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

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

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PERMEABILITY OF CORN, SOYBEANS, AND SOFT RED AND WHITE WINTER WHEAT AS AFFECTED BY BULK DENSITY

M. D. Montross, S. G. McNeill

ABSTRACT. *Darcy's law is a function of viscosity, permeability, and velocity and can be used to predict the airflow resistance in granular materials at low air velocities. Permeability also governs the magnitude of natural convection currents during periods of non-aerated grain storage. The permeability of corn, soybeans, soft white winter wheat, and soft red winter wheat were measured as a function of bulk density and moisture content. Air was passed through a column of grain and the flow rate and pressure drop measured. Bulk density and kernel density were also measured to determine the porosity of grain in the test column. Two filling methods were used to change the bulk density of grain by approximately 50 kg/m*^{3}*, an increase of 7%. This resulted in a reduction in porosity of approximately 4 percentage points. However, permeability decreased by a maximum of 45%. Wheat had the lowest permeability (between* 1.15×10^{-8} *and* 7.29×10^{-9} *m*^{2} *or highest resistance coefficient between 1591 and 2510 Pa·s/m*^{2}*, respectively, depending on bulk density and moisture content), while corn and soybeans were similar (permeability varied between* 1.30×10^{-8} *and* 3.03×10^{-8} *m*^{2} *or resistance coefficient between 1,408 and 604 Pa·s/m*^{2}*, respectively). Experiments were conducted up to an air velocity of 0.0052 m/s that resulted in a Reynolds number of 2.5, which was slightly above the maximum air velocity expected during non-aerated grain storage. Nevertheless, Darcy's law would be appropriate for predicting natural convection currents during non-aerated storage.*

Keywords. *Darcy's law, Grain storage, Non-aerated.*

Prediction of natural convection currents during non-aerated grain storage can be accomplished using Darcy's law (Darcy, 1856). Darcy's law is valid for creeping flows and is a function of the permeability of the porous media (sometimes reported as resistance coefficient that is defined as the fluid viscosity divided by the permeability). Numerous researchers have utilized Darcy's law to predict natural convection during periods of non-aerated grain storage (Singh et al., 1993; Casada and Young, 1994; Khankari et al., 1995; Montross et al., 2002).

All of these numerical models of heat, mass, and momentum transfer during grain storage have indicated that the permeability of grain was one of the primary unknowns. Natural convection currents significantly effected moisture migration and the amount of time required for grain to cool or rewarm during storage. To improve the accuracy of grain storage models, permeability needs to be better quantified. A wide range of permeabilities has been reported for shelled corn. Khankari et al. (1995) analyzed Patterson's et al. (1971) data to calculate the permeability for corn in the range of 2.06×10^{-8} and 3.45×10^{-8} m^2 (resistance coefficient of 888 and 530 Pa·s/m^2, respectively) between the moisture content of 16.0% and 23.7%. Khankari et al. (1995) measured the permeability of 13.1% moisture corn as 3.5×10^{-9} m^2 (523 Pa·s/m^2) and 12.7% wheat as 2.55×10^{-9} m^2 (7177 Pa·s/m^2). In an earlier study, Hunter (1983) reported a permeability of 2.55×10^{-8} and 5.84×10^{-9} m^2 (or a resistance coefficient of 719 and 3131 Pa·s/m^2, respectively) for corn and wheat based on Shedd's data (Shedd, 1953).

Grain during storage experiences packing and compaction due to the vertical pressure exerted by the grain mass. Packing results in a change in bulk density of the grain mass, which in turn results in a change in porosity since little particle deformation is expected at the low pressures typically experienced during grain storage (Thompson and Ross, 1983). Determining the permeability of grain as a function of bulk density is important for predicting natural convection currents in stored grain.

The objective of this study was to measure the resistance coefficient (or permeability) of corn, soybeans, and soft red and white winter wheat as a function of bulk density and moisture content.

THEORY

Traditionally the basis of nearly all engineering calculations for flow through porous media has been based either on Darcy's law or on empirical findings. Darcy's law can be written as:

$$\frac{\partial P}{\partial x} = -\frac{\mu}{k} v = -Rv \qquad (1)$$

Darcy's law states that the pressure drop varies linearly with the velocity (v). The permeability (k), or the resistance coefficient (R), reflects the difficulty in moving a fluid

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The authors are **Michael D. Montross,** Assistant Professor, **ASAE Member Engineer,** Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky; and **Samuel G. McNeill, ASAE Member Engineer,** Associate Extension Professor, Biosystems and Agricultural Engineering, University of Kentucky Research and Education Center, Princeton, Kentucky. **Corresponding author:** Michael D. Montross, Biosystems and Agricultural Engineering, 128 Barnhart Bldg., University of Kentucky, Lexington, KY 40546-0276; phone: 859-257-3000 ext. 106; fax: 859-257-5671; e-mail: montross@bae.uky.edu.

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through a porous media and in principle is only a function of the pore structure and viscosity (μ) of the fluid (Greenkorn, 1983). Higher values of the resistance coefficient (R) indicated a porous media that created a greater pressure drop; conversely higher values of permeability (k) indicated a porous media that created a lower pressure drop.

The resistance coefficient can be determined by measuring the pressure drop through a material at a given flow rate under steady state conditions. Equation 1 can be rearranged and a linear regression performed to determine the resistance coefficient and permeability.

It was assumed that Darcy's law was valid in three dimensions and permeability was a second-order tensor dependent on directional properties. Numerous researchers have investigated the anistropic behavior of grains related to permeability and airflow resistances. However, kernel orientation and therefore filling method would influence this behavior.

Bin filling methods would be expected to influence the structure of the grain mass, i.e. bulk density, porosity, and kernel orientation. Bins filled through a spout would have a kernel orientation that would be similar to the filling angle of repose and a lower bulk density due to the lower kinetic energy of the kernels during filling. A grain spreader results in a higher bulk density (Chang et al., 1983; 1986) and a more random kernel orientation.

There has been a large range in measured resistance values based on airflow direction and kernel orientation. Hood and Thorpe (1992) reported the resistance coefficient of 12% w.b. wheat as 3420 and 3740 Pa s m^{-2} in two dimensions, a difference of 10%. However, linseed was strongly anistropic with a resistance coefficient of 7710 and 14,400 Pa s m^{-2} in two dimensions. Kumar and Muir (1986) found at an airflow rate of 0.077 $m^3/m^2 \cdot s$ the resistance to flow in the horizontal direction was 63% of that in the vertical direction for cleaned spout filled wheat. Jayas et al. (1987) reported the resistance of canola in the horizontal direction to be 60% of that in the vertical direction.

MATERIALS AND METHODS

Corn, soybeans, soft red and white winter wheat were allowed to equilibrate to three moisture content levels (at 20°C/55%, 20°C/65%, and 20°C/75%) that would be typical of moisture contents for short, moderate, and long-term storage. Grain moisture was determined using the oven method (*ASAE Standards*, 1999a) and test weight using the Winchester cup. Samples were screened according to USDA-GIPSA procedures and the percentage of fines, splits, or broken kernels determined.

The system used for measuring permeability is shown in figure 1. A cylindrical PVC pipe with an inside diameter of 0.254 m (10 in.) and a height of 0.61 m (23.8 in.) was used for the test column. Air was introduced at the bottom of the cylinder and the static pressure measured 0.10 m from the bottom. The static pressure was measured using a Validyne DP103 (Northridge, Calif.) variable reluctance differential pressure transducer, using a diaphragm with a maximum pressure rating of 124 Pa (0.55 in H_2O) with an accuracy of ±0.25% full scale. The pressure transducer was calibrated using a Furness Controls PPC 500 static pressure calibrator (East Sussex, United Kingdom). The flow rate was controlled using a Scienceware (Fischer Scientific, Pittsburgh, Pa.) flow meter with a maximum flow rate of 0.00041 m^3/s (0.87 ft^3/min) and an accuracy of ±1% at full scale. The flow rate was verified using a recently calibrated Omega FMA 1720 with a full scale range of 0.00017 m^3/s and an accuracy of ±1.5% full scale.

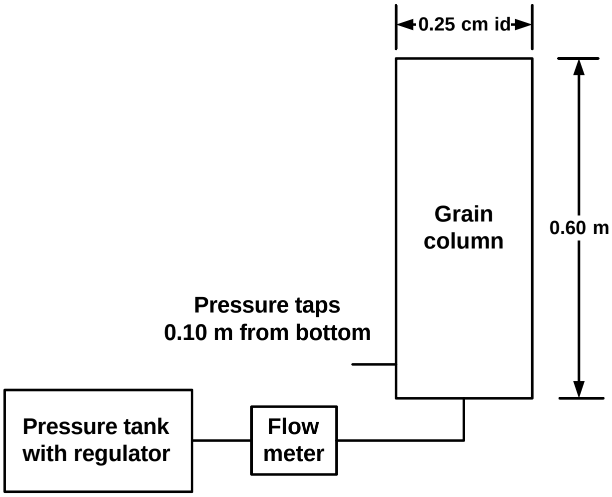

Figure 1. Schematic for apparatus to measure permeability of grains.

The apparatus was weighed using a digital scale to calculate the bulk density and determine the average porosity. The porosity of each grain sample was determined using an air-comparison pycnometer Quantachrome MVP-2 (Boynton Beach, Fla.). The porosity was determined using the following equation (Mohsenin, 1986):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_k} \qquad (2)$$

where ρ_b is the bulk density and ρ_k is the kernel density.

The resistance coefficient (or permeability) was determined by measuring the pressure drop per unit depth and the superficial velocity (Goedeken and Tong, 1993). Pressure drop per unit depth was plotted versus the air velocity and a linear regression performed. Under conditions of Darcy flow, the slope of the line should be linear with an intercept of zero. The resistance coefficient represented the slope of the line and permeability could be calculated by dividing the fluid (air) viscosity by the slope of the line. Results from this study were reported in terms of the resistance coefficient (R) to allow for comparison to previous work.

The apparatus was filled using two methods to produce varying bulk densities and kernel orientations. The column was filled through a screen to simulate a bin filled using a grain spreader and termed sprinkle filled. A wire mesh screen was placed on top of the column and grain was poured by hand through the screen. The second method utilized a funnel that was kept within 2 cm of the grain surface that simulated a spout-filled bin. Sprinkle filled produced a higher bulk density and a random kernel orientation. The orientation of the kernels using the funnel filled method was approximately equal to the filling angle of repose and would simulate a bin filled through a spout. The container was also filled at angles that resulted in particle orientations that were 10° and 20° greater than the angle of repose (fig. 2). This was done using the screen and funnel to determine the anisotropic behavior of wheat.

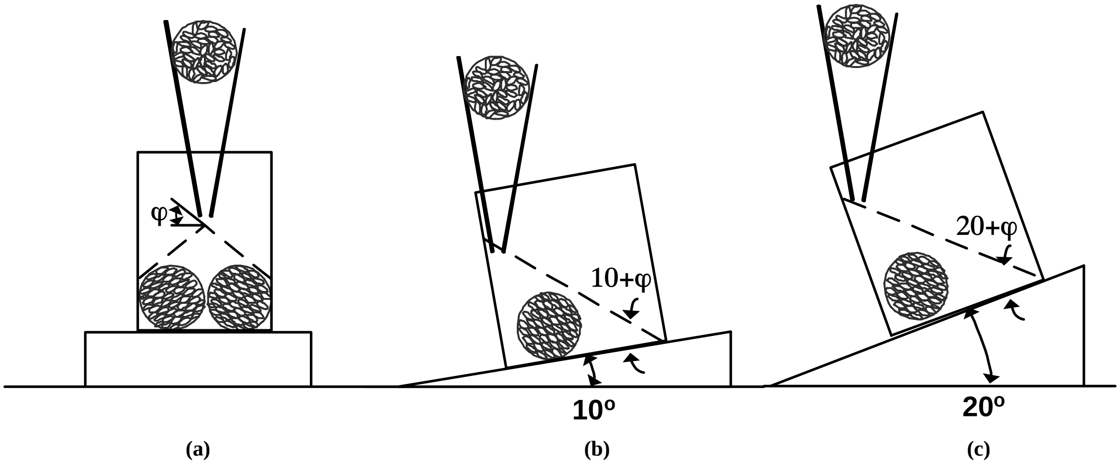

Figure 2. Filling methods used to orient kernels at the angle of repose (a) (φ), 10° greater than the angle of repose (b) (10° + φ), and 20° greater than the angle of repose (c) (20°+ φ).

RESULTS AND DISCUSSION

The fine material, moisture content, bulk density, and kernel density of the four grain types investigated at the three moisture content levels are shown in table 1. The bulk density of wheat increased as the moisture content decreased but did not follow a trend 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%.

The bulk density (fig. 3) and porosity (fig. 4) of the four grain types within the test column when filled using the centric sprinkle and funnel filling at three moisture content levels. The average bulk density was 5.5% greater when the column was sprinkle filled compared to funnel filled. Porosity changes were due to particle arrangement from differences between the two filling methods. The porosity decreased by an average of 3.4 percentage points for all grain types at the three moisture content levels when the column was sprinkle filled compared to funnel filled. The porosity change was a function of bulk density and kernel arrangement within the column, i.e. no change in kernel size or shape would be expected due to the lack of external vertical compression forces.

The pressure drop versus airflow of shelled corn with a high (sprinkle filled) and low (funnel filled) bulk density and three moisture contents are shown in figure 5. The slopes of the lines were similar at all three moisture content levels and were primarily a function of filling method. The slopes were linear which indicated Darcy's law was valid at the flow rates investigated with an r^2 greater than 0.99. The slope for the sprinkle filled corn was between 1055 and 1258 Pa·s/m^2 compared to a slope between 604 and 778 Pa·s/m^2 for funnel filled corn. The moisture content changed the resistance coefficient by less than 20% for the three moisture content levels. However, changes in the bulk density resulted in a 48% change in the resistance coefficient at a moisture content of 10.1%

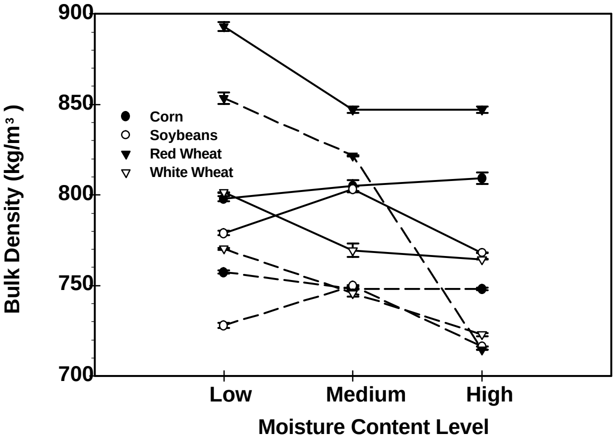

Figure 3. Average and standard error of the increase in bulk density of the four grain types at three moisture content levels using two filling methods. Solid lines are high bulk density (sprinkle filled) and dashed lines are low bulk density (funnel filled).

Table 1. Fine material[a] (FM), moisture content[b] (MC), uncompacted bulk density[c] (BD), and kernel density[c] (KD) of the four grain types investigated at the three moisture levels.

	Low MC				Medium MC			High MC		
Material	FM	MC	BD	KD	MC	BD	KD	MC	BD	KD
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
Red wheat	0.1	10.5	1015	1380	12.7	818	1330	14.6	798	1370
White wheat	0.2	10.1	944	1370	12.8	750	1300	14.6	734	1330

[a] FM includes fine material, split soybeans and broken kernels as appropriate for each grain type.
[b] Moisture content is in % wet basis.
[c] Bulk and kernel density are expressed in kg/m^3.

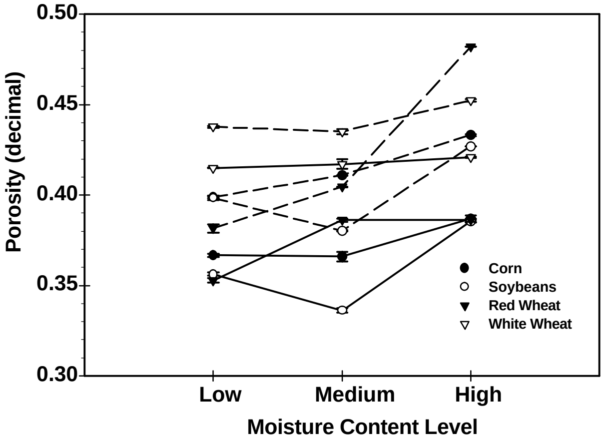

Figure 4. Average and standard error of porosity of the four grain types at three moisture content levels using two filling methods. Solid lines are high bulk density (sprinkle filled) and dashed lines are low bulk density (funnel filled).

Values of the resistance coefficient for the four grains, three moisture content levels, and two bulk densities are presented in figure 6. Permeability could be calculated by dividing the viscosity of the fluid (air) by the resistance coefficient. Corn and soybeans behaved similarly with the two filling methods and three moisture contents. High bulk density soybeans and corn had a 40% greater resistance compared to the lower bulk density grain. As expected, red and white wheat at a low bulk density had a higher resistance than corn and soybeans due to the lower porosity. Increasing the bulk density of red and white wheat by an average of 4.7% resulted in a 41% increase in the resistance coefficient.

The primary factor that affected the change in resistance was the increase in bulk density and the corresponding decrease in porosity between funnel and sprinkle filled grain. Corn and soybeans had an average bulk density increase of 7.1% between the funnel and screen filled methods. In contrast, red and white wheat experienced an average bulk density increase of only 4.7% when sprinkle filled. The change in bulk density resulted in a change of porosity within the test column. Interestingly, the porosity of corn and soybeans was lower than red and white wheat at the high and medium grain moisture content levels.

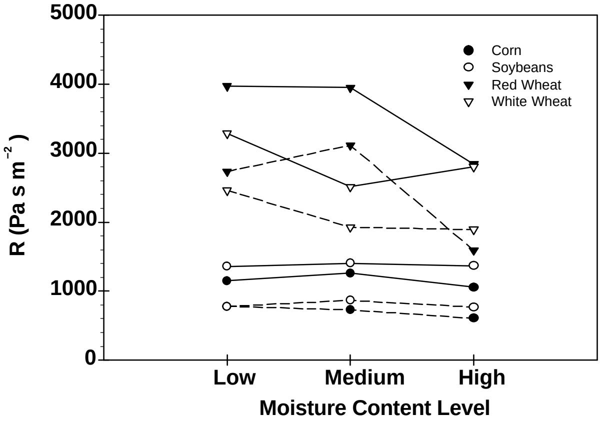

Figure 6. Resistance coefficient (R) of corn, soybeans, red wheat, and white wheat at three moisture content levels and two bulk densities. Solid lines are high bulk density (sprinkle filled) and dashed lines are low bulk density (funnel filled).

Patterson et al. (1971) found a resistance coefficient of 530 and 888 Pa·s/m^2 for corn at a moisture content of 16% and a porosity of 43% and 38%, respectively. This was similar to the values measured in this study of 604 and 1052 Pa·s/m^2 for corn at 14.5% and a porosity of 43.3% and 38.7%, respectively. Hunter (1983) reported a resistance coefficient of 719, 646, and 3131 Pa·s/m^2 for corn (12.4%), soybeans (10%), and wheat (11%), respectively.

EFFECT OF KERNEL ORIENTATION

Soft red wheat at the low moisture content was filled using the apparatus shown in figure 2 for both sprinkle and funnel filling and pressure drop determined for different airflow rates (fig. 8). This resulted in kernel orientations of approximately the angle of repose, 10° greater, and 20° greater than the angle of repose. The slope of the line for funnel-filled wheat was approximately the same for all three filling angles (fig. 8). This would indicate that kernel orientation did not significantly influence the resistance of the grain bed at typical kernel orientations that would occur in storage structures filled through a spout. Sprinkle filled wheat at a 20° angle had a slightly greater slope than funnel

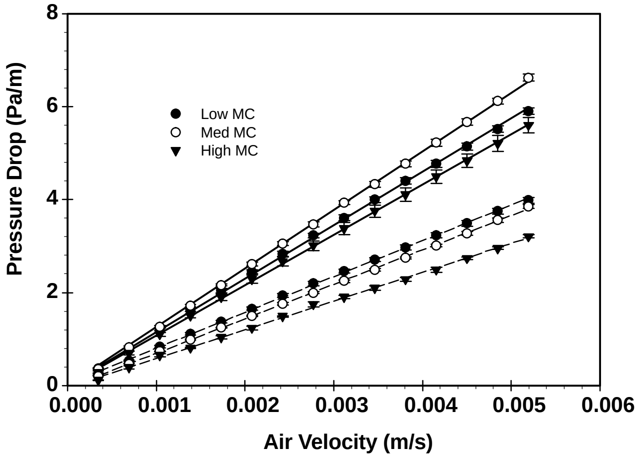

Figure 5. Average and standard error of the pressure drop versus flow rate for corn filled using two methods and three moisture content levels. Solid lines are high bulk density (sprinkle filled) and dashed lines are low bulk density (funnel filled).

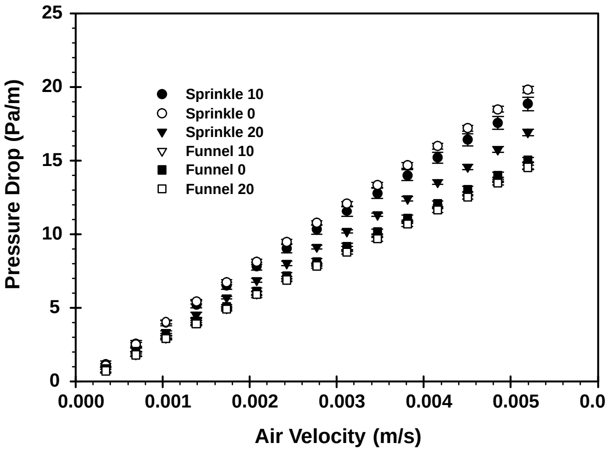

Figure 7. Average and standard error of the pressure drop versus flow rate for soft red winter wheat when sprinkle and funnel filled at three angles shown in figure 2.

filled wheat. However, sprinkle filled wheat at the 0 and 10° angle had the greatest slope and were approximately equal.

The porosity and resistance coefficient are summarized in table 2 for sprinkle- and funnel-filled red wheat at three filling angles. Porosity values ranged between 38.4% and 39.6% when sprinkle filled between the angles of 0 and 20° greater than the angle of repose. The porosity of the sprinkle filled column at an angle of 0 and 10° was the lowest. Funnel-filled wheat resulted in a more porous and a more uniform bed with a porosity between 40.8 and 41.0.

There was a greater range in resistance coefficient values with sprinkle filled wheat. However, this was probably due to the larger variation in porosity between the three filling angles when sprinkle filled. The porosity increased from 38.4% to 39.6% when the fill angle increased from 0 to 20° probably caused the large decrease in the resistance coefficient. Similar trends were observed for the other grain types and other moisture content levels.

The anisotropic behavior of grain was not as significant as previous studies have indicated. Hood and Thorpe (1992) reported a 10% difference in two dimensions with wheat that was similar to this study. Kumar and Muir (1986) and Jayas et al. (1987) found the resistance in the horizontal direction to be 60% of the vertical direction. The data indicates that accurate models of kernel orientation and porosity through a grain bin are required to accurately quantify the airflow resistance of a grain mass.

APPLICATION OF RESULTS

Models of grain packing and granular mechanics have been developed to predict the packing and bin loads exerted in structures (*ASAE Standards*, 1999b). This data could be used to provide an indication of the appropriate resistance coefficient to use at various regions within a grain bin during modeling studies. For example, the average pack factor for corn in an 11.9-m diameter bin level filled to a height of 11.9 m was estimated to be 3.8% (*ASAE Standards*, 1999b). Corn at the low moisture content when sprinkle filled had a 5.4% greater bulk density than the uncompacted bulk density. This indicated that the resistance coefficient for the bin would be between the funnel and sprinkle filled results from this study. Due to the variation of the loads within the grain bin, the amount of packing that occurred at different depths varied. Bulk density (porosity) was the primary variable that influenced the resistance coefficient. Thus, changes in bulk density during storage due to compaction should be well quantified to estimate variations in resistance within a grain bin. Changes in kernel orientation would be expected to vary

CONCLUSIONS

The resistance of corn, soybeans, soft white wheat, and soft red wheat were measured as a function of filling method, bulk density, and moisture content. Low bulk density corn and soybeans had the lowest resistance coefficient, between 863 and 604 Pa·s/m^2 (or a permeability between 2.12×10^{-8} and 3.03×10^{-8} m^2, respectively). Increasing the bulk density by 7%, decreased the permeability by approximately 40%. Wheat had the highest resistance, between 3112 and 1591 Pa·s/m^2 (or a permeability between 5.88×10^{-9} and 1.15×10^{-8} m^2, respectively) at the low bulk density. A 4.7% increase in bulk density resulted in a 41% greater resistance coefficient for white and red wheat. The effect of kernel orientation was not as significant as changes in the porosity. Darcy's law was valid for predicting natural convection currents during non-aerated storage.

Table 2. Porosity (ε) and resistance coefficient (R) of soft red wheat at the low moisture content level (10.5%) when sprinkle and funnel filled at three angles using the apparatus shown in figure 2.

	Sprinkle Filled		Funnel Filled	
Angle	ε (%)	R (Pa s m^{-2})	ε (%)	R (Pa s m^{-2})
0°	38.4	3839	40.9	2909
10°	38.6	3665	40.8	2841
20°	39.6	3259	41.0	2799

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NOMENCLATURE

ε = porosity
μ = air viscosity (Pa s)
ρ_b = the bulk density (kg/m^3)
ρ_k = the kernel density (kg/m^3)
k = permeability (m^2)
v = superficial velocity (m/s)
x = length (m)
P = pressure drop (Pa)
R = resistance coefficient (Pa·s/m^2)