Effects of Physical Properties and Operating Parameters on Soybean Flaking

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ABSTRACT: The soybean crushing industry aims at attaining greater oil extraction by optimizing flake thickness. This involves modifying the physical and viscoelastic properties of cracked soybeans and adjusting operational settings of the flaking roll stands. Vibratory feeders distributed 20–32% fewer cracked soybeans at the roll ends and 12% fewer cracks at the center. This increased the variability in roll wear and flake thickness along the length of the rolls. The flow rate distribution produced by rotary feeders was more uniform. Vibratory feeders produced a uniform particle size distribution of cracks (diameter range 2.71–2.76 mm) along the length of the rolls. At constant roll pressure, the increased flow rate of cracks increased the flake thickness and power consumption. While roll stands were operating at their rated flow capacity, the desired flake thickness range (0.25–0.38 mm) could not be obtained by merely increasing the roll pressure, because it caused hot spots in the rolls. Modifications of the metallurgical properties of the rolls and the viscoelastic properties of the soybeans are possible means of reducing flake thickness. During six plant visits, 73.2% of the sampled flakes were thicker than the maximum desired value (0.38 mm). This may be costing the U.S. soybean milling industry an annual loss in oil revenues of $7–16 million.

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KEY WORDS: Cracked soybeans, flakers, flake thickness, flaking, hot spots, oil yield, soybean flakes.

In the oilseed crushing industry, cracked soybeans are flaked by pressing and shearing them through a pair of smooth rolls rotating with a slight differential. In this operation, cells are distorted and ruptured and oil contained in spherozomes is freed. In the next step, oil is extracted from flakes by solvent extraction, screw pressing, or a combination of these two methods.

The aim of flaking is to form flakes of desired thickness at the highest possible flow rate with minimal energy consumption. Experiments on oil extraction with hexane have shown that for the same oil concentration, decreasing flake thickness by one-third increases the extraction rate 80 times (1). At the same time, flakes must have sufficient strength so that they do not crumble into powder during subsequent processing steps. If flakes are thin, solvent penetration is better and mass transfer distance is less (2); therefore, more oil can be extracted within a set time period. King *et al.* (3) have established the volumetric composition of a raw soybean flake with 8% moisture (wet basis, w.b.) to be 51% dry solid, 22% oil, and 19% air.

The thickness of flakes depends upon the physical, thermal, and viscoelastic properties of the cracked soybeans in the feed stream, the design of the flaking roll stands, the roll surface characteristics, and the operating parameters of the roll stands. The soybean crushing industry has developed hypotheses regarding factors influencing the flaking process (4–7). Most are subjective in nature. Levine (8) concluded that the flaking of discrete particles is a three-dimensional and nonsteady state process. This type of process is difficult to model.

Properties of cracked soybeans that affect the thickness of flakes are physical (size and shape, distribution of particle sizes, moisture content), thermal (temperature, conductivity, specific heat, diffusion coefficients), and viscoelastic (stress relaxation and creep compliance behaviors; the relationships between elasticity, temperature, moisture, and time). The purpose of this study was to quantify moisture content and particle size distribution of soybean cracks and flakes, and the thickness of individual soybean flakes; and to study the effect of mass flow rate of cracked soybeans on flake thickness and the energy consumed by flaking rolls.

MATERIALS AND METHODS

Cracking and flaking. Samples of cracked and flaked soybeans were collected from three flaking machines (designated A, B, and C) at a soybean crushing plant by making approximately one plant visit each month over a 12-mon period. From visit 8 onward, three more flaking machines (designated D, E, and F), located at the same plant, were included to study the effect of flaking on different types of roll material. The length and diameter of the flaking rolls were 157.5 and 71.1 cm, respectively. The gap between the rolls was adjusted by applying hydraulic pressure (300–550 psi) on both roll ends. The front and rear rolls rotated at fixed speeds of 280 and 310 rpm, respectively. The cracks directed to Flakers A, B, and C came from the same conditioner. This reduced variability in the feed stream. Flakers D, E, and F received cracks from a

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second conditioner. Before conditioning, the soybeans were cracked and hulls were removed by air aspiration. Conditioners were of the stacked-bed type with seven layers. The beans were heated by contact with hot plates without adding steam or hot air. The temperature and moisture content of the cracked beans at the inlet to the conditioner varied between 27–38°C (80–100°F) and 10–11% (w.b.) during different plant visits. The temperature of the cracked beans inside the conditioner was increased from 63 to 80 ± 5.5°C (145 to 160 ± 10°F) between the first and seventh stage during a conditioning time of 30 min. After conditioning, aspiration was again performed to remove the remaining hulls. The temperature of cracks in the stream fed to the flakers was 60–69°C (140–157°F). In these six flakers, cracks were distributed along the roll length by vibratory feeders. The extractors used in the plant were shallow-bed chain-type (Crown Iron Works, Minneapolis, MN). The plant's goal was to produce 48% protein meal. To study the effect of feeder type on the distribution of cracked soybeans, one visit was made to another plant in which rotary feeders were installed over the flakers.

Samples were carried to the Grain Quality Laboratory at Purdue University in sealed plastic bags and stored in a cold room at 4°C until they were evaluated.

Moisture content. The moisture content of the soybean cracks was determined by drying them in a convection oven at 103°C for 72 h, the method recommended for unground materials (ASAE Standard S352.2; Ref. 9). Flakes were dried in a convection oven at 103°C for 24 h (ASAE Standard S358.2; Ref. 9), a method recommended for forage products.

Mass flow rate of feed. A stainless-steel hopper (15.5 cm wide) connected to a shop vacuum machine was used to collect the feed from different locations along the roll length. The collection time varied from 30–90 s depending upon the flow-rate setting of the flaker. The equivalent roll flow rate was calculated by multiplying the measured crack weight values by the ratio of roll length to hopper width.

Energy consumption. To study the effect of mass flow rate of cracked soybeans on energy consumption, an experiment was conducted on Flaker C. The energy consumption was measured with a three-phase energy meter (ABB Portable Alpha Meter; ABB Power T&D Company Inc., Raleigh, NC) installed on the electrical motor of this flaker. A measurement without cracked soybeans flowing through the flaking rolls revealed that the energy required to just run the rolls was 5 kW, only 6% of the energy consumed at normal flow rate settings.

Flake thickness. Flake thickness was measured with an electronic gauge (Positector 6000; DeFelsko Corp., Ogdensburg, NY). Samples were placed on an iron plane and a spring loaded hand-held gauge was placed on top of a flake whose thickness was being measured. The device generated a magnetic field, which was affected by the distance separating the plate and the gauge. The gauge stored data in onboard memory and subsequently transferred it to a personal computer. After shaking a sample bag lightly, 25 flakes were randomly selected and laid over the iron plane. Since the surface of the flakes was rough, a standard-sized flat plastic strip was placed over each flake before the gauge was used to take the average thickness reading. The size of the plastic strip was subtracted from the indicated gauge reading.

Particle size distribution of cracks and flakes. ASAE Standard S319.2 (9) recommends the use of ASTM Standard E11 wire cloth sieves to be used for analyzing particle size distribution of granular materials. A bottom pan was used along with half-height sieves having U.S. Standard sizes of Nos. 4, 6, 8, 12, 14, 16, 20, and 30. The sieves were also used to determine the amount of fines in flakes, which is an accepted practice in the soybean crushing industry. A sample was placed in the top sieve, and the sieve set was shaken at the rate of 600 vibrations/min for 10 min using a Fisher Wheeler automatic sieve shaker (Fisher Scientific Co., Hampton, NH). During preliminary tests, it was observed that after 10 min, the mass of material on the lowest sieve became constant. Shaking at this rate did not appear to generate more fines.

RESULTS AND DISCUSSION

Moisture content. The moisture content of soybean cracks collected during all plant visits was about 10.1 ± 0.2% (w.b) and the moisture content of the flakes was about 9.7 ± 0.2% (w.b.). The slight difference in moisture content between the cracks and the flakes is likely the result of evaporation during flaking. However, the difference could also have been affected by the longer time used to dry cracks in the convection oven. In the soybean crushing industry, the final moisture contents and temperatures of cracks and flakes are usually used as an index to monitor the properties of the cracks in the feed stream (4). However, this is not an adequate indicator of the flake thickness, which depends upon the viscoelastic properties of cracks. The viscoelastic properties further depend on the temperature and moisture profiles the cracks experience during conditioning rather than on the final moistures. Cracks conditioned at higher temperatures and moistures during the intermittent stages may have cooled and dried. They would have higher creep compliance than cracks conditioned only at the lower moistures and temperature. (Note: Creep compliance refers to the deformation of a viscoelastic solid, in this case a crack being flaked, during the time when a given force is applied for a specified time.) Therefore, the former would be expected to form thinner flakes. Obviously, the exposure time during conditioning at a given combination of temperature and moisture is also critical. This time-temperature-moisture relationship for soybean cracks has not been documented in the scientific literature and should be investigated further.

Mass flow rate of cracks. The distribution of cracks by vibratory feeders was not uniform (Fig. 1). The extreme ends received 30 to 22% fewer cracks than at positions L2 and R2, respectively, and the center received 12% fewer cracks than at positions L2 and R2, respectively. The lower amounts of cracks at the extreme ends caused less wear. This caused the

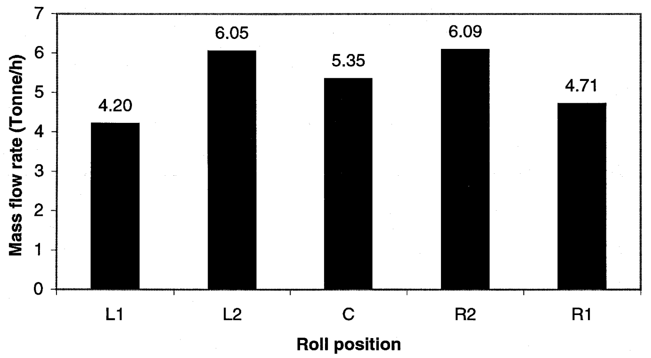


FIG. 1. The mass flow rate of cracks measured at five locations along the length of a flaker equipped with a vibratory feeder. The figure shows data collected during one visit. L, left end of flaker; C, middle of the roll, located at 78.7 cm from each end; R, right end of flaker.

roll diameter to become greater there than along the rest of the roll length. In most soybean crushing plants, the extreme ends of rolls are regularly ground to reduce the end diameters to the roll diameter at other locations.

In flakers fed with rotary feeders, the mass flow rate was uniform along the flaker length (Fig. 2). The maximum difference was less than 5%. Due to uniform wear along the length of these rolls, less end grinding was needed compared to rolls at the first plant. These observations indicate that the design of vibratory feeders should be improved to ensure more uniform flow of cracks along the length of flaking rolls. This should in turn provide more uniform roll wear and reduce the need for end grinding. In old designs of flaking roll stands rotary feeders were routinely incorporated. They were not as easily integrated with the electronic control system of the flakers as were the vibratory feeders. Therefore, flaking machine manufacturers decided several years ago to install the vibratory feeders. Now technology has become available to easily integrate the rotary feeders with flaking machines.

Flake thickness. Flake thickness of 0.25–0.38 mm is striven for in shallow-bed chain-type extractors (Crown Iron Works) and 0.38–0.46 mm in deep-bed basket-type extractors (French Oil Mill Machinery Co., Piqua, OH). Flake thickness is controlled by adjusting hydraulic pressure at both ends of the flaking rolls but can vary along the length of a roll stand.

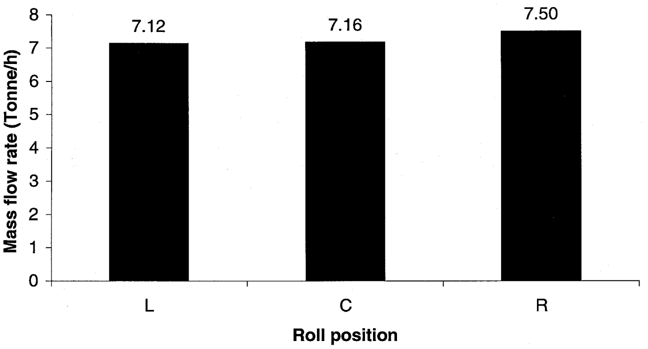


FIG. 2. The mass flow rate of cracks measured at three locations along the length of a flaker equipped with a rotary feeder. L and R are located 10 cm from each end. C is located at middle of the roll.

Flake samples are taken intermittently by operators so that thickness can be checked and necessary adjustments made. Often the flake sample size used is not large enough to be representative and provide meaningful results. This leads to erroneous pressure adjustments by operators. Incorrect pressure adjustments can cause increased friction on one side of the rolls, which can lead to increased roll wear and a tapered shape. This causes imbalance and leads to excessive temperature gradients within a roll. Such gradients are probably the reason for end-spalling, a commonly observed form of roll damage. During one plant visit, surface temperature gradients in the range of 5–29°C (9–52°F) were measured along the length of rolls of different flakers. The average temperature of roll surfaces was 53–66°C (127–150°F).

The correct sample size of flakes will avoid improper roll adjustments and lead to correctly estimating flake thickness distribution. Based upon the statistical method suggested by Sokal and Rohlf (10), Figure 3 was developed to predict the sample size needed to detect a given difference in two means at the 95% confidence level with 85% certainty. In multiple samples collected from any given location of a roll stand, the flake thickness had a coefficient of variation of about 0.16. Thus, according to Figure 3, a sample size of 25 flakes would detect a 15% difference in two means. This was considered a reasonable level of accuracy by the soybean crushing company where the study was conducted.

The average thickness of flakes along the flaker length during one visit is shown in Figure 4. To quantify the significance of the difference between thickness of flakes across the length of flaking rolls, one-way analysis of variance was performed at the 95% confidence level on the samples collected during seven visits to a plant. The *P* values (type 1 error) are shown in Table 1. In all cases but two (Flaker B, Visit 2; Flaker A, Visit 7), the flake thickness was significantly different ($P <$ 0.05) between the center and sides. This likely results from the interaction of several factors. First, the high-pressure side of the rolls tends to produce thinner flakes. Second, at locations receiving higher flow rates, more cracks tend to squeeze through the gap resulting in thinner flakes. Third, the condi-

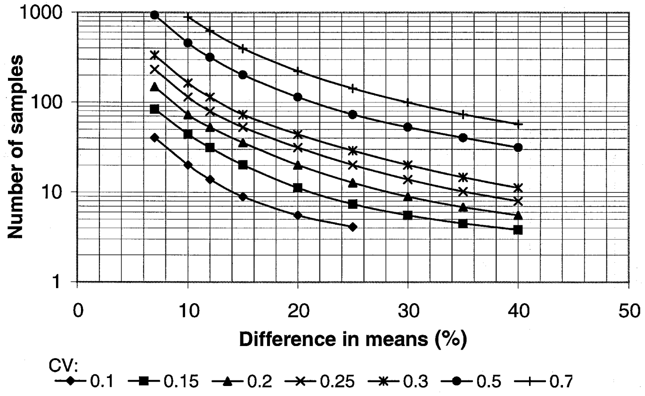


FIG. 3. Number of samples required to detect a given difference in two means at 95% confidence level with 85% certainty for a given coefficient of variation (CV).

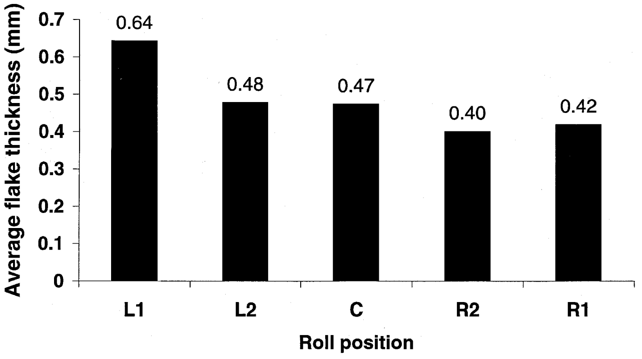


FIG. 4. The average thickness of flakes during one visit measured at five locations along the length of a flaker. L1 and R1 are the extreme left and right ends of the flakers; L2 and R2 are located at 25 cm from L1 and R1, respectively. C is the middle of the roll, located at 78.7 cm from each end.

tioner causes periodic fluctuations in crack temperature and since flake samples are collected from different locations one after the other, the flakes collected at higher crack temperature would be thinner. Fourth, if the roll ends were not recently ground prior to a visit, the locations with a higher roll gap would yield thicker flakes.

In Flaker B on visit 2 and Flaker A on visit 7, the flake thickness was not significantly different along the length. Sometimes the presence of excessive amounts of fines in the feed stream produces uniformly distributed powdery flakes (resembling powder), which are not desirable because they are not suitable for oil extraction. In soybean crushing, particles finer than U.S. Sieve No.14 (size of 1.3 mm) are generally considered fines. However, particle size analysis of cracks in these two cases showed that the feed stream to Flaker B and Flaker A contained less than 2 and 0.3% fines, respectively (Fig. 5). The flake thickness may have been uniform in these two cases because of end grindings given shortly before the visit.

The crushing plant under study aims for a flake thickness range between 0.25–0.38 mm (0.01–0.015 in.). To determine the flake thickness range that the roll stands at the plant were actually producing, the data from three roll stands (A, B, C) during six plant visits were pooled together, and a box plot and a distribution curve were plotted (Fig. 6). The mean flake

TABLE 1
***P* Values (type 1 error) of One-Way Analysis of Variance at the 95% Confidence Level to Determine the Significance of the Difference in Flake Thickness Across the Length of a Flaker**

Visit	Flaker A	Flaker B[a]	Flaker C
1	2.67×10^{-8}	2.69×10^{-16}	2.90×10^{-7}
2	5.40×10^{-3}	4.00×10^{-1}	2.10×10^{-3}
3	1.57×10^{-7}	1.20×10^{-3}	4.20×10^{-3}
4	3.30×10^{-9}	4.96×10^{-6}	1.41×10^{-9}
5	1.19×10^{-10}	1.8×10^{-2}	1.70×10^{-7}
6	3.69×10^{-38}	—	2.43×10^{-18}
7	5.5×10^{-1}	1.75×10^{-19}	2.64×10^{-12}

[a] The sample for Flaker B on visit 6 was lost due to a damaged sample bag.

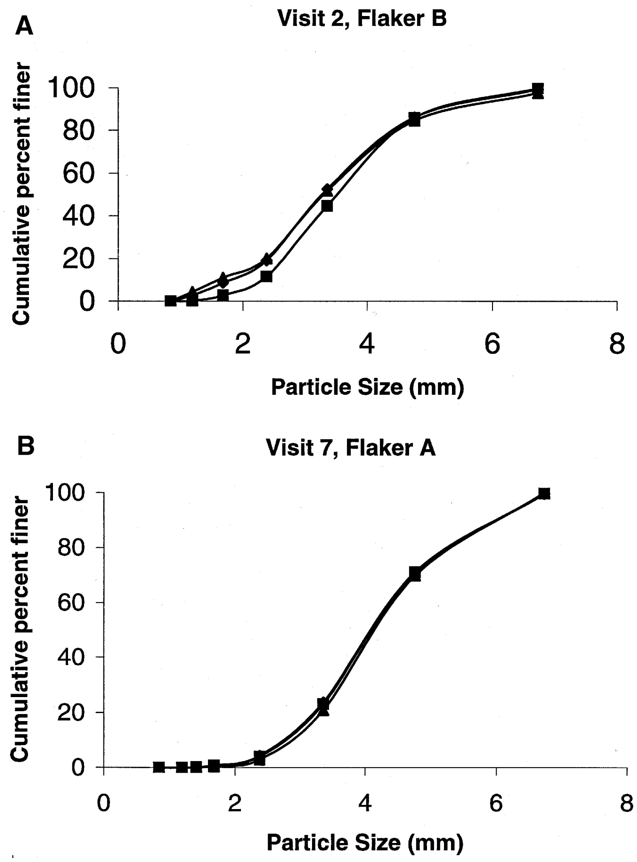


FIG. 5. Particle size analysis of cracks collected during (A) Visit 2 from Flaker B and (B) Visit 7 from Flaker A. L (◆) and R (■) are located at 25 cm from each end. C (▲) is located at the middle of the roll.

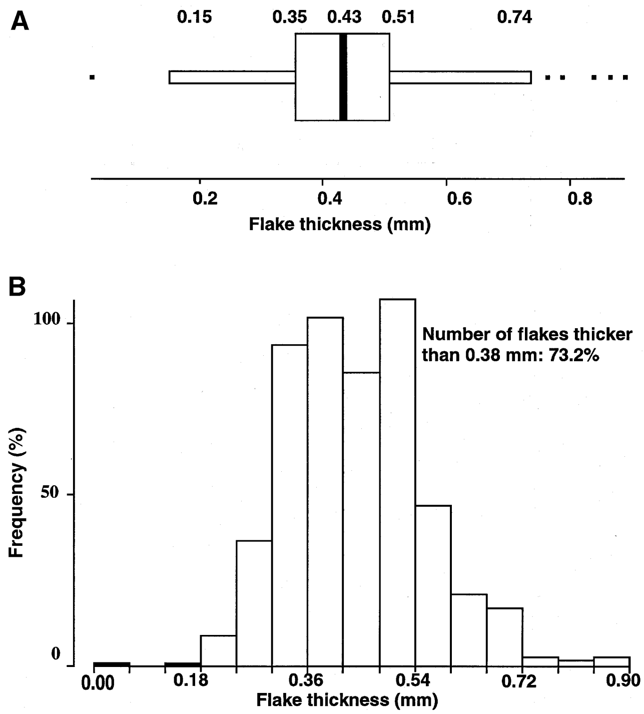


FIG. 6. Distribution of flake thickness obtained by pooling data from six plant visits.

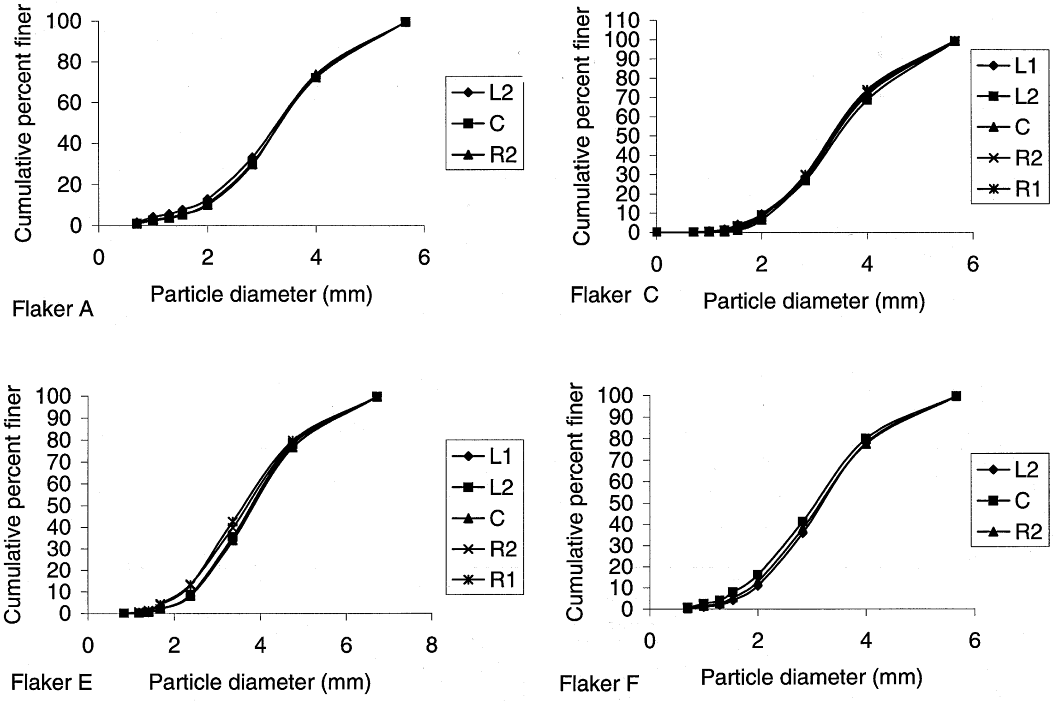


FIG. 7. Particle size analysis of cracks collected from different locations along the length of Flakers A, C, E, and F. For abbreviations, see Figure 4.

thickness of the pooled data was 0.44 mm (0.0173 in.). This was significantly larger than the upper limit of 0.38 mm (0.015 in.) desired by the industry. The box plot shows that 50% of the flakes had thickness of 0.36–0.51 mm (0.014–0.02 in.). A calculation from the distribution curve indicated that 73.2% of the flakes had a thickness greater than 0.38 mm (0.015 in.). The residual oil content in these average-sized flakes was estimated to be 1.26%, which was 0.33 to 0.82 percentage points higher than the desired range (7). Based on information previously provided by the industry, it is estimated that if flakes in all plants in the United States had such a large thickness, then the soybean milling industry may be losing \$7–16 million annually in oil revenues. In the calculation of the mean flake thickness, the data from Flaker B were also included. This tends to lower the average value of flake thickness due to the high amount of fines in the feed stream of this flaker. If that data were excluded, the estimate of losses would have been even higher.

Particle size distribution of cracks. A general belief in the industry is that vibratory feeders lead to the segregation of particles of different sizes along the flaker length. However, analysis of the collected samples showed that the size of cracked soybeans was not significantly different along the length of a flaker (Fig. 7 and Table 2). Even the particles collected from the extreme ends of Flakers C and E were not significantly different from those along the rest of the roll length. For Flaker C, the geometric mean diameter of cracks was 2.71 mm at the extreme ends and 2.76 mm at the center. For Flaker E, the mean particle diameter along the flaker length was 2.48–2.64 mm. The standard deviations of particle sizes were essentially constant along the flaker length (Table 2). Similar results were observed during other visits. The particle size of

TABLE 2
Geometric Mean Diameter (Dgw) and Geometric Standard Deviation (Sgw) by Mass of Soybean Cracks Along the Length of Flakers A, C, E, and F Collected During One Visit to a Soybean Crushing Plant[a]

	Dgw (mm)					Sgw				
Flaker	L1	L2	C	R2	R1	L1	L2	C	R2	R1
A	—	2.56	2.63	2.62	—	—	0.17	0.16	0.16	—
C	2.71	2.76	2.76	2.71	2.71	0.14	0.14	0.13	0.14	0.13
E	2.63	2.51	2.64	2.51	2.48	0.13	0.13	0.13	0.15	0.14
F	—	2.57	2.43	2.52	—	—	0.14	0.16	0.15	—

[a] L1 and R1 are the extreme left and right ends of the flakers. L2 and R2 are located at 25 cm from L1 and R1, respectively. C is the middle of the roll located at 78.7 cm from each end. For flakers A and F, samples were collected at L2, C, and R2 positions only.

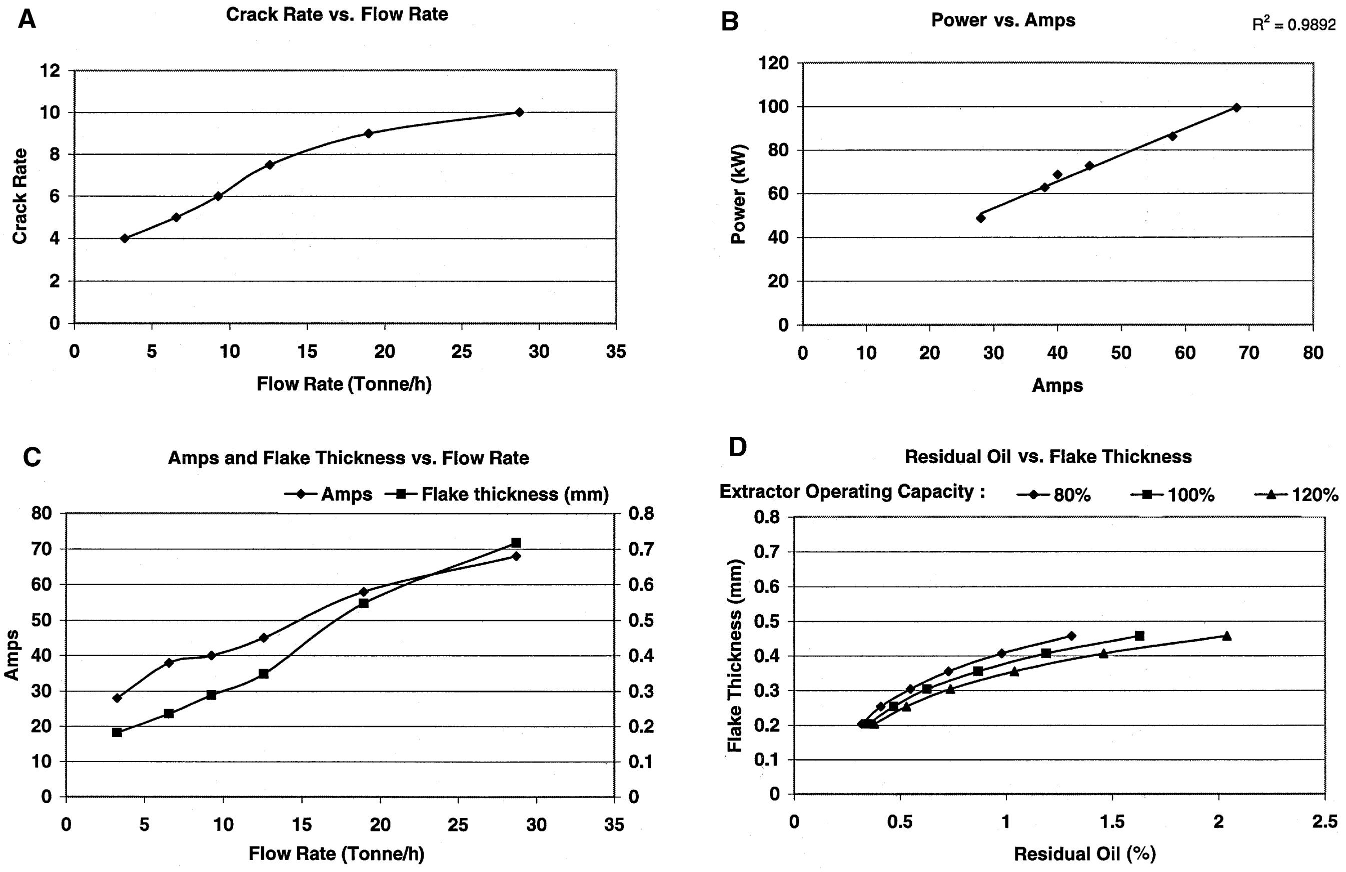
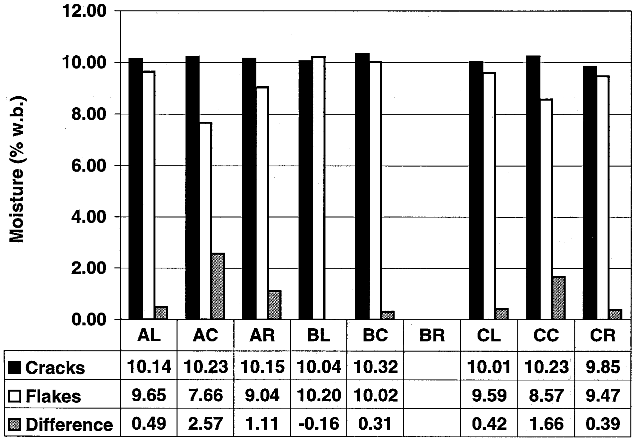


FIG. 8. The effect of mass flow rate of cracked soybeans on power consumption and flake thickness for Flaker C. Hydraulic pressures were 480 and 400 psi at the left and right roll ends, respectively. The data of Figure 8D are taken from Reference 7.

cracks was not intentionally varied; thus, its effect on flake thickness and surface area could not be determined.

Effect of mass flow rate of cracked soybeans on power consumption and flake thickness. An experiment was conducted on Flaker C to study the effect of mass flow rate of cracks on flake thickness and energy consumption. Each flaker had a cracking rate setting control that could regulate the amount of cracks feeding into a roll stand. Figure 8A shows that mean mass flow rate of cracks along the length of the flaker correlated well with cracking rate setting. Similarly, power consumption was essentially linearly related ($R^2 = 0.98$) to the electric current drawn by the roll stand motor (Fig. 8B).

Figure 8C shows that as mass flow rate of cracks increased, flake thickness as measured at the center of the roll stand also increased. In other words, an increase in flow rate from 10 tonne/h to 29 tonne/h would result in a flake thickness increase of 0.40 mm. This would result in significantly higher oil residuals (Fig. 8D). When the mass flow rate was increased, the hydraulic pressure settings of the roll stand were kept constant (left 480 psi, right 400 psi). Therefore, with increased mass flow rate, the gap between the flaking rolls increased, resulting in thicker flakes. No attempt was made during this experiment to increase the hydraulic pressure in order to decrease flake thickness. Thus, at these hydraulic pressures the industrial goal of producing flakes between 0.25 and 0.38 mm (0.01–0.015 in.) would be achieved between 9 and 14 tonne/h flow rate. At this flow rate the power consumed would be 60–75 kW. This is about half of the maximum rated roll stand capacity of 110 kW. In order to achieve thinner flakes and operate closer to the rated capacity, the hydraulic pressure would have to be increased on the rolls. Unfortunately, an increase in hydraulic pressure increases frictional heating and therefore increases the temperature of the roll surfaces. Excessive heating ("hot spots") causes the flakes to sheet and then break into powder. To utilize the rated capacity of the roll stand, the mass flow rate of cracks could be increased in combination with increasing the roll speed. The maximum roll speed is limited by the coefficient of kinetic friction between the cracks and the roll surface, which must remain sufficiently high to process the cracks without slipping. An experiment quantifying the change in the coefficient of kinetic friction for an increase in the flow rate of cracks would have to be conducted to determine the upper limit of the roll speed. Alternatively, the viscoelastic properties of the soybean cracks could be changed (e.g., by changing conditioning temperature) in order to produce thinner flakes and reduce energy consumption. In any event, it appears that the roll stands in the crushing plant investigated do not operate within the desired optimal combination of flake thickness, flaking capacity, and energy con-



	AL	AC	AR	BL	BC	BR	CL	CC	CR
■ Cracks	10.14	10.23	10.15	10.04	10.32		10.01	10.23	9.85
□ Flakes	9.65	7.66	9.04	10.20	10.02		9.59	8.57	9.47
▨ Difference	0.49	2.57	1.11	-0.16	0.31		0.42	1.66	0.39

FIG. 9. The moisture content of cracks and flakes for samples collected on Visit 6, the day when hot spots were observed at the center of the rolls in flakers A and C. On the horizontal axis, the first letter represents the flaker and the second letter represents the position. The data of location BR were rejected due to a damaged sample bag.

sumption. This implies that either the design and operation of flaking rolls should be modified, or the conditioning procedure should be changed, or both, so that flaking rolls operate at higher capacity and produce thinner flakes.

Effect of hot spots on moisture content and thickness of flakes. On visit 6, bands with a temperature of 56°C (100°F) higher than the adjoining roll surface were observed at the center positions of Flakers A and C. Such high temperature patches are called "hot spots" in the crushing industry. On this date, flakers were being operated at significantly higher hydraulic pressures (700–800 psi) in order to achieve thinner flakes at higher roll stand capacities.

The effects of these hot spots on moisture content and flake thickness are shown in Figures 9 and 10, respectively. Figure 9 shows that the difference in moisture content between cracks and flakes was greater at the center positions of Flakers A and C. It is likely that the higher temperature at the center position caused more moisture to evaporate from these flakes than from the flakes processed through the sides. Figure 10 shows that the thickness of flakes at the center of the rolls was significantly lower than at the sides. Usually the lower mass flow rate at the center yielded thicker flakes, but the high temperature of the rolls apparently modified the viscoelastic properties of the cracks making them thinner and more fragile. Based on these findings, monitoring the flake thickness along the length of the rolls can also serve as an early indication of emerging hot spots. The flake thickness data at the right position of Flaker B were rejected because the bag containing the flakes was found damaged during transit from the plant to the Purdue Grain Quality Lab. This allowed the flakes to exchange moisture with the air.

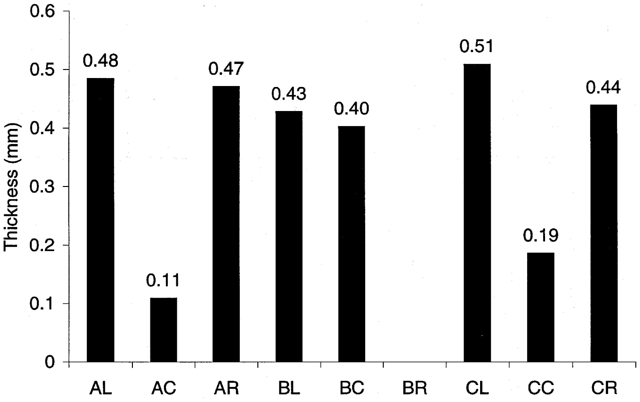


FIG. 10. Flake thickness of samples collected on visit 6, the day when hot spots were observed at the center of the rolls in flakers A and C. For abbreviations, see Figures 1 and 9.

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REFERENCES

1. Othmer, D.F., and J.C. Agarwal, Extraction of Soybeans, *Chem. Eng. Prog. 51*:372–378 (1955).
2. Johnson, L.A., and E.W. Lusas, Comparison of Alternative Solvents for Oils Extraction, *J. Am. Oil Chem. Soc. 60*:229–242 (1983).
3. King, C.O., D.L. Katz, and J.C. Brier, The Solvent Extraction of Soybean Flakes, *Trans. Am. Inst. Chem. Engineers 40*:533–556 (1944).
4. Fetzer, W., *Theory and Practice of Designing Flakers,* Buhler Ltd., UZWIL, Switzerland (year of publication unknown).
5. California Pellet Mill Co., Soybean Flaking: Preparation for Extraction, Nashua, NH, 1993.
6. Agriculture Canada, Size Reduction and Mixing, Handling Agricultural Materials, Research Branch, Publication 1843/E, Ottawa, Canada, 1990.
7. Crown Iron Works Company, Factors Affecting Residual Oil in the Solvent Extraction of Soybeans, Copyright: E-910912-2, Minneapolis, 1994.
8. Levine, L., Musing on the Mechanics of Flaking Rolls, *Cereal Foods World 38*:872–873 (1993).
9. *ASAE Standards,* American Society of Agricultural Engineers, St. Joseph, 1992.
10. Sokal, R.R., and F.J. Rohlf, *Biometry, the Principles and Practice of Statistics in Biological Research,* 3rd edn., W.H. Freeman and Company, New York, 1995.

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