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Resistance of bulk grain to airflow – a review. Part II: Effect of process parameters

KRZYSZTOF GÓRNICKI, AGNIESZKA KALETA
Department of Fundamental Engineering, Warsaw University of Life Sciences – SGGW

Abstract: *Resistance of bulk grain to airflow – a review. Part II: Effect of process parameters.* Effects of process parameters on the resistance of bulk grain to airflow were discussed. The resistance to airflow decreased with an increase in grain moisture content. Dense filling resulted in an increase in pressure drop. The resistance to airflow through bulk grain in the horizontal direction is, in most cases, smaller than in the vertical direction. Grains mixed with foreign materials offer more resistance to airflow than cleaned grains.

Key words: airflow resistance, pressure drop, bulk grain, ventilation, aeration, drying

INTRODUCTION

Cereals are one of the most spread and economically the most important field crops [Jánský and Živělová 2008]. Theory and practical experience indicate that the storage of grain in silo requires the passage of a forced air stream through grain layer. Subject to the volume and the temperature of the airflow, the purpose of this procedure is to air, cool or dry the stored grain [Kaleta 2001, Waszkiewicz and Sypuła 2007, Myhan 2009]. Grain is a live organism, with continuous transformations doing inside it. The purpose of proper storage is to inhibit biological processes to the highest possible extent and to eliminate unfavourable environmental factors, which limit duration of the safe storage [Waszkiewicz and Sypuła 2008].

The airflow resistance in grain packed bed is an important parameter in determining the static pressure requirements of a fan for drying, cooling, and ventilation such as in insecticide application. The airflow rate through the packed bed will determine the rate of drying and cooling. The higher the flow rate the faster the operations can be carried [Chuma et al. 1983]. The intensity and quality of the discussed processes are determined by, among others, the distribution of airflow velocity throughout the silo. Airflow distribution in grain bulk depends on various factors, including the filling method and grain bulk porosity, the depth of the grain bed, the grain morphology and configuration and size of the interstitial space in the mass, the air velocity, the form and size of any extraneous impurity in the mass, etc. [Khatchatourian et al. 2009].

EFFECT OF PROCESS PARAMETERS ON RESISTANCE OF BULK GRAIN TO AIRFLOW

Effect of moisture content

The resistance to airflow generally decreased with an increase in grain moisture content. The reduction in pressure drop is because of an increase in porosity with an increase in moisture content. The second possible effect of moisture is on the grain surface characteristics. The change of surface characteristics due to higher moisture content may tend to increase resistance to airflow. The effect of moisture on void fraction, is more prominent than surface characteristics on the resistance to airflow and hence, results in a net decrease in pressure drop at higher levels of moisture [Haque et al. 1982]. Jekayinfa [2006] stated, however, that at low moisture level, the locust beans cotyledons are hard and smooth thereby causing an increase in frictional losses (high resistance to airflow).

Many researches reported that the pressure drop decreased with the increase in moisture content due to an increase in porosity of bulk materials: Jayas et al. [1987a] for canola (moisture content 6.5–11.5% wet basis – w.b.), Gunasekaran and Jackson [1988] for sorghum (moisture content 16.5–23% w.b.), Sokhansanj et al. [1988] for laird lentils (moisture content 10.4–19.9% w.b.), Al-Yahya and Moghazi [1988] for barley (moisture content 8–21.7% w.b.), Abou-El-Hana et al. [2008] for shelled corn (moisture content 14–20% w.b.).

Jayas and Sokhansanj [1989] stated that at moisture contents of 14.5% wet basis, the measured pressure drops were about 85% of the pressure drop across dry canola (6.5% moisture content wet basis). According to Sokhansanj et al. [1990], an increase in moisture content of laird lentils by 9.5 percentage points caused a decrease in pressure drop by about 22.5%. For airflow rates between 0.0028 and 0.5926 $m^3/(m^2 \cdot s)$ pressure drop decreased by an average of 2.4% as moisture content increased by 1.0 percentage points. Paddy produced on an average of 19% lower pressure drops at 15% moisture content (w.b.) than at 11% m.c. for airflow rates between 0.01 and 0.1 $m^3/(m^2 \cdot s)$ [Nalladurai et al. 2002]. Results obtained by Nimkar and Chattopadhyay [2002] indicated that 1% increase in moisture content of green gram decreased the pressure drop by 2.43%. An increase in the moisture content of poppy seeds range of 6.21–18.37% dry basis (d.b.) resulted in about 24.67% decrease in pressure drop [Sacilik 2004]. Molenda et al. [2005] reported that for wheat samples of moisture contents of 10.2, 13.4, 15, and 19% decrease in airflow resistance between levels of 15 and 19% was particularly high, found from 0.81 to 1.39 kPa at velocity of 0.4 m/s. Kobus et al. [2011] measured airflow resistance values through oat at the velocity ranging from 0.1 to 1.0 m/s. Airflow resistance depended on moisture content. An increase in the moisture content from 14 to 22% w.b. resulted in lower airflow resistance from 0.95–15.63 kPa/m to 0.69–11.26 kPa/m, depending on the airflow velocity. Results obtained by Kenghe et al. [2011, 2013] confirmed that the airflow resistance decreased with increase in moisture content. The experiments concerned the three varieties of lathyrus at moisture content of 6.75 to 19.40% d.b. for superficial air velocities ranging from 0.04 to 1.48 $m^3/(m^2 \cdot s)$.

The discussed tendency observed also Farmer et al. [1981], Patil and Ward [1988], Alagusundaram et al. [1992], Giner and Denisienia [1996], Chung et al. [2001], Jekayinfa [2001], Reed et al. [2001].

Effect of variety

The effect of variety on resistance of bulk grain was studied by Sokhansanj et al. [1990] for lentils and by Nalladurai et al. [2002] for paddy. They observed the difference in slopes of the pressure drop lines of different varieties. The difference in slopes may be due to different physical seed characteristics, such as shape, size, surface roughness, and porosity. Data presented by Shedd [1953] also shown the same behaviour for large and small seeded grains. The effect of variety on resistance to airflow was confirmed by Kenghe et al. [2013] for lathyrus.

Effect of method of fill

The method of filling affects the grain bulk porosity and density and, hence, the resistance against airflow. Prokwarun et al. [2013] presented the model of three standard packing patterns of spherical particles which are primitive, body center cubic, and face center cubic. The bulk porosity amounted to 0.482, 0.319, and 0.268 respectively.

Chang et al. [1981] observed an increase in the bulk density from 6 to 10% for corn, 11 to 12.5% for sorghum, and 5 to 9% for wheat when spreaders were used. These increases in bulk density increased the resistance to airflow more than doubled in corn and by about 55 to 67% in wheat at an airflow range of 0.08 $m^3/(m^2 \cdot s)$. Kumar and Muir [1986] reported that based on an air velocity of 0.077 m/s airflow resistances for layer filling (e.g. similar to filling a bin with a spreader) were higher than end filling (e.g. similar to filling a bin with stationary spout) by 25 to 35% for vertical airflow and 50 to 75% for horizontal airflow.

Jayas et al. [1987b] stated that sprinkle fill gave consistently higher bulk densities for canola by approximately 7% comparing to spout fill. Resistance to airflow was also significantly affected by fill method. Yang and Williams [1990] reported that the pressure drop across grain sorghum bed to airflow rate was linearly related to bulk density over airflow range of 0.005 to 0.2 $m^3/(m^2 \cdot s)$. Nimkar and Chattopadhyay [2002] observed that 1% increase in bulk density increased the pressure drop across green gram bed by 6.6% for superficial air velocities which ranged between 0.0104 and 1.0875 $m^3/(m^2 \cdot s)$. Sacilik [2004] reported that an increase in bulk density of poppy seeds by about 6.16% caused an increase in pressure drop by about 28.25% for airflow range of 0.03 to 0.08 $m^3/(m^2 \cdot s)$. Łukaszuk et al. [2008] stated that gravitational axial filling of the grain column from three heights (0.0, 0.95, and 1.8 m) resulted in the pressure drops through wheat bed 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 maximum 2.2 times increase in airflow resistance. Kenghe et al. [2013] observed that the increase in density of lathyrus grain bulk at any moisture level (6.75–19.40% d.b.) resulted in an increase in pressure drop at all airflow rates (0.1679–1.0972 $m^3/(m^2 \cdot s)$). Bulk density of the densely packed lathyrus grain was found to be 9.63 –11.67% denser as compared to the loose fill conditions. The corresponding increase in airflow resistance was about 1.41 times higher than that of loose fill conditions.

Other researches confirmed that dense fill resulted in an increase in pressure drop [Bern and Charity 1975, Stephens and Foster 1976, Farmer et al. 1981, Sokhansanj et al. 1990, Jayas et al. 1991b, Dairo and Ajibola 1994, Agullo and Marenya 2005, Jekayinfa 2006].

Dense packing and decreased porosity contributed to an increased pressure drop, but the increase in pressure drop cannot be explained solely by changes in bulk density and porosity. Orientation of the seeds for each type of fill may play a significant role [Sokhansanj et al. 1990, Jayas et al. 1991b, Pabis et al. 1998, Kashaninejad and Tabil 2009].

Effect of airflow direction

The effect of airflow direction on airflow resistance may be related to kernel orientation. Filling the grains from top of the box caused the grains lie with the major axes horizontal. It is likely that different porosities and pathway configurations are presented horizontally and vertically causing a variation in the airflow resistance in each direction [Lamond and Smith 1982, Kumar and Muir 1986].

Grains lying with the major axes horizontal give easy path to airflow. This cause reduction in the pressure drop in the horizontal direction of airflow than in the vertical direction [Nalladurai et al. 2002].

Kumar and Muir [1986] measured the resistance of wheat and barley for horizontal and vertical airflow. They reported that at an airflow value of 0.077 $m^3/(m^2{\cdot}s)$ the ratio of horizontal to vertical pressure drop for wheat was 0.63 and for barley 0.47. Kay et al. [1989] stated that for airflow rates range of 0.1 to 0.4767 $m^3/(m^2{\cdot}s)$ horizontal airflow resistance of shelled corn was about 0.58 of the vertical resistance and for airflow rates at or below 0.1 $m^3/(m^2{\cdot}s)$, horizontal resistance was about 0.45 of the vertical resistance.

The resistance of laird lentils to horizontal airflow was one-half of the resistance to vertical airflow for an airflow range of 0.003 to 0.6 $m^3/(m^2{\cdot}s)$ [Sokhansanj et al. 1990]. The resistance to airflow through bulk flax seed in the horizontal direction was 0.38 to 0.65 of the resistance to airflow in the vertical direction for an airflow range of 0.036 to 0.25 $m^3/(m^2{\cdot}s)$ [Jayas et al. 1991b]. Hood and Thrope [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. The ratio of horizontal to vertical pressure drop for bird's foot trefoil, canary seed, lentils, meadow fescue, oats and timothy was 0.30 to 0.67 in the airflow range of 0.035 to 0.28 $m^3/(m^2{\cdot}s)$, and for faba beans, tara peas and alfalfa pellets was 1 in the same airflow range [Alagusundaram et al. 1992]. The resistance to airflow of paddy and its byproducts in the horizontal direction was 0.19 to 0.31 times the resistance to airflow in the vertical direction in the airflow range of 0.01 to 0.1 $m^3/(m^2{\cdot}s)$ [Nalladurai et al. 2002]. The tests done by Łukaszuk et al. [2008] showed that the pressure drop in wheat in vertical direction was maximum 1.5 times higher than in horizontal direction. Jayas et al. [1987b] reported that even for spherical-shaped canola particles the resistance to airflow in the horizontal direction was 0.5 to 0.7 the resistance to airflow for the vertical direction in the airflow range of 0.0158 to 0.1709 $m^3/(m^2{\cdot}s)$.

Jayas et al. [1991b] noticed the different behaviour of flax seed to changes in the moisture content in horizontal and vertical directions. The resistance to airflow decreased with an increase in seed moisture content for airflow in the horizontal direction but did not change for airflow in the vertical direction. Jayas et al. [1991b] gave the following explanation. When dropped into the container, flax seed kernels will lie flat on the supporting screen and will create a stack of flat particles for vertical airflow. Any expected increase in thickness due to increased moisture content will have a minimum impact on the exposed cross section presented to vertical airflow. In the horizontal direction, however, any expected increases in the seed thickness due to moisture content could alter the flow path considerably.

Neethirajan et al. [2006] analysed X-ray CT images to explain the airflow resistance differences in grain bulks. Morphological information of the airpaths from the tomographic images showed that the size and number of airpaths vary between horizontal and vertical directions of the examined grain bulks. Airpath area and airpath lengths along the horizontal direction were 100% higher than in the vertical direction for wheat, barley and flax seed bulks, however, as for pea and mustard bulks, they were only 30% higher in the horizontal direction than in the vertical direction. Neethirajan et al. [2006] stated also that the numbers of airpath along the horizontal direction for wheat, barley and flax seeds, respectively, were 92, 145 and 187% more than along the vertical direction. In pea and mustard bulks, however the increase in the number of airpath was only 28 and 17%.

Effect of foreign materials

When fines and chaff are present in the bulk they modify the structure and the porosity of the bulk. Foreign materials are smaller than grains and they fill up the void spaces, causing an increase in bulk density and a decrease in bed porosity. Therefore grains mixed with fines and/or chaff offer more resistance to airflow than cleaned grains. The same problem arises according to biomass, which very often is divided into fractions of various size [Nurek and Roman 2014]. Growing interest in waste forest biomass as an energetic raw material enforce its drying [Zawistowski et al. 2010].

Grama et al. [1984] reported that the airflow resistance for a mixture of fines and shell corn changed linearly with the percentage of fines present in corn. A similar linear relationship for a mixture of fines and laird lentils observed Sokhansanj et al. [1990]. Jayas et al. [1991a] stated that at constant fraction of chaff, the resistance to airflow through canola increased linearly as fine increased. At a constant fraction of fines, the resistance to airflow through canola decreased linearly as chaff increased. Jayas et al. [1991a] observed that depending on the airflow rate, the resistance to airflow through fines was 2.3 to 3.1 times the resistance of canola, while the resistance to airflow through chaff was 0.12 to 0.15 times the resistance of canola. Jayas et al. [1991b] reported that an increase in fines from 0 to 15% increased the resistance to airflow through flax seed by 140 to 155%. The increase in airflow resistance was not linear with an increase in fines. Resistance to airflow decreased with an increase in chaff to 5% but further increases in chaff to 10 or 15%

resulted in an increase in the resistance to airflow through flax seed.

Nalladurai et al. [2006] observed an increase in the resistance to airflow of paddy bulk with the increase in the fraction of fines and chaff. The higher resistance to airflow of paddy was created due to the fines content than the chaff content at equal fraction. Chaff content of 5, 10 and 15% by weight increased the pressure drop on an average by 6, 18 and 27%, respectively, than those of cleaned paddy bulk. Fines content of 5, 10 and 15% by weight increased the pressure drop on an average by 102, 177 and 457%, respectively, than those of cleaned paddy bulk. Sacilik [2004] reported that an increase in fines content from 0 to 10% caused an increase in pressure drop through the poppy seed beds by about 30.08%.

CONCLUSION

Drying (to remove moisture) and aeration (to remove heat) are important processes during grain storage. In most practical cases, however, the losses of energy, product quality and consumer value occur. The designing of an proper drying and aeration system depends on the understanding of the resistance to airflow through bulk grain. The relationship between a drop in pressure and the rate of airflow through an agricultural product is a function of both products and air properties. The air pressure, required to force air through a bed of grain, is dissipated continuously due to friction and turbulence. The resistance to airflow through grains is affected by several factors: airflow rate, shape and size of the grain, grain variety, grain moisture content, method of filling, airflow direction, amount, size and distribution of foreign materials. Dependences are generally following.

The resistance to airflow decreased with an increase in grain moisture content. Dense filling resulted in an increase in pressure drop. The resistance to airflow through bulk grain in the horizontal direction is, in most cases, smaller than in the vertical direction. Grains mixed with foreign materials offer more resistance to airflow than cleaned grains.

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Streszczenie: *Opory przepływu powietrza przez warstwę ziarna – przegląd. Część II: Wpływ parametrów procesu*. W artykule omówiono czynniki, od których zależy spadek ciśnienia powietrza w warstwie ziarna podczas suszenia i wietrzenia: prędkość przepływu, kształt i rozmiar ziarna, jego odmiana, zawartość wody w ziarnie, metoda wypełniania zbiornika, kierunek przepływu powietrza, ilość, rozmiar i rozkład zanieczyszczeń. Z przeglądu literatury wynika, że można zaobserwować następujące zależności. Opór przepływu malał ze wzrostem zawartości wody w ziarnie i rósł ze wzrostem gęstości w stanie zsypnym. Opory przepływu w kierunku poziomym były przeważnie mniejsze od oporów w kierunku pionowym. Warstwa ziarna zanieczyszczona plewami i pyłem powodowała większy opór przepływu niż warstwa bez zanieczyszczeń.

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Authors' address:
Krzysztof Górnicki
Wydział Inżynierii Produkcji SGGW
Katedra Podstaw Inżynierii
02-787 Warszawa, ul. Nowoursynowska 166
Poland
e-mail: krzysztof_gornicki@sggw.pl