There is not much information on the resistance to airflow of pelleted feed products. This study focuses on air resistance through airflow and pressure drop per unit depth of material has been published for several types of biological material. Airflow through feed products, fans can be selected to efficiently achieve proper aeration. Extensive data defining the relationship between airflow and pressure drop per unit depth of material was obtained for four pelleted feed sizes (4.0 mm, 6.7 mm, and 19.4 mm diameters and 33.2 × 34.9 mm cubes). Data have been published for sizes similar to the 6.7 mm pellets and the cubes, but no data are available for the other two sizes. Three bin shapes (round, square, rectangular) containing equal airflow areas were tested. A “loose” and a “packed” fill were also tested for each product size except for the cubes, which was tested at a loose fill only. The data obtained were well represented by Shedd’s equation. Shape of the test bin appeared to have no effect on measured airflow resistance. The pressure drop increased with the packed fill over the loose fill, but graphically, the variation of airflow with pressure drop appeared to be the same for both conditions.

**Keywords.** Airflow resistance, Bin shape, Feed, Pellets.

Extended stability of pelleted animal feeds depends on effective cooling and drying immediately after their production in the pelleting process. Pellet cooling is therefore undertaken (1) to remove heat added to the product during steam conditioning and extrusion and (2) to remove excess moisture resulting from steam conditioning. In typical animal feed production, pelleted feed products exit the conventional extrusion process at about 60°C to 85°C and 12% to 17.5% m.c. (moisture contents presented in this article are wet basis unless stated otherwise). In pellet cooling, air is forced through the pellets to reduce the temperature and to remove a specific amount of moisture from the material quickly. For long-term storage, it is desirable to reduce pellet temperatures to as close to ambient as possible and to reduce moisture content to less than 12% (Robinson, 1984). A general rule is that proper cooling should reduce the pellet temperature in temperate climates to between 3°C and 5°C (7°F and 10°F) above ambient and reduce moisture to between 10.5% and 12.5% m.c. (Robinson, 1984). This process both improves pellet durability and reduces the possibility of spoilage from mold, so that sticking in bins will be prevented and breakage and crumbling during handling and transporting will be minimized. From the standpoint of pellet quality, the pellet cooler is generally considered as the weak link in a feed mill (McElhinney, 1986).

Pellet cooling is accomplished by drawing ambient air through a bed of pellets. Pellet coolers used in the feed industry are of three basic types: vertical, horizontal, and counterflow (Fairfield, 1994), with the former two being more common. Pellet cooler design is based on retention time and airflow. These factors are controlled by bed surface area, bed thickness, air velocity, and material flow rate in the cooler. In the case of counterflow cooling, Maier and Bakker–Arkema (1992) established that the most important operating and design parameters are pellet bed depth and air-to-pellet mass flow ratio. Fundamentally, these are airflow resistance parameters.

While there is extensive information on the airflow resistance of grains and seeds compiled in ASAE Standard D272.3 (ASAE Standards, 2001a), data specifically for pelleted feed are scant. Available data come from Sokhansanj et al. (1993), who evaluated alfalfa pellets of 6.4, 7.9, and 9.5 mm diameter and cubes with a 34.4 × 34.3 mm cross-section. The test apparatus employed by Sokhansanj et al. (1993) had a material holding bin with a circular cross-section. Al–Yahya and Moghaz (1998), Bakker–Arkema et al. (1969), Gunasekaran et al. (1983), Henderson (1943), and Siebenmorgen and Jindal (1987) likewise undertook airflow resistance evaluations in test apparatus with holding bins having circular cross-sections. Others have used test bins with square (Gunasekaran and Jackson, 1988; Shedd, 1953; Hellevang et al., 2001) or rectangular cross-sections (Kumar and Muir, 1986). An issue that needs to be addressed is “Does bin shape have an effect on the airflow resistance data obtained?” No information was found on the effect of bin shape on the measured resistance to airflow. With larger particles packed in a bed, an “edge effect” may occur in the test bin corners. This would reduce the airflow resistance measured for a given airflow rate.

The objectives of this study were: (1) to determine the airflow resistance of different sized pelleted feed, and (2) to evaluate the effect of test column cross-section on the airflow.
resistance measurements. Reliable airflow resistance data are needed when selecting fans to efficiently design an aeration system for pellets.

**MATERIALS AND METHODS**

**Test Materials**

Four types of commercially available pelleted feed varying in shape and dimensions were used as test materials in this study; these were: rabbit feed, dehydrated (“dehy”) alfalfa pellets, range cubes, and horse cubes. All these products selected for testing except for the range cubes were alfalfa-based products to allow a direct comparison/integration with the results obtained by Sokhansanj et al. (1993). Three pellet diameters were tested, based on the estimated die hole size, the results obtained by Sokhansanj et al. (1993). Three pellet-based products were selected for testing except for the range cubes: alfalfa pellets, range cubes, and horse cubes. All these products were included in the study.

Measured linear dimensions and bulk properties of the test materials are presented in tables 1 and 2, respectively. Linear dimensions were measured with a dial caliper. The data presented are the mean of measurements made on 50 pellets/cubes of each product type. Bulk properties presented represent the mean of three measurements. Moisture content was determined using the air oven procedure in ASAE Standard S358.2 (ASAE Standards, 2001b). To determine porosity, bulk and unit densities of each of the products were measured. Two methods were employed to determine bulk density. In the in situ method involved dividing the mass of the material loaded during testing by the known volume of the test column. The standard method followed the procedure in ASAE Standard S269.4 (ASAE Standards, 2001c). Range cubes and horse cubes were cut with a band saw into 25 mm (1 in.) pieces, and the unit densities were obtained by weighing the pieces and calculating the volumes from their perpendicular dimensions. Unit densities of the smaller pellets were determined by fluid displacement using toluene (Mohsenin, 1986). From the measured densities, the void space or porosity was calculated using the relationship given by Mohsenin (1986):

\[ \varepsilon = 1 - \frac{\rho_b}{\rho_u} \]  

where \( \rho_b \) and \( \rho_u \) are, respectively, bulk density and unit density of the tested materials in kg/m\(^3\).

**Table 1. Test product linear dimensions.**

<table>
<thead>
<tr>
<th>Product</th>
<th>Shape</th>
<th>Dia./Width (mm)</th>
<th>Length (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rabbit feed</td>
<td>Cylinder</td>
<td>4.1 (0.04)</td>
<td>8.6 (1.89)</td>
<td></td>
</tr>
<tr>
<td>Dehy pellets</td>
<td>Cylinder</td>
<td>6.7 (0.21)</td>
<td>11.9 (3.34)</td>
<td></td>
</tr>
<tr>
<td>Range cubes</td>
<td>Cylinder</td>
<td>19.4 (0.23)</td>
<td>46.9 (11.90)</td>
<td></td>
</tr>
<tr>
<td>Horse cubes</td>
<td>Cuboid</td>
<td>33.2 (2.0)</td>
<td>34.9 (1.1)</td>
<td>45.0 (18.6)</td>
</tr>
</tbody>
</table>

**Table 2. Test product bulk properties.**

<table>
<thead>
<tr>
<th>Product</th>
<th>MC w.b. (%)</th>
<th>Bulk Density, kg/m(^3)</th>
<th>Unit Density, kg/m(^3)</th>
<th>Porosity in situ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in situ (s.d.)</td>
<td></td>
<td>Standard (s.d.)</td>
<td></td>
</tr>
<tr>
<td>Loose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rabbit feed</td>
<td>9.5</td>
<td>716.4 (6.8)</td>
<td>1338 (3)</td>
<td>0.46</td>
</tr>
<tr>
<td>Dehy pellets</td>
<td>7.0</td>
<td>711.7 (3.2)</td>
<td>1357 (7)</td>
<td>0.48</td>
</tr>
<tr>
<td>Range cubes</td>
<td>8.3</td>
<td>667.6 (8.8)</td>
<td>1167 (5)</td>
<td>0.43</td>
</tr>
<tr>
<td>Horse cubes</td>
<td>7.6</td>
<td>427.9 (2.9)</td>
<td>681 (26)</td>
<td>0.37</td>
</tr>
<tr>
<td>Packed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rabbit feed</td>
<td>9.5</td>
<td>753.6 (2.1)</td>
<td>1338 (3)</td>
<td>0.44</td>
</tr>
<tr>
<td>Dehy pellets</td>
<td>7.0</td>
<td>753.5 (3.9)</td>
<td>1357 (7)</td>
<td>0.44</td>
</tr>
<tr>
<td>Range cubes</td>
<td>8.3</td>
<td>698.2 (2.9)</td>
<td>1167 (5)</td>
<td>0.40</td>
</tr>
<tr>
<td>Horse cubes</td>
<td>7.6</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

**TEST APPARATUS**

The apparatus used in testing is illustrated in figure 1. A centrifugal fan (fan model 4C108, 10–9/16 in. diameter; motor model 5K90IC, 1 hp; Dayton Electric Manufacturing Co., Chicago, Ill.) supplied the airflow for all tests. Variation in air delivery was achieved using a ball valve to restrict airflow. The air was conveyed through a 5.08 cm (2 in.) nominal PVC pipe and was then constricted through a 3.49 cm (1–3/8 in.) orifice meter (sharp-edged, flange taps) located more than ten diameters downstream of the fan to ensure fully developed flow for flow measurement. Before entering the plenum, the flow was divided into two 10.16 cm (4 in.) flexible ducts for improved flow distribution. From the plenum, the air moved up through a perforated floor and then through the column of material to the atmosphere. The 0.61 × 0.61 × 0.30 m (2 × 2 × 1 ft) plenum was constructed of 3/4 in. plywood and sealed with silicone caulk. The perforated sheet metal serving as the material-holding bin floor was built into the system as the top part of the plenum. It had 1.6 mm (1/16 in.) perforations giving it a 44% open area, which was consistent with measurements in industrial pellet coolers used in a commercial feed manufacturing (B. Moechnig, personal communication, 30 May 2001). A high percentage of open area minimized the pressure drop across the floor, and the perforation size was appropriately selected so that particles of significant volume would not fall into the plenum. A resistance of 1.24 Pa (0.005 in. H\(_2\)O) was approximated for the perforated floor at a flow rate of 0.25 m\(^3\)/s m\(^2\) (49 ft\(^3\)/min ft\(^2\)).

Three 60.9 cm (24 in.) high Plexiglas columns of different cross-sections (circle, square, rectangle) were fabricated to serve as the material-holding columns. Each column was constructed with a base that completely covered the plenum’s perforated top, thereby leaving the column cross-section as the only opening for airflow. Each test column had a cross-sectional area of 0.16 m\(^2\) (1.72 ft\(^2\)). The cross-sectional dimensions were 45.1 cm (17.8 in.) diameter, 40.0 × 40.0 cm (15.7 × 15.7 in.), and 30.9 × 51.6 cm (12.2 × 20.3 in.) for the circle, square, and rectangle, respectively. Limitations in
space, fan capacity, and test material availability constrained the sizes of the test columns. The test columns were held in place over the plenum top by a square mounting frame that was fabricated from angle iron and held by setscrews into the plenum walls. A relatively airtight seal between the test columns and the plenum was achieved using foam weather-stripping.

Carman (1937) suggested that the effects of the bounding wall on the overall pressure drop through a packed bed could be neglected if the diameter of the container was greater that ten times the diameter of packed spherical particles. Considering that material in packed beds may be of shapes other than spheres, Geankoplis (1993) stated that the ratio of the diameter of a column holding packed material to the effective particle diameter should be a minimum of 8:1 to 10:1 for wall effects to be small. As given by Geankoplis (1993), effective particle diameter is calculated as:

\[ D_p = \frac{6}{\alpha_v} \]  

(2)

where \( \alpha_v \) is the specific surface area of a particle in 1/m. Dividing the surface area of a particle by its volume gives \( \alpha_v \). Beavers et al. (1973) defined the equivalent diameter of beds that are not cylindrical as:

\[ D_e = \frac{2wh}{w + h} \]  

(3)

where \( h \) and \( w \) are, respectively, the height and width of the bed. The calculations undertaken (table 3) indicate that for the test columns and test materials used in this study, the wall effects are small. Shedd (1945, 1953) used a test column that was 2.1 m (7.0 ft) square in his studies on the airflow resistance of grains, so there was no question of wall effects affecting his data.

Pressure readings were taken with two manometers (model 400, Dwyer Instruments Inc., Michigan City, Ind.) with marks at 2.5 Pa (0.01 in. H₂O) increments below 249 Pa (1 in. H₂O) and at 25 Pa (0.1 in. H₂O) increments above 249 Pa. One manometer measured the pressure drop across the orifice using standard flange taps. This measured pressure drop was then used to calculate the airflow rate using the ISO–ASME equation (ASME, 1981). The other manometer was used to measure static pressure in the plenum, thus determining the static pressure drop across the column of feed. Four small pressure pickup cans, of 6.99 cm dia. × 5.08 cm depth (2.75 in. dia. × 2 in. depth) with multiple 0.032 cm dia. (0.125 in.) perforations in their outer walls and connected to a common manifold, were used in the plenum to obtain a representative plenum pressure value. The manifold provided a single “average pressure” input to the manometer.

**TEST PROCEDURE**

Pressure drop through the pelleted feed was measured at airflow rates varying from 0.006 to 0.24 m³/s m² (1.2 to 47.2 ft³/min ft²) for the different test conditions. As a reference, the normal rates for drying grain range from 0.02 to 0.7 m³/s m². Key factors evaluated in this study were product geometry, bin shape, and degree of packing. The effects of these factors were evaluated in three experiments, as specified in table 4. Three repetitions were performed for each treatment factor combination, and a randomized approach was used in the sequencing of tests within each experiment. Efficiency in testing was achieved by reusing data that had already been obtained when examining the effects of different treatment factors in subsequent experiments.

All tests were undertaken using pelleted feed cleaned of any fine material. The rabbit feed and dehy pellets were cleaned by screening with a 3.2 mm (1/8 in.) sieve. Only intact pellets

| Table 3. Computational assessment of wall effects in the different test situations. |
|-----------------|-----------------|-----------------|-----------------|
| **Product**     | **Test Bin**    | **Dp (m)**      | **Cc (Dc = 0.45 m)** | **Sc (Dc = 0.40 m)** | **Rect (Dc = 0.39 m)** |
| Rabbit feed     | Circle          | 4.97E−03        | 90.81             | 80.54             | 77.83             |
| Dehy pellets    | Circle          | 7.70E−03        | 58.54             | 51.92             | 50.17             |
| Range cubes     | Circle          | 2.41E−02        | 18.70             | 16.59             | 16.03             |
| Horse cubes     | Circle          | 3.70E−02        | 12.18             | 10.80             | 10.44             |

| Table 4. Experiments undertaken and factors evaluated. |
|-----------------|-----------------|-----------------|-----------------|
| **Test Bin**    | **Cross-section** | **Degree of Packing** | **Product**    |
| Comparisons    | Circle          | Loose           | Rabbit feed    |
| Rabbit feed    | Dehy pellets    | Range cubes     | Horse cubes    |
| Bin shape      | Circle          | Square          | Rectangle      |
| Effects        | Circle          | Packed          | Rectangle      |
| Rabbit feed    | Dehy pellets    | Range cubes     | Horse cubes    |
retained on the sieve were used. In the process of manually handling the range cubes and horse cubes for loading into the test bins, most of the fine material was already separated out, so there was no need to screen these products. After cleaning, the material was weighed in approximately 10 kg increments with a digital scale with an accuracy of 1 g for loading in the test bins.

Each test was started by loading the test column for a loose fill. This was achieved by pouring feed into the test columns from a height of less than 5.1 cm (2 in.) until the 45.7 cm (18 in.) fill level was reached. The manometers were then zeroed. Pressure drop readings were then taken for the predetermined series of increasing airflow rates achieved by adjusting the ball valve in the test apparatus. After the loose fill measurements, the feed was packed by alternately agitating and tamping the test column with a rubber mallet and adding weighed amounts of feed to bring the fill level back to the original depth of 45.7 cm. This probably was not a fully packed fill since the material was not poured from a greater height as was done by Jayas et al. (1989), and settling was not induced after each increment of fill as was done by Beavers et al. (1973). Pressure drop readings for the packed fill were then taken for the predetermined series of increasing airflow rates.

RESULTS AND DISCUSSION

Airflow resistance of agricultural products is typically presented in the form of pressure drop per unit depth of material. This is the form of presentation in ASAE Standard D272.3 (ASAE Standards, 2001a). This assumes that pressure drop across a unit depth of material is uniform through each incremental depth. Shedd (1953) reported that, in reality, slightly higher airflow resistance occurs in the lower increments of the stack. He found that the difference in average pressure drop per unit depth across a 2.7 m (9 ft) column of clean shelled corn compared to a 1.2 m (4 ft) column was 1.1% of the total pressure for a loose fill and 0.2% for a packed fill. For comparison with previously published data, results for this study are presented in the common format of log–log plots of airflow per unit area versus pressure drop per unit depth.

Figure 2 shows resistance to airflow of a loose fill for the four types of pelleted feed in the cylindrical test bin (data points presented in this figure and in succeeding figures are the means of three replications). Clearly, pressure drop increases with increasing airflow rate and with decreasing particle size. Sokhansanj et al. (1993) measured airflow resistance of two pellet sizes, 7.9 mm (5/16 in.) and 9.5 mm (3/8 in.), not tested in this study. Their data, also shown in figure 2, fitted proportionately with the measured data in this study.

Compared to data obtained by Shedd (1953) for various agricultural products, the resistance through rabbit feed was similar to that of shelled corn and yellow popcorn. Results for the dehy pellets closely matched the results obtained for blue lupine. The resistance through range cubes was slightly less than that of peanuts. Lastly, the curve from horse cubes indicated that the airflow resistance was little more than that of potatoes. As expected from the results of previous studies, the degree of change in airflow resistance for increasing increments of flow rates was less for products with larger particle sizes.

Sokhansanj et al. (1993) measured airflow resistance of alfalfa cubes with dimensions similar to the horse cubes in this study. However, the moisture content of the alfalfa cubes in their study was 12%, compared to 7.6% for the horse cubes in this study. In addition, the bulk and unit densities were lower for this experiment, mainly due to the difference in moisture content. Consistent with what has been reported for grains, the higher–moisture product had a lower airflow resistance than the lower–moisture product (fig. 3).

BIN SHAPE EFFECTS

For a loose fill, the effect of test bin cross–section on measured airflow resistance of pelleted feeds is presented in figure 4. Test runs were initially performed with rabbit pellets and horse cubes. The curves were nearly collinear for each product. Since there was no difference in measured airflow resistance of these two products in test bins of different cross–section, further testing using the other two test materials was deemed unnecessary. The various bins containing the rabbit

Figure 2. Airflow resistance data for clean, loosely filled, pelleted feed measured in a circular test column. Data for the 7.9 and 9.5 mm pellets are from Sokhansanj et al. (1993).
Figure 3. Effects of moisture content on airflow resistance of cuboid horse cubes. Data for the 12% m.c. alfalfa cubes are from Sokhansanj et al. (1993).

Figure 4. Effects of varying test bin shape.

Packing Effects

Figure 5 indicates that agitating and tamping the bins had an obvious effect on airflow resistance. For the tested flow range, the airflow resistance for packed rabbit pellets, dehy pellets, and range cubes was approximately 14% greater than for their corresponding loose fill. This result is in agreement with results obtained by others studying corn. Shedd (1951) found that a bin of clean shelled corn had a 20% increase in resistance for packed fill over loose fill. Bern (1975) found that the measured pressure drop was greater for corn columns of greater bulk density. Henderson (1943) found that after tamping and agitating a 2.4 m (8 ft) column of clean shelled corn, the rate of airflow was reduced by 15% from the previous runs with a loose fill. As shown in figure 4, the packed fill airflow resistance curves are relatively parallel to the loose fill curves, indicating that the variation in airflow with pressure drop between the two conditions is the same. It was difficult to induce packing of horse cubes due to their larger size and cubical shape; therefore, this product was not tested in packed fill.

Packing or degree of settling basically involves increasing bulk density. Bulk density for a given biological product is also affected by moisture content and percentage of fines or foreign material. Considerable research has been done on the effects of bulk density increase, caused by varying these factors, on airflow resistance. Shedd (1953) explained that increasing the moisture content of grains, resulting in a decrease in bulk density, decreases airflow resistance for a given airflow. Bulk density also increases with the percentage of fines. Sokhansanj et al. (1993) evaluated the effect of varying the percentage of fines incorporated into a column of 6.4 mm diameter pellets. Fine levels ranged from 0% to 25% on a mass basis, and the airflow ranged from 0.0025 to 0.82 m³/s m². They found that...
increasing the level of fines increased the pressure drop at a higher rate for higher airflows. Increasing the fines from 0% to 5% increased the pressure drop three to eight fold depending on the flow rate, clearly showing the effect of bulk density upon airflow resistance.

REPRESENTATION OF AIRFLOW RESISTANCE DATA

Numerous formulas to describe the relationship between resistance pressure through a product and the airflow rate have been empirically determined or derived based on the physical properties of the material and the air flowing through it. While mathematically derived relationships are fairly complex, most of the empirical equations are relatively simple. The simplest and most widely used formula for expressing the relationship is Shedd’s equation (1953):

\[ Q = A(\Delta P)^B \]  

where \( Q \) is airflow rate in \( \text{m}^3/\text{s} \) \( \cdot \text{m}^2 \), \( \Delta P \) is pressure drop per unit depth of material in \( \text{Pa/m} \), and \( A \) and \( B \) are constants depending on product type and condition. This is a log–linearized regression that is only useful for a narrow range of airflows. The actual curve is slightly convex upward.

Sokhansanj et al. (1993) found their airflow resistance data for alfalfa herbage, pellets, and cubes for an airflow range of 0.003 to 1.0 \( \text{m}^3/\text{s} \) \( \cdot \text{m}^2 \) (0.6 to 197 \( \text{ft}^3/\text{min} \) \( \cdot \text{ft}^2 \)) were accurately represented by Shedd’s equation. Results from this study were
therefore fitted to Shedd’s equation (table 5). The fit for all products was exceptionally good, with $r^2 > 0.99$ for all relationships.

**CONCLUSIONS**

Just as in the case of different granular materials of agricultural nature, airflow resistance of pelleted feed was found to increase with increasing airflow rate and with packing. Plotting airflow per unit area as a function of pressure drop per unit depth of material for pellets ranging from rabbit pellets to horse cubes resulted in a nearly log-linear curve. Therefore, the data obtained for the range of airflows tested can be represented by Shedd’s equation. Results from testing with different test bin cross-sections indicated that bin shape had no effect on the measured airflow resistances. This indicates that data obtained by various researchers using different test apparatus can be universally applied, provided that wall effects have been minimized in the testing.

**ACKNOWLEDGEMENTS**

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