5-2005

Airflow Resistance of Seeds at Different Bulk Densities Using Ergun's Equation

Marek Molenda
Polish Academy of Sciences, Poland

Michael D. Montross
University of Kentucky, michael.montross@uky.edu

Samuel G. McNeill
University of Kentucky, sam.mcneill@uky.edu

Jozef Horabik
Polish Academy of Sciences, Poland

Airflow Resistance of Seeds at Different Bulk Densities Using Ergun's Equation

Notes/Citation Information
Published in *Transactions of the ASAE*, v. 48, issue 3, p. 1137-1145.

Digital Object Identifier (DOI)
https://doi.org/10.13031/2013.18487

Airflow Resistance of Seeds at Different Bulk Densities Using Ergun's Equation

M. Molenda, M. D. Montross, S. G. McNeill, J. Horabik

Abstract. *Airflow resistance of grains and oilseeds has been extensively studied. Traditionally the data has been presented using Shedd's curves. However, this assumes that airflow resistance is independent of grain depth. Grain undergoes compaction during storage that changes the bulk density, porosity, and therefore the airflow resistance. Ergun's equation is a function of particle size and porosity of the granular material. Airflow resistance by Ergun's equation was used to predict the pressure drop across a column of corn, soft white winter wheat, soft red winter wheat, and soybeans at three moisture content levels and two bulk densities. The maximum root mean square error when predicting airflow resistance using Ergun's equation was less than 23 Pa/m when the pressure drop was less than 500 Pa/m. If all data was included up to a pressure drop of 1800 Pa/m, the average root mean square error for calculating airflow resistance was 76 Pa/m. The effect of grain orientation that would be typical in storage bins was negligible, less than a 10% increase in airflow resistance over a range of kernel orientations that varied between −10°, +10°, and 20° from the angle of repose. However, the fill method and resulting bulk density increased the airflow resistance by an order of magnitude. Ergun's equation, with an appropriate model of porosity variation within a storage bin, could be utilized for the design and analysis of grain aeration systems.*

Keywords. *Aeration, Bulk density, Kernel orientation, Porosity, Stored grain.*

Airflow resistance data for airflow through agricultural products are usually presented as curves or equations (Brooker et al., 1992). These formulations imply that airflow resistance (pressure drop) is independent of the depth of the grain. This assumption is not correct, because the density and porosity of grain in the silo changes along the height due to compaction from the grain load (Grundas et al., 1978; Bakker-Arkema et al., 1969). Li and Sokhansanj (1994) compiled the pressure drop versus airflow resistance of numerous grains to develop a generalized equation based on Ergun's (1952) equation or Leva's (1959) equation that are both physical models based on a semi-theoretical analysis.

Pressure drop data for airflow through agricultural grains has traditionally been presented as curves on a log-log scale that relate the superficial air velocity ($m^3/m^2/s$) to the pressure drop per unit depth (Pa/m). Shedd (1953) plotted data for numerous grains with a wide range of airflow rates using a log-log plot.

Article was submitted for review in April 2004; approved for publication by the Food & Process Engineering Institute Division of ASAE in March 2005.

The authors are **Marek Molenda, ASAE Member Engineer,** Associate Professor, and **Jozef Horabik, ASAE Member,** Vice-Director, Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland; **Michael D. Montross, ASAE Member Engineer,** Assistant Professor, and **Samuel G. McNeill, ASAE Member Engineer,** Associate Extension Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky. **Corresponding author:** Michael Montross, 128 Barnhart Building, University of Kentucky, Lexington, KY 40546-0276; phone: 859-257-3000, ext. 106; fax: 859-257-5671; e-mail: montross@bae.uky.edu.

The data Shedd collected assumed that the pressure drop per foot of grain was independent of the depth of grain. It has been shown that this assumption is not accurate for deep masses of grain (Matthies, 1956). Because of the effect of other variables, such as filling method, amount of fines, and increased bulk density in bins (packing), the data collected by Shedd were only valid for bins typically found for on-farm storage.

Calderwood (1973) considered the effect of increased bulk density (packing) and moisture content on the pressure drop. He found that the data from his tests were related to the data of Shedd (1953) by a Shedd's curve multiplier (SCM). The SCM was the ratio of the pressure drop through a grain mass to the pressure drop predicted by Shedd's curve for the grain at the same airflow rate. With a fill density of 639 and 729 kg/m^3, the SCM was 1.18 and 2.72, respectively, for rough rice at a moisture content of 15.2%.

Other researchers have investigated the effect of fines (Haque et al., 1978; Grama et al., 1984), moisture content (Haque et al., 1982), combination of fines and moisture content (Abdelmonsin, 1983), the effect of filling method (Stephens and Foster, 1976, 1978), and the effect of airflow direction (Kumar and Muir, 1986) on the pressure drop versus airflow rate.

Ergun's Equation

Li and Sokhansanj (1994) and Bakker-Arkema et al. (1969) concluded that Ergun's equation could be the basis for a generalized model of airflow resistance through agricultural products. Based on Reynolds' theory for resistance to fluid flow, Ergun (1952) hypothesized that the pressure drop was the summation of the viscous and kinetic energy losses. Ergun's general equation for uniform products can be written as (Li and Sokhansanj, 1994):

$$\frac{\Delta P}{\Delta L} = aV + bV^2 = 2 f_E \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho V^2}{D_p}$$

$$= 2\left(\frac{75}{(\mathrm{Re})_{D_p}} + 0.875 \right) \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho V^2}{D_p} \quad (1)$$

The Reynolds number was defined using the specific surface equivalent diameter (D_p) as:

$$(\mathrm{Re})_{D_p} = \frac{\rho V D_p}{(1-\varepsilon)\mu} \quad (2)$$

Ergun's equation in this form is simple to use after the appropriate parameters have been determined. However, the specific surface equivalent diameter is difficult to determine with irregular and random-sized shapes. However, the volume equivalent particle diameter can be determined by submersion in a graduated cylinder with ethanol and the equation for a sphere. Therefore, Ergun's equation can be rewritten using the volume equivalent particle diameter and two product-dependent constants as (Li and Sokhansanj, 1994):

$$\frac{\Delta P}{\Delta L} = 2 f_E \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho V^2}{d_p}$$

$$= 2\left(\frac{k_1}{(\mathrm{Re})_{d_p}} + k_2 \right) \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho V^2}{d_p} \quad (3)$$

The product-dependent constants (k_1 and k_2) are a function of grain type, quantity of fines, particle size and shape distribution, sphericity, and other surface characteristics.

Patterson et al. (1971) used Ergun's equation to describe the pressure drop through cherry pits. They stated that equations based on Shedd's empirical relationship were useful, but they did not give an explanation of why airflow resistance was changing. Ergun's equation was simple to use and was based on semitheoretical relationships. A multiplier that was product specific was required when using Ergun's equation due to irregular particle shapes and sizes. However, they concluded that the changes in porosity in a grain bed and bulk density were difficult to determine and that Ergun's equation would not be very useful for grain aeration.

Porosity Changes During Storage

During storage, granular materials experience an increase in bulk density (packing) relative to the uncompacted density (test weight) as a result of the vertical pressures exerted by the grain in the bin. The increase in bulk density of grain during storage is influenced by the type of grain, uncompacted bulk density, coefficient of friction between the grain and wall, moisture content, and filling method (Thompson et al., 1987).

Thompson et al. (1987) solved Janssen's (1895) equation to determine bin pressures. Using variable material properties, Janssen's equation was numerically solved to determine the vertical pressure and the resultant change in bulk density. The change in bulk density as a result of overburden pressure was primarily due to realignment of kernels immediately after filling. This realignment of kernels resulted in a higher bulk density and a lower porosity (Thompson et al., 1987).

Shedd's model does not allow for the solution of airflow resistance due to a change in bulk density, except through the use of experimentally determined curve multipliers. Therefore, Ergun's equation is more useful in developing relationships for airflow resistance, since porosity and therefore bulk density are part of the equation. Grundas et al. (1978) measured the change in bulk density and porosity due to vertical static forces that would be typical in grain storage structures. They observed that vertical pressures up to approximately 1 MPa would result in a rapid change in porosity due to movement of kernels to a permanent state of equilibrium.

The objective of this research was to determine the applicability of Ergun's equation to model airflow resistance in grains with variable bulk density and porosity.

Materials and Methods

Pressure Drop

Corn, soybeans, soft red winter wheat, and soft white winter wheat were conditioned to three moisture content levels (55%, 65%, and 75%) using air at 20°C and were referred to as low, medium, and high moisture content, respectively. The initial moisture content of the samples was approximately 13% for the white wheat, corn, and red wheat. The initial moisture content of the soybeans was 11%. The grain was allowed to equilibrate in environmental chambers for three weeks and was mixed by hand once each weekday. The moisture content was determined using the oven method (*ASAE Standards*, 2002b). The uncompacted bulk density was determined using the Winchester cup due to its use in industry (test weight) and for describing the increase in bulk density that occurred for each test. Bulk density of the grain column was determined using a digital scale and the volume of the grain column. The samples were screened according to USDA-GIPSA (1999) procedures, and the percentage of fines, splits, or broken kernels was determined as appropriate. The quantity of fines, splits, or broken kernels was expressed as a weight percentage.

The system used for measuring airflow resistance is shown in figure 1. A cylindrical PVC pipe with a diameter of 0.25 m (10 in.) and a height of 0.61 m (23.75 in.) was used to hold the grain sample during the testing procedures. Air was introduced through a plenum in the bottom of the cylinder. The differential static pressure was measured at depths of 0.05 (2 in.) and 0.45 m (17.75 in.) above the bottom of the cylinder. The static pressure was measured using a variable reluctance differential pressure transducer (Validyne DP103, Northridge, Cal.) with a diaphragm (maximum pressure rating of 1370 Pa (5.5 in. H_2O) and an accuracy of ±0.25% full scale). The pressure transducer was calibrated using a static pressure calibrator (PPC 500, Furness Controls, East Sussex, U.K.). The flow rate was measured using a multiple-nozzle outlet chamber according to ANSI/ASHRAE standard 51-1985 (Colliver et al., 1992) and was based on the pressure drop across a nozzle. In addition, a hot wire anemometer (model 2106, Alnor, Shoreview, Minn.) was used on the outlet of the grain sample container to verify operation of the nozzle chamber.

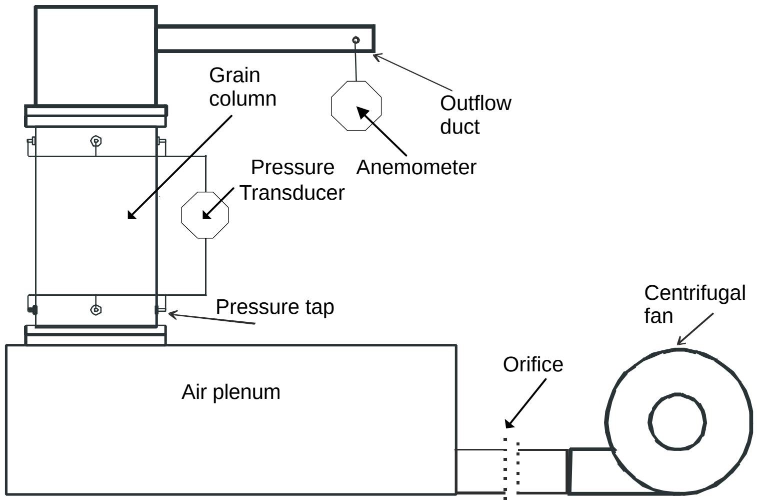

Figure 1. Schematic of the apparatus for measuring airflow resistance in grains as a function of bulk density.

Filling Methods

The grain column was filled using a funnel, as shown in figure 2a. The funnel was kept within 2 cm of the grain surface during filling, and this method was termed funnel +0° filling. In this case, the grain during filling formed a conical sloping surface approximately equal to the filling angle of repose (φ).

To produce different kernel orientations, the grain column was inclined during funnel filling. Kernel orientation was controlled by placing the grain column at an angle of 10° or 20°, which resulted in a kernel orientation 10° or 20° greater than the angle of repose (fig. 2b) and was designated funnel +10° or funnel +20° filling. Kernels were orientated parallel to the bottom of the grain column using the procedure shown in figure 2c, which was referred to as funnel −20° filling.

To obtain a higher bulk density, a "sprinkle" filling method was used. Grain was transferred using a handheld scoop and poured through a wire mesh screen at the top of the column. This resulted in kernels being evenly dispersed over the area of the column. The kinetic energy of the kernels falling through the wire mesh resulted in a denser (less porous) grain column.

Particle Diameter And Porosity

The effective particle diameter is difficult to determine for atypical shapes, and the volume equivalent particle diameter was used as the characteristic dimension in Ergun's equation and the Reynolds number. The volume equivalent particle diameter was determined using a 10 mL graduated cylinder filled with a known volume of ethanol, placing 100 whole kernels at each moisture content into the cylinder, and measuring the change in ethanol volume. The volume equivalent particle diameter was calculated using the equation for a sphere, and three replications were performed for each moisture content.

Kernel density was obtained using the ratio of the mass of a grain sample to volume measured using an air-comparison pycnometer (Quantachrome MVP-2, Boynton Beach, Fla.). The porosity was determined using the following equation:

$$\varepsilon = 1 - \frac{\rho_b}{\rho_k} \tag{4}$$

The bulk density (ρ_b) of the column was determined by weighing the grain column and dividing by the column volume.

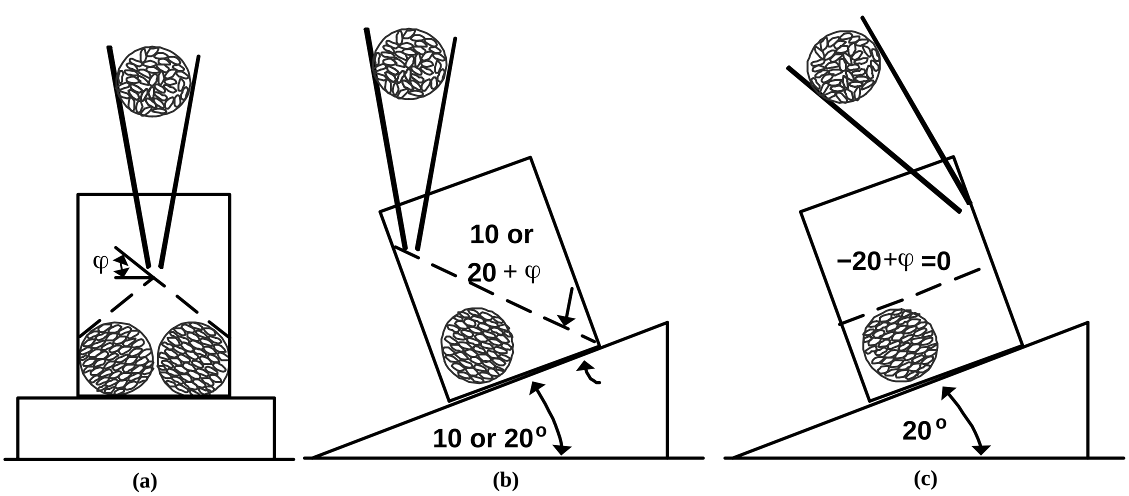

Figure 2. Methods used to fill the grain column using a funnel: (a) funnel +0°, (b) funnel +10° or +20°, and (c) funnel −20° filling.

Table 1. Average (three replications) of fine material, uncompacted bulk density, kernel density, and moisture content of the four grain types investigated at the three moisture levels.

Grain	FM[a]	Low MC: MC (% w.b.)	Low MC: Bulk Density (kg/m³)	Low MC: Kernel Density (kg/m³)	Medium MC: MC (% w.b.)	Medium MC: Bulk Density (kg/m³)	Medium MC: Kernel Density (kg/m³)	High MC: MC (% w.b.)	High MC: Bulk Density (kg/m³)	High MC: Kernel Density (kg/m³)
White wheat	0.2	10.1	944	1370	12.8	750	1300	14.6	734	1330
Red wheat	0.1	10.5	1015	1380	12.7	818	1330	14.6	798	1370
Corn	1.4	10.1	940	1260	12.5	949	1270	14.5	943	1320
Soybeans	3.4	7.9	902	1210	9.2	711	1180	12.9	902	1250

[a] FM includes fine material, split soybeans, and broken kernels as appropriate for each grain type.

Results and Discussion

Table 1 presents the fine material, moisture content, bulk density, and kernel density of the four grain types investigated at the three moisture content levels. The uncompacted bulk density of red and white wheat increased as the moisture content decreased, but remained virtually unchanged for corn and soybeans. The kernel density remained approximately the same for all moisture contents. White wheat had a kernel density of 1330 kg/m^3 at a moisture content of 14.6% and 1370 kg/m^3 at a moisture content of 10.1%.

Bulk Density and Porosity Changes

Bulk density differences were achieved by filling the chamber using the sprinkle and funnel methods. Sprinkle filling resulted in a bulk density that was 2.6% to 11.5% greater than the initial uncompacted bulk density (test weight). Funnel filling resulted in a bulk density that was slightly greater or less than the uncompacted bulk density determined using the Winchester cup method (fig. 3). The increase in bulk density with sprinkle and funnel filling for the three moisture contents averaged 41 and 0 kg/m^3, respectively.

The primary variable that determines the resistance of grain to airflow is the porosity. Using the two filling methods resulted in grain with repeatable differences in bulk density and therefore repeatable differences in porosity. The kernel density was measured (table 1) and porosity determined using the measured bulk density. Figure 4 shows the porosity of the grain column using the four different grain types, three moisture levels, and two filling methods. The variation in porosity was not uniform and depended on the grain type and moisture content. For instance, white wheat at the low moisture content (10.1%) had a porosity of 36.4% and 40.5% when sprinkle and funnel filled, respectively. At the high moisture content (14.6%), the porosity was 39.6% and 43.5% when sprinkle and funnel filled, respectively. Grain at the medium moisture content level had a consistently lower porosity for the sprinkle filling method and therefore would be expected to have the highest airflow resistance.

Sprinkle filling was not as repeatable as the filling methods utilizing a funnel. The filling method with the funnel was mechanized, and the bulk density within the column had lower variability. The level of fines, splits, or broken kernels in the grains samples was not varied. However, these variables would be expected to significantly influence the porosity and therefore the pressure drop. Previous research indicated that the level of damage and fines in grain significantly influenced the pressure drop (Grama et al., 1984; Giner and Denisienia, 1996).

Effect of Particle Orientation

The bulk density of soft red winter wheat at a moisture content of 12.7% (medium) using the four funnel filling methods resulted in a consistent bulk density of approximately 820 kg/m^3. Changing the kernel orientation did not change the bulk density of the grain column since the kinetic energy of grain during filling was approximately equal. The pressure drop of soft red wheat at a moisture content of 12.7% using five filling methods (sprinkle, funnel +0°, funnel +10°, funnel +20°, and funnel −20°) is shown in figure 5. A kernel orientation of −20° and +20° from the angle of filling repose

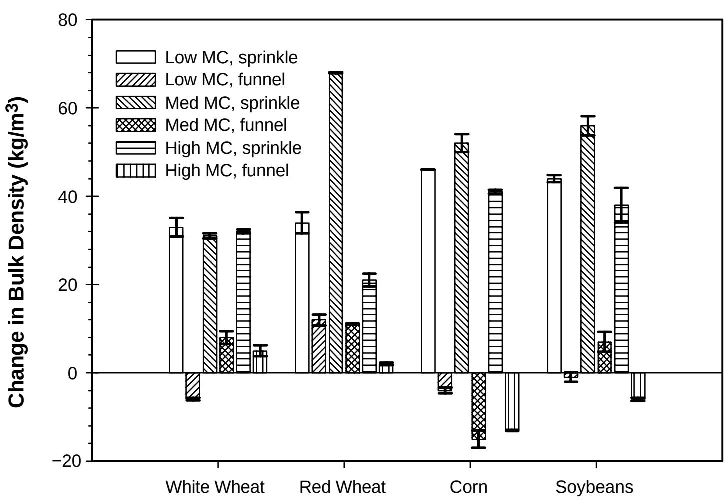

Figure 3. Average change in bulk density and standard error (three replications) using the four grain types, two filling methods, and three moisture content levels compared to the uncompacted bulk density (test weight) determined using the Winchester cup.

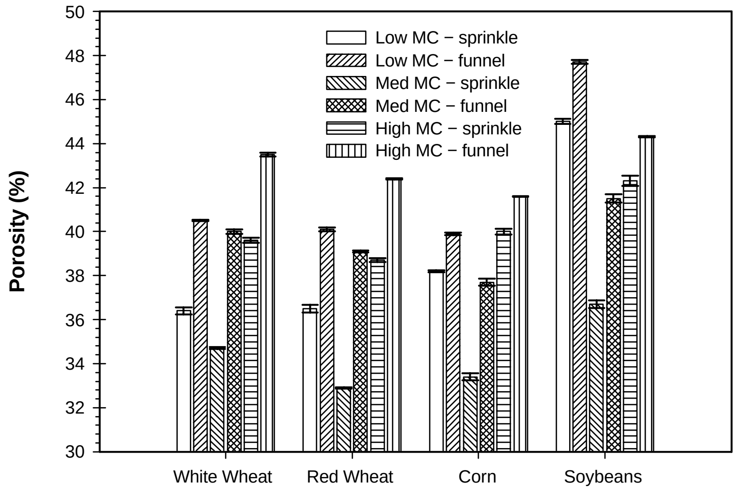

Figure 4. Average porosity and standard error (three replications) with four grain types, two filling methods, and three moisture content levels.

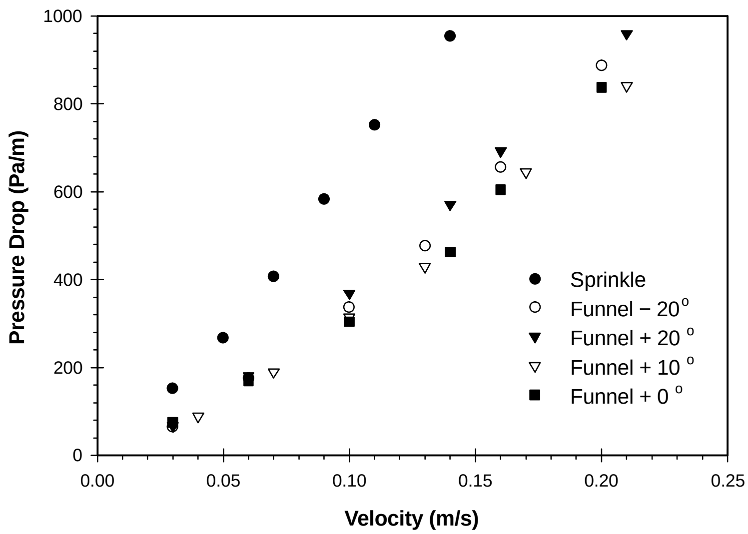

Figure 5. Airflow resistance of soft red wheat at a moisture content of 12.7% using five filling methods: sprinkle, funnel +0°, funnel +10°, funnel +20°, and funnel −20°.

resulted in a slightly higher airflow resistance; however, it was within 10% of the funnel +0° and funnel +10° filled red wheat. This difference was not as large as the 60% difference reported by Kumar and Muir (1986) for wheat with different kernel orientations. Possible reasons for the discrepancy could be the result of using clean wheat in this study and differences in the porosity. However, the sprinkle-filled grain column had a pressure drop almost 100% greater than any of the funnel-filled data. Results from Kumar and Muir (1986) could have been due to denser packing, which would have approximated the sprinkle filled results in this study. The effect of kernel orientation was most evident with the red and white wheat and was less noticeable with corn and soybeans. The medium moisture content level and red wheat had the largest differences in pressure drop due to kernel orientation. The change in pressure drop due to kernel orientation was not as great at the low and high moisture, and these data are not shown.

Volume Equivalent Particle Diameter and Friction Factor

The volume equivalent particle diameter for the four grain types and three moisture content levels determined using displacement of ethanol is shown in table 2. The average volume equivalent particle diameter was largest for corn at all moisture content levels and varied between 7.95 and 6.23 mm at moisture contents of 10.1% and 14.5%, respectively. The red and white wheat had the smallest average volume equivalent particle diameter (between 2.82 and 3.72 mm at all moisture levels).

The friction factor is plotted in figure 6 as a function of the Reynolds number calculated using the average volume equivalent particle diameter for red wheat at the three moisture contents, two bulk densities, and three kernel orientations. The data for different kernel orientations at the low and high moisture content were combined with the

Table 2. Average (three replications of 100 kernels) of volume equivalent particle diameter (mm) determined using immersion in ethanol of the four grain types at three moisture levels.

	Volume Equivalent Particle Diameter (mm)		
Grain	Low MC	Medium MC	High MC
White wheat	3.30	3.72	3.60
Red wheat	3.27	3.62	2.82
Corn	7.95	7.90	6.23
Soybeans	5.75	5.84	4.70

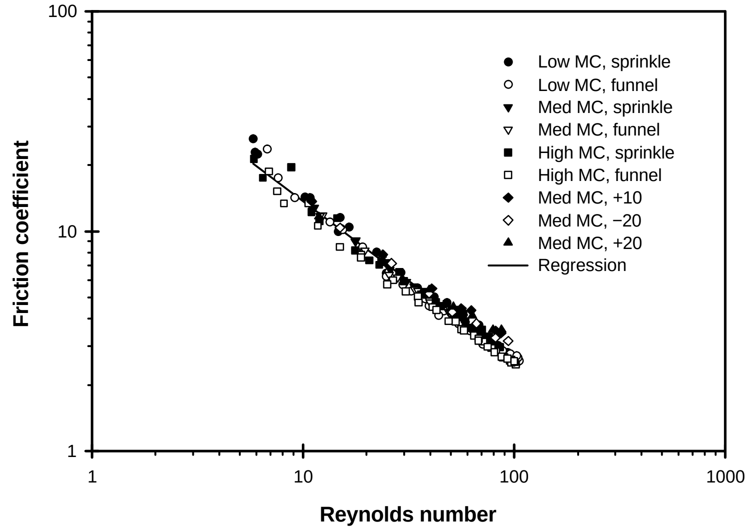

Figure 6. Friction coefficient (*f*) versus Reynolds number for red wheat at three moisture content levels, two bulk densities, and different kernel orientations (number of tests = 220).

funnel filled data to simplify figure 6. A regression was performed through the entire data set for red wheat with an r^2 of 0.98. There was little variation between different moisture contents, bulk densities, and kernel orientations for the red wheat. This indicated that equation 3 would be a good generalized model to predict the product-dependent constants required to estimate the airflow resistance for a specific grain type over a wide range of conditions.

Regressions were performed in a similar manner for white wheat, corn, and soybeans over the entire data range (fig. 7). The friction factor for red and white wheat was considerably higher than corn and soybeans. On a log-log plot, the friction factor decreased linearly with increased Reynolds number.

Estimation of Ergun's Coefficients

Table 3 lists the values of k_1 and k_2 in equation 3 that were determined using the regressions performed with the data in figure 7. Red wheat resulted in values of 198.5 and 1.628 for k_1 and k_2, respectively. Li and Sokhansanj (1994) reported values of 237.6 and 2.297 for k_1 and k_2 for wheat, respectively, which are similar to this study. Ergun's derivation of the coefficients resulted in values of 75 and 0.875 for k_1 and k_2, respectively. The coefficients determined in this study were considerably larger than Ergun's derivation but reflect the non-uniform shape and size distribution of the wheat kernels. Ergun's coefficients were based on a theoretical analysis of uniform, spherical particles. The non-spherical shape of grains and random size distribution resulted in coefficients k_1 and k_2 being considerably greater than the theoretical values for spherical particles.

The coefficients for corn in this study were 191.2 and 2.176 for k_1 and k_2, respectively (table 3). This compared favorably to the results of Li and Sokhansanj (1984), who obtained values of 298.8 and 3.084 for k_1 and k_2, respectively. Patterson et al. (1971) used a multiplier with Ergun's equation between 4.2 and 6.5, which resulted in a k_1 value between 315 and 488 and a k_2 value between 3.675 and 5.688 for corn. The multipliers they determined were fit to individual tests of varying moisture content and porosity.

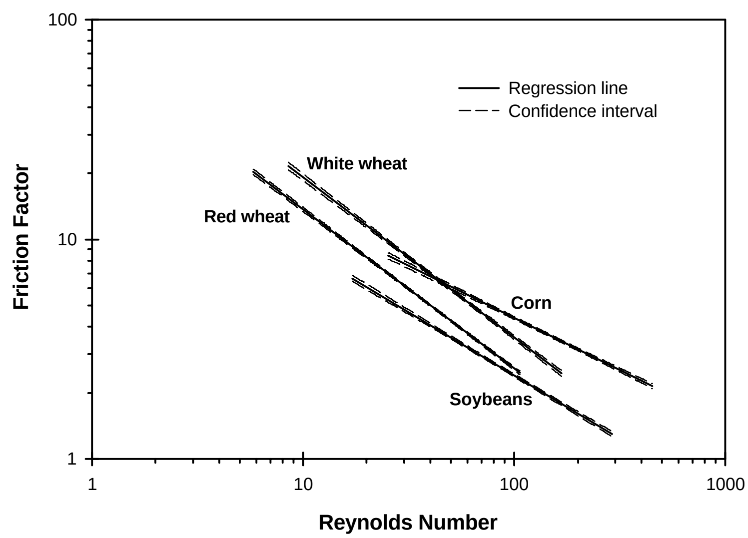

Figure 7. Friction coefficient (*f*) versus Reynolds number and the 95% confidence interval for red wheat (N = 220), white wheat (N = 169), corn (N = 184), and soybeans (N = 203) at three moisture content levels, two bulk densities, and different kernel orientations.

Table 3. Summary of regressed coefficients k_1 and k_2 from figure 7.

Grain	k_1	k_2
White wheat	198.5	1.628
Red wheat	123.9	1.657
Corn	191.2	2.176
Soybeans	113.2	1.186

Figure 8 presents the measured and predicted pressure drop for soft red wheat at the 10.5% (low) and 12.7% (medium) moisture content using two filling methods. The predicted pressure drop was based on the average value of the porosity for each replication, and there were slight variations in porosity between replications. Red wheat sprinkle filled at the medium moisture content (12.7%) had porosity values of 33.4%, 33.4%, and 33.3%. However, when 10.5% moisture content red wheat was sprinkle filled, the porosity was 38.5% and 38.1%, and those differences in the pressure drop can be seen in figure 8. At an air velocity of 0.20 m/s, the pressure drop was 1120 and 890 Pa/m for sprinkle and funnel filling, respectively, at a moisture content of 10.5%. The pressure drop at an air velocity of 0.20 m/s at the medium moisture content (12.7%) was 1610 and 1010 Pa/m for sprinkle and funnel filling, respectively. Sprinkle filling at an air velocity of 0.2 m/s resulted in a pressure drop increase of 26% and 59% compared to funnel filling at a moisture content of 10.5% (low) and 12.7% (medium), respectively.

The differences in the pressure drop with funnel filled red wheat at a moisture content of 10.5% and 12.7% were not substantially different, less than a 14% difference at an air velocity of 0.2 m/s. This was due to the similarities in the porosity that are shown in figure 4. The increase in the pressure drop with sprinkle filled red wheat at a moisture content of 10.5% and 12.7% were due to the differences in porosity. At a moisture content of 12.7% with sprinkle filling, the porosity was 32.9%, which was 3.6 percentage points less than the porosity at a moisture content of 10.5% with sprinkle filling. The predicted pressure drop using the equation from Haque et al. (1982) at a moisture content of 12.7% is included in figure 8. Data from Haque are very similar to the results found in this study for funnel filled wheat. Not shown are the data for wheat funnel filled at a moisture content of 10.5% and 14.6%, which were also similar to Haque's prediction. However, Haque's equation does not take into account differences in bulk density and did not accurately predict the sprinkle filled data.

The measured and predicted pressure drop for soybeans at a low (7.9%) and medium (9.2%) moisture content with sprinkle and funnel filling is shown in figure 9. Moisture content had less influence on pressure drop for soybeans than for red wheat in all tests. The large errors in the predicted pressure drop for soybeans sprinkle filled at a moisture content of 9.2% were due to differences in the calculated porosity between replications. The porosity was 32.8%, 32.8%, and 33.1% for the three replications. If the predicted pressure drop was calculated using the coefficients determined for individual replications, the error was considerably lower.

Table 4 summarizes the root mean square errors when the airflow resistance up to a maximum pressure drop of 500 and 1800 Pa/m for the four grain types, three moisture content levels, two bulk densities, and three kernel orientations was predicted using equation 3 and constants from table 3. At a maximum pressure drop of 500 Pa/m, the root mean error was less than 23 Pa/m for all four crop types. Data were collected up to a maximum pressure drop of 1800 Pa/m, considerably higher than most aeration systems, and the maximum root mean square error increased to 108 Pa/m.

Moisture content and variety would be expected to have considerable influence on the airflow resistance. Crop varieties have a wide range in kernel size and shape distribution, which would be expected to influence the porosity and bulk density within a bin. Thompson et al. (1987) investigated the change in bulk density of six varieties of wheat as a function of moisture content and vertical pressure. The bulk density and porosity within a grain bin varied due to moisture content and vertical pressure. Moisture content, quantity of fines, and variety would be expected to influence the airflow resistance, but this could be taken into account using the volume equivalent particle diameter and the porosity of the grain bulk due to fines.

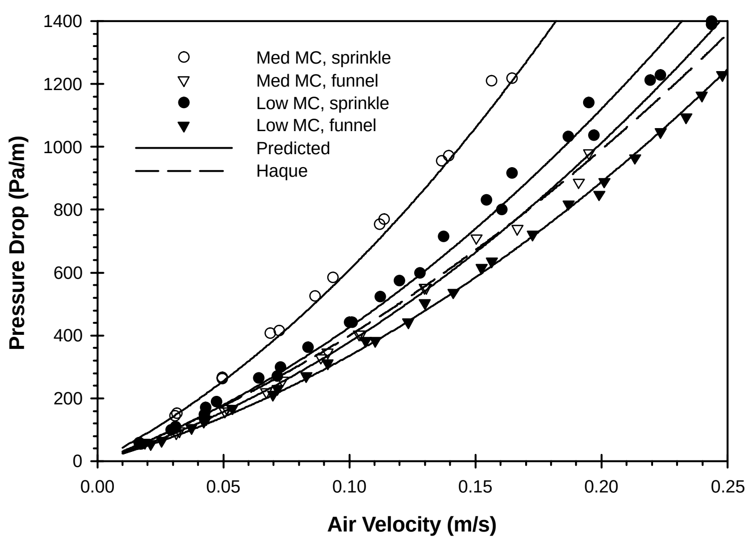

Figure 8. Measured and predicted pressure drop versus air velocity for soft red wheat at the low (10.5%) and medium (12.7%) moisture content for sprinkle and funnel filling, including prediction using the equation from Haque et al. (1982) for wheat at a moisture content of 12.7%.

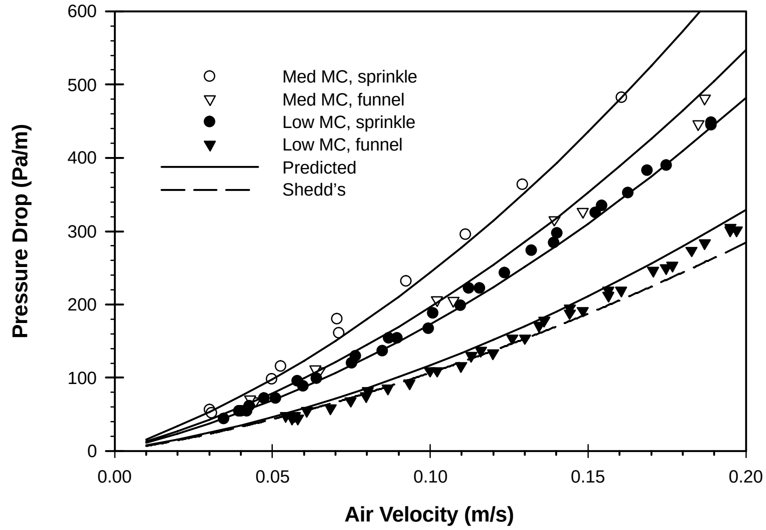

Figure 9. Measured and predicted pressure drop versus air velocity for soybeans at the low (7.9%) and medium (9.2%) moisture content sprinkle versus funnel filling, including Shedd's prediction using data from *ASAE Standards* (2002a).

Table 4. Root mean square errors in predicting airflow resistance up to a maximum pressure drop of 500 and 1800 Pa/m using equation 3 and the product constants in table 3 for the four grain types, three moisture content levels, two bulk densities, and three kernel orientations (number of tests is in parentheses).

	Root Mean Square Errors	
Grain	500 Pa/m	1800 Pa/m
White wheat	23 (95)	56 (169)
Red wheat	18 (80)	78 (194)
Corn	19 (88)	108 (184)
Soybeans	19 (104)	63 (203)

CONCLUSIONS

The data collected indicated that Ergun's equation could be successfully applied to grain aeration design and analysis. Previous work indicated that Ergun's equation would not be applicable to grain aeration due to variations in bulk density and therefore porosity within a grain bin. However, previous research indicated that variations in bulk density and porosity could be estimated using granular mechanical models. The overall error using Ergun's equation was less than 23 Pa/m when the pressure drop was less than 500 Pa/m. When all data were included up to a pressure drop of 1800 Pa/m, the standard error averaged 76 Pa/m. The effect of grain orientation that would be typical in storage bins was negligible, accounting for less than a 10% increase in airflow resistance. However, the fill method and resulting bulk density increased the airflow resistance by an order of magnitude. Ergun's equation, with an appropriate model of porosity variation during storage, can be utilized for the design and analysis of grain aeration systems.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support from USDA-NRI under contract number 2001-35503-10025. The authors would also like to thank Wei Chen and Robert Prewitt for assisting with the laboratory work. This article is published with the approval of the Director of the Kentucky Agricultural Experiment Station and designated paper number 04-05-065.

REFERENCES

Abdelmonsin, G. A. 1983. Airflow characteristics under grain aeration and drying conditions. Unpublished MS thesis. Manhattan, Kansas: Kansas State University.

ASAE Standards. 2002a. D272.3: Airflow resistance of grains, seeds, other agricultural products, and perforated metal sheets. St. Joseph, Mich.: ASAE.

ASAE Standards. 2002b. S352.2: Moisture measurement - Unground grain and seeds. St. Joseph, Mich.: ASAE.

Bakker-Arkema, F. W., R. J. Patterson, and W. G. Bickert. 1969. Static pressure-airflow relationships in packed beds of granular biological materials such as cherry pits. *Trans. ASAE* 12(1): 172-174, 178.

Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1992. *Drying and Storage of Grains and Oilseeds.* New York, N.Y.: Van Nostrand Reinhold.

Calderwood, D. L. 1973. Resistance to airflow of rough, brown, and milled rice. *Trans ASAE* 16(3): 525-527, 532.

Colliver, D. G., W. E. Murphy, and W. Sun. 1992. Evaluation of the techniques for the measurement of air leakage of building components. ASHRAE Research Project 438-RP. Atlanta, Ga.: ASHRAE.

Ergun, S. 1952. Fluid flow through granular beds. *Chem. Eng Progress* 48(2): 89-94.

Giner, S. A., and E. Denisienia. 1996. Pressure drop through wheat as affected by air velocity, moisture content, and fines. *J. Agric. Eng. Res.* 63(1): 73-86.

Grama, S. N., C. J. Bern, and C. R. Hurburgh, Jr. 1984. Airflow resistance of mixtures of shelled corn and fines. *Trans. ASAE* 27(1): 268-272.

Grundas, S., B. Szot, and W. Wozniak. 1978. Variability of the porosity of cereal grain layer under the influence of static loading. *Zeszyty Problemowe Postepow Nauk Rolniczych*. 203: 32-40.

Haque, E., G. H. Foster, D. S. Chung, and F. S. Lai. 1978. Static pressure drop across a bed of corn mixed with fines. *Trans. ASAE* 21(5): 997-1000.

Haque, E., Y. N. Ahmed, and C. W. Deyoe. 1982. Static pressure drop in a fixed bed of grain as affected by grain moisture content. *Trans. ASAE* 25(4): 1095-1095.

Janssen, H. A. 1895. Versuche uber getreidedruck in silozellen. *Zeitschrift des Vereines Deutscher Ingenieure*. 39(35): 1045-1049.

Kumar, A., and W. E. Muir. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method, and dockage. *Trans. ASAE* 29(5): 1423-1426.
Leva, M. 1959. *Fluidization*. New York, NY.: McGraw-Hill.
Li, W., and S. Sokhansanj. 1994. Generalized equation for airflow resistance of bulk grains with variable density, moisture content, and fines. *Drying Tech*. 12(3): 649-667.
Matthies, H. J. 1956. Stromungswiderstand beim Beluften landwirtschaftlicer Ernteguter. VDI-Forschungsheft, Nr. 454, Dusseldorf, Germany.
Patterson, R. J., F. W. Bakker-Arkema, and W. G. Bickert. 1971. Static pressure-airflow relationships in packed beds of granular biological materials such as grain - II. *Trans ASAE* 14(1): 172-174,178.
Shedd, C. K. 1953. Resistance of grain and seeds to airflow. *Agric. Eng*. 34: 616-619.
Stephens, L. E., and G. H. Foster. 1976. Grain bulk densities as affected by mechanical grain spreaders. *Trans. ASAE* 19(2): 354-358, 363.
Stephens, L. E., and G. H. Foster. 1978. Bulk properties of wheat and grain sorghum as affected by a mechanical grain spreader. *Trans. ASAE* 21(6): 1217-1218, 1221.
Thompson, S. A., S. G. McNeill, I. J. Ross, and T. C. Bridges. 1987. Packing factors of whole grains in storage structures. *Applied. Eng. In Agric.* 3(2): 215-221.
USDA-GIPSA. 1999. Official United States Standards for Grain. Washington, D.C.: USDA Grain Inspection, Packing, and Stockyards Administration (USDA-GIPSA).

NOMENCLATURE

a, b = product-dependent coefficients
d_p = volume equivalent particle diameter (m)
f_E = friction factor (dimensionless)
k_1, k_2 = product-dependent coefficients
$(Re)_{dp}$ = Reynolds number based on volume equivalent diameter (dimensionless)
$(Re)_{Dp}$ = Reynolds number based on specific surface equivalent diameter (dimensionless)
V = superficial velocity (m/s)
D_p = specific surface equivalent diameter (m)
ΔL = length (m)
ΔP = pressure drop (Pa)
ε = porosity (dimensionless)
μ = viscosity of air (N/m s)
ρ = density of air (kg/m^3)
ρ_b = bulk density
ρ_k = kernel density