Each replicate was the average of at least 10 torque and die pressure measurements and six throughput measurements.

TABLE I
Particle Size Distribution of the Original Streams (% wt)

Sieve No.	Sieve Opening (mm)	Grits	Cones	Flour	Ground Grits
16	1.19	23.72[a]	0.04	1.54	0.23
20	0.841	64.98[a]	2.81	1.98	0.63
30	0.595	10.63	29.81[a]	3.50	9.16
40	0.42	0.44	23.53[a]	1.96	6.84
50	0.297	0.12	23.60[a]	23.89[a]	40.57[a]
70	0.21	0.04	14.58	54.96[a]	30.31[a]
100	0.149	0.04	3.96	8.39	6.39
140	0.105	0.03	0.71	1.44	2.05
200	0.074	0.02	0.08	0.15	2.75

[a] Selected sizes.

TABLE II
Selected Corn Dry-Milling Streams Used for Extrusion Evaluations

Milling Streams	Separated/ Ground Corn	Nominal Sieve Opening (mm)	Ash Content (% db)	Crude Fat Content (% db)	Protein Content (% db)
Corn grits	Unseparated	···	0.42	0.49	5.61
	16-mesh	1.19[a]	0.53	1.08	5.73
	20-mesh	0.841[a]	0.39	0.65	5.52
	50-mesh	0.297[b]	0.35	0.51	6.38
	70-mesh	0.210[b]	0.37	0.69	5.62
Corn cones	Unseparated	···	0.31	0.36	4.90
	30-mesh	0.595[a]	0.28	0.48	5.30
	40-mesh	0.420[a]	0.26	0.47	4.98
	50-mesh	0.297[a]	0.33	0.50	4.72
Corn flour	Unseparated	···	0.21	0.34	3.26
	50-mesh	0.297[a]	0.30	0.39	3.49
	70-mesh	0.210[a]	0.23	0.35	3.27

[a] Separated streams.
[b] Ground streams.

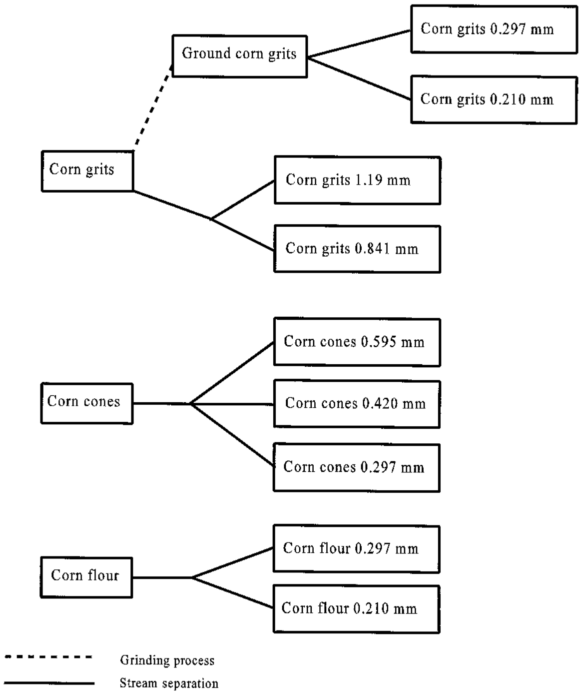

Fig. 1. Particle size reduction and separation diagram.

RESULTS AND DISCUSSION

The average final moisture contents after extrusion for LTP, MTP, and HTP were 15.14 ± 1.44, 14.06 ± 1.48, and 11.33 ± 1.49%, wb, respectively. Table III shows the ER and the BD of all extrudates at LTP and HTP.

Low Temperature Profile

At LTP, extrudates made of corn grits with additional grinding (0.297- and 0.210-mm corn grits) had significantly higher BD values than extrudates from the original corn grits and extrudates made of corn grits with additional separation. Extrudates made of 0.210-mm corn grits had significantly lower ER values than the original corn grits extrudates. There was no significant difference in WAI and WSI between extrudates made of original corn grits and extrudates made of corn grits with additional separation or with additional grinding. At $P < 0.05$, extrudates made of 0.297-mm corn grits were significantly different in WSI value from extrudates made of original corn grits and from those made of 0.841-mm corn grits.

The extrudates made of original corn cones had no significant differences in ER, BD, WAI, and WSI values when compared with extrudates made of corn cones with additional separation. However, at $P < 0.05$, there were significant differences in ER between extrudates made of original corn cones and those made of separated corn cones.

At $P < 0.01$, the extrudates made of original corn flour were not significantly different in ER, BD, WAI, and WSI from extrudates made of separated corn flour. However, at $P < 0.05$, extrudates made of corn flour differed significantly from those made of 0.210-mm corn flour (corn flour with additional separation) in BD, ER, and WSI. Therefore, at LTP, additional separation of corn grits affected the ER and BD values of the extrudates made from those streams at $P < 0.01$. At a 95% level of significance, additional separation caused higher ER value of 0.595-mm corn cones and also caused lower BD and WSI values of extrudates with additional separation.

Medium Temperature Profile

At MTP, there was no significant difference in ER, BD, WAI, and WSI between extrudates made from original corn grits and from corn grits with additional separation and grinding. However, at $P < 0.05$, there were significant differences in WSI between extrudates made of 0.297-mm corn grits and those made of corn grits with additional separation. Also, there was no significant difference in ER, BD, WAI, and WSI values among extrudates made of original corn cones (without separation) and corn cones with additional separation. No significant difference in ER, BD, WAI, and WSI values was found among extrudates made of original corn flour and extrudates made of corn flour with additional separation. Therefore, additional separation of corn grits, corn cones, and corn flour and additional grinding of corn grits does not significantly affect the ER, BD, WAI, and WSI values of the extrudates processed at MTP.

High Temperature Profile

LSD analysis showed significant differences in the ER between extrudates made from corn grits with additional grinding and original corn grits and also between extrudates from corn grits with additional grinding and corn grits with additional separation. However, there were no significant differences in ER, BD, WAI, and WSI values of extrudates made from original corn cones and from corn cones with additional separation. Additional separation of corn cones did not affect the characteristics of the HTP extrudates at $P < 0.01$. However, at $P < 0.05$ (Table III), there was a significant difference in ER between extrudates made of original corn cones and extrudates made of 0.595-mm corn cones. Extrudates made from corn flour with additional separation were significantly lower in WSI than were corn flour extrudates. The extrudates made from 0.210-mm corn flour had a significantly lower BD than corn flour extrudates. Lower BD usually means higher ER. The 0.210-mm corn flour extrudates had higher ER than did corn flour extrudates, although they were not significantly different. At $P < 0.05$ (Table III), the extrudates made from corn flour with additional separation had significantly lower BD and WSI values than those made from original corn flour.

This study shows that, at HTP, additional grinding of corn grits causes the extruded products made from them to expand better than those made from the original corn grits. However, at LTP, additional grinding and separation caused less expansion of extruded products.

The WSI values of extrudates increased with temperature. The correlation analysis of all the extrudates for all temperatures showed strong positive relationships between ER and WAI ($r = 0.91$), ER and WSI ($r = 0.72$), WAI and WSI ($r = 0.71$), and final moisture content (MCF) and BD of extrudates ($r = 0.83$). Strong negative correlations occurred between MCF and ER ($r = -0.72$), MCF and WAI ($r = -0.76$), BD and ER ($r = -0.94$), BD and WAI ($r = -0.85$), and BD and WSI ($r = -0.66$).

The SME values, throughput, and the torque of all 12 samples were recorded during the extrusion process at a constant screw speed (50 rpm) and at HTP. The die pressure was also recorded to compare between different samples. Table IV shows that during the extrusion process there was no significant difference in torque, SME, and P_{die} between corn grits and corn grits with additional

TABLE III
Least Significant Difference ($P < 0.05$) of Extrudates Processed at Two Temperature Profiles

	LTP[a]			HTP[b]		
Extrudates	Expansion Ratio (mm/mm)	Bulk Density (g/cm^3)	WSI[c] (g/g)	Expansion Ratio (mm/mm)	Bulk Density (g/cm^3)	WSI[c] (g/g)
Corn grits	1.36a[d]	0.93h	0.060n	1.63b	0.61f	0.109j
1.19 mm	1.29ab	1.04i	0.063np	1.65b	0.63f	0.110j
0.841 mm	1.29a–c	1.04i	0.060n	1.67b	0.63f	0.117j
0.297 mm	1.22bc	1.21j	0.077p	1.79a	0.63f	0.120j
0.210 mm	1.19c	1.28j	0.071np	1.87a	0.57f	0.115j
Corn cones	1.38d	0.99k	0.064q	1.80d	0.53g	0.106k
0.595 mm	1.28e	1.05k	0.066q	1.88c	0.56g	0.113k
0.420 mm	1.27e	1.06k	0.067q	1.83c,d	0.54g	0.109k
0.297 mm	1.25e	1.05k	0.070q	1.87c,d	0.52g	0.111k
Corn flour	1.34f	1.21l	0.068r	2.01e	0.55h	0.131l
0.297 mm	1.22g	1.24lm	0.057rs	2.02e	0.46i	0.100m
0.210 mm	1.24g	1.32m	0.051s	2.08e	0.41i	0.101m

[a] Low temperature profile (100–110–120°C).

[b] High temperature profile (120–130–140°C).

[c] Water solubility index.

[d] Means with at least one letter in common within a column are not significantly different ($\alpha = 0.05$).

separation or additional grinding. However, as the particle size of corn grits decreased, the torque and SME values increased, although they were not significantly different.

There were significant differences in torque, SME, and P_{die} of 0.595-mm corn cones and original corn cones during extrusion. The 0.595-mm corn cones had very high values of torque, SME, and P_{die} when compared with other corn cone samples. Table IV also shows no significant difference in torque, SME, and die pressure between corn flour and corn flour with additional separation.

Corn cones have significantly lower SME than corn flour. The mechanical energy needed to produce corn flour extrudates is greater than that needed to produce corn cones or corn grits. These differences could be due to the different proportion of horny and floury endosperm in each sample. The high SME values of corn flour could be caused by the smaller particle size of the corn flour and the high amount of floury endosperm. Therefore, at the same temperature, the smaller the particle size, the higher the SME required. The lower SME values could be the result of less absorption of water into the larger and harder grits. The more water that can be absorbed into the raw material, the higher the torque and SME values.

TABLE IV
Mechanical Energy Results for the Corn Grits Group of Extrudates Processed with the High Temperature Profile (120–130–140°C)

Extrudates	Torque (N•m)	SME[a] (W•hr/kg)	P_{die}[b] (kPa)
Corn grits	22.91a[c]	35.30e	371.2i
1.19 mm	22.14a	37.54e	347.1i
0.841 mm	21.51a	34.61e	332.1i
0.297 mm	26.18a	40.97e	421.3i
0.210 mm	24.63a	43.70e	403.0i
Corn cones	19.69c	31.30g	276.7k
0.595 mm	32.72b	49.14f	581.2j
0.420 mm	26.95bc	41.49fg	443.5jk
0.297 mm	26.50bc	41.01fg	426.3jk
Corn flour	22.32d	49.87h	376.9l
0.297 mm	23.34d	46.21h	447.2l
0.210 mm	27.19d	49.70h	482.2l

[a] Specific mechanical energy.
[b] Die pressure.
[c] Means with at least one letter in common within a column are not significantly different (α = 0.01).

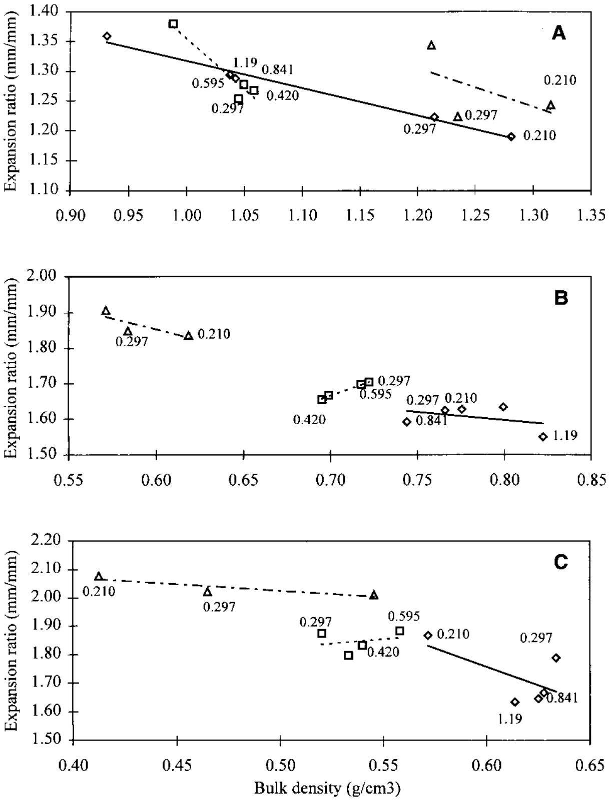

Fig. 2. Bulk density and expansion ratio relationships for three types of corn extrudates with different particle sizes at three process temperature profiles: low 100–110–120°C (**A**); medium 110–120–130°C (**B**); and high 120–130–140°C (**C**). Particle sizes not indicated for original streams. ◇ = Grits; □ = cones; Δ = flour.

Correlation coefficients ($P < 0.01$) were found between throughput and protein content ($r = 0.73$), SME and ER ($r = 0.83$), P_{die} and torque ($r = 0.95$), and P_{die} and SME ($r = 0.77$). The higher the protein content, which could mean higher amounts of horny endosperm, the higher the throughput rate. The higher the SME, the more starch was broken and gelatinized, which caused higher expansion. Die pressure correlated well with SME and torque.

A temperature increase was followed by an ER increase. This behavior could be seen in the ER of extrudates at LTP, MTP, and HTP. Figure 2 shows the relationships between BD and ER at the three temperature settings for the different extrudate groups with particle sizes shown. Each group includes extrudates made from the original stream and those from the stream with additional separation or additional grinding. Each line represents the extrudates that came from the same original stream group with the particle size shown. Regression lines in Fig. 2A at LTP for the cones, grits, and flour have coefficients of determination (r^2) of 0.918, 0.984, and 0.307, respectively. The regression lines show a negative relationship between BD density and ER. For extrudates made of corn grits streams and extrudates made of corn cone streams, the BD values of extrudates increase with decreases in particle size, whereas ER of extrudates decrease with decreases in particle size. At LTP, the extrudates made from original streams have higher ER values than those made from streams with additional separation and grinding.

Figure 2B shows BD and ER of extrudates processed at MTP. Compared with the LTP, extrudates from all streams of corn grits have smaller ranges of BD and ER. The BD values of all extrudate samples at this temperature are lower than those with the LTP. The ER of the extrudates are also higher than those of LTP. Extrudates made from original corn flour, 0.297-mm corn flour, and 0.210-mm corn flour have the highest ER and the lowest BD compared with other extrudates at the same processing temperature. Unlike at LTP, the extrudates made from original corn cones and original corn grits do not have higher ER values than the extrudates made from the streams with additional separation and grinding. At MTP, the group of corn flour extrudates have higher ER values and lower BD values than other extrudates. The r^2 values for the lines at MTP (Fig. 2B) were 0.985, 0.151, and 0.663 for cones, grits, and flour, respectively.

Compared with other extrudate groups at HTP, the corn flour group of extrudates had a larger range of BD values. At HTP, the position of the corn flour group of extrudates in Fig. 2C is higher than the corn grits group of extrudates and is similar to that at MTP. At almost all temperature profiles, the position of the corn cones group of extrudates is in between those of the corn grits and corn flour groups of extrudates (Fig. 2C). This behavior corresponds with the fact that the corn cones group has more starch or floury endosperm than the corn grits group but less than the corn flour group. At this temperature profile, the ER values of the extrudates are higher and the BD values are lower than those at the other temperature profiles. At HTP, the ER values of the extrudates made from the original streams are lower than those of the extrudates made from streams with additional separation. The r^2 values for the lines at HTP (Fig. 2C) were 0.054, 0.392, and 0.780 for cones, grits, and flour, respectively.

There were significant differences in torque, SME, and P_{die} between 0.595-mm corn cones and original corn cones. The torque and die pressure increased with particle size up to 0.595 mm, then decreased with increasing particle size. At the same particle size, there is no significant difference in torque, SME, and P_{die} among corn grits, corn cones, and corn flour. There are good positive correlation coefficients between P_{die} and torque, P_{die} and SME, and SME and ER and between throughput and protein content of the raw material.

CONCLUSIONS

At LTP and HTP, additional grinding of corn grits affected the ER values of extrudates at $P < 0.01$. Additional separation of corn flour affected the BD and WSI values of the extrudates processed at HTP. At $P < 0.01$, additional separation of corn cones caused the extrudates made from 0.595-mm corn cones to have significantly higher torque, SME, and die pressure compared with extrudates made from original corn cones. At LTP, the extrudates made from original streams had higher ER values than the extrudates made from streams with additional separation or grinding. However, this behavior at LTP did not happen at HTP. The additional separation and grinding seem to have more influence on the extrudates processed at HTP than that at LTP. Additional grinding caused better expansion of corn grits, and additional separation caused better expansion of corn grits, corn cones, and corn flour. With additional grinding of corn grits or additional separation of corn cones or corn flour, extruded products could be produced with more expansion and more protein content than the original streams. This type of corn extruded product could be beneficial for snack or cereal products that need high protein but still have more puffing or expansion than regular snacks. These additional steps of separating and grinding require unit operations already existing in the regular flow process of most corn mills. Thus, a dry miller could produce two corn streams: one with a high protein content that would produce high-protein snacks and the other with a lower protein content that could still be used to produce regular snacks.

ACKNOWLEDGMENTS

We would like to thank the Center for Crops Utilization Research at Iowa State University, Ames, for providing financial support for this study. Also, we thank Desmond Lam, Maria Ambert, and Linfeng Wang for their assistance during the experiments and David F. Cox, Fernando Perez-Munoz, and Jian Yuan for their assistance in statistical design and analysis.

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[Received November 26, 1997. Accepted July 13, 1998.]