# Influence of Physical Grain Characteristics on Optimal Rotor Speed During Impact Dehulling of Oats

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## ABSTRACT

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Central to commercial oat (*Avena sativa* L.) processing is impact dehulling. During impact dehulling, oats are fed into a spinning rotor that expels the grains against an impact ring. The impact frees the groat from the hulls. To optimize dehulling protocols, we examined the effects of physical grain characteristics and rotor speed on oat dehulling using an impact dehuller. We separated grain of three cultivars (Gem, CDC Dancer, Ronald) according to size by sieve fractionation (separation by width), disk fractionation (separation by length), and by gravity table (separation by density). Grains were characterized by mass, digital image analysis, and bulk density. Samples (50 g) were adjusted to 9% moisture and dehulled at four different rotor speeds. Groat percentage, dehulling efficiency, and groat breakage were measured after dehulling. In general, oats with higher bulk density dehulled more efficiently at slower rotor speeds, regardless of grain mass. Groat breakage increased with rotor speed and with grain mass. Adjusting dehulling conditions according to grain size improved groat yields over optimal dehulling conditions for unfractionated grains for some cultivars. More refined fractionation of grain according to bulk density may provide further improvement of groat yield during impact dehulling.

The processing of oats for human food generally requires the dehulling of the grain (Deane and Commers 1986; Ganssmann and Vorwerck 1995). In modern oat processing, the impact dehuller is usually used for this process. The impact oat dehuller (Cleve 1948; Stuke 1955; Deane and Commers 1986; Ganssmann and Vorwerck 1995) consists of a spinning rotor, which expels oats on to an impact ring. The force of the impact breaks the hulls away from the groat and the free hulls are then removed by aspiration. The speed of the rotor can be adjusted so that the force of the impact can be adjusted according to the needs of the oat batch.

Commercial oat mills generally fractionate oat grains according to size before dehulling (Deane and Commers 1986; Ganssmann and Vorwerck 1995). Ganssmann and Vorwerck (1995) report how oat grains separated according to width would dehull most efficiently at different rotor speeds. Their results indicated that wider, more massive grains dehulled to 85% efficiency at slower rotor speeds than did smaller, less massive grains. One might conclude that larger oat grains dehulled more efficiently at slower rotor speeds because more massive grains may contain more inertial energy upon collision with the impact wall than a less massive grain at the same rotor speed. It is important to maximize dehulling efficiency in an oat dehulling operation so that the proportion of hulled oats remaining is minimized. However, excessive impact energy is also undesirable because of groat breakage that can also occur that subtracts from groat yields (Doehlert et al 1999; Doehlert and McMullen 2001). Thus, the impact rotor speed must be adjusted to strike a balance between dehulling efficiency and groat breakage. Oats that retain their hull after the pass through the dehuller must be separated from the groats and recycled back for a second pass through the dehuller. Broken groats are separated away from whole groats and used for flour production (Deane and Comers 1986).

Even though the size fractionation of oat grains before dehulling is common practice by commercial oat mills, very few scientific studies of this practice have appeared in the public literature (Ganssmann and Vorwerck 1995). Public knowledge of relationships between dehulling efficiency and grain size may be useful to oat breeders in their efforts to generate higher quality oats for the high-value human food market. This study sought to fill this gap in the oat science literature.

Oat grain size is complex, and size distributions can best be described with bimodal models (Doehlert et al 2004a, 2005). Size can be described by mass, linear dimensions, or by density. Oats can be easily separated by width using slotted sieves. Properties of oat grain size fractions separated by width have been described recently (Doehlert et al 2004a). Grains can be separated by length with a disk separator that consists of a disk with pockets of a specified dimension. Grains short enough to fit into the pockets are carried out of the sample, whereas the longer grains fall out of the pockets (Deane and Comers 1986). By applying progressively larger sized pocket disks, oat fractions of distinct length size intervals can be generated. Oats can also be separated according to grain density and aerodynamic properties by fractionation on a gravity table. In gravity fractionation, grains are fed onto a vibrating inclined table. As grain moves across the incline, the more dense grains separate from less dense grains (Deane and Comers 1986) and can be collected in different streams. Density differences of grains are reflected by differences in bulk density of samples collected. In this study, we will refer to bulk density as the mass of oat grain that fits into a particular size container (expressed here as kg/m$^3$) and to grain density as the density of individual grains (as defined by the mass of the grain divided by the envelope volume of the individual grain). The difference between these characteristics is defined by the packing efficiency of grains in the container.

In this study, we tested the hypothesis that oat grain physical characteristics including grain mass, grain linear dimensions, and bulk density may affect dehulling efficiency. We report the fractionation of oats from three cultivars according to width, length, and density. We dehulled samples of these oats (adjusted to constant moisture) with an impact dehuller at four rotor speeds to determine the effects of grain size and rotor speed on dehulling efficiency and groat breakage. We have also made detailed analyses of oat grain physical characteristics in the size fractions to relate these to dehulling characteristics. We used information from these experiments to suggest physical characteristics of oat grains best suited to impact dehulling.

## MATERIALS AND METHODS

Oats (*Avena sativa* L., cvs. Gem, CDC Dancer, and Ronald) were grown in the field in increase plots in Fargo, ND, during the growing season of 2002. Increase plots were 30 m long four-row

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plots with 30 cm row spacing. The seeding rate was 1.65 × $10^6$ kernels/ha. Other cultural conditions were essentially identical to those reported in Doehlert and McMullen (2006). Grain was harvested in bulk with a small plot combine and cleaned before storage in coarse cloth sacks at 4°C until used. Cultivars used for this study were essentially chosen randomly.

## Sample Preparation

Grain from bulked samples was divided into subsamples for size fractionation with a Boerner divider (Seedburo Equipment, Chicago IL). Initially four subsamples were generated for width, length, and density and for an unfractionated sample. Each of these four subsamples was then further divided into four additional subsamples to allow for three replicates of each size fractionation treatment. Bulk density, mean grain mass, and linear dimensions of grain in these samples was determined before size fractionation.

Grain was fractionated according to width with slotted sieves and a sizer-shaker (Seedburo). Samples (150 g) were sieved sequentially on slotted 2.58, 2.38, and 1.98 mm sieves. All slots were 19.05 mm long. Grains held back by these sieves after 20 shakes were labeled as wide, medium, and thin, respectively. Undersized grains that passed through the 1.98 mm sieve were discarded.

Fractionation of grains by length was done with a hand-cranked disk-tester separator (Carter-Day, Minneapolis, MN) with RR (8.9 × 12.7 × 4.0 mm), B (8.3 × 10.2 × 4.0 mm), and MM (8.3 × 8.7 × 4.8 mm) disks (disk dimensions listed as length × width × depth). Grains lifted by the MM disk were referred to as short, grains lifted by the B disk were referred to as medium, and grains lifted by the RR disk were referred to as long.

Grains were separated by density and aerodynamic properties on a gravity table (Forsberg Equipment, Thief River Falls, MN). Grain was allowed to fill the entire table before sample collection was initiated. Table incline and vibrational intensity were set empirically to allow for the generation of three nearly proportionally equal fractions.

All size fractionation procedures were repeated three times to generate replicates of treatments. After size fractionation, bulk density, mean grain mass, and grain linear dimensions were determined for each size fraction.

Bulk density (test weight) was determined with a test weight filling hopper (Seedburo). Mean grain mass was determined by counting grains in a 10-g sample. Grain linear dimensions were determined by digital image analysis as described in detail in Doehlert et al (2004a), except that images were gathered with a digital camera, and 5.2 megapixel images were processed by photo-editing software (Photoshop 7.0, Adobe Systems, San Jose, CA). Image lengths, widths, and areas were determined by the Aphelion computer package (Amerinex Applied Imaging, Amherst, MA).

## Impact Dehulling

Three 50-g samples from each size sample (or from the unfractionated control) were placed in 450-mL glass jars. Grain moisture was determined by measuring the mass loss in a 2-g grain sample after 2 hr at 130°C in a convection oven. Moisture of grain was then adjusted to 9% by adding water to the grain in the jars, sealing for 24 hr, and shaking at intervals.

The North Dakota State University Agricultural and Biosystems Engineering Department manufactured the impact dehuller. It consisted of a 50 cm diameter, 12 vein rotor, and a granite impact ring. Rotor speed was controlled with a variable frequency drive and calibrated with a tachometer. Rotor speeds of 1,502, 1,661, 1,807, and 1,949 rpm corresponded to peripheral speeds of 39.3, 43.5, 47.3, and 51.0 m/sec. Samples (50 g) equilibrated to 9% (db) moisture were poured by hand into the dehuller at a rate of ≈200 g/min. Dehulled samples were collected at the bottom of the dehuller. Free hulls were removed by initially passing the sample through a laboratory aspirator (Kice Metal Products, Wichita, KS), and afterwards passing the sample through a Bates type laboratory aspirator (Seedburo). Hulls were discarded without examination. Immediately after aspiration, the mass of the crude groat preparation was recorded and the samples were stored in paper envelopes until sorting.

Moisture changes in the storage of the grain samples between the time of dehulling and sorting required that the mass of crude groat samples be measured again immediately before sorting. This allowed for the calculation of the moisture correction factor (MCF), which was the original sample mass divided by the current sample mass (Doehlert and McMullen 2001). Samples were then sorted by hand into whole groats, broken groats, and hulled oats remaining. Groat percentage was corrected for the hulled oats remaining after dehulling

$$\%\ \text{Groat} = 100\left[\frac{[(G+B)\times \text{MCF}]}{[\text{WO}-(R\times \text{MCF})]}\right] \tag{1}$$

where WO is the whole oat mass, $R$ is the mass of hulled oats remaining, $G$ is the mass of unbroken groats, and $B$ is the mass of broken groats. Dehulling efficiency (DHE) was the proportion of oats dehulled with a single pass through the dehuller. The DHE and percent broken groats (%$B$) were calculated as in Doehlert and McMullen (2001)

$$\text{DHE} = 100\frac{[\text{WO}-(R\times \text{MCF})]}{\text{WO}} \tag{2}$$

$$\%\ B = 100\left[\frac{B}{(G+B)}\right] \tag{3}$$

Unbroken groat yield (GY) of individual fractions was the unbroken groat mass as a proportion of the whole oats after one pass through the dehuller. The optimized GY was calculated from the summation of unbroken groat yields of size fractions from the rotor speed that provided the highest unbroken groat yield for that size fraction, multiplied by the mass proportion of that size fraction relative to the total sample

$$\text{GY} = 100\left[\frac{G\times \text{MCF}}{\text{WO}}\right] \tag{4}$$

$$\text{Optimized GY} = \sum_{\text{Size Fractions}}(\text{GY}_{\max}\times \text{MP}) \tag{5}$$

Here, MP is the mass proportion of a size fraction relative to the original sample, and $\text{GY}_{\max}$ is the unbroken groat yield at the rotor speed where unbroken groat yield was maximized for that size fraction and replicate. Mill yield (MY) was calculated in an identical way as GY, except broken groats were included

$$\text{MY} = 100\left[\frac{(G+B)\times \text{MCF}}{\text{WO}}\right] \tag{6}$$

Optimized mill yield was then calculated from the summation of mill yields at the optimal rotor speed for that size fraction and replicate, as with optimized GY (equation 5).

All treatments were replicated three times. Means and standard deviations of size fractions were calculated with the Statistix computer package (Analytical Software, Tallahassee, FL). Results of dehulling were subjected to analysis of variation (ANOVA) and mean separation was determined by the least significant difference (LSD).

These results were also calculated with the Statistix computer package where rotor speed and size fraction were both considered fixed variables. Cultivar was not replicated, nor was environmental replication included in the experimental design, thus no cultivar effects can be inferred from this study. Correlation coefficients were calculated for grain characteristics and dehulling properties among the size fractions of each cultivar separately as obtained at the 1,661 rpm rotor speed with the Statistix computer package and then pooled among all cultivars using the procedure described in Steel et al (1997).

## RESULTS

Grain not fractionated for size from three oat cultivars was dehulled in an impact dehuller at four different rotor speeds (rpm) (Table I). Both dehulling efficiency and percentage broken groats increased with increasing rotor speed for all cultivars tested.

Bulk density (BD), mean grain mass (MGM), groat percentage (% groat), and linear dimensions of three size fractions as separated by length, width, and density, and the original samples are shown for Gem, CDC Dancer, and Ronald oats (Tables II–IV). Some trends were apparent. In grain separated by length, the longest grains were the most massive and had the largest linear dimensions but had lower bulk densities and % groat than the short grains. The largest grains separated by width were also most

**TABLE I**
**Dehulling Efficiency and Percent Broken Groats from Samples of Three Oat Cultivars Not Fractionated for Size When Dehulled at Four Different Rotor Speeds[a]**

| | Dehulling Efficiency (%) | | | Broken Groats (%) | | |
|---|---|---|---|---|---|---|
| Rotor Speed (rpm) | Gem | Dancer | Ronald | Gem | Dancer | Ronald |
| 1,502 | 86.5c | 93.2c | 74.9c | 7.9d | 3.80d | 0.73c |
| 1,661 | 92.3b | 94.5b | 81.0b | 12.0c | 6.11c | 1.87c |
| 1,807 | 95.9a | 95.8a | 87.4a | 18.9b | 11.31b | 4.57b |
| 1,949 | 97.2a | 96.6a | 89.7a | 28.2a | 18.29a | 7.20a |

[a] Values with the same letter in the same column do not differ significantly at $P < 0.05$ (means separation, LSD).

**TABLE II**
**Bulk Density (BD), Mean Grain Mass (MGM), Groat Percentage (% Groat), and Linear Measurements (± standard deviations) of Gem Oat Grains and Size Fractions Used in Dehulling Study**

| Separation | Size | BD (kg/m$^3$) | MGM (mg/grain) | Width (mm) | Length (mm) | Area (mm$^2$) | % Groat |
|---|---|---|---|---|---|---|---|
| None | Original | 489 ± 1 | 36.9 ± 2.0 | 2.97 ± 0.35 | 10.8 ± 2.04 | 22.2 ± 3.3 | 75.4 ± 1.8 |
| Length | Long | 476 ± 5 | 47.2 ± 0.5 | 3.18 ± 0.21 | 11.3 ± 0.60 | 26.9 ± 2.7 | 71.6 ± 1.7 |
| Length | Medium | 515 ± 6 | 37.0 ± 0.2 | 3.07 ± 0.29 | 10.5 ± 0.80 | 23.9 ± 4.0 | 73.0 ± 1.5 |
| Length | Short | 541 ± 4 | 26.9 ± 0.8 | 2.94 ± 0.27 | 8.0 ± 1.36 | 15.1 ± 3.3 | 77.8 ± 1.0 |
| Width | Wide | 429 ± 4 | 51.5 ± 3.2 | 3.20 ± 0.34 | 11.6 ± 1.59 | 26.2 ± 5.6 | 68.8 ± 2.4 |
| Width | Medium | 498 ± 5 | 40.3 ± 1.1 | 3.14 ± 0.26 | 11.0 ± 1.36 | 25.3 ± 5.1 | 73.5 ± 1.4 |
| Width | Thin | 508 ± 4 | 31.2 ± 0.8 | 2.91 ± 0.27 | 10.3 ± 1.73 | 21.8 ± 5.4 | 77.8 ± 1.8 |
| Density | Heavy | 537 ± 6 | 29.9 ± 0.5 | 2.77 ± 0.33 | 9.0 ± 1.95 | 18.1 ± 5.7 | 77.7 ± 2.9 |
| Density | Medium | 471 ± 4 | 34.8 ± 0.4 | 3.00 ± 0.34 | 10.8 ± 1.70 | 23.6 ± 5.9 | 74.0 ± 2.2 |
| Density | Light | 457 ± 5 | 33.9 ± 0.4 | 2.95 ± 0.36 | 10.6 ± 1.73 | 22.6 ± 6.0 | 72.4 ± 3.7 |

**TABLE III**
**Bulk Density (BD), Mean Grain Mass (MGM), Groat Percentage (% Groat), and Linear Measurements (± standard deviations) of CDC Dancer Oat Grains and Size Fractions Used in Dehulling Study**

| Separation | Size | BD (kg/m$^3$) | MGM (mg/grain) | Width (mm) | Length (mm) | Area (mm$^2$) | % Groat |
|---|---|---|---|---|---|---|---|
| None | Original | 562 ± 4 | 34.1 ± 0.9 | 2.89 ± 0.27 | 9.9 ± 1.58 | 21.5 ± 4.6 | 79.8 ± 1.3 |
| Length | Long | 559 ± 3 | 40.7 ± 0.6 | 3.12 ± 0.19 | 11.3 ± 0.50 | 26.7 ± 2.1 | 78.5 ± 1.5 |
| Length | Medium | 571 ± 4 | 39.9 ± 1.2 | 2.98 ± 0.26 | 10.1 ± 0.96 | 22.5 ± 4.2 | 81.0 ± 1.1 |
| Length | Short | 624 ± 3 | 24.0 ± 0.9 | 2.66 ± 0.20 | 7.9 ± 0.94 | 15.3 ± 2.4 | 89.5 ± 1.2 |
| Width | Wide | 561 ± 1 | 46.5 ± 0.3 | 3.21 ± 0.14 | 11.3 ± 0.74 | 27.3 ± 2.1 | 78.3 ± 1.0 |
| Width | Medium | 566 ± 1 | 34.9 ± 0.7 | 3.03 ± 0.16 | 10.7 ± 0.98 | 24.4 ± 3.0 | 78.8 ± 1.0 |
| Width | Thin | 560 ± 4 | 26.9 ± 0.2 | 2.74 ± 0.19 | 9.2 ± 1.14 | 18.3 ± 3.9 | 84.2 ± 1.5 |
| Density | Heavy | 592 ± 1 | 31.5 ± 0.2 | 2.76 ± 0.30 | 9.0 ± 1.71 | 18.8 ± 5.4 | 85.7 ± 1.2 |
| Density | Medium | 543 ± 1 | 33.6 ± 1.1 | 2.85 ± 0.27 | 9.9 ± 1.52 | 20.8 ± 5.0 | 80.6 ± 1.0 |
| Density | Light | 503 ± 1 | 32.3 ± 0.3 | 2.80 ± 0.29 | 10.2 ± 1.49 | 21.0 ± 4.9 | 79.0 ± 1.2 |

**TABLE IV**
**Bulk Density (BD), Mean Grain Mass (MGM), Groat Percentage (% Groat), and Linear Measurements (± standard deviations) of Ronald Oat Grains and Size Fractions Used in Dehulling Study**

| Separation | Size | BD (kg/m$^3$) | MGM (mg/grain) | Width (mm) | Length (mm) | Area (mm$^2$) | % Groat |
|---|---|---|---|---|---|---|---|
| None | Original | 521 ± 4 | 32.5 ± 0.6 | 2.75 ± 0.30 | 10.2 ± 1.84 | 20.2 ± 5.4 | 77.3 ± 3.5 |
| Length | Long | 532 ± 3 | 38.9 ± 0.7 | 2.85 ± 0.25 | 11.2 ± 0.75 | 23.9 ± 3.1 | 76.2 ± 1.0 |
| Length | Medium | 552 ± 3 | 32.5 ± 0.2 | 2.72 ± 0.25 | 9.7 ± 0.90 | 19.4 ± 3.7 | 79.3 ± 1.1 |
| Length | Short | 556 ± 5 | 20.6 ± 0.5 | 2.45 ± 0.21 | 7.9 ± 0.70 | 13.7 ± 1.9 | 81.0 ± 2.0 |
| Width | Wide | 517 ± 4 | 46.8 ± 0.5 | 3.10 ± 0.21 | 11.5 ± 1.34 | 26.3 ± 4.3 | 79.2 ± 2.0 |
| Width | Medium | 526 ± 1 | 40.5 ± 0.5 | 2.92 ± 0.17 | 11.0 ± 1.29 | 23.7 ± 3.6 | 78.6 ± 0.8 |
| Width | Thin | 511 ± 1 | 28.6 ± 0.8 | 2.65 ± 0.20 | 10.0 ± 1.74 | 18.8 ± 4.3 | 79.0 ± 3.0 |
| Density | Heavy | 531 ± 4 | 29.5 ± 0.8 | 2.69 ± 0.29 | 9.7 ± 1.83 | 19.0 ± 5.4 | 81.3 ± 0.9 |
| Density | Medium | 501 ± 3 | 30.4 ± 1.1 | 2.78 ± 0.26 | 10.5 ± 1.62 | 21.3 ± 4.8 | 78.6 ± 2.7 |
| Density | Light | 476 ± 3 | 30.4 ± 0.3 | 2.69 ± 0.31 | 10.3 ± 1.74 | 20.1 ± 5.3 | 77.6 ± 3.1 |

massive and had greater linear dimensions that the other size fractions, but bulk density and % groat characteristics of these size fractions differed among cultivars. Wide Gem oats had lower bulk densities and % groat than did the medium and thin width fractions of this cultivar (Table II). CDC Dancer and Ronald width fractions exhibited relatively little variation in bulk density and % groat (Tables III, IV). The heavy size fraction from oats separated by density exhibited higher bulk densities and % groat than did the medium and light density fractions. The heavy density fraction also contained smaller grains by mass and by linear dimensions than the other density fractions.

Dehulling efficiency and percent broken groats of different size fractions are shown for Gem (Fig. 1), CDC Dancer (Fig. 2), and Ronald (Fig. 3). For all size fractions, dehulling efficiency increased with increasing rotor speed. For fractions separated by length, the short fraction dehulled more efficiently at the slower rotor speeds than did the larger size fractions. In contrast, the smallest of the width fractions, the thin fraction, dehulled less efficiently than the other size fractions at the slowest rotor speeds. Dehulling efficiency of density fractions was consistently greatest in the heavy fractions at the slowest rotor speeds and decreased progressively with decreasing sample density.

Groat breakage, like dehulling efficiency, also increased with rotor speed. In general, the heaviest grains by mass were broken more at any given rotor speed than were the lighter size fractions, although this trend was not universal. Frequently there were only small differences among size fractions in groat breakage at the same rotor speed (Figs. 1–3).

Groat yields from different size fractions at increasing rotor speeds showed different patterns among cultivars. For the most

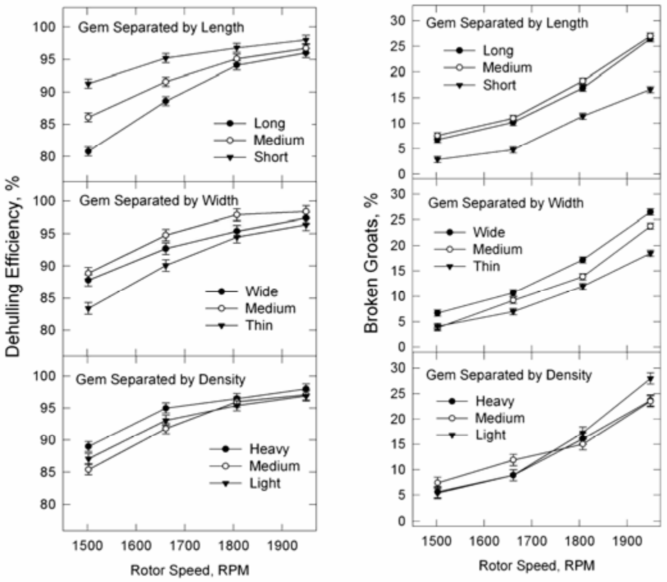

**Fig. 1.** Dehulling efficiency and percent broken groats for Gem oat size fractions separated by length, width, and density when dehulled at four different rotor speeds.

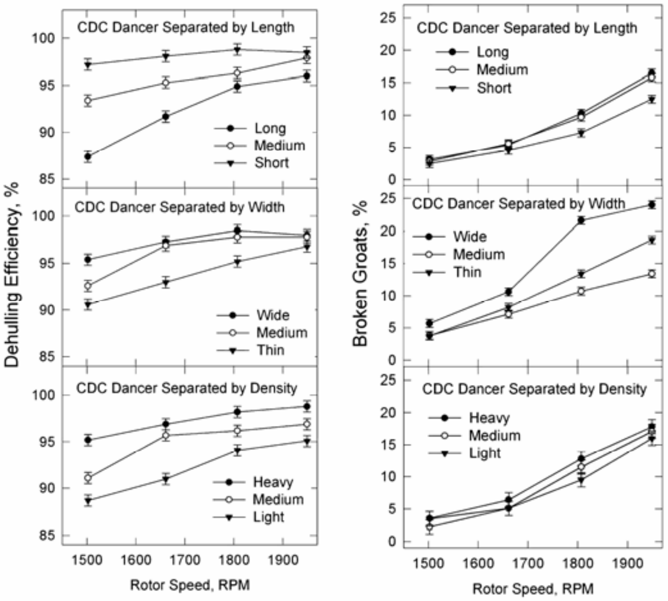

**Fig. 2.** Dehulling efficiency and percent broken groats for CDC Dancer oat size fractions separated by length, width, and density when dehulled at four different rotor speeds.

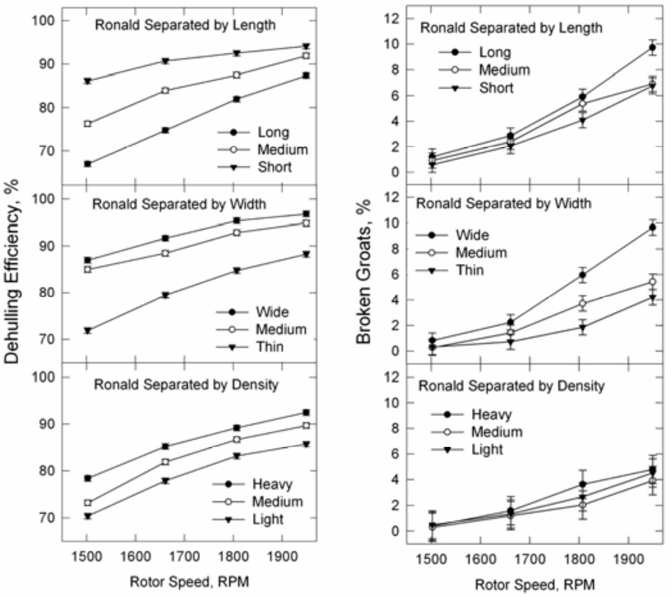

**Fig. 3.** Dehulling efficiency and percent broken groats for Ronald oat size fractions separated by length, width, and density when dehulled at four different rotor speeds.

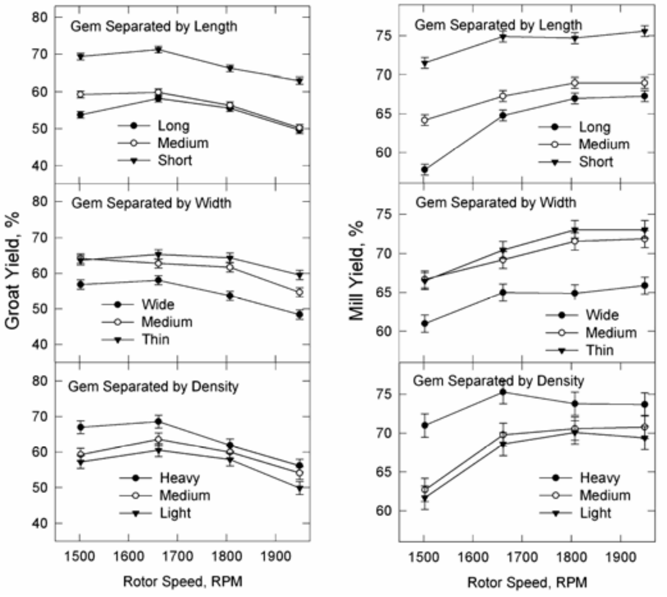

**Fig. 4.** Groat and mill yields from size fractions of Gem oats separated according to length, width, and density when dehulled at four different rotor speeds.

part, groat and mill yields among size fractions appeared to be related to % groat. The optimal rotor speed for groat yield with Gem oats was most frequently the second slowest rotor speed for most size fractions (Fig. 4). The optimal rotor speed for groat yield for CDC Dancer oats was the slowest speed for most size fractions (Fig. 5), whereas the optimal rotor speed for Ronald oats for groat yield was the fastest rotor speed for most size fractions (Fig. 6). Mill yields of most size fractions of all cultivars increased with increasing rotor speed.

Pooled correlation coefficients of dehulling characteristics with size characteristics among size fractions of all three cultivars analyzed here (Table V) indicated that the correlations of % groat with bulk density, dehulling efficiency, groat yield, and mill yield were significant and positive. Correlations of % groat with grain mass, width, length, and area were also significant but negative. Correlations of bulk density with dehulling efficiency and groat yield were significant and positive. Correlations of percentage broken groats was significant and positive with grain mass, length, and area, although the association was strongest with grain area. Correlations of groat yield were strongly significant and positive with % groat and bulk density but negative and significant with grain mass, width, length, and area. Mill yield was negatively and significantly correlated with kernel length.

Calculation of optimized groat and mill yields indicated that size fractionation improved yields over unfractionated grain with CDC Dancer and Ronald but not with Gem. Length and density fractionation provided the best groat and mill yields with CDC Dancer oats. The best groat yields with Ronald oats were obtained from width fractionation, but length and width fractionation both

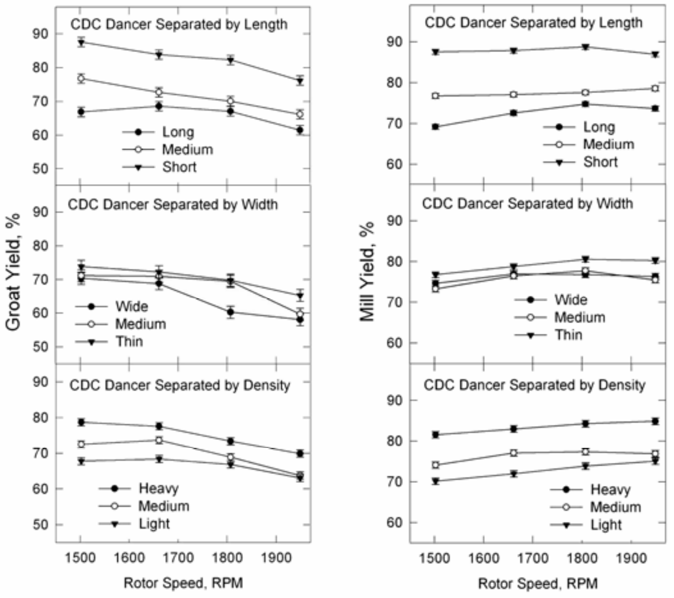

**Fig. 5.** Groat and mill yields from size fractions of CDC Dancer oats separated according to length, width, and density when dehulled at four different rotor speeds.

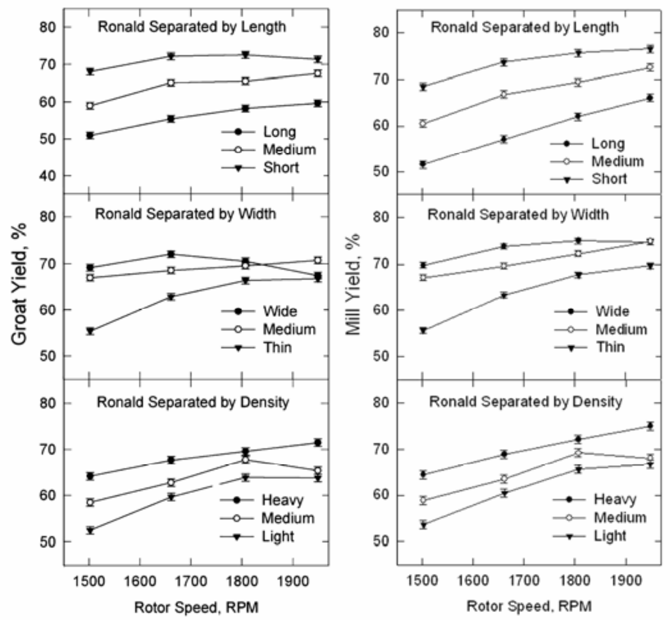

**Fig. 6.** Groat and mill yields from size fractions of Ronald oats separated according to length, width, and density when dehulled at four different rotor speeds.

### TABLE V
### Pooled Correlations of Oat Dehulling Characteristics with Oat Physical Characteristics[a,b]

| | % Groat | DHE[c] | % Broken | Groat Yield | Mill Yield |
|---|---|---|---|---|---|
| % Groat | – | 0.562** | –0.288 | 0.876** | 0.664** |
| Bulk density | 0.660** | 0.568** | 0.040 | 0.701** | 0.377 |
| Grain mass | –0.727** | –0.115 | 0.498* | –0.446** | –0.143 |
| Grain width[d] | –0.739** | –0.063 | 0.394 | –0.464** | –0.204 |
| Grain length[d] | –0.803** | –0.380 | 0.508* | –0.744** | –0.520* |
| Grain area[d] | –0.762** | –0.258 | 0.544** | –0.691** | –0.396 |

[a] Dehulling characteristics taken from a rotor speed of 1,661 rpm (df = 21).

[b] *,** Indicate significance at $P < 0.05$ and $P < 0.01$.

[c] Dehulling efficiency.

[d] Determined by digital image analysis; grain area is the mean grain image area.

### TABLE VI
### Optimized Groat and Mill Yields from Fractionated and Unfractionated Samples of Gem, CDC Dancer, and Ronald Oat Samples[a]

| | Optimized Groat Yield (%) | | | Optimized Mill Yield (%) | | |
|---|---|---|---|---|---|---|
| Separation | Gem | Dancer | Ronald | Gem | Dancer | Ronald |
| None | 62.1 | 71.6b | 61.9c | 73.1 | 76.8b | 69.4b |
| Length | 62.0 | 75.6a | 68.4b | 70.1 | 79.8a | 73.1a |
| Width | 61.6 | 72.1b | 71.9a | 70.1 | 78.7a | 74.6a |
| Density | 64.5 | 74.1a | 67.8b | 72.7 | 78.7a | 70.3b |
| LSD (0.05) | ns | 1.9 | 2.2 | ns | 1.6 | 1.5 |

[a] Values with the same letter in the same column do not differ significantly at $P < 0.05$; ns is not significant; LSD is least significant difference at $P < 0.05$.

provided improved mill yields over the unfractionated sample (Table VI). Size fractionation improved groat yields in CDC Dancer by as much as 4% and improved groat yields in Ronald oats by as much as 6.5%.

## DISCUSSION

The results indicated dehulling characteristics of size fractions of three different cultivars of oats dehulled at different rotor speeds. The experiments were designed to investigate the behavior of the dehulling process with oat grains of differing physical characteristics. Although three cultivars were used in the study, cultivar was not replicated sufficiently to allow statistically valid comparison of cultivar effects. Thus, discussions will be restricted to fractionation methods, physical characteristics and rotor speeds.

Our results are consistent with the results of Ganssmann and Vorwerck (1995), in that we found that larger oat grains separated by width usually dehulled more efficiently at slower rotor speeds. Our results, however, are not consistent with our initial hypothesis, in which we suggested that oat grains with greater mass would dehull more easily at slower rotor speeds. We assumed that if all grains were accelerated to the same velocity by the rotor, those with greater mass would carry greater inertial energy and would therefore dehull more efficiently upon impact. This was clearly not the case. Although the wider grains from width fractionation dehulled more easily and were more massive than thinner fractions (Figs. 1–3), the shorter grains from length fractionation that had the least massive grains dehulled more easily than the more massive longer grains. In length fractions, the longest, most massive grains required the highest rotor speeds to dehull. Indeed, correlation analysis indicated no significant correlation between dehulling efficiency and any grain size parameter (Table V).

Bulk density was the only physical characteristic of oats that was significantly correlated with dehulling efficiency (Table V). With all fractionation mechanisms, it was the fractions with the highest bulk densities that dehulled most efficiently at slower rotor speeds, although it was the larger kernels separated by width and the smaller kernels separated by length that had higher bulk densities. Grain density is presumably an important component of bulk density (Doehlert and McMullen 2006) and may be an important determinant of dehulling efficiency. Dehulling efficiency was also positively correlated with the % groat. Results of Ganssmann and Vorwerck (1995), Doehlert et al (1999), and Browne et al (2002) also indicated positive correlations of dehulling efficiency with % groat, although differences in units used in different studies have led to some confusion in literature reports (Browne et al 2002).

In contrast to dehulling efficiency, groat breakage appeared to be strongly dependent on grain mass. This observation at least is consistent with the concept that increased grain inertial energy can lead to more groat breakage during dehulling (Doehlert et al 1999; Doehlert and McMullen 2001). A relationship between rotor speed, dehulling efficiency, and groat breakage was first shown by Bruckner (1953). Engleson and Fulcher (2002a,b) provided a mechanical analysis of groat breakage during dehulling. Differences among cultivars in grain breakage was addressed by Doehlert and McMullen (2002), who found that grains with higher % groat tended to break more on dehulling. Here we found negative correlations between % groat and grain breakage, but these correlations were not significant and were calculated from size fractions within a cultivar, not among cultivars. Thus this result is not inconsistent with earlier results.

Groat yields indicate the balance between dehulling efficiency and groat breakage. Although increased rotor speed increases dehulling efficiency, which increases milling yield, increased rotor speed also causes increased groat breakage, which decreases the groat yield. Optimal rotor speeds for groat yield are the speeds at which dehulling efficiency is optimized relative to groat losses due to breakage. Our data indicated different trends for different cultivars. CDC Dancer, which exhibited the highest dehulling efficiencies at the slowest rotor speed, also had maximal groat yields at slow rotor speeds. Ronald, which required faster rotor speeds to obtain 85% dehulling efficiency, required faster rotor speeds to maximize groat yields.

Calculation of optimized groat and milling yields indicated that cultivars differed as to the fraction methods that best improved yields. Length fractionation appeared to improve yields in CDC Dancer better than other size fractionations. Width fractionation seemed to improve yields in Ronald better than other methods. Fractionation did not improve yields of Gem at all. Correlation analysis would suggest that fractionation according to bulk density might result in best yields. All fractionation procedures resulted in fractions with distinctively different bulk densities. Stepwise regression analysis (not shown) indicated that bulk density predicted 62% of the variation in groat yield and 52% of the milling yield, and no other physical characteristic (including mean grain mass, grain area, length, and width) added significantly to the prediction model.

A number of relationships among the size characteristics of oat grains can be derived from data presented here (Tables II–IV). These include the significant negative correlations between bulk density and length, area, and mass, and the positive correlations of all linear grain size measurements among themselves and with grain mass. These have been discussed in detail in earlier reports from this laboratory (Doehlert et al 2004a,b) and will not be discussed further here.

Industry appears to already understand the value of bulk density in predicting milling yields. Bulk density (or test weight) is a primary indicator of grade according to USDA grain grading standards (USDA 1978) and milling companies generally require bulk density >530 kg/m$^3$ (Ganssmann and Vorwerck 1995). Although the physical basis for bulk density in oats has not been thoroughly characterized (Doehlert and McMullen 2006), it is presumably related to grain density and is correlated with groat percentage. One possible explanation as to why higher bulk densities are related to improved dehulling efficiency would be related to internal kernel structure. The physical structures related to higher grain density such as lighter hulls or more fragile attachments of hulls with the groat may allow for the dehulling event to occur with lower energy input than with grain with lower densities. Alternatively, the association of bulk density with dehulling efficiency may be related to differences in the acceleration of the grains by the impact dehuller. High density grains may be more efficiently accelerated by the spinning rotor than lower density grains. Thus more dense grains may impact with higher inertial energy than less dense grains. A combination of these factors, or additional factors not considered, may also be responsible for the observed effects. This emphasizes the importance of the production of high bulk density oats for the high value market products for human consumption.

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## LITERATURE CITED

Browne, R. A., White, E. M., and Burke, J. I. 2002. Hullability of oat varieties and its determination using a laboratory dehuller. J. Agric. Sci. 138:185-191.

Bruckner, G. 1953. Der Einfluss der Korneigenschaften auf die Schalung des Hafers. Die Muhle 90:434-436.

Cleve, H. 1948. Das Hamringverfahren bei der Haferschulung. Getreide Mehl Brot 2:32-36.

Deane, D., and Commers E. 1986. Oat cleaning and processing. Pages

371-412 in: Oats: Chemistry and Technology. F. H. Webster, ed. AACC International: St. Paul, MN.

Doehlert, D. C., and McMullen, M. S. 2000. Genotype and environment effects on oat milling characteristics and groat hardness. Cereal Chem. 77:148-154.

Doehlert, D. C., and McMullen, M. S. 2001. Optimizing conditions for experimental oat dehulling. Cereal Chem. 78:675-679.

Doehlert, D. C., McMullen, M. S., and Baumann, R. R. 1999. Factors affecting groat percentage in oat. Crop Sci. 39:1858-1865.

Doehlert, D. C., McMullen, M. S., Jannink, J.-L., Panigrahi, S., Gu, H., and Riveland, N. R. 2004a. Evaluation of oat kernel size uniformity. Crop Sci. 44:1178-1186.

Doehlert, D. C., McMullen, M. S., Jannink, J.-L., Panigrahi, S., Gu, H., and Riveland, N. 2004b. Influence of oat kernel size and size distributions on test weight. Cereal Res. Comm. 32:135-142.

Doehlert, D. C., McMullen, M. S., Jannink, J.-L., Panigrahi, S., Gu, H. and Riveland, N. R. 2005. A bimodal model for oat kernel size distributions. Can. J. Plant Sci. 85:317-326.

Doehlert, D. C., Jannink, J.-L., and McMullen, M. S. 2006. Oat/groat size ratios: A physical basis for test-weight. Cereal Chem. 83:114-118.

Engleson, J. A., and Fulcher, R. G. 2002a. Mechanical behavior of oats: The groat effect. Cereal Chem. 79:787-789.

Engleson, J. A., and Fulcher, R. G. 2002b. Mechanical behavior of oats: Specific groat characteristics and relation to groat damage during impact dehulling. Cereal Chem. 79:790-797.

Ganssmann, W., and Vorwerck. K. 1995. Oat milling, processing and storage. Pages 369-408 in: The Oat Crop: Production and Utilization. R. W. Welch, ed. Chapman and Hall: London.

Steel, R. G. D., Torrie, J. H., and Dickey, D. A. 1997. Principles and Procedures of Statistics: A Biometrical Approach, 3rd Ed. McGraw-Hill: Boston.

Stuke, H. 1955. Eine Schnellmethock zur Bestinimung des Spelzengehaltes beim Hafer. Der Zuchter 25:90-92.

USDA. 1978. The Official United States Standards for Grain, Federal Grain Inspection Service. U.S. Government Printing Office: Washington, DC.

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