Effect of Hybrid and Physical Properties of Individual Popcorn Kernels on Expansion Volume

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ABSTRACT

The relationships between expansion volume and physical properties of three varieties of popcorn kernels were investigated on a single kernel basis. Physical properties studied were kernel size, kernel sphericity, and kernel density. Methods of measuring densities and popped volumes of individual popcorn kernels were developed. Popcorn kernels were separated into seven kernel sizes by screening with round-hole sieves. Thirty kernels from each of three kernel sizes (4.76 < D < 5.16, 5.56 < D < 5.95, 6.35 < D < 6.75 mm) of three popcorn varieties were individually measured for sphericity, density, and popped volume. Density and sphericity measures of popcorn kernels showed little variability. Variety, kernel sphericity, and kernel density had minor effects on expansion volume. Kernel size had no effect. There were no strong linear relationships (R^2 = 0.28) among expansion volume and physical properties of the three varieties of popcorn kernels. The variety with the highest mean density and the highest mean sphericity showed a tendency of producing higher mean expansion volumes.

Among studies looking at the factors affecting popping characteristics (especially expansion volume) of popcorn, many have focused on physical properties of the popcorn kernels. These physical properties include kernel size (Willier and Brunson 1927; Lyerly 1942; Haugh et al 1976; Lin and Anantheswaran 1988; Pordesimo et al 1990; Song et al 1991), length, width, and thickness or kernel sphericity (Willier and Brunson 1927; Lyerly 1942; Haugh et al 1976; Pordesimo et al 1990), and kernel density (Lyerly 1942; Haugh et al 1976; Chang 1988). Due to differing moisture contents, varieties, methods of popping, term definitions, measurements, and experimental conditions in previous studies, results have been contradictory and inconclusive at best.

Willier and Brunson (1927) explained that small kernels were much more likely than large kernels to have a large proportion of hard endosperm, which is why the expansion volume was highest in the lightest kernels. Lyerly (1942) conducted the experiments by oil popping and obtained results in agreement with Willier and Brunson (1927). In contrast, Lin and Anantheswaran (1988) reported that large kernels had higher expansion volumes than small kernels when microwave popping methods were used. Pordesimo et al (1990) indicated that expansion volume increased from kernels retained on standard sieves 13 to 15, then decreased from kernels retained on sieves 15 to 17 when popped by a microwave popping method. Song et al (1991) also concluded the middle-sized (retained on sieves 13 and 14) popcorn kernels had the highest expansion volume by oil popping.

Willier and Brunson (1927) showed that length, breadth, and thickness of kernels were correlated negatively with expansion of popcorn. Among these three dimensions, length had the greatest negative correlation with expansion and thickness had the least. Lyerly (1942) used the oil popping method and reported that length and width of kernels had negative correlations with popping expansion but thickness of kernels had a positive correlation. Haugh et al (1976) did not mention the relationship between sphericity and expansion volume directly, although they did notice that kernels at the butt location of the ear had the greatest value for sphericity, and popcorn with greater test weights had greater expansion volumes. Pordesimo et al (1990) popped five varieties of popcorn in a microwave oven and expansion volumes were positively correlated with sphericity (r = 0.87). They concluded that smaller, shorter, and broader kernels with higher sphericities had higher expansion volumes.

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Lyerly (1942) showed that density of kernels had a weak positive correlation with expansion (r = 0.26). Haugh et al (1976) investigated 12 varieties of popcorn and used a specific gravity gradient tube to measure kernel densities. No statistically significant differences in specific gravities were found at 15.5% moisture content for 12 varieties of popcorn, but hybrids with higher specific gravities had higher expansion volumes. Pordesimo et al (1990) measured the specific gravity of popcorn in three solutions with different known specific gravities. They found that the mean specific gravities of four out of five varieties were not significantly different from each other, but expansion volume significantly increased as specific gravity of kernels increased within one variety investigated. Chang (1988) measured density of grain kernels using a gas pycnometer.

Previous researchers concentrated on popping characteristics of bulk popcorn kernels, not individual kernels. For bulk popcorn kernels, expansion volumes included the air spaces between popped kernels when measuring popped volumes. To eliminate this air space when measuring expansion volume and to obtain an exact expansion volume of popcorn kernels, an investigation on a single kernel basis was explored. The objectives of this study were to 1) develop methods of measuring density and popped volume of individual popcorn kernels and 2) investigate the effects of hybrids and physical properties (kernel size, sphericity, density) of individual popcorn kernels on expansion volumes.

MATERIALS AND METHODS

Three varieties (A, B, and C) of yellow commercial popcorn were obtained from the Swiss Miss Foods Company, Brookston, IN. The corn was grown near Brookston, IN, and harvested in 1998. All samples were kept in plastic bags at room temperature before experiments. Initial moisture contents of the three varieties were 14.3, 14.2, and 13.3%, respectively, as reported by the supplier. Moisture was determined for individual hybrids and kernel sieve size fractions using a 103°C forced-air oven method (ASAE 1989).

Kernels

Each variety was separated into seven size fractions using a set of U.S. standard testing sieves: 17, 16 (Precision Sizer, Carter-Day Co., Minneapolis, MN), 15, 14, 13, and 12 (Dockage Tester, Cea-Carter-Day Co., Minneapolis, MN) with hole openings of 6.75, 6.35, 5.95, 5.56, 5.16, and 4.76 mm, respectively. Three size fractions of popcorn were investigated. Kernels that passed through sieve 17 and retained on sieve 16 were designated large size. Kernels that passed through sieve 15 and retained on sieve 14 were designated medium size. Kernels that passed through sieve 13 and retained on sieve 12 were designated small size. The rationale of selecting the three size fractions of popcorn kernels instead of seven as study objects was to maximize the difference of each size and eliminate the possibility of size overlap. Thirty-five kernels were chosen randomly from each size fraction to be tested individually for sphericity and density before popping. Pericarp damage from sieving was not observed. To further control potential popping error that might have resulted from any unobserved pericarp damage, 35 kernels were randomly selected from each size fraction to obtain the 30 popped kernels needed for the study.

A digital micrometer with 0.001-mm resolution (MDC-25, Mitutoyo, Japan) was used to measure three dimensions of the individual popcorn kernels. The three dimensions were the length (the distance from the tip cap to the kernel crown), width (the widest point-to-point measurement taken parallel to the face of the kernel), and thickness (the distance between the two kernel faces) as described by Pordesimo et al (1990). Sphericity was defined as sphericity = (length × width × thickness)$^{1/3}$/length (Mohsenin 1986).

The method used to determine single kernel density was based on Archimede's principle of liquid displacement. A 200-mL beaker containing 100 mL of vegetable oil was put on an analytical balance with a resolution of 0.0001 g. Then the balance was reset to make the initial reading 0.0000 g. A single popcorn kernel was placed on a metal wire (gage 28) loop and was carefully inserted into the vegetable oil to a premarked point on the wire. The reading on the balance represented the weight of vegetable oil displaced by the popcorn kernel and the piece of metal wire (Fig. 1). After the reading was recorded, the kernel and wire were removed from vegetable oil and a paper towel was used to clean the oil from the wire and the kernel. The metal wire was inserted into the vegetable oil to the premarked point again to obtain the weight of oil displaced by the wire. The difference between these two readings divided by the density of oil was the volume of the popcorn kernel. The density of the popcorn kernel was determined by the ratio of weight to volume of the kernel. Using vegetable oil instead of water or other chemical solutions as the displacement liquid prevented changes in the moisture content of the popcorn kernels or damage to the popcorn kernels. This method had a coefficient of variance <0.002.

Popping

The hot-air popper used in this study was a gourmet-regular hot air popper (120 volts, 60 Hz, 1,440 watts; National Presto). The popper was modified for popping individual kernels (Fig. 2). The top plastic part with lid of the popper was removed. A piece of round hardware cloth, 1/8 in. (0.3175 cm) diameter, connected to a metal rod in the center was positioned in the popper ≈3.5 in. from the bottom of the popper after a single popcorn kernel was placed inside. The purposes of this modification were to confine the popcorn kernel to a limited space and to guarantee sufficient heat during the popping process.

After determining sphericity and density, 30 of 35 kernels from each size fraction were popped. The hot-air popper was preheated for 10 min, followed by the individual kernel popping. The number of unpopped kernels was not investigated in this study. If a kernel did not pop, it was replaced randomly by one of the five extra kernels.

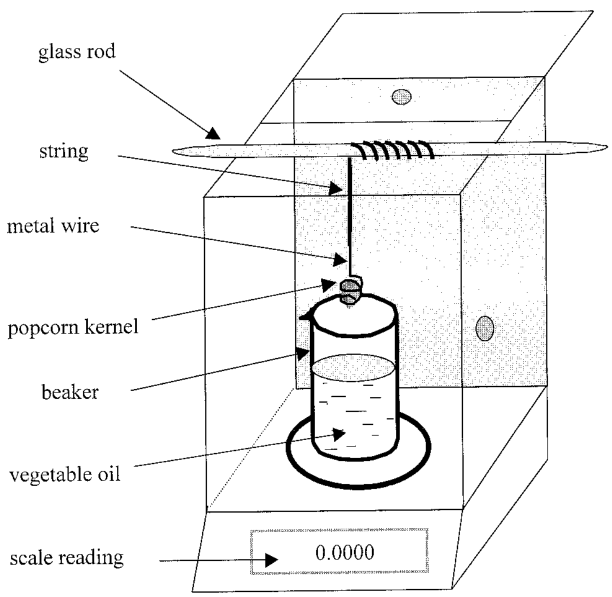

Fig. 1. Measurement of kernel density.

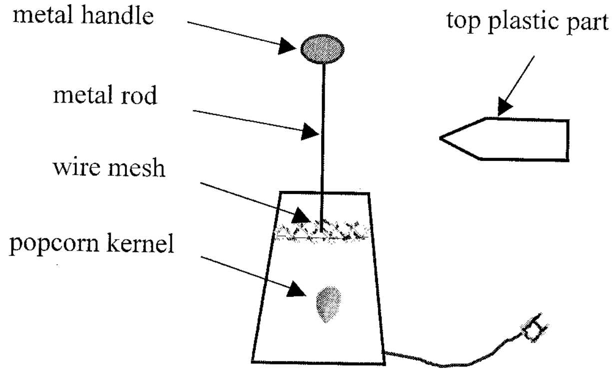

Fig. 2. Modified popper.

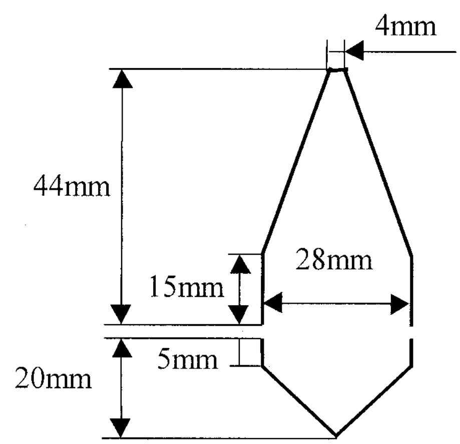

Fig. 3. Dimensions of popcorn container.

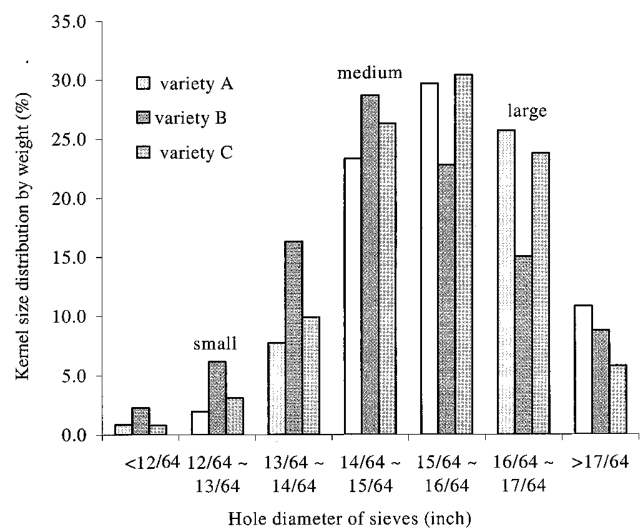

Fig. 4. Kernel size distribution of three popcorn varieties.

Expansion Volume Measurement

The solid displacement method (with colored sand bought locally) was used to measure the expansion volume of popped kernels. Each kernel was tested five times and the highest and lowest values were removed. Expansion volume of each popped kernel was obtained by averaging the three measurements and calculated by the formulas:

$$\text{Popped volume (cm}^3\text{)} = \text{wt of sand displaced by popped kernel (g)}/\text{density of sand (g/cm}^3\text{)}$$

$$\text{Expansion volume (cm}^3\text{/g)} = \text{popped volume (cm}^3\text{)/wt of unpopped kernel (g)}$$

A small two-piece container (Fig. 3) was designed to measure volume of individual popped kernels. The top of the container was modified to form a small opening that allowed sand particles to enter. A popped kernel was placed in the container before measurement and the two parts of the container were connected by tape. After the container was completely filled with sand using a funnel to direct the flow of the sand, the container was put on a mini Vortexer (Troemner Inc., Philadelphia, PA) to agitate for 10 sec, assisting the sand to fill the void spaces produced by kernel flakes. The filling and agitating process was repeated two more times. Then the container was weighed with the sand and the kernel. The container was emptied and refilled with sand, agitated, and weighed by the same process to obtain the second measurement. The weight of sand displaced by the popped kernel was obtained from the above two measurements. This expansion volume measurement of individual popcorn kernel had a coefficient of variance <0.1.

TABLE I
Mean Sphericities (MS) of Popcorn Kernels by Size and Variety[a,b]

	Variety			
Kernel Size	A	B	C	MS
Small	0.72 ± 0.04	0.70 ± 0.04	0.75 ± 0.04	0.72b
Medium	0.73 ±0.05	0.71 ±0.03	0.75 ± 0.05	0.73b
Large	0.74 ± 0.70	0.74 ± 0.06	0.77 ±0.08	0.75a
MS	0.73b	0.71c	0.76a	· · ·

[a] Mean sphericities ± standard deviations.
[b] Values followed by the same letter in the same column or the same row are not significantly different ($P < 0.05$).

TABLE II
Mean Densities (MD) of Popcorn Kernels by Size and Variety[a,b]

	Variety			MD
Kernel Size	A	B	C	(g/cm³)
Small	1.375 ± 0.024	1.359 ± 0.021	1.376 ± 0.011	1.370a
Medium	1.364 ± 0.010	1.367 ± 0.018	1.379 ± 0.011	1.370a
Large	1.370 ± 0.007	1.371 ± 0.011	1.373 ± 0.009	1.371a
MD (g/cm³)	1.370b	1.366b	1.376a	· · ·

[a] Mean densities ± standard deviations
[b] Values followed by the same letter in the same column or the same row are not significantly different ($P < 0.05$).

TABLE III
***F* Values for All Independent Variables**

Source	DF	Squares	Sum of Square	Mean *F* Value	*Pr* > *F*
Model	18	217.19334	12.06630	5.46	0.0001
Error	251	554.56374	2.20942	· · ·	· · ·
Corrected total	269	771.75707	· · ·	· · ·	· · ·
R^2	0.281427				
CV	11.37979				
Root MSE	1.4864				
Mean volume	13.062				

Source	DF	Type I SS	Mean Square	*F* Value	*Pr* > *F*
Variety (V)	2	119.42607	59.71304	27.03	0.0001
Size (S)	2	9.60452	4.80226	2.17	0.1159
V × S	4	21.80281	5.45070	2.47	0.0455
Density (D)	1	10.67089	10.67089	4.83	0.0289
Sphericity (Sp)	1	32.45554	32.45554	14.69	0.0002
D × V	2	1.59084	0.79542	0.36	0.6980
D × S	2	20.14677	10.07338	4.56	0.0114
Sp × V	2	0.35461	0.17730	0.08	0.9229
Sp × S	2	1.14128	0.57064	0.26	0.7726

RESULTS AND DISCUSSION

General linear model (GLM), analysis of variance (ANOVA), and Duncan's multiple range were used to analyze the experimental data. A value of $P \leq 0.05$ was considered the criterion of significance.

Physical Properties

Kernel size distributions for the three varieties were similar (Fig. 4). Kernels retained on sieves 14, 15, and 16 accounted for ≈70% of the weight for all three varieties.

Kernel sphericities were significantly different among the three varieties in this study (Table I). Variety C had the highest sphericity (0.76) and variety B had the lowest sphericity (0.71). Sphericities of small and medium kernels were not significantly different for the three varieties. Large kernels, however, were significantly different and had the highest sphericity (0.75) when compared with kernels in the other two sizes. In addition, within each of the three varieties, large kernels tended to have higher sphericities than medium and small kernels. The result was consistent with that of Haugh et al (1976), who found that kernels at the butt location of the ear had the greatest value for sphericity. The sphericities of the three varieties of kernels showed little variability.

TABLE IV
Mean Expansion Volumes (MEV) of Popcorn Kernels by Size and Variety[a,b]

	Variety			
Kernel Size	A	B	C	MEV (cm³/g)
Small	12.8 ± 1.6	12.2 ± 1.0	14.4 ± 2.1	13.1a
Medium	13.5 ± 1.5	12.5 ± 1.4	13.7 ± 1.8	13.3a
Large	12.4 ± 1.5	12.4 ±1.4	13.7 ±1.3	12.7a
MEV (cm³/g)	12.9b	12.3c	13.9a	· · ·

[a] Mean expansion volumes ± standard deviations
[b] Values followed by the same letter in the same column or the same row are not significantly different ($P < 0.05$).

TABLE V
Mean Expansion Volume (cm³/g) by Variety and Sphericity[a]

	Variety			
Sphericity Group	All	A	B	C
High	13.4a	13.1a	12.6a	14.5a
Low	12.7b	12.7a	12.0a	13.3b
Without grouping	· · ·	12.9	12.3	13.9
Mean sphericities of varieties		0.73	0.71	0.76

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

TABLE VI
Mean Expansion Volumes (cm³/g) by Variety and Density[a]

	Variety			
Density Group	All	A	B	C
High	13.3a	13.5a	12.5a	14.0a
Low	12.7b	12.4b	12.0a	13.9a
Without grouping	· · ·	12.9	12.3	13.9
Mean densities of varieties		1.370	1.366	1.376

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

Mean density for variety C was the highest (1.376 g/cm³). The mean densities of the other two varieties were not significantly different from each other (Table II). The results are consistent with findings of Pordesimo et al (1990), who found that four of five varieties of popcorn they investigated showed no differences by density. Over all three varieties, the mean densities of three kernel sizes were not significantly different, which indicated that small kernels have the same density as large kernels. However, within each of the three varieties, the relationships between mean density and kernel size were different. In variety A, small kernel size had the highest mean density and medium kernel size had the lowest. In variety B, large kernels showed the highest mean density and small kernels showed the lowest. In variety C, kernels of medium and large size had the highest and lowest mean densities, respectively. Obviously, density distribution according to kernel size differed by popcorn variety.

Expansion Volume

ANOVA was used to test effects of variety, size, density, and sphericity and the possible interactions on the expansion volume at $P < 0.05$ (Table III). Variety ($P < 0.0001$), density ($P < 0.0289$), and sphericity ($P < 0.0002$) showed significant effect on expansion volume but kernel size ($P < 0.1159$) did not. The interaction of density and size was significant ($P < 0.0114$, $R^2 = \approx 0.28$), suggesting that variety, size, density, and sphericity were not able to predict expansion volume.

Mean expansion volumes of popcorn kernels were significantly different among the three varieties (Table IV). Variety C had the highest mean expansion volume (13.9 cm^3/g) and variety B had the lowest (12.3 cm^3/g).

Although there were no statistically significant differences by kernel size, medium kernels had the highest expansion volumes and large kernels had the lowest expansion volumes. For three varieties investigated, variety C had the highest mean expansion volume in small kernels and both varieties A and B had the highest mean expansion volume in medium kernels. Therefore, kernel size may affect expansion volume differently for different varieties of popcorn. This finding supports the work of previous investigators, who found inconsistent results on expansion volume by kernel size.

Sphericity was correlated positively with expansion volume (Table V) with all three varieties. Variety C, with the highest mean sphericity (0.76), had the highest mean expansion volume (13.9 cm^3/g) and variety B, with the lowest mean sphericity (0.71), had the lowest mean expansion volume (12.3 cm^3/g).

To further investigate how sphericity affects expansion volume, with or without effects of variety, kernels were sorted according to sphericity and the top 10 kernels and the bottom 10 kernels in each size of each variety were grouped as “sphericity high” and “sphericity low” to maximize variability. Expansion volumes were significantly different at $P < 0.05$ by sphericity for all three varieties of popcorn kernels (Table V). The sphericity high group had a mean expansion volume of 13.4 cm^3/g and the sphericity low group had a volume of 12.7 cm^3/g. Within each of the three varieties, results of sphericity and expansion volume correlations showed that expansion volume was significantly different for the two sphericity groups (high and low) in variety C but not different in varieties A and B. Kernels with higher sphericities had higher expansion volumes. Sphericity data were consistent with results from previous published studies (Lyerly 1942; Pordesimo et al 1990). A possible explanation for the relationships between expansion volume and sphericity might be that popcorn kernels with a greater spherical shape would resist more internal pressures. The greater the pressures built inside popcorn kernels at popping, the greater the expansion of starch granules, which could result in higher expansion volumes of popcorn kernels.

To investigate how density affects expansion volume, with or without the effects of variety, kernels were sorted according to densities. The top 10 kernels and the bottom 10 kernels in each size of each variety were grouped as “density high” and “density low”, again to maximize variability. Statistical analysis showed that density had significant effects on expansion volume at $P < 0.05$ when grouped data from the three varieties were analyzed (Table VI). The density high group had a mean expansion volume of 13.3 cm^3/g and the density low group had a mean expansion of 12.7 cm^3/g. Kernels with higher densities had higher expansion volumes. Mean density and mean expansion volume are shown in Table VI. Popcorn is flint corn and, by nature, has high percentages of hard endosperm. Popcorn kernels with higher kernel density may have more hard endosperm inside the kernels. Therefore, when heated, more pressure would be built up inside kernels and greater explosions could occur, thus producing greater expansion volume. However, within the three varieties investigated, only variety A showed kernel density had significant effects on expansion volume (Table VI). Although not statistically significant for the other two varieties, expansion volume increased with increasing kernel density.

Density data in this study showed that varieties had little variability in density and the relationships between density and expansion volume were not strong, although kernels with higher densities tended to have higher expansion volumes for all three varieties. The results were in agreement with previous reports. Lyerly (1942) found that the correlation coefficient between density and expansion volume was 0.26. Haugh et al (1976) observed no differences in density for 12 hybrids investigated; hybrids with higher density tended to have higher expansion volume.

Even though density variance within variety had a limited range, kernels with higher densities tended to have higher expansion volumes. This information could be useful to popcorn producers. If popcorn kernels can be separated by density, it would be beneficial to popcorn processors in practical production. However, after one variety of popcorn was tested by a gravity table in the study, the results showed that it was difficult to separate kernels by densities because there was little variability in density within a variety.

Moisture content was assumed to be a constant instead of a variable in this study. The best practices were observed to hold moisture constant throughout the testing. Popcorn kernels from different varieties and different sizes require different optimum moisture content to produce maximum expansion volume; therefore, conclusions drawn from these data might vary if the moisture content of kernels changed. In addition, the moisture content of individual kernels could be difficult to quantify on a per kernel basis.

CONCLUSIONS

There were no strong linear relationships ($R^2 = 0.28$) among expansion volume and factors (variety, kernel size, density, and sphericity) investigated in this study. Among the four factors tested, variety, kernel sphericity, and kernel density had effects on expansion volume. Kernel size showed no effects on expansion volume but the interaction of density and size showed an effect on expansion volume. The variety with a higher mean density and a higher mean sphericity showed a tendency to produce higher mean expansion volumes. However, within the three varieties, only one showed a statistically significant difference by density. Another variety showed differences by sphericity. Although expansion volume may or may not be different by density and sphericity within varieties, all three varieties in the study indicated that expansion volume increased as a kernel density or sphericity increased.

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