Airflow Resistance of Mixtures of Shelled Corn and Fines

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Disciplines
Agriculture | Bioresource and Agricultural Engineering

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ABSTRACT

TESTS were carried out to define the effects on airflow resistance of adding various percentages of various sizes of fines to whole corn kernels. The relationship between clean corn multiplier and percentage fines was defined for seven size grades of fines. Effect of fines on fan power requirements for aeration and drying was estimated.

INTRODUCTION

Present grading standards for corn allow certain percentages of broken corn and foreign material (BCFM) to be present in corn of each grade. BCFM is defined as all material that will pass a 4.8-mm (12/64-in.) round-hole sieve, plus all material other than corn that remains in the sieved sample (USDA, 1970).

The presence of fine material increases the airflow resistance of shelled corn, making the corn more difficult to aerate and dry. The effect on airflow resistance of adding BCFM has been quantified by Haque et al. (1978). Even though corn normally contains fines of other sizes in addition to those classed as BCFM, reports on effects of other sizes on airflow resistance were not found in the literature. This information is needed to order to formulate models to predict what level of cleaning, if any, will produce the most economic benefits for farmers and grain dealers.

REVIEW OF LITERATURE

Airflow resistance prediction is fundamental to the design of any system involving aeration of grain. The most common approach used in estimating pressure drop through grain or seeds is reference to empirical curves relating airflow and pressure drop. Data for many grains and seeds are recorded in American Society of Agricultural Engineers (ASAE) literature.

Shedd (1953) developed curves for common seeds and grains. "Shedd's Curves" are widely used and have been in ASAE Data S272.1 (Resistance to airflow through grains, seeds, and perforated sheets) since 1948 (ASAE, 1982). Included in these curves is one for loose-filled, clean shelled corn at 12.4% moisture.

Shedd (1953) stated that foreign material mixed with the grain tends to increase the resistance to airflow if the foreign material is finer than the grain. Haque et al. (1978) developed an equation for predicting changes in pressure drop through a bed of corn due to presence of BCFM fines (fine material passing through a 4.8-mm (12/64-in.) round hole sieve). Their equation, which is also included in ASAE Data S272.1, is applicable for airflows from 0.076 to 0.20 m$^3$/s m$^2$ (15 to 40 cfm/ft$^2$) and for BCFM fractions from 0 to 20%. Effects of other sizes of fines were not considered.

OBJECTIVES

The objectives of this study were:
1. To quantify the increase in airflow resistance caused by addition of fine material of various sizes and quantities to whole corn kernels.
2. To estimate the potential for energy and cost savings from screening corn.

PROCEDURE

Size Distribution of Fines

To determine the usual size distribution of fines occurring in dried corn, 16,000-g random samples (15.5% moisture), previously dried in different country elevators in Iowa, South Dakota, and Minnesota, were analyzed. (In this paper, "fines" is defined as all material from the corn mass which can pass through a 6.4-mm round-hole sieve.) The samples were divided into 7 fractions by use of a Carter Dockage Tester equipped with round-hole seives of sizes given in Table 1. The average size distribution of fines (size 1 through 7) from these country elevator samples is shown in column 4 of Table 1. The largest size of fines, size 1, (smaller than 6.4 mm but larger than 5.6 mm) contributed 33% of the total weight of fines, and the smallest, size 7, (less than 1.8 mm), was 5% by weight. The range of fines distribution is shown in column 5 of Table 1.

Hurburgh et al. (1981) separated 567 samples of field-shelled, undried Iowa corn into whole kernels, particles through 6.4 mm but over 4.8 mm (sizes 1 and 2), and particles through 4.8 mm (sizes 3 to 7). In these samples, sizes 1 and 2 composed 70% of total fines, as opposed to...
59% in the 16 test samples.

Experimental Grain

The whole-kernel grain for this study was yellow dent corn of unknown genotype, initially at 15% MCWB, obtained from the University Farm Service. All the corn was cleaned on a Carter Dockage Tester, equipped with a 7.1-mm (18/64-in.) round-hole sieve.

Experimental Test Apparatus

The complete test apparatus for this experiment is shown in Fig. 1. It consists of a variable-flow blower system, an airflow measurement system, and the grain column.

The variable-flow blower system is an Ace Model AIX, 115-V, 0.75-kW (1-hp) universal motor and blower (1) controlled by a variable transformer (8).

The airflow resistance measurement system is composed of a Meriam model 50 MC2 laminar-flow meter (2), a Meriam model 34 FB2 micromanometer (9), a Meriam model 40 HE2S inclined manometer (4), and a steel grain column. The Meriam laminar-flow meter consists of a stainless steel matrix within a metal enclosure. Flow passages are small enough to maintain laminar flow over the operating range of the meter (0.00 to 0.05 m/s). The calibration curve for the operating range was supplied by the meter manufacturer.

The Meriam micromanometer consists of a well-type manometer, with the well movable in the vertical plane with a precision-ground screw. The smallest graduation is 0.001 in. of water (0.249 Pa). The Meriam inclined manometer has a range of 10.0 in. of water (2490 Pa), with the smallest graduation being 0.01 in. of water (2.49 Pa). Meriam 1000 green indicating fluid was used in both manometers.

Pressure drop across the laminar-flow element was measured by the inclined manometer. Pressure drop across the main bed was measured by the micromanometer. All air pressure lines are 4.8-mm latex rubber pressure hose.

The grain column has an inside diameter of 240 mm and a length of 585 mm. It was built from 3.2-mm-thick steel tubing. The perforated floor was installed 47.6 mm from the bottom of the column. The pipe was sectioned at this level, and a floor of 1.2-mm hole diameter perforated stainless steel with 40.3% open area was inserted.

Piezometer orifices were installed at levels of 28.6 mm and 333 mm above the bin floor. All pressure drop readings were made across 304.4 mm (12.0 in.) of grain between the orifices. A filter constructed from 100-mesh copper screen was placed above the grain column to prevent dust from clogging the matrix of the laminar flow element.

In Fig. 1, the airflow path through the experimental apparatus can be traced. Air entered the bottom of the column, passed through the grain, filter, duct system, airflow element, and out through the blower discharge. All duct work is styrene pipe having an inside diameter of 100 mm. Transition pieces were fabricated of galvanized steel with soldered seams.

Preparing Test Mixtures

In preparing test mixtures, fines were added in the same proportions found in the country elevator samples (Table 1). In successive tests 0.0, 1.0, 3.0, 5.0, 7.0 and 10.0% by weight of each grade of fines was added. Fines consisted of the coarsest fraction (size 1), then the two coarsest fractions (sizes 1 and 2), and so on until, in one series, all sizes of fines were being added. Each condition was replicated. The coarsest (size 1) was defined as Grade I. The combination of the two coarsest sizes (sizes 1 and 2) was defined as Grade II, and so on.

Uniformity of Fines Distribution

To get uniform distribution of fines in the test corn, a mixing chamber with a movable slide gate at the bottom was filled manually with five layers of mixtures of corn and fines (Fig. 2). We poured clean corn and fines simultaneously with circular movement to form a layer of uniform mixture. The other four layers were added similarly. The mixing chamber was mounted on the test column. Quick removal of the slide gate allowed the mixture of grain and fines to fall into the test column.

A test was conducted to estimate the uniformity of fines distribution after dropping from the mixing chamber. In this test, a sack probe was inserted at five different levels to check the mixing. For a mixture of 5% fines, the distribution of fines at five levels (from the bottom) was 4.8, 5.1, 4.9, 4.8, and 5.2% respectively with an average of 4.96%. The uniformity was judged to be adequate.

Drop Height

Two drop heights were used. The first drop height was 649 mm (2.13 ft). In a second series of tests, an empty
column was inserted between the mixing chamber and the test column to increase drop height to 1340 mm (4.10 ft).

Airflow Tests
For each test, static pressure across 304.4 mm (12.0 in.) of grain was measured for each of 10 airflow rates between 0.017 and 0.510 m³/m²·s (3.3 and 100 cfm/ft²).

Before each test, the empty test column was weighed and placed on a roller cart for easy handling. The column was rolled directly under the mixing chamber containing corn and fines. Following removal of the slide gate, the filled column was rolled to a platform scale for weighing.

Grain volume was determined by levelling the corn and fines with a cross blade lowered to the grain by means of a 13-mm (1/2-in.) threaded rod. Proper grain level was reached when the cross blade contacted many kernels but did not push any along. The distance from the levelled height of grain to the top of the column was measured and recorded.

RESULTS AND DISCUSSION
Airflow resistance characteristics for Grade VII at a 649-mm drop height are shown in Fig. 3. Six different curves (clean corn and five different percentages of fines) were fitted to the data by inspection. Each data point is the average of two replications. Curves for all 14 tests conditions (seven size grades and two drop heights) were similar in shape. Experimental data is listed in Grama (1982).

Our clean corn had a Shedd's curve multiplier (SCM) of about 0.95. SCM is the ratio of the pressure drop of any test grain to the pressure drop predicted by Shedd's curve at the same airflow rate. In this paper clean corn multiplier (CCM) is defined as the ratio of the pressure drop of corn with fines to the pressure drop of our clean corn (649-mm drop height) at the same airflow rate.

An equation was developed for predicting CCM as a function of percent of fines for each of the seven grades of fines (Fig. 4). This form of equation was chosen after analysis showed that the correlation coefficient ($r_{x_1,x_2}$) between airflow and CCM was not statistically significant and that percent of fines and bulk density were closely correlated ($r_{x_1,x_3} = 0.995$). The close correlation between percent fines and bulk density eliminated the effect of the second (1340 mm) drop height. Therefore our analysis is based on data from both drop heights pooled.

The correlation coefficients between airflow and CCM though not statistically significant, were all positive, indicating that at constant percent of fines, CCM may increase with airflow. The pressure drop equation of Haque et al. (1978) includes airflow and predicts that CCM will decrease with an increase in airflow. The line for 10% BCFM from Haque et al. is shown on Fig. 3. The explanation for this disagreement is not known.

We developed two least squares linear regression models to predict CCM as a function of percentage fines. One had an intercept calculated statistically and one was forced through the point (0, 1). The forced model (Fig. 4) was developed for continuity at low values of percent fines even though some error was introduced, especially at the 1 and 10% levels. At the 3, 5, and 7% levels, the forced model was in good agreement with the intercept model. Because most samples contain more than 1 but less than 10% fines, we selected the forced model for the economic analysis.

Table 2 shows the forced model, standard deviation of
prediction and the R-square for the 7 grades. As the size of the fines decreases, the R-square increased. Standard deviation generally increased as the R-square increased.

Effects of Screening

To illustrate the effect of screening on fan power requirement for several typical farm situations, we estimated fan power input, energy use, and energy cost to aerate for 100 h. The corn was assumed to contain 3.0% BCFM with fines in sizes distributed as in Table 1. Total fines was therefore 7.31%. The corn, if screened using a 6.4-mm round-hole sieve, was assumed to have a CCM of 1.0. Electrical energy cost was assumed to be 6$/kWh. Table 3 summarizes these calculations.

For several bin conditions we determined the airflow needed, estimated the fan power input (from Fig. 5 derived from data for 10 axial flow fans) and calculated the power index. The power index is the ratio of aeration power for this corn to that for clean corn, multiplied by 100. For grade VII, which corresponds to no screening, the power index went up to 364 for low-temperature drying at 0.028 m³/s·t (1.5 cfm/bu), 4.88-m (16-ft) depth. But for minimum aeration 0.0034 m³/s·t (0.2 cfm/bu) at 6.10-m (20.4-ft) depth, the power index increased to only 110. Typical high-temperature column drying and in-bin counterflow drying had power indices between these extremes.

CONCLUSIONS

1. Airflow resistance of shelled corn increases when fine material is added. The increase in airflow resistance becomes greater as the size of fines is decreased.

2. Airflow resistance, as described by CCM, was predictable as a linear function of percent fines for seven size grades of fines.

3. The presence of fines increases fan power.

### Table 2: Model, Standard Deviation, R-Square for Grades I Through VII Forced Model

<table>
<thead>
<tr>
<th>Screen size, mm</th>
<th>Through</th>
<th>Over</th>
<th>Grade</th>
<th>Model*</th>
<th>s†</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 5.6 1</td>
<td>I</td>
<td>Y = 0.030X+1.0</td>
<td>0.076</td>
<td>0.850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4 4.8 1#2</td>
<td>II</td>
<td>Y = 0.042X+1.0</td>
<td>0.098</td>
<td>0.869</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4 4.0 1+2+3</td>
<td>III</td>
<td>Y = 0.056X+1.0</td>
<td>0.108</td>
<td>0.909</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4 3.2 1+2+3+4</td>
<td>IV</td>
<td>Y = 0.079X+1.0</td>
<td>0.125</td>
<td>0.937</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4 2.4 1+2+3+4+5</td>
<td>V</td>
<td>Y = 0.109X+1.0</td>
<td>0.157</td>
<td>0.947</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4 1.8 1+2+3+4+5+6</td>
<td>VI</td>
<td>Y = 0.134X+1.0</td>
<td>0.185</td>
<td>0.955</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4 0 1+2+3+4+5+6+7</td>
<td>VII</td>
<td>Y = 0.173X+1.0</td>
<td>0.182</td>
<td>0.971</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Y = Clean corn multiplier, X = percent fine.
† Standard deviation of individual tests with respect to model, in dimensionless pack factor units.

### Table 3: Effect of Screen Size on Fan Power and Fan Energy Use

<table>
<thead>
<tr>
<th>Screen size, mm</th>
<th>Size</th>
<th>Fines grade</th>
<th>Percent fines</th>
<th>Clean corn multiplier, CCM</th>
<th>Aeration* (0.0034 m³/s·t) (0.2 cfm/bu)</th>
<th>Low temp. bin dryer† (0.019 m³/s·t) (1.0 cfm/bu)</th>
<th>Low temp. bin dryer‡ (0.028 m³/s·t) (1.5 cfm/bu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 5.6 1</td>
<td>I</td>
<td>1.0</td>
<td>80</td>
<td>0.65</td>
<td>3.9</td>
<td>100</td>
<td>359</td>
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<tr>
<td>6.4 4.8 1#2</td>
<td>II</td>
<td>1.2</td>
<td>88</td>
<td>0.66</td>
<td>3.9</td>
<td>101</td>
<td>395</td>
</tr>
<tr>
<td>6.4 4.0 1+2+3</td>
<td>III</td>
<td>1.3</td>
<td>104</td>
<td>0.66</td>
<td>4.0</td>
<td>102</td>
<td>440</td>
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<tr>
<td>6.4 3.2 1+2+3+4</td>
<td>IV</td>
<td>1.5</td>
<td>120</td>
<td>0.67</td>
<td>4.0</td>
<td>104</td>
<td>538</td>
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<tr>
<td>6.4 2.4 1+2+3+4+5</td>
<td>V</td>
<td>1.7</td>
<td>135</td>
<td>0.68</td>
<td>4.1</td>
<td>105</td>
<td>610</td>
</tr>
<tr>
<td>6.4 1.8 1+2+3+4+5+6</td>
<td>VI</td>
<td>1.9</td>
<td>159</td>
<td>0.70</td>
<td>4.2</td>
<td>107</td>
<td>718</td>
</tr>
<tr>
<td>None 1+2+3+4+5+6+7 VII</td>
<td>2.1</td>
<td>183</td>
<td>0.71</td>
<td>4.3</td>
<td>110</td>
<td>825</td>
<td>5.7</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Screen size, mm</th>
<th>Size</th>
<th>Fines grade</th>
<th>Percent fines</th>
<th>Clean corn multiplier, CCM</th>
<th>High temperature column dryer** (0.1 cfm/bu)</th>
<th>High temperature in-bin counterflow dryer†† (7 cfm/bu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 5.6 1</td>
<td>I</td>
<td>1.0</td>
<td>282</td>
<td>17.3</td>
<td>104</td>
<td>583</td>
</tr>
<tr>
<td>6.4 4.8 1#2</td>
<td>II</td>
<td>1.2</td>
<td>338</td>
<td>18.2</td>
<td>107</td>
<td>610</td>
</tr>
<tr>
<td>6.4 4.0 1+2+3</td>
<td>III</td>
<td>1.3</td>
<td>366</td>
<td>18.8</td>
<td>109</td>
<td>758</td>
</tr>
<tr>
<td>6.4 3.2 1+2+3+4</td>
<td>IV</td>
<td>1.5</td>
<td>422</td>
<td>19.8</td>
<td>119</td>
<td>874</td>
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<tr>
<td>6.4 2.4 1+2+3+4+5</td>
<td>V</td>
<td>1.7</td>
<td>479</td>
<td>21.0</td>
<td>126</td>
<td>991</td>
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<tr>
<td>6.4 1.8 1+2+3+4+5+6</td>
<td>VI</td>
<td>1.9</td>
<td>563</td>
<td>23.0</td>
<td>138</td>
<td>1116</td>
</tr>
<tr>
<td>None 1+2+3+4+5+6+7 VII</td>
<td>2.1</td>
<td>648</td>
<td>25.0</td>
<td>152</td>
<td>1434</td>
<td>33.4</td>
</tr>
</tbody>
</table>

* Quality maintenance aeration 7.32-m (24.0-ft) diameter bin, 6.10-m (20.4-ft) depth.
† Low-temperature drying, 7.32-m diameter (24.0-ft) diameter bin, 4.88-m (16.0-ft) depth.
‡ Pa, static pressure drop in pascals.
§ S, Energy input to fan (Operation of axial fans at static pressures exceeding 1000 Pa (4 in. water) is not recommended).
# Pi is the power index, Pi = 100 for clean corn.
** High-temperature column dryer, 46.45-m² (500-ft²) column area, 0.31-m (1.0-ft) depth.
†† High-temperature in-bin counterflow dryer, 7.32-m (24.0 ft) diameter, 1.82-m (6.0-ft) depth.
efficiencies would increase since the turbine would operate at a higher and more efficient tip speed ratio. For example, at a wind speed of 10 m/s the turbine would turn at 209 r/min to maintain a tip speed ratio of 5.0, corresponding to an efficiency of 39% (Fig. 2). However, since the turbine can only operate up to 180 r/min the tip speed ratio decreases to less than 4.3 and the corresponding efficiency becomes less than 35%. Since the turbine rotational speed cannot respond instantly to changing wind conditions, the tip speed ratio will not always be optimal and operating efficiency will decrease. Response time of the rotor would have increased if the load had been decreased between rotational speeds of 120 and 180 r/min, and if the inertia of the system would have been less, but the corresponding increase in efficiency was not determined.

CONCLUSIONS

Variable-speed operation of the cantilevered Darrieus was successful below a turbine rotational speed of 180 r/min. Vibrations due to a mass imbalance prevented operation at higher rotational speeds. Resonance was detected near a shaft rotational speed of 50 r/min but did not cause significant vibrating as shaft speeds changed rapidly in starting and stopping processes.

Performance of the variable-speed Darrieus was adequately determined using a modified form of the statistical averaging technique called the "Method of Bins". The variable-speed system operated near the predicted optimal efficiency to a rotational speed of 120 r/min. Above this speed efficiencies decreased because the tip speed ratio of the turbine decreased as the rotor was loaded down to prevent overspeeding, and because of the inertial effect of the turbine. Variable-speed operation resulted in an average efficiency of 31.8%. Improved efficiency can be obtained by operating the turbine to higher rotational speeds and optimizing the loading method.

References