Resistance of alfalfa cubes, pellets and compressed herbage to airflow

S. SOKHANSANJ, W. LI and O.O. FASINA

Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, Canada S7N 0W0.

Received 30 March 1993; accepted 25 August 1993.

Sokhansanj, S., Li, W. and Fasina, O.O. 1993. Resistance of alfalfa cubes, pellets and compressed herbage to airflow. Can. Agric. Eng. 35:207-213. The airflow resistance of bulk alfalfa cubes, alfalfa pellets and compressed herbage alfalfa was measured in the laboratory for the range of airflow of 0.003 to 1.0 m³·s⁻¹·m⁻². The effect of fines concentration up to 25% (dry mass basis) on airflow resistance of alfalfa pellets also was measured. The pressure drop versus airflow data on a log-log scaled plot were nearly linear and parallel for all the material types considered. Coefficients of Hukill-Ives' and Shedd's equations were determined for airflow resistance data of alfalfa cubes, pellets, and compressed herbage.

INTRODUCTION

Alfalfa is processed into pellets, cubes, and bales to facilitate handling, storage, and feeding to animals. Pellets and cubes are, respectively, made from ground and unground dehydrated chops using an extruding process. These products must be cooled immediately after extrusion. Cooling improves the durability and storability of pellets and cubes due to removal of about one to two points of moisture. Artificial drying of herbage alfalfa, baled or in mow, is becoming a necessity to minimize field losses, especially for the production of compressed bales for export. Also, stored alfalfa cubes and pellets are ventilated to prevent moisture migration and spontaneous heating.

Airflow resistance of alfalfa cubes, pellets, and baled hay is important in the design and analysis of drying and aeration systems. Numerous data are compiled in ASAE data D272.2 (ASAE 1991b) on resistance of most grains and seeds to airflow. This information is not available in the literature for alfalfa cubes and pellets and scanty for baled alfalfa hay.

Sitkei (1986) showed that the resistance of ventilated hay or straw pellets depends greatly on the percent of trimmings (fines) in the bulk of the feed pellets. The airflow resistance of the pellets mixed with fines was found to increase up to ten fold over the values for clean pellets. Sitkei (1986) did not mention the type of hay used for the study.

Data on effect of fines on airflow resistance of grains and seeds are summarized in ASAE data D272.2 (ASAE 1991b). The authors' experience with the alfalfa pelleting industry shows that present handling techniques in the industry can lead to generation of fines up to concentrations of 20% (mass basis) in a bulk of alfalfa pellets.

Numerous studies have been carried out on the airflow resistance of baled hay (Shedd 1946; Hendrix 1945, 1946; Davis and Baker 1951; Marchant 1976; Yiljep et al. 1992). Except for the degree of compaction, the researchers adequately covered the effect of density of material, length of compressed sample, bale orientation, and moisture content on the resistance of baled hay to airflow.

This study reports the resistance of alfalfa cubes, clean pellets, and fines mixed pellets to airflow. The data obtained are presented in a format similar to ASAE D272.2 data. Results of limited tests performed on alfalfa stems and leaves compressed to different densities also are presented.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Test apparatus

Figures 1 and 2 show the major components of experimental equipment consisting of a cylindrical sample container and instrumentation for airflow and static pressure measurements. Equipment configuration in Fig. 1 was used for airflow rates greater than 0.02 m³·s⁻¹·m⁻². Airflow resis-
Fig. 2. Equipment for measuring static pressures at low airflow.

Table I: Wet bulk density and specific density of alfalfa pellets and cubes

<table>
<thead>
<tr>
<th>Pellets</th>
<th>Cubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehy</td>
<td>Suncure</td>
</tr>
<tr>
<td>Av. dimensions (mm)</td>
<td>D = 6.4</td>
</tr>
<tr>
<td></td>
<td>L = 11.0</td>
</tr>
<tr>
<td>Bulk density (kg·m⁻³)</td>
<td>ASAE 269.2</td>
</tr>
<tr>
<td></td>
<td>In-situ</td>
</tr>
<tr>
<td>Specific density (kg·m⁻³)</td>
<td>1250</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.53</td>
</tr>
</tbody>
</table>

*D = diameter of pellets.
*L = length of pellets
pieces. Uneven ends of a cube were cut with a band saw to give an approximately 25 mm thick cube. The volume of cubes was calculated from three perpendicular dimensions and that of pellets was measured by placing several pellets into a measuring cylinder filled with toluene. Wet bulk densities of cubes and pellets were measured using two procedures: ASAE S269.3 (ASAE 1991a) and in-situ measurements. In-situ bulk density was obtained from volume measurements of a known mass of the material. The material was allowed to flow out of a loading funnel into the test container with zero height of fill. Table I lists the wet specific and bulk densities of tested pellets and cubes.

Fines samples were obtained by grinding dehydrated pellets. The fines samples had a geometric mean diameter of 0.366 mm and geometric standard deviation of 2.30. Particle size analysis was carried out on the fines according to ASAE Standard S319.2 (ASAE 1991c). Fines samples were mixed with the pellets in a concrete mixer. Airflow and static pressure measurements for 6.4 mm diameter alfalfa pellets were made at fines concentrations of 0%, 5%, 10%, 16%, 20% and 25% on dry mass basis. The highest airflow rate used at each of the fines concentrations was such that it caused minimum disturbance to the fines mixed pellets.

Samples used for pressure drop measurements of compressed alfalfa were obtained from field cut hay. After partial drying in the field, the plants were brought to the laboratory and stored in a controlled environment room until testing. Alfalfa stems were cut to pieces of about 300 mm length. The cut pieces of alfalfa were placed randomly between the two perforated plates in the sample container and compressed with the hydraulic press. Airflow and static pressure measurements were made at five wet bulk densities of 93, 118, 142, 173 and 210 kg m$^{-3}$ and two moisture levels of 20% and 36% wet basis.

Static pressures were measured from the lowest possible airflow to the highest that the centrifugal fan could supply without excessive noise and vibration. The airflow rate ranges used for the different materials are listed in Table II.

### Table II: Values of constants A and B of Equation 1 and constants a and b of Equation 2

<table>
<thead>
<tr>
<th>Moisture level (%)</th>
<th>Bulk density (kg m$^{-3}$)</th>
<th>A</th>
<th>B</th>
<th>a</th>
<th>b</th>
<th>Airflow range (m$^3$ s$^{-1}$ m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Herbage alfalfa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>93</td>
<td>0.0076</td>
<td>0.614</td>
<td>10700</td>
<td>36.148</td>
<td>0.0385 to 1.03</td>
</tr>
<tr>
<td>20</td>
<td>118</td>
<td>0.0054</td>
<td>0.604</td>
<td>20600</td>
<td>33.767</td>
<td>0.0385 to 0.96</td>
</tr>
<tr>
<td>20</td>
<td>142</td>
<td>0.0041</td>
<td>0.598</td>
<td>36400</td>
<td>36.124</td>
<td>0.0385 to 0.96</td>
</tr>
<tr>
<td>20</td>
<td>173</td>
<td>0.0024</td>
<td>0.612</td>
<td>62300</td>
<td>26.613</td>
<td>0.0385 to 0.45</td>
</tr>
<tr>
<td>20</td>
<td>210</td>
<td>0.0004</td>
<td>0.725</td>
<td>206000</td>
<td>17.190</td>
<td>0.0385 to 0.18</td>
</tr>
<tr>
<td>36</td>
<td>93</td>
<td>0.009</td>
<td>0.602</td>
<td>8660</td>
<td>31.263</td>
<td>0.0193 to 0.96</td>
</tr>
<tr>
<td>36</td>
<td>118</td>
<td>0.0051</td>
<td>0.612</td>
<td>19300</td>
<td>29.831</td>
<td>0.0193 to 0.92</td>
</tr>
<tr>
<td>36</td>
<td>142</td>
<td>0.0027</td>
<td>0.631</td>
<td>39400</td>
<td>25.050</td>
<td>0.0193 to 0.83</td>
</tr>
<tr>
<td>36</td>
<td>173</td>
<td>0.0015</td>
<td>0.642</td>
<td>85600</td>
<td>26.581</td>
<td>0.0193 to 0.58</td>
</tr>
<tr>
<td>36</td>
<td>210</td>
<td>0.0006</td>
<td>0.700</td>
<td>149000</td>
<td>19.916</td>
<td>0.0193 to 0.29</td>
</tr>
<tr>
<td><strong>Cubes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>477</td>
<td>0.0433</td>
<td>0.508</td>
<td>1270</td>
<td>22.991</td>
<td>0.13 to 3.15</td>
</tr>
<tr>
<td><strong>Pellet 6.4 mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>588</td>
<td>0.0091</td>
<td>0.605</td>
<td>9270</td>
<td>44.932</td>
<td>0.0053 to 0.82</td>
</tr>
<tr>
<td><strong>Pellet 7.9 mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>648</td>
<td>0.0054</td>
<td>0.641</td>
<td>18000</td>
<td>68.720</td>
<td>0.0053 to 0.63</td>
</tr>
<tr>
<td><strong>Pellet 9.5 mm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>633</td>
<td>0.0102</td>
<td>0.599</td>
<td>9520</td>
<td>76.644</td>
<td>0.0053 to 0.82</td>
</tr>
<tr>
<td><strong>Pellet 6.4 mm mixed with fines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fines 5%</td>
<td>685</td>
<td>0.0075</td>
<td>0.545</td>
<td>34620</td>
<td>140.52</td>
<td>0.0025 to 0.79</td>
</tr>
<tr>
<td>fines 10%</td>
<td>703</td>
<td>0.0057</td>
<td>0.547</td>
<td>53210</td>
<td>159.80</td>
<td>0.0025 to 0.60</td>
</tr>
<tr>
<td>fines 16%</td>
<td>718</td>
<td>0.0058</td>
<td>0.500</td>
<td>76050</td>
<td>157.96</td>
<td>0.0025 to 0.42</td>
</tr>
<tr>
<td>fines 20%</td>
<td>726</td>
<td>0.0035</td>
<td>0.509</td>
<td>145480</td>
<td>385.50</td>
<td>0.0025 to 0.42</td>
</tr>
<tr>
<td>fines 25%</td>
<td>727</td>
<td>0.0033</td>
<td>0.500</td>
<td>179480</td>
<td>290.01</td>
<td>0.0025 to 0.30</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

Cubes and pellets

Figure 3 shows the test data for clean pellets and cubes on a log-log scale. The data for the three sizes of pellets are parallel but the data for cubes are not parallel to those of pellets. A lower pressure drop measured for the 6.4 mm pellets compared to that for 7.9 mm pellets was due to longer pieces of the 6.4 mm pellets. Compared to other agricultural products reported in ASAE (1991b), alfalfa cubes have airflow resistance slightly greater than clean ear corn at 16% moisture while the 7.9 mm diameter pellets have an airflow resistance similar to pea beans at 15% moisture. The resistance patterns of clean cubes and pellets as a function of airflow are parallel to curves of other products reported in ASAE (1991b).

Figure 4 shows the test data for pellets mixed with fines. The lines are nearly parallel for the different fines concentrations. Pressure drop increases more rapidly at higher airflows with increasing level of fines in pellets. Increasing fines concentration from 0% to 5% increased the pressure drop three to eight fold depending on the level of airflow. When the pressure gradient reached 1000 Pa m⁻¹, there was an increase in airflow rate when the fines concentration was less than 10%. This indicates that fines dispersed within the bulk are lifted at these pressures. At higher fines concentrations, this change in airflow was not noticed but there was an increase in pressure drop. At higher fines concentration levels, fines would have occupied most of the airspaces between the granules of pellets and thus resist being lifted by air. As the fines concentration increases, the curves of pressure drop for pellets mixed with fines increasingly deviate from the straight line relationship reported for other products in ASAE (1991b). At low airflow, the air resistance of pellets mixed with 25% fines is similar to rough rice. At high airflow, the air resistance is similar to that of flax seed.

A concern was that the edge effect may be significant due to a relatively large size of cubes compared to the small diameter of the container. Carmen (1937) recommended that the cross sectional dimension of a bed should be at least ten times the characteristic dimension of the individual particles in the bed in order to ignore the effects of the confining wall on airflow pattern in the bed. Imposing such a requirement in our study would have required a test column with a minimum diameter of 0.5 m for cubes. In the present study, the maximum measurement error of pressure drop of cubes due to the wall effect could be as high as 10%. The procedure for error estimation is outlined in Appendix A.

Compressed herbage

Figures 5 and 6 show the pressure drop versus airflow for five densities of the compressed herbage alfalfa at moisture contents of 20% and 36% w.b. As expected, an increase in wet bulk density from 93 kg m⁻³ to 210 kg m⁻³ increased the resistance to airflow. At low bulk densities of 93 kg m⁻³ and 114 kg m⁻³, the difference between pressure drops was small for the two moisture contents tested. For the bulk densities larger than 142 kg m⁻³, airflow resistance in herbage alfalfa at 36% moisture content was higher than that at 20% moisture content.

Airflow resistance prediction equations

Several equations are available in the literature to represent airflow pressure drop data. In this study, the experimental data are represented with Shedd’s equation (Shedd 1953):

\[ Q = A (\Delta P)^B \]  \hspace{1cm} (1)

and Hukill-Ives’ equation (Hukill and Ives 1955):

\[ \Delta P = \frac{\alpha Q^2}{\ln(1 + bQ)} \]  \hspace{1cm} (2)

where:

- \( Q \) = airflow rate \( (m^3 \cdot s^{-1} \cdot m^{-2}) \),
- \( \Delta P \) = pressure drop per unit depth of material in the container \( (Pa \cdot m^{-1}) \), and
- \( A, B, \alpha, b \) = constants.

Due to its simple form, Eq. 1 is used for numerical solution.
Fig. 5. Airflow vs. pressure drop for herbage alfalfa at moisture content of 20% for bulk densities of 93 kg/m³ to 210 kg/m³.

Fig. 6. Airflow vs. pressure drop for herbage alfalfa at moisture content of 36% for bulk densities of 93 kg/m³ to 210 kg/m³.

Table III. Coefficients for velocity and density terms in airflow prediction of Equation 6 for hay

<table>
<thead>
<tr>
<th>Source</th>
<th>Theoretical</th>
<th>$A$</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guillo (1946)</td>
<td>Theoretical</td>
<td>1.50</td>
<td>3.00</td>
</tr>
<tr>
<td>Matthies (1956)</td>
<td>Lucerne, few leaves, compressed</td>
<td>1.60</td>
<td>2.40</td>
</tr>
<tr>
<td></td>
<td>Lucerne, more leaves</td>
<td>1.54</td>
<td>2.74</td>
</tr>
<tr>
<td>Day (1957)</td>
<td>Compressed alfalfa, high stems</td>
<td>1.41</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>Compressed alfalfa, moderate leaf</td>
<td>1.40</td>
<td>3.26</td>
</tr>
<tr>
<td>VanDuyne and Kjelgaard (1964)</td>
<td>Baled alfalfa</td>
<td>1.60</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>Baled clover</td>
<td>1.46</td>
<td>2.62</td>
</tr>
<tr>
<td>Present study</td>
<td>Alfalfa stems and and leaves</td>
<td>1.23</td>
<td>3.12</td>
</tr>
</tbody>
</table>

\[ A = 0.0121 - 6.02 \times 10^{-2} f_m + 9.12 \times 10^{-2} f_m^2 \]  
\[ R^2 = 0.970, \quad s.e. = 0.0066 \]  

where:  
- $f_m$ = fines content in sample (mass fraction), and  
- $\rho_w$ = wet bulk density (kg·m⁻³).

To incorporate the effect of fines on pressure drop, Eq. 5 proposed by Haque et al. (1978) and given in ASAE data D272.2 (ASAE 1991b) was developed.

\[ (\Delta P)_{\text{fines}} = (\Delta P)_{\text{clean}} \left[ 1 + (0.361 + 1.298 Q f_m) \right] \]  
\[ R^2 = 0.87 \]  

The NLIN procedure in SAS (SAS 1982) was used to estimate the constants of Eq. 1.

The ratio of pressure drop of fines mixed pellets to that for samples of clean pellets increased with fines concentration and airflow rate. A maximum value of about 27 was obtained at an airflow rate of 0.299 m³·s⁻¹·m⁻² and fines concentration of 25%. The same observation was obtained by Haque et al. (1978) while studying airflow resistance of corn mixed with fines. However, for canola mixed with fines, Jayas and Sokhansanj (1989) found that the ratio was relatively constant with airflow rate. This is because of the small difference in pressure pattern and airflow lines within the bulk (Segerlind 1983). Equation 2 on the other hand is used extensively for estimation of overall static pressures. Equation 1 was transformed to a linear form by taking log of both sides of the equation. The NLIN procedure in SAS (SAS 1982) was used to estimate the constants for Eqs. 1 and 2. Table II lists the estimated constants.

Generally, Eq. 1 gave a better prediction of the experimental data than Eq. 2 for alfalfa herbage, pellets, and cubes. $F$ statistics of 236 to 5900 were obtained from the use of Eq. 1, while Eq. 2 gave $F$ values of 73 to 2600.

Inspection of the values of $A$ and $B$ for fines mixed pellets and herbage alfalfa showed that while values for $A$ varied from test to test, the values for $B$ did not vary significantly. By assigning a constant value of $B=0.634$ to herbage and a constant value of $B = 0.520$ for fines mixed pellets, new values of $A$ were estimated as:

for herbage alfalfa:

\[ A = 8.87 \times 10^{-3} - 3.93 \times 10^{-5} \rho_w \]  
\[ R^2 = 0.995, \quad s.e. = 0.0049 \]

for pellets:
in size of canola and the fines.

VanDuyne and Kjelgaard (1964) developed Eq. 6 to express the relationship between the airflow resistance, the dry bulk density, and airflow rates in baled hay:

$$\Delta P = K \rho_d^m Q^n$$

(6)

where $K, m, n =$ constants. The constants of Eq. 6 were estimated by using NLIN in SAS to obtain:

$$\Delta P = 4.071 \times 10^{-3} \rho_d^{3.12} Q^{1.23}$$

(7)

Table III lists values of $m$ and $n$ for hay as reported by VanDuyne and Kjelgaard (1964). Inspection of constants reveals that the exponents of velocity and density of this study are in close agreement with those of Day (1957) for compressed leafy alfalfa. It appears that with an average value of $m=3.0$ and $n=1.5$, Eq. 6 can be extrapolated to other airflows.

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. The pressure drop versus airflow curves for forage cubes, clean pellets, and fines mixed pellets are nearly straight lines on log-log scale and can be expressed by either Shedd’s or Hukill-Ives’ equations.
2. The pressure drop in herbage alfalfa can be determined from wet bulk density and airflow rate.
3. The pressure drop versus airflow relationship previously developed for hay can be used for herbage alfalfa over a wide range of bulk densities.

ACKNOWLEDGMENT

This project was funded by Saskatchewan Agriculture and Food under the Agricultural Development Fund Program and by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES


APPENDIX A

ESTIMATION OF ERROR DUE TO EDGE EFFECT

Beaverg et al. (1973) investigated the influence of the size of the cross section of bed on the flow characteristics and porosity of randomly packed beds of spheres. They extended the Forchheimer (1901) relationship to predict the airflow resistance through a granular bed as:

\[
\frac{1}{\mu Q} \left( \frac{dp}{dx} \right) = \frac{1}{k} \frac{cQ}{\sqrt{k}} \frac{1}{\nu}
\]

(A1)

where:

- \( Q \) = airflow rate \((m^3 \cdot s^{-1} \cdot m^{-2})\),
- \( k \) = permeability of the bed \((m^2)\),
- \( \mu \) = viscosity of air \((Pa \cdot s)\),
- \( \nu \) = dynamic viscosity, \( \mu/\rho \), \((m^2 \cdot s^{-1})\),
- \( c \) = coefficient of inertia in Forchheimer relation,
- \( \frac{dp}{dx} \) = pressure gradient \((Pa \cdot m^{-1})\), and
- \( \rho \) = density of air \((kg \cdot m^3)\).

According to Eq. A1, a graph of \( \frac{(-dp/dx)}{(\mu Q)} \) versus \( Q \) should be a straight line with slope \( c/\sqrt{k} \nu \) and intercept \( 1/k \). Since both \( (-dp/dx)/(\mu Q) \) and \( Q \) are available from the experimental data, such a graph can be prepared, and \( k \) and \( c \) can be determined using viscosity and density of air. For cubes, \( k = 1.616 \times 10^{-6} \) m and \( c = 0.495 \).

Beaverg et al. (1973) justified experimentally \( k \) to be independent of the ratio of bed size to particle size. For an infinitely large bed, they obtained a value of \( c = 0.55 \) using Eq. A1. Thus the measurement error of pressure drop of cubes due to wall effect can be written as:

\[
\text{Error}\% = \left( \frac{\frac{dp}{dx}}{dx} \right)_\infty - \left( \frac{\frac{dp}{dx}}{dx} \right)_0
\]

(A2)

Substituting \( c = 0.495 \) and \( c_\infty = 0.55 \) into Eq. A1, Eq. A2 becomes:

\[
\text{Error}\% = \frac{1 - \frac{c}{c_\infty}}{1 + \frac{\nu}{c_\infty \sqrt{k} Q}}
\]

(A3)

since \( \nu/(c_\infty \sqrt{k} Q) \) is positive, the maximum error is 10%.