2008

# Airflow Resistance of Wheat Bedding as Influenced by the Filling Method

J. Łukaszuk
*Polish Academy of Sciences, Poland*

M. Molenda
*Polish Academy of Sciences, Poland*

J. Horabik
*Polish Academy of Sciences, Poland*

B. Szot
*Polish Academy of Sciences, Poland*

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

**Airflow Resistance of Wheat Bedding as Influenced by the Filling Method**

**Notes/Citation Information**

Published in *Research in Agricultural Engineering*, v. 54, no. 2, p. 50-57.



**Digital Object Identifier (DOI)**
https://doi.org/10.17221/8/2008-RAE

# Airflow resistance of wheat bedding as influenced by the filling method

**J. Łukaszuk[1], M. Molenda[1], J. Horabik[1], B. Szot[1], M.D. Montross[2]**

[1]*Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland*
[2]*Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, USA*

**Abstract**: A study was conducted to estimate the degree of variability of the airflow resistance in wheat caused by the filling method, compaction of the sample, and airflow direction. Two types of grain chambers were used: a cylindrical column 0.95 m high and 0.196 m in diameter, and a cubical box of 0.35 m side. All factors examined were found to influence considerably the airflow resistance. Gravitational axial filling of the grain column from three heights (0.0, 0.95 and 1.8 m) resulted in the pressure drops of 1.0, 1.3, and 1.5 kPa at the airflow velocity of 0.3 m/s. Consolidation of axially filled samples by vibration resulted in a maximum 2.2 times increase in airflow resistance. The tests with cubical sample showed that in axially filled samples the pressure drop in vertical direction was maximum 1.5 times higher than in horizontal directions. In the case of asymmetrically filled samples, the pressure drop at the airflow velocity of 0.3 m/s in vertical direction Z was found to be 1.3 of that in horizontal direction X and 1.95 times higher than with horizontal direction Y, perpendicular to X. Variations in airflow resistance in values comparable to that found in the present project may be expected in practice.

**Keywords**: airflow resistance; grain; drying; aeration; packing structure

The relationship between the airflow resistance of granular material and airflow velocity is usually presented in the form of equations or tables (Brooker *et al.* 1992). Usually, assumptions are made that airflow resistance is constant in the volume of the material and is independent of the packing structure. Numerous investigations performed recently have shown that such an assumption is not always true. In practice, local changes of the airflow resistance in various areas of grain bulk may cause serious disturbances in processes involving the flow of gases such as aeration, drying, fumigation, or cooling. According to Navarro and Noyes (2002) the values of airflow resistance calculated by means of the proposed equations or taken from tables correspond to clean, loosely packed grain and apply to vertical direction of airflow and, in consequence, are usually lower than in practical conditions. These authors pointed out that the efficiency of the aeration systems depends to a large extent on a uniform distribution of the airflow within the volume of grain.

Early experiments studied the influence of the bulk density (related to porosity) on airflow resistance. Calderwood (1973) in his experiments with rice of different varieties stated that the bulk density modified the airflow resistance in an essential way. Stephens and Foster (1976) conducted their project with corn in a commercial grain silo and found that the use of a grain spreader resulted in threefold increase of airflow resistance. The same authors performed a similar project with wheat and grain sorghum (Stephens & Foster 1978) and reported that the use of a spreader resulted in an increase in airflow resistance to 110% in sorghum, while in the case of wheat airflow resistance increased to 101%. The authors explained the observed effect by the difference in the fine content that was from 1.5 to 2% in the case of sorghum and 0.2% in that of wheat. In the grain bulk containing a higher amount of fines, these filled pores and caused an increase in airflow resistance.

The results of later experiments showed that airflow resistance depended also on the airflow direction. Kumar and Muir (1986) in their tests with wheat and barley stated that with the airflow velocity of 0.077 m/s, the airflow resistance in vertical direction was by as much as 60% higher than that in horizontal direction. Hood and Thorpe (1992) determined the airflow resistance of 10 types of seeds and found that at the airflow velocity of 0.2 m/s, the airflow resistance in vertical direction was approximately two times higher than in horizontal direction. Standard ASAE D272.3 (2003) recommend for a number of enlisted seeds to use the airflow resistance in horizontal direction of 60 to 70% of that in vertical direction, the code also informed that for some seeds no difference may be observed between the airflow resistance in horizontal and vertical directions. Neethirajan *et al.* (2006) used X-ray computed tomography to reconstruct the internal structure of the bulk and explained the differences between the airflow resistance in horizontal and vertical directions. The authors tested wheat, barley, flax seeds, peas, and mustard and found that the airspace area is uniformly distributed in both horizontal and vertical directions with grain bulks of spherically shaped kernels unlike with oblong kernels. For wheat, barley, and flax seed, the bulk airpath area and airpath lengths along horizontal direction were by 100% higher than those in horizontal direction, while for pea and mustard bulks the parameters were only 30% higher. The authors concluded that the non-uniform distribution of airpaths and the number of airpaths inside grain bulks were the reasons for the airflow resistance difference along horizontal and vertical directions in many grain bulks.

The objective of the project reported here was to estimate the variability of the airflow resistance of wheat due to non-homogeneity of the bulk caused by compaction and the filling method.

## MATERIALS AND METHODS

The experimental setup using the cylindrical grain column is shown in Figure 1. A cylindrical acrylic plastic pipe with a diameter of 0.196 m and a height of 1.08 m was used to hold the grain during the testing procedures. Air was introduced through a plenum supporting the bottom of the cylinder. The differential static pressure was measured at a distance of 0.95 m.

Four taps evenly distributed along the column circumference were mounted at both levels and all four were connected to average the possible pressure fluctuations. In the case of testing the longitudinal distribution of airflow resistance three more levels of air taps were used that were evenly distributed between the two. A variable reluctance pressure transducer with accompanying equipment (Validyne DP45, Northridge, CA) applying a diaphragm with maximum pressure rating of 2.25 kPa and accuracy of ± 0.25% full scale was used to measure the pressure drop. Leaving the column, the air flew through the outlet air plenum and through the 0.05 m diameter outlet duct in that air velocity was measured. A commercial hot-wire anemometer was used to measure the air velocity in the range from 0 to 30 m/s with the resolution of 0.1 m/s. Airflow resistance versus air velocity relationships were determined for the apparent velocity in the range from 0.03 to 0.4 m/s. Two replicates of the air-velocity-pressure-drop curve were performed with each variant of the experiment (with emptying and refilling the column) and the results were averaged.

Three methods were used to fill the grain column. The loosest filling was termed "A filling method" and was accomplished using a funnel that was kept 2 cm from the grain surface during filling. In this case, the grain formed a conical sloping surface during filling with the vertex directed upward and the grains tending to rest with their long axes along the line of the cone formed. To obtain a higher bulk density, the outlet of the conical filling hopper was located at the top of the grain column (method "B") or at the height twice of that of the grain column (method "C"). After filling the column, the grain was weighed using a digital scale and the bulk density was calculated.

To obtain higher densities, the test column after funnel filling was placed on a vibrating table and shaken with frequency of 15 Hz and amplitude of 10 mm.

Airflow resistance along three perpendicular directions: two horizontal X and Y, and vertical

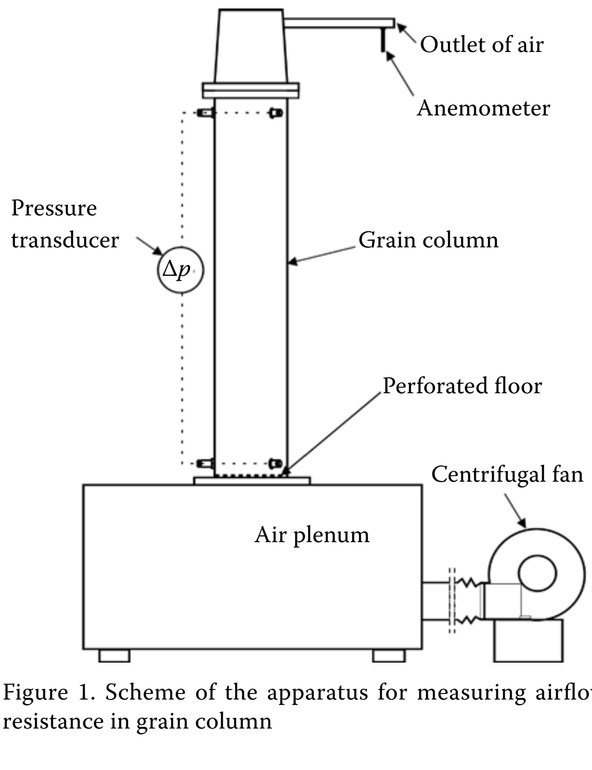


Figure 1. Scheme of the apparatus for measuring airflow resistance in grain column

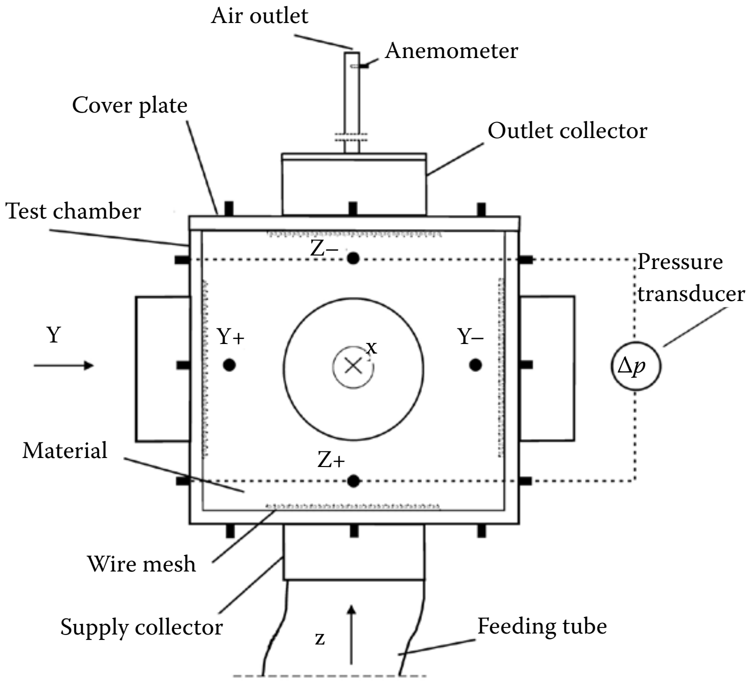


Figure 2. Scheme of the apparatus for measuring airflow resistance in cubic sample of granular material

direction Z, was examined with an experimental setup using cubical grain chamber of 0.35 m side as shown in Figure 2 (details see in Łukaszuk *et al.* 2006). In each wall of the cube circular openings of 0.16 m in diameter were machined and covered with perforated steel. The apertures of perforation were 2 mm in diameter and amounted to 29.7% so that the following of ASAE D273.2 (2003) did not produce additional resistance to the airflow. Each wall of the chamber was equipped with cylindrical air collectors (supply or outlet) 0.16 m in diameter, and with four connectors for the installation of the pressure transducer. The pressure drop was measured at the distance of 0.25 m using the same equipment as that for the cylindrical grain chamber. The pressure drop was measured for the airflow velocity in the range from 0.03 m/s to 0.35 m/s.

The airflow direction was changed between X, Y or Z by connecting the supply and outlet air ducts to proper connectors. The sensing element of the anemometer and pneumatic tubing of the pressure transducer were also located in proper positions. The air collectors that were not used in the actual test were closed with elastic membranes, the unused instrument connectors were also plugged. For one filling event, the measurements were made subsequently in Z, X, and Y directions, and the measurement cycle was repeated three times with a new sample of grain. To obtain different structures of the bulk, three filling methods were used as shown in Figure 3.

Method D used 1 m long funnel with openings of diameters of 0.2 and 0.03 m. Method F used a wedge shaped filling container as wide as the chamber

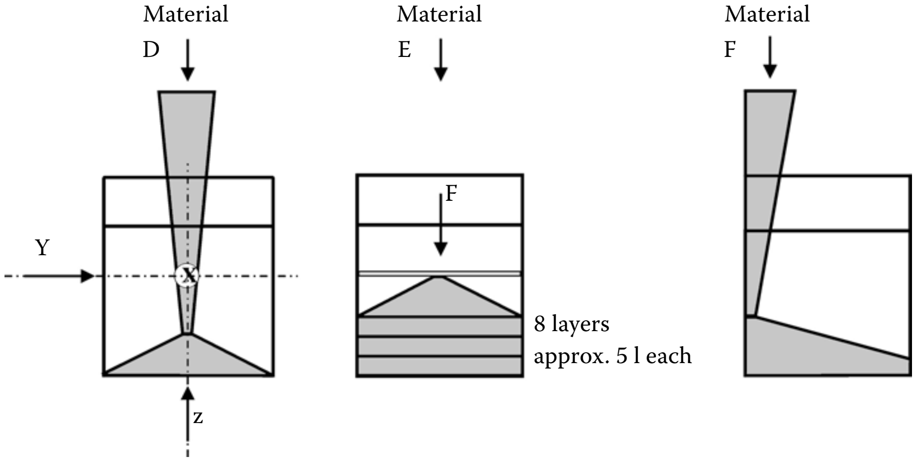


Figure 3. Methods of filling cubical test chamber

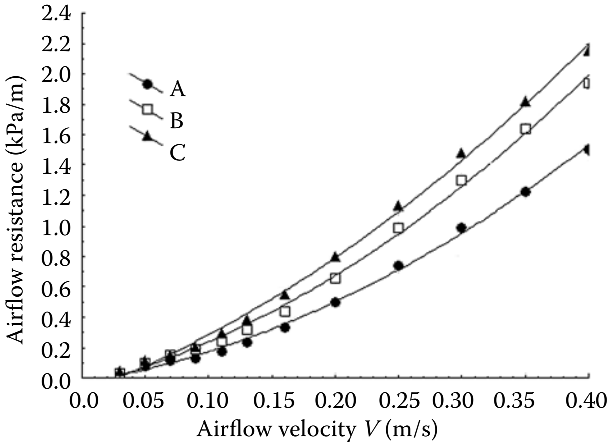


Figure 4. Airflow resistance of the sample formed by means of funnel filling and axial stream filling from the heights: (A) 0, (B) H and (C) 2H

width (0.35 m) and having supply and outlet slots of the width of 0.15 and 0.015 m, respectively. With both filling methods, the chamber was filled by slowly rising up the appliance that was earlier filled with grain, maintaining continuous outflow of the material. The chamber was overfilled and excess material was removed while the upper surface was levelled. The third filling method E used the same funnel that was used in method A but the chamber was filled in 8 steps with compaction of the bulk covered with a plate by 10 taps with 4 kg of mass deadweight after adding each portion of grain. The tests were performed with winter wheat of initial moisture content of 11% and uncompacted bulk density of 773 kg/m$^3$.

## RESULTS

### Influence of the height of filling – cylindrical sample

The influence of the height of filling on airflow resistance is presented in Figure 4. Filling methods A, B and C produced samples of densities: 773, 790 and 810 kg/m$^3$, respectively. The higher kinetic energy of the grain falling from a grater height produced grain bedding of a higher bulk density. An increase in the sample density resulted in an increase in airflow resistance, at the air velocity of 0.3 m/s the pressure drop with the sample of the lowest density was found to be 1.0 kPa/m while with the densest sample it was 1.5 kPa/m. Thus the 1.047 increase in the sample density resulted in 1.5 times increase of the pressure drop.

### Longitudinal distribution of airflow resistance in the column

The values of the pressure drop calculated in the laboratory experiments are related to the length of the grain column and do not bring information about the distribution of the pressure drop along the column. Figure 5 shows the pressure drop at the air velocity of 0.3 m/s as measured in four sections of the grain column in the case of grain bedding formed by three filling methods. The earlier observed tendency (ASAE D272.3 2003) that a higher density and a higher pressure drop was found with a grater height of the grain fall was confirmed in these tests. In the case of methods B and C, higher pres-

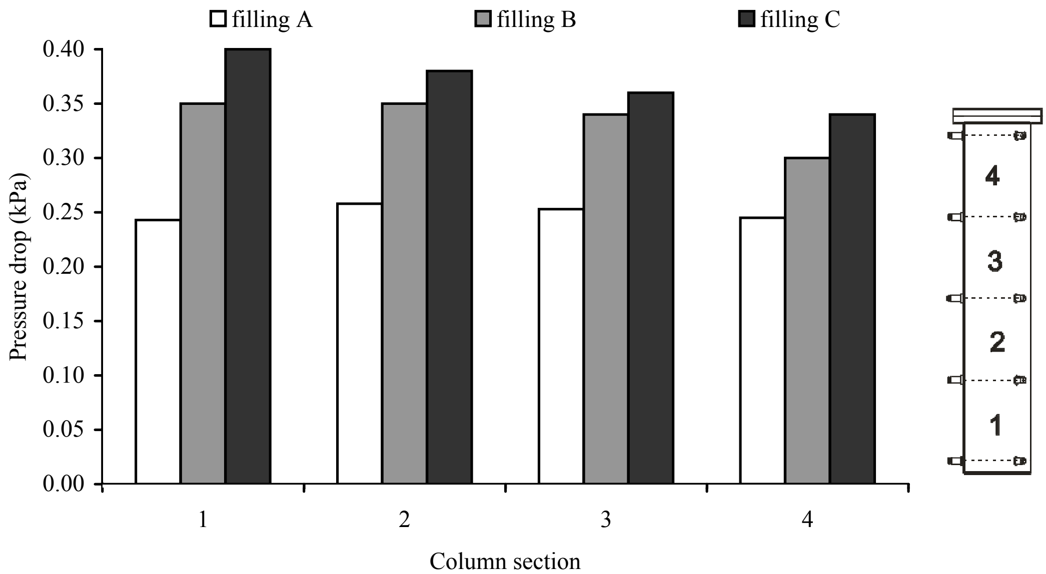


Figure 5. Airflow resistance at air velocity of 0.3 m/s for wheat bedding, formed by the three filling methods, measured in four fragments of the column

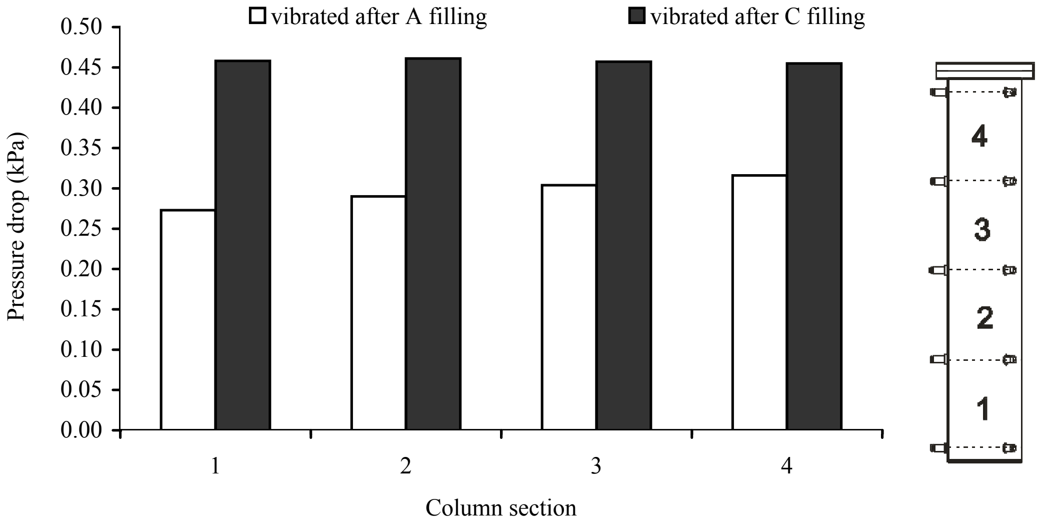


Figure 6. Airflow resistance at air velocity of 0.3 m/s for wheat bedding formed by filling methods A and C and vibrated, measured in four fragments of the column

sure drops were found for the sections of the grain column situated in lower positions. This effect is the result of higher kinetic energy of grains reaching the free surface of the grain column, and possibly of the pressure of higher layers of grain. In the case of method C, the greatest pressure drop observed in the lowest section of the column was approximately 1.18 higher than the lowest one found in the highest section. In the case of the filling method A, no clear differences in the pressure drop were observed between different sections of grain column. Method A was quasi – static filling through the funnel moving slowly up, thus grains had very low kinetic energy that did not change during the filling of the column. The ratio between the greatest and the smallest pressure drops for the tests results given in Figure 5 was found to be 1.65.

**Consolidation of the bulk by vibration – cylindrical sample**

The compaction of the bedding by vibration resulted in an increase of airflow resistance as shown in Figure 6 for filling methods A and C and for the air velocity of 0.3 m/s. The pressure drops after vibration were found approximately equal for the bedding in particular sections of the column, thus the highest increase in the pressure drop occurred in the lowest quarter of the column. The ratio of the pressure drops after and before vibration was found

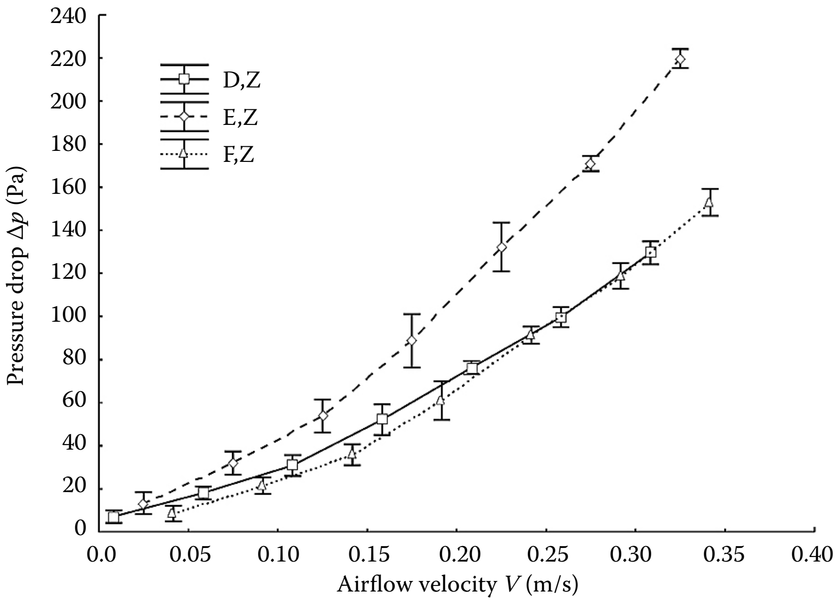


Figure 7. Pressure drop versus air velocity in vertical direction Z for three methods of filling cubical test chamber

to be 1.34 and 1.29 for C and A filling methods, respectively. The vibration, as applied in the reported project, resulted in an increase of airflow resistance in an order of 30% but did not eliminate the influence of the filling method. Originally looser samples gained more airflow resistance after vibration than originally denser samples.

**Influence of filling method on pressure drop in vertical direction – cubical sample**

Similarly to the tests with the cylindrical column, various filling methods resulted with the cubical chamber in various densities and pressure drops. Method D resulted in the lowest bulk density of 766 ± 1 kg/m$^3$, while the highest density, 831 ± 0.35 kg/m$^3$, was the density obtained with method E. The changes in density resulted in various airflow resistance of the bulks of wheat. Figure 7 illustrates the relationships of the pressure drop at the distance of 0.25 m versus the airflow velocity in vertical direction Z with the samples formed using the three filling methods. The pressure drop increased with an increase in bulk density, and with the airflow velocity $V$ of 0.3 m/s $\Delta p$ it was found to be 100 ± 2 Pa for filling method D, while in the case of method E it was found to be 171 ± 1 Pa, that is 1.7 times higher.

**Pressure drop in vertical and horizontal directions – cubical sample**

In all tests performed, the airflow resistance in vertical direction Z was found to be higher than in horizontal directions X and Y, the finding being in accord with the results of other researchers. The relationships $\Delta p(V)$ for filling method F and two directions of the airflow, vertical Z and horizontal Y, are shown in Figure 8. In the whole range of the airflow velocity, the curve of $\Delta p(V)$ for vertical direction runs above the curve obtained for horizontal direction. With the airflow velocity of 0.3 m/s, the pressure drop found in Y direction was 61 ± 2 Pa, while in Z direction it was 119 ± 3, that is 1.95 times higher.

Figure 9 illustrates $\Delta p(V)$ relationships determined for two horizontal directions X and Y with D, E, and F filling methods. The lowest one found was the airflow resistance in direction Y posed by the bulk formed using method F. The relationships $\Delta p(V)$ with method D were slightly higher and very close for X and Y horizontal directions. Also in the case of filling method E that produced the highest airflow resistance, the courses of $\Delta p(V)$ relationships were close to one another. These results showed that axial filling using methods D and E produced grain samples nearly axial-symmetric. In the case of filling method F, the pressure drop in direction X was grater over the whole range of velocity than that in direction Y (see Figure 9). In this case, at the airflow velocity of 0.3 m/s, the pressure drop found in Y direction was 61±2 Pa, while in X direction it was 90 ±1, that is approximately 1.5 times higher. Method F that used the wedge shaped filling container produced the grain sample that was not axially symmetric. Subsequent layers of grain moved down the surface of the natural repose, their velocity was approximately perpendicular to X axis, and in this direction the airflow resistance was higher than in Y direction.

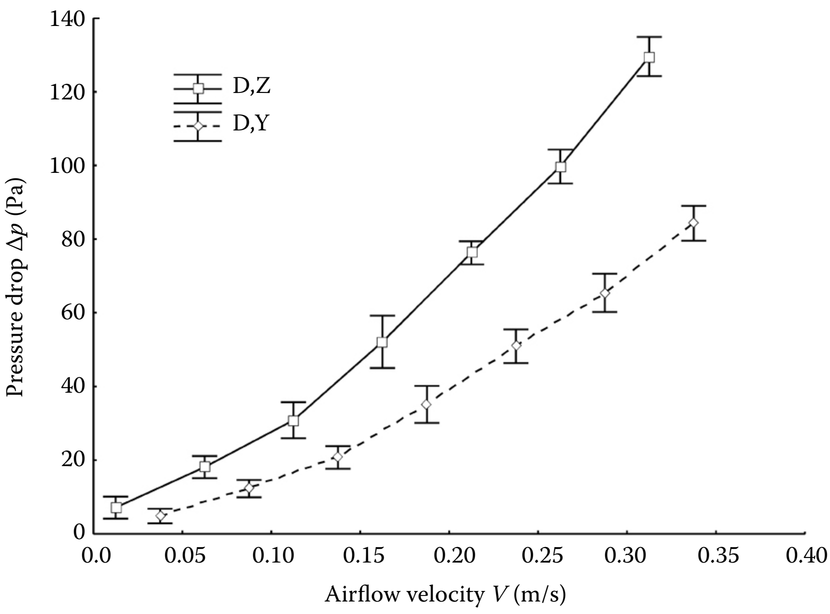


Figure 8. Pressure drop versus air velocity in vertical direction Z and horizontal direction Y for samples formed using method F

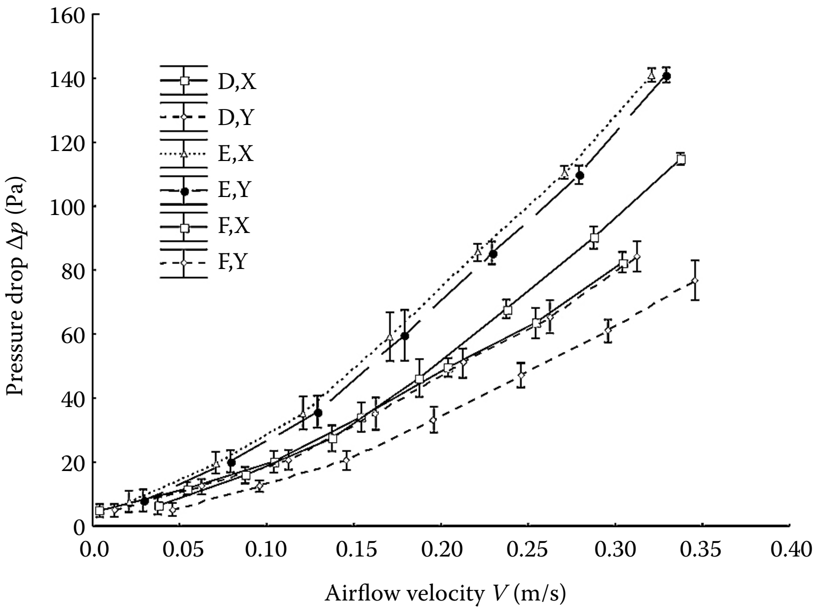


Figure 9. Pressure drop versus air velocity in horizontal directions X and Y for three methods of filling cubical test chamber

## CONCLUSIONS

(1) Different methods of filling of the test column produced packing structures of various density and porosity that resulted in a considerable variability of airflow resistance. Axial gravitational filling methods with grain falling from the heights of 0, 0.95 and 1.9 m over the column floor produced bulks of densities in a range from 773 to 829.9 kg/m$^3$ and the pressure drop at $V$ of 0.3 m/s ranging from 1.0 to 1.5 kPa/m. The observed increase in airflow resistance was the result of the increase in bedding density as a consequence of higher kinetic energy of grains falling from greater height.

(2) Airflow resistance varied also along the length of the grain column where, in the case of the highest location of the outlet of the filling container, it was found, to increase from 0.34 to 0.4 kPa/m. Consolidation of the bedding through vibration brought about equalisation and an increase of airflow resistance up to 0.45 kPa/m, i.e. in a factor of 1.3 as compared to the lowest value of 0.34 kPa/m.

(3) In the cubical grain sample filled axially layer by layer and compacted (method F), the pressure drop in vertical direction Z was 1.7 times greater than in horizontal directions X and Y, the two latter being approximately equal.

(4) When filling the cubical chamber through a long slot (method E), the values of the pressure drop $\Delta p$ in horizontal directions X and Y were not equal. Along direction X, the direction of the velocity of grains moving down the slope of the surface of the natural repose, $\Delta p$ was higher than in the perpendicular direction Y. At the airflow velocity of 0.3 m/s, the pressure drop in direction Y was of 61 ± 2 Pa while in direction X, $\Delta p$ of 90 ± 1 Pa was found i.e. 1.5 times higher.

### References

ASAE D272.3 DEC01 (2003): Resistance to airflow of grains, seeds, other agricultural products and perforated metal sheets. ASAE Standards, 569–576.

Brooker D.B., Baaker-Arkema F.W., Hall C.W. (1992): Drying and Storage of Grains and Oilseeds. Van Nostrand Reinhold, New York.

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

Hood T.J.A., Thorpe G.R. (1992): The effects of the anisotropic resistance to airflow on the design of aeration systems for bulk stored grains. Agricultural Engineering Australia, **21**: 18–23.

Kumar A., Muir. W.E. (1986): Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. Transactions of the ASAE, **29**: 1423–1426.

Łukaszuk J., Molenda M., Horabik J. (2006): Influence of the method sample formation on airflow resistance in wheat. Acta Agrophysica, **8**: 881–891. (in Polish)

Navarro S., Noyes R. (2002): The Mechanics and Physics of Modern Grain Aeration Management. CRC Press, Boca Raton.

Neethirajan S., Karunakaran C., Jayas D.S., White N.D.G. (2006): X-ray computed tomography image analysis to explain the airflow resistance differences in grain bulks. Biosystems Engineering, **94**: 545–555.

Stephens L.E., Foster G.H. (1976): Grain bulk properties as affected by mechanical grain spreaders. Transactions of the ASAE, **19**: 354–358.

Stephens L.E., Foster G.H. (1978): Bulk properties of wheat and grain sorghum as affected by a mechanical grain spreaders. Transactions of the ASAE, **21**: 1217–1221.

Received for publication February 27, 2008
Accepted after corrections February 29, 2008

**Abstrakt**

Łukaszuk J., Molenda M., Horabik J., Szot B., Montross M.D. (2008): **Vliv způsobů přípravy vrstvy pšenice na velikost ventilačního odporu vzduchu.** Res. Agr. Eng., **54**: 50–57.

Byla provedena studie s cílem odhadnout variabilitu ventilačního odporu v pšenici, která je způsobená metodou plnění, způsobem zkompaktnění a směrem proudění vzduchu. Byly použity dva typy uspořádání: válcový vzorek 0,95 m vysoký a 0,196 m v průměru a krychlový box o hraně 0,35 m. Bylo zjištěno, že všechny faktory výrazně ovlivňovaly výsledný ventilační odpor. Přirozené osové plnění samospádem ze tří různých výšek (0,0; 0,95 a 1,8 m) mělo za následek pokles tlaku 1,0; 1,3; a 1,5 kPa při rychlosti vzduchu 0,3 m/s. Konzolidace axiálně plněných vzorků s použitím vibrací mělo za následek až 2,2 násobný růst ventilačního odporu. Test s axiálně plněným kubickým boxem vykázal ve vertikálním směru až 1,5 násobně vyšší ventilační odpor než ve směru vodorovném. U asymetricky plněných vzorků při rychlosti vzduchu 0,3 m/s ve vertikálním směru byl pozorován ventilační odpor 1,3 násobně větší než ve směru vodorovném a 1,95 vyšší než ve vodorovném směru kolmém na předchozí horizontální směr. Změny ventilačního odporu srovnatelné s námi získanými hodnotami se dají také očekávat v reálných případech.

**Klíčová slova**: odpor vzduchu; zrno; sušení; ventilace; sypná struktura

*Corresponding author:*

Prof. dr. hab. Józef Horabik, Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin 27, Poland
tel.: + 4881 744 50 61, fax: + 4881 744 50 67, e-mail: jhorabik@ipan.lublin.pl.