

Effect of Kernel Size, Location, and Type of Damage on Popping Characteristics of Popcorn

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ABSTRACT

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Popping characteristics, specifically expansion volume and popping time, were studied for damaged popcorn. A single variety of commercial undamaged yellow popcorn was separated into four size fractions ($D < 4.36$, $4.36 < D < 5.16$, $5.16 < D < 5.95$, and $D > 5.95$ mm) by screening with round-hole sieves. Kernels were damaged using a razor knife by either slicing a 2-mm diameter piece of the endosperm or the germ or by cutting through the pericarp and seed coat into the endosperm or the germ ≈ 2 mm. A total of five combinations of location and damage were studied (tip cap removed, side cut, side sliced, germ cut, and germ sliced) for each kernel size. A control sample with no damage was also analyzed

for each size fraction. All of the damaged kernels (regardless of type of damage) popped, but they had expansion volumes 9.1–47.5% smaller than those of undamaged kernels. The expansion volume of damaged kernels increased by 52.5–85.7%, depending on the damage, when the size of the kernel increased from <4.36 mm to >5.95 mm. Removing the tip cap and slicing through the germ caused less loss of expansion volume than did other types of damage. Damaged popcorn kernels had faster popping times (12.2–24.0 sec) than did undamaged kernels (30.9–34.6 sec). Popping times increased with increasing kernel size for all types of damage.

Popcorn quality is measured primarily by expansion volume and the number of unpopped kernels (Song et al 1991). Factors known to affect popcorn expansion volume include kernel size (Willier and Brunson 1927, Haugh et al 1976, Lin and Anantheswaran 1988), kernel shape (Lyerly 1942, Haugh et al 1976, Pordesimo et al 1990), endosperm type (Lyerly 1942, Hosenev et al 1983), test weight (Eldredge and Thomas 1959, Haugh et al 1976), moisture content (Lin and Anantheswaran 1988, Song and Eckhoff 1994), pericarp thickness (Mohamed et al 1993), and structural damage (Walton 1968). Expansion volume is related to popped corn texture, mouthfeel, and appearance characteristics. Unpopped kernels (UPKs) are undesirable because of their failure to contribute to expansion volume and are perceived as defective. UPKs are classified as the kernels that do not pop or pop very little and can pass through a 7.14 mm (18/64 in.) square hole screen (Song et al 1991).

Structural damage to the kernel occurs as a result of mechanical harvesting and shelling (Chowdhury and Buchele 1976, Paulsen and Nave 1980) and during handling and marketing of corn (Chowdhury and Buchele 1976), where the kernels are subjected to slicing or shearing forces greater than the pericarp can resist. Pericarp damage has been shown to drastically reduce expansion volume (Hosenev et al 1983). The prevailing theory on UPKs is that they result from excess mechanical damage or from inadequate heating during popping. The theory on UPKs due to a particular type of mechanical damage has not been verified because most studies pop kernels in batches ranging from ≈ 100 to 1,000 kernels. In batches, it is not possible to observe individual kernels and ensure uniform treatment either in the extent of mechanical damage or in the uniformity of heating.

The effect of location and type of physical kernel damage on UPKs or expansion volume has not been reported. Unpublished research, where ears of popcorn were excessively damaged by grinding off the crowns of the kernels using a stone grinder, showed that most of the kernels still exhibited some degree of expansion and did not classify as UPKs. If the physical damage controlled the number of UPKs, nearly all of the kernels should

have been UPKs. Song et al (1991) showed that smaller kernels were more likely to be unpopped than were larger kernels. Larger kernels would seem more likely to be mechanically damaged than smaller kernels during harvesting and shelling. Apparently damage is not the only factor affecting the number of UPKs. Type or location of damage also influences that number.

The objectives of this study were to: 1) investigate the effect of different types of physical kernel damage on individual kernel popping characteristics, and 2) determine the effect of damage on the popping time of kernels.

MATERIALS AND METHODS

Sample Preparation

A single commercial popcorn hybrid acquired from the Orville Redenbacher Popcorn Co., Brookston, IN, was screened over three round-hole sieves (4.36, 5.16, and 5.95 mm diameter) using a Carter-Day Dockage Tester. Corn kernels of diameter <4.36 mm represented 7.8% of the total sample; corn kernels of diameter >4.36 mm but <5.16 mm represented 14.6% of the total sample; corn kernels of diameter >5.16 mm but <5.95 mm represented 39.7% of the total sample; and corn kernels of diameter >5.95 mm represented 37.7% of the total sample. The screened samples were held in nylon mesh bags in an incubator for one week at 20°C and 75% rh. Whole kernel moisture content analysis was performed in triplicate 15-g subsamples using the 103°C forced-air oven method (ASAE 1989).

Two full-factorial experiments were performed with 10 replicates to determine the effects of kernel size and kernel damage on popping characteristics. In the first experiment four kernel sizes ($D < 4.36$ mm, $4.36 < D < 5.16$ mm, $5.16 < D < 5.95$ mm, and $D > 5.95$ mm) and five types of kernel damage (removal of the tip cap, 2-mm deep cut through the germ, 2-mm diameter slice across the germ, 2-mm deep cut through the pericarp on the side opposite the germ, and 2-mm diameter slice on the side opposite the germ) plus a control sample with no visible damage were used to determine effects on expansion volume. In the second experiment, the same treatment conditions were used to determine the effects on popping time.

Damage was inflicted on kernels previously undamaged with the sharp blade of a utility knife. The types of damage (slice and cuts) were selected to simulate damage incurred during harvesting, handling, and marketing of corn. The slice simulates abrasion, where the pericarp is damaged, but the seed coat and aleurone layer are

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kept intact. This type of damage (slice) represents kernels with hairline cracks and spots of pericarp missing (Chowdhury and Buchele 1976) or with scratched pericarp (Lien and Haugh 1975). The cut simulates mechanical damage that results in damage to the pericarp, seed coat, and the endosperm. A cut would represent kernels with open cracks, chips, and severe pericarp damage (Chowdhury and Buchele 1976) or pericarp separation (Lien and Haugh 1975). While selection of kernels for actual mechanical damage would have been possible, artificial creation of damage decreased unaccounted variability.

In a preliminary study, no significant differences were found between samples with damage on the side and crown locations of the popcorn kernel. Therefore, in this study only damage to the side of the popcorn kernel was studied. Kernels deemed undamaged had been visually inspected for any deformities (e.g., breaks in the pericarp or missing tip caps).

Popping Method

Due to the difficulty of monitoring popping behavior of individual kernels in a regular oil popper, a single kernel popper was developed for this study (Fig. 1). The popper consisted of an aluminum plate electric skillet (model 0681815, National Presto Industries, Eau Claire, WI) divided into 50 rectangular compartments. The evenness of heating for household electric skillets varies from model to model, but the thermostat accuracy of most of the electric skillets is quite accurate (Anonymous 1990). The model used for this study was rated good for heating evenness and its thermostat accuracy was also within a few degrees of the set temperature (Anonymous 1990). A screen cover was used that had holes large enough through which kernels could be dropped into the popper but small enough to prevent popped kernels from jumping out.

Preliminary experiments were done to determine the uniformity of the skillet's surface temperature. A 0.63-cm (0.25 in.) layer of oil was required to provide even heating across the surface. Temperature was measured in each compartment using a mercury thermometer, and it was found that the outer 26 compartments around the edge of skillet did not achieve uniform heating. The temperature of the electric skillet was set at 204°C (400°F) and at this setting the temperature of the oil in the center 24 compartments was 213 ± 1°C. This temperature (213 ± 1°C) was before sample addition to the skillet and did not necessarily hold throughout the popping operation. There would be a few degrees drop in the temperature of the oil after addition of the sample.

Twenty-four kernels were popped at a time, one in each compartment of the popper. Kernels were dropped into the popper one at a time after the oil had heated up to its set temperature. The location of the kernels in the popper was randomized to prevent biasing of results due to placement on the heating surface.

Grading and Volume Measurement

The popped kernels were carefully removed from the popper with forceps so that the flakes were not broken. Each of the popped kernels was graded into one of five categories: 0) unpopped or

split open with no expansion, 1) white matrix being pushed out, 2) for partially popped or irregular, 3) fully popped or mushroom-shaped, and 4) fully popped or butterfly-shaped. The average grade value was denoted as the popping index (PI). For each condition the volume of the 10 kernels was measured using the displacement method. These measurements were taken three times and the values were averaged. Volume measurement was performed using rapeseed (≈2 mm diameter) in a 100-mL glass cylinder. The rapeseed was small enough to fill major kernel voids but was not adsorbed or absorbed by the flake.

Popping Time Measurement

Popping time was measured from the moment the kernel was dropped into the skillet until the kernel popped. This measurement was taken with a digital stopwatch.

Statistical Analysis

Analysis of variance (ANOVA) and Duncan's Multiple Range test were used (SAS Institute, Cary, NC) to analyze the data. The level of statistical significance was selected to be 5% ($P < 0.05$).

RESULTS AND DISCUSSION

Effect of Kernel Size, Location, and Type of Physical Damage on Expansion Volume

The effects of kernel size and location of kernel damage on expansion volume were statistically significant ($P = 0.001$) and the interaction between the two main effects was also significant ($P = 0.0025$). However, the interaction term accounted for only a small percentage (5.72%) of the total variation. The effect due to damage location was more pronounced than the effect due to kernel size.

Increasing the size of undamaged kernels from <4.36 mm to 5.95 mm increased the expansion volume by 11.4 mL (Table I). An increase in expansion volume with kernel size also occurred for three of the five types of damage to the kernels. The expansion volume of damaged kernels increased by 52.5–85.7%, depending on the type of damage, when the size increased from <4.36 mm to >5.95 mm. Also, when the expansion volume was averaged across the type of damage to the kernels, kernels >5.95 mm in size and between 5.16 and 5.95 mm had statistically higher expansion volumes than did kernels <4.36 mm in size and those between 4.36 and 5.16 mm (Table I).

All of the damaged kernels (regardless of type of damage) popped but had 9.1–47.5% smaller expansion volumes than undamaged kernels. A smaller expansion volume results from a decrease in the ability of the pericarp to withstand the initial water vapor pressure created by heating (Hoseney et al 1983). Pericarp damage also decreases expansion volume due to the increased rate of water vapor loss during heating. Visual monitoring of the individual popping kernels yielded several observations. Water vapor bubbles could be seen exiting the kernel from the tip cap region in undamaged and tip cap damaged kernels and from the tip cap and area of damage for the damaged kernels. The amount of vapor escaping caused some kernels to be propelled in circles or to randomly oscillate in the cell until the kernel popped.

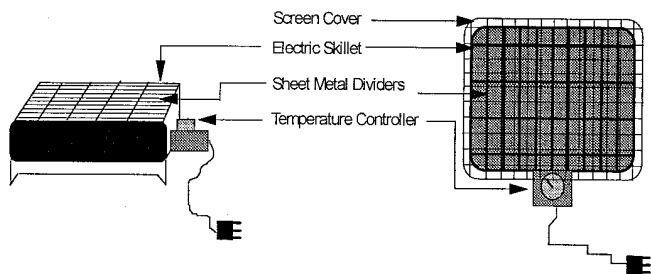


Fig. 1. Side (left) and top (right) view of an electric skillet used for popping corn. Side view does not show screen cover.

TABLE I
Analysis of Variance for Expansion Volumes of Four Popcorn Kernel Sizes and Six Types of Damage to Popcorn Kernels

Source	df	Sum of Squares	Mean Squares	F Value ^a
Size	3	845.277	281.759	93.14***
Damage	5	1,414.606	282.921	93.53***
Size × damage	15	132.406	8.827	2.92***
Error	48	145.198	3.025	...

^a *** = Significant at $P < 0.05$.

Once the damaged kernels began to pop, they did not explode immediately but fluid endosperm material was observed exiting out of the damaged site. As it exited, this fluid endosperm material expanded as if forced out of an extruder. The amount of material being forced out of the damaged site continued to increase until the whole kernel exploded. The whole process took <1.5 sec but was evident in many of the damaged kernels. The undamaged kernels tended to pop more explosively with little evidence of the extruded material.

The effect of mechanical damage on popcorn seems to be two-fold. First, the damaged site acts as a major pathway for the escape of water vapor from the endosperm during the heating of the kernels. This decreases the water vapor available to fuel the expansion. Low moisture contents are known to decrease expansion volumes (Song and Eckhoff 1994). Second, the damage weakens the mechanical strength of the pericarp. This allows the kernel to pop earlier because of the buildup of vapor pressure.

Table II shows that removing the tip cap and making a 2-mm diameter slice through the germ had less effect on reducing the expansion volume than did the other types of damage. Both types of damage (removal of the tip cap and a 2-mm diameter slice through the germ) gave statistically similar expansion volumes. Although the kernels with the tip cap removed gave lower expansion volumes than did undamaged kernels, they had similar popping index values (Table III). Popping index values for kernels

with the tip cap removed and a slice over germ were also statistically similar (Table III). Removal of the tip cap had less effect on reducing the expansion volume than did other types of damage because removal of the tip cap does not change the pathway's resistance to flow, particularly if the hilar layer remains intact. No effort was made in this study to determine whether the hilar layer was damaged with tip cap removal. A slice over the germ had only a small effect on the expansion volume, presumably because the pericarp is thinnest over the germ already (Wolf et al 1952) and because the germ does not participate in the expansion.

Kernels that were cut (side and germ) had significantly lower expansion volumes than did kernels for which the damage was a slice (Table II). Cuts made to the kernels were deeper than slices and resulted in faster moisture loss during heating and, consequently, lower expansion volumes. Although the slice removed more surface area, it was not as deep as the cut.

Effect of Kernel Size, Location, and Type of Physical Damage on Popping Times

Both of the main effects (kernel size and location of physical damage) had statistically significant ($P = 0.001$) effects on popping time (Table IV). The interaction between the two main effects was not significant.

Undamaged kernels had the longest popping time (30.9–34.6 sec) for all popcorn kernel sizes, but there was no trend observed

TABLE II
Average Expansion Volumes^a (mL) of Four Popcorn Kernel Sizes and Six Types of Damage to Popcorn Kernels

Type of Damage	D < 4.36	4.36 < D < 5.16	5.16 < D < 5.95	D > 5.95	Average Volume ^b
Undamaged	17.0 ± 0.4	21.4 ± 2.5	26.9 ± 0.8	28.4 ± 1.4	23.4a
Tip removed	13.3 ± 1.6	19.4 ± 0.6	26.3 ± 1.9	24.6 ± 0.4	20.9b
Side cut	9.4 ± 0.9	10.2 ± 0.3	14.5 ± 1.8	15.0 ± 1.3	12.3d
Side sliced	11.1 ± 1.3	14.2 ± 2.5	15.1 ± 2.4	17.6 ± 1.8	14.5c
Germ cut	10.3 ± 0.9	10.7 ± 1.6	15.2 ± 0.6	15.7 ± 0.4	13.0d
Germ sliced	15.9 ± 1.7	18.7 ± 0.3	26.0 ± 0.7	24.5 ± 1.7	21.3b
Average volume	12.8a ^c	15.8b	20.7c	21.0d	

^a All values are mean ± standard deviation of three observations.

^b Average expansion volume values for types of damage followed by the same letter are not significantly different ($P < 0.05$).

^c Average expansion volume values for kernel sizes followed by the same letter are not significantly different ($P < 0.05$).

TABLE III
Popping Indices^a (PI) of Four Popcorn Kernel Sizes and Six Types of Damage to Popcorn Kernels

Type of Damage	D < 4.36	4.36 < D < 5.16	5.16 < D < 5.95	D > 5.95	Average PI ^b
Undamaged	3.4 ± 0.84	3.8 ± 0.42	3.1 ± 0.87	3.3 ± 0.48	3.4a
Tip cap removed	2.7 ± 0.95	3.4 ± 0.84	3.5 ± 0.71	3.4 ± 0.97	3.2ab
Side cut	1.6 ± 1.07	1.2 ± 0.92	1.1 ± 1.10	1.3 ± 0.67	1.3d
Side sliced	1.9 ± 1.10	2.2 ± 0.79	1.3 ± 1.06	1.9 ± 1.19	1.8c
Germ cut	2.4 ± 0.70	1.2 ± 0.79	1.5 ± 0.85	1.8 ± 1.23	1.7c
Germ sliced	2.9 ± 0.57	2.8 ± 0.63	3.1 ± 0.87	2.8 ± 0.63	2.9b
Average PI	2.5a ^c	2.4a	2.3a	2.4a	

^a All values are the mean ± standard deviation of 10 observations. One person graded 10 independently popped samples for each condition.

^b Average PI values for types of damage followed by the same letter are not significantly different ($P < 0.05$).

^c Average PI values for kernel sizes followed by the same letter are not significantly different ($P < 0.05$).

TABLE IV
Average Popping Times^a (sec) of Four Popcorn Kernel Sizes and Six Types of Damage to Popcorn Kernels

Type of Damage	D < 4.36	4.36 < D < 5.16	5.16 < D < 5.95	D > 5.95	Average Time ^b
Undamaged	32.2 ± 14.1	31.9 ± 6.1	30.9 ± 11.8	34.6 ± 12.2	32.4a
Tip removed	19.2 ± 7.4	29.8 ± 12.2	33.8 ± 9.2	33.7 ± 11.8	29.1b
Germ cut	15.4 ± 2.4	15.5 ± 3.6	20.2 ± 4.8	24.0 ± 6.6	18.7c
Germ sliced	13.1 ± 4.7	17.2 ± 5.9	21.1 ± 1.8	19.8 ± 6.6	17.8c
Side cut	12.2 ± 3.9	16.1 ± 5.1	17.7 ± 1.8	19.2 ± 6.2	16.3c
Side sliced	14.2 ± 4.5	18.4 ± 5.5	22.7 ± 9.7	21.6 ± 8.8	19.2c
Average popping time	17.7c ^c	21.5b	24.4a	25.5a	

^a All values are the mean ± standard deviation of 10 observations.

^b Average popping time for types of damage followed by the same letter are not significantly different ($P < 0.05$).

^c Average popping time for kernel sizes followed by the same letter are not significantly different ($P < 0.05$).

according to size. All types of damage, except for kernels with the tip cap removed, had statistically similar popping times ranging from a low of 12.2 sec to a high of 24.0 sec. Kernels with the tip cap removed had significantly higher popping times when compared to other types of damaged kernels, but significantly lower popping times when compared to undamaged kernels. These findings again show that kernels with the tip cap removed behave very much like undamaged kernels and have a very small negative effect on popping characteristics.

Kernel popping time increased with increasing kernel size. This trend was not evident with undamaged kernels. Average (across structural damage) popping time increased from 17.8 to 25.5 sec as kernel size increased. These results show that: 1) damaged kernels will take less time to pop compared to undamaged kernels and 2) popping times will increase with an increase in kernel size for damaged kernels.

CONCLUSIONS

This study indicates that mechanical damage causes considerable reduction (9.1–47.5%) in expansion volume of popcorn kernels. Moreover, it is not just any physical damage, but the type and location of damage that significantly effects the expansion volume. Removal of the tip cap and a slice through the germ had the least effect on the expansion volume compared to other types of damage. In fact, kernels with the tip cap removed behaved almost like undamaged kernels. The study also shows that mechanical damage significantly ($P = 0.001$) reduces the popping time of popcorn kernels. Results of this study also provide understanding of how the mechanical damage reduces the expansion volume. Based on our observations in this study, there are two reasons why mechanical damage affects expansion volume: 1) the damaged site creates a major pathway for the escape of water vapor from the endosperm and 2) damage reduces the mechanical strength of the pericarp.

Information from this study cannot be directly applied but gives a good idea to popcorn processors of the importance of quality control in relation to damaged popcorn. This study also helps in verifying that UPKs result from only certain types of mechanical damage and not just any kind of physical damage.

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