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Resistance of bulk grain to airflow – a review. Part I: Equations for airflow resistance

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Abstract: *Resistance of bulk grain to airflow – a review. Part I: Equations for airflow resistance.* For long-term safe storage of grains, they must be kept cool and dry. Drying or cooling is done by forcing air through the grains to remove high moisture and temperature gradients within the bulk. Fan selection for drying and aeration systems requires knowledge of how much airflow resistance will be developed in a particular bed of grain. Theoretical, semitheoretical, and empirical models were discussed relating pressure drop to airflow, among others Ergun model, modified Ergun equations, Shedd model, Hukill and Ives model, and statistical models.

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

INTRODUCTION

The resistance which has to be overcome by air flying through packed bed of biological materials (e.g. bulk grain) is defined as a pressure drop per unit bed depth.

Cereals are one of the most spread and economically the most important field crops [Jánský and Živělová 2008]. Cereal grains and oilseeds stored for long durations are susceptible to invasion and damage by insect, mites and fungi. The grain temperature and moisture content are the two important abiotic factors that affect the grown and activity of these biological organisms in the stored grain. To ensure safe storage, it is often necessary to dry or to cool the grain by forcing air through it [Alagusundaram et al. 1991, Kaleta 2001a, b, Waszkiewicz and Sypuła 2007, 2008].

Air is used in drying, aeration and storage systems of biological materials. In drying, air carries heat to and moisture from the product, while in aeration, air cools the product by carrying away the heat. Moisture removal or cooling, in these cases, cannot be achieved if air is not forced through the material. When air is forced through a layer of bulk agricultural materials, resistance to the flow, the so-called pressure drop, develops as a result of energy lost through friction and turbulence [Hall 1980, Brooker et al. 1992]. The prediction to airflow resistance, which is fundamental to the design of efficient drying and aeration systems, has been studied for the past 70 years. Fan selection for drying and aeration systems requires knowledge of how much airflow resistance will be developed in a particular bed of grain [Yang and Williams 1980, Jayas et al. 1991a, Kaleta 1996].

EQUATIONS FOR AIRFLOW RESISTANCE OF BULK GRAIN

Several theoretical, semitheoretical, and empirical models have been developed relating pressure drop to airflow.

For the values of superficial velocity used in drying and aeration the Ergun [1952] equation could be applied to the pressure drop of air in packed beds. Ergun developed an equation based on fluid – dynamic principles. He assumed that the pressure loss can be treated as the sum of the viscous and kinetics energy losses. Ergun model has two-terms. It is simply the sum of equation for laminar flow (this term is a linear function of air flow rate) and equation for turbulent flow (this term is a function of v_0^2). Ergun model has the following form:

$$\Delta P = 150 \frac{v_0 \mu}{d_e^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + 1.75 \frac{\rho v_0^2}{d_e} \frac{(1-\varepsilon)}{\varepsilon^3} \tag{1}$$

where:
ΔP – pressure drop per unit height [Pa/m];
v_0 – superficial velocity [m^3/(m^2·s)];
d_e – equivalent particle diameter [m];
ε – bulk porosity, fraction;
μ – dynamic viscosity of air [Pa·s];
ρ – air density [kg/m^3].

Yang and Williams [1990] assumed that pressure in the circular pipes represents the airflow resistance of the grain bed. They developed the similar model to that presented by Ergun and applied it to describe the airflow resistance of clean grain sorghum over an airflow range from 0.005 to 0.34 m^3/(m^2·s) and bulk density from 772 to 852 kg/m^3. For such conditions Young and Williams model is of the form:

$$\Delta P = 358.35 \frac{v_0 \mu}{d_e^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + 2.82 \frac{\rho v_0^2}{d_e} \frac{(1-\varepsilon)}{\varepsilon^3} \tag{2}$$

The reviewed literature showed that Ergun model (1) is the most comprehensive model to be used for airflow – pressure drop calculations. This model requires information about bulk porosity, the particle equivalent diameter, and properties of air [Li and Sokhansanj 1994]. There is a problem in the determination of the equivalent particle diameter. The variations in the shapes and sizes of materials make it impossible to accurately determine d_e. Also, the problem in measuring porosity is evident. It is difficult to produce a sample for pycnometer similar to the sample on which the pressure drop is measured and this is true for other methods of porosity measurements [Pabis et al. 1998]. Therefore, several modified Ergun equations can be found in the literature.

If the air density and viscosity do not vary much and the particle size is nearly constant, all the terms in equation (1) except the porosity and velocity can be damped to constant coefficients. By adding an intercept term equation (1) becomes:

$$\Delta P = X_1 + X_2 \frac{(1-\varepsilon)^2}{\varepsilon^3} v_0 + X_3 \frac{(1-\varepsilon)}{\varepsilon^3} v_0^2 \tag{3}$$

where: X_1, X_2, X_3 – constants.

This is the model used by Bern and Charity [1975]. They studied the pressure drop of bulk grain corn as influenced by bulk density. An increase in the bulk density resulted in an increase in the airflow resistance. Yang and Williams [1990] stated that model (3) which related the pressure drop across grain sorghum bed to airflow rate and bed voidage, can be used to a good approximation.

Porosity is calculated by $\varepsilon = 1 - \rho_b/\rho_k$ and therefore the equation (3) can be written as follows:

$$\Delta P = X_1 + X_2 \frac{(\rho_b/\rho_k)^2}{(1-\rho_b/\rho_k)^3} v_0 + X_3 \frac{(\rho_b/\rho_k)}{(1-\rho_b/\rho_k)^3} v_0^2 \quad (4)$$

where:
ρ_b – bulk density [kg/m^3];
ρ_k – kernel density [kg/m^3].

Equation (4) was used by Kay et al. [1989] to describe the airflow resistance of shelled corn in both horizontal and vertical directions. Wilcke and Bern [1986] applied this equation for calculating airflow resistance in bulk corn.

Bakker-Arkema et al. [1969] modified Ergun model (1) to describe the airflow – pressure drop relationship in packed bed of cherry pits. The modified equation was given as:

$$\Delta P = K_B \left[150 \frac{v_0 \mu}{d_e^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + 1.75 \frac{\rho v_0^2}{d_e} \frac{(1-\varepsilon)}{\varepsilon^3} \right] \quad (5)$$

where: K_B – product-dependent constant.

Bakker-Arkema et al. [1969] stated that equation (5) can be used to describe airflow–pressure drop relationships for agricultural products.

Patterson et al. [1971] studied the resistance of beans and corn to airflow and reported that equation (5) correlated the predicted airflow resistance data to the experimental data quite well.

Matthies [1956], as well as Matthies and Petersen [1974] proposed the following pressure drop equation:

$$\Delta P = K_M \left(\frac{11.98}{\mathrm{Re}} + \frac{0.295}{\mathrm{Re}^{0.1}} \right) \frac{2\rho v_0^2}{\varepsilon^4 d_e} \quad (6)$$

where:
Re – Reynolds number, $\mathrm{Re} = \rho d_e v_0 / \mu$;
K_M – product-dependent constant, is a function of the size, shape, distribution and surface characteristics of particles.

They stated that this equation can be used to describe the resistance to airflow of agricultural products.

Based on Ergun model (1), Li and Sokhansanj [1994] developed the following equation to describe the airflow–pressure drop relationship in packed beds of grains:

$$\Delta P = 2k_1 \frac{v_0 \mu}{d_e^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + 2k_2 \frac{\rho v_0^2}{d_e} \frac{(1-\varepsilon)}{\varepsilon^3} \quad (7)$$

where: k_1, k_2 – product-dependent constants obtained from the experiment.

Equation (7) was fitted to the data of wheat, alfalfa seed, laird lentil, asilike clover, red clover, flax, oats, barley and shelled corn over an airflow range from $0.754 \cdot 10^{-4}$ to about 0.9 m^3/(m^2·s). Li and Sokhansanj [1994] stated that equation (7) is a good general model to predict the airflow resistance of tested granular grains. Variations of k_1 and k_2 among seeds are due to dependence of product constant on the seed shape and size. It is worth to notice that Yang and Williams [1990] determined the airflow resistance of grain sorghum as affected by bulk density and developed equation (2) similar to equation (7) with k_1 = 179.2 and k_2 = 1.41 for sorghum.

Li and Sokhansanj [1994] studied the effect of fines in grain on the model (7). When fines are present in the bulk they modify the structure and the porosity of the bulk because they are smaller than seeds. Authors proposed in this case to replace the equivalent particle diameter (d_e) with modified equivalent particle diameter (d_e^*) calculated as:

$$d_e^* = d_e(1 - f_m) \tag{8}$$

The fines concentration (f_m) is in decimal mass fraction and range from 0.05 to 0.25.

It results from equations (1)–(8) that the main factors that affect the resistance of bulk granular materials to airflow are superficial air velocity, air viscosity and density, porosity of the bulk material, size distribution of particles, irregularity in particles shape, surface roughness characteristics, orientation of the particles and tortuosity. Such variables as porosity and all the characteristics of the particles are extremely difficult to measure. For this reason, an empirical approach is very often used [Haque et al. 1982, Pabis et al. 1998], although there are also attempts to describe e.g. the irregularity in particles shape using mathematical models [Mieszkalski 2014a, b].

For simplicity of use, factors in Ergun model (1) other than airflow rate can be lumped in two parameters for each agricultural material, so model (1) becomes equation of the form [Hunter 1983, Giner and Denisienia 1996]:

$$\Delta P = A_1 v_0 + B_1 v_0^2 \tag{9}$$

where:
A_1, B_1 – product-dependent constants obtained from experiment.

Equation (9) is empirical in the nature but has a theoretical background. It can be treated as an another form of the Ergun model. Molenda et al. [2005] stated that two parameters Ergun equation well fitted the experimental results for wheat in a relatively large air velocity range. The parameter of quadratic term was about five times higher that of the linear term. Abou-El-Hana and Younis [2008] measured the pressure drop in shelled corn beds for airflow rates in range from 0.081 to 0.242 $m^3/(m^2 \cdot s)$ and stated that two parameter Ergun equation fitted the results better than Shedd equation. Kobus et al. [2011] used Ergun equation to describe airflow resistance through oat bed.

Haque et al. [1982] conducted experiments to determine pressure drop in airflow through clean grains such as corn, sorghum, and wheat. The tested airflow range was 0.01 to 0.22 m/s and grain moisture content varied between 12.4 to 25.3 percent wet basis (w.b.). They reported that the following empirical equation adequately described the airflow–pressure drop relationship in a fixed bed of grain:

$$\Delta P = A_2 v_0 + B_2 v_0^2 - C M v_0 \tag{10}$$

where:
M – grain moisture content [percent w.b.];
A_2, B_2, C – product-dependent constants obtained from experiment.

The most commonly used empirical model is the one proposed by Shedd

[1953]. Shedd suggested the use of following equation to describe the relationship between the pressure drop in fixed bed of grain and the air velocity:

$$v_0 = A_3(\Delta P)^{B_3} \tag{11}$$

where: A_3, B_3 – product-dependent constants obtained from experiment.

Shedd suggested the use of this equation for narrow ranges of airflow rates only (0.005–0.3 $m^3/(m^2 \cdot s)$) due to non--linearity of the log–log plot. The Shedd model was recommended by Brooker [1969], Segerlind [1983], Gunasekaran and Jackson [1988], and Sokhansanj et al. [1990], but with constants A_3 and B_3 as piecewise constants. Physically, the reciprocal of A_3 is this equation represents the resistance to airflow through the product. The reciprocal of A_3 was used to compare resistance of different samples [Kashaninejad and Tabil 2009].

The Shedd equation is easy to incorporate into mathematical models from predicting air pressure patterns in stored grain [Segerlind 1983]. Many designers use Shedd model to estimate pressure drop in grain bulks due to its simplicity and ease of handling [Stephens and Foster 1976, Kumar and Muir 1986, Jayas et al. 1987, Sokhansanj et al. 1990, Jayas et al. 1991a, b, Alagusundaram et al. 1992, Al-Yahya and Moghazi 1998, Nalladurai et al. 2002, Nimkar and Chattopadhyay 2002, Sacilik 2004, Agullo and Marenya 2005, Jekayinfa 2006].

Although Shedd equation is empirical in nature, it has a theoretical background. Ergun model is the sum of equation for laminar flow and equation for turbulent flow. For the case of laminar flow, the pressure drop is proportional to the velocity, whereas, for the case of turbulent flow, the pressure drop is proportional to the velocity squared. During the flow through packed beds, the transition from laminar to turbulent flow is very gradual and, therefore, the exponent of the velocity should be somewhere between 1 and 2 [Pabis et al. 1998].

Yang and Williams [1990] studied the effect of bulk density on airflow resistance of grain sorghum and modified Shedd equation as follows:

$$\Delta P_{packed} = \Delta P_{Shedd}(-7.04 + 0.0102\rho_b) \tag{12}$$

where:
ΔP_{packed} – pressure drop per unit height across packed bed [Pa/m];
ΔP_{Shedd} – pressure drop per unit height across loose-filled bed [Pa/m].

Equation (12) is valid over airflow range of 0.005 to 0.2 $m^3/(m^2 \cdot s)$.

Jayas et al. [1991b] studied the effect of the amount of chaff and fines in canola on airflow resistance and obtained the following linear relationship which describes the dependence of constant A_3 on fractions of chaff, fines and canola:

$$A_3 = X1 \cdot CANF + X2 \cdot CHAF + X3 \cdot FINF \tag{13}$$

where:
CANF – canola concentration [%];
CHAF – chaff concentration [%];
FINF – fines concentration [%];
*X*1, *X*2, *X*3 – constants.

Equation (13) is valid for airflow from 0.0004 to 0.758 $m^3/(m^2 \cdot s)$.

The constant *X*2 is positive, indicating a decrease in airflow resistance with an increase in the chaff fraction while the constant $X3$ is negative, indicating an increase in airflow resistance with an increase in the fines fraction. For loose--filled columns and with airflow less than 0.02 $m^3/(m^2 \cdot s)$, the pressure of fines did not contribute significantly to the resistance of the samples [Jayas et al. 1991b].

Because of the limitation of equation (11) for being able to predict airflow resistance over only a narrow range of airflow rate, Hukill and Ives [1955] proposed an empirical equation to represent the airflow resistance data over an airflow range of 0.01–2.0 $m^3/(m^2 \cdot s)$. The equation is of the following form:

$$\Delta P = \frac{A_4 v_0^2}{\ln(1 + B_4 v_0)} \tag{14}$$

where: A_4, B_4 – product-dependent constants obtained from experiment.

Hukill and Ives equation accounts for the non-linear nature of resistance to airflow data. The model is used in standard D272.3 of the American Society of Agricultural and Biological Engineers (ASABE) to represent the airflow pressure drop data for selected grain. The only drawback of the Hukill and Ives equation according to Segerlind [1983] is that air velocity cannot be expressed explicitly as a function of pressure drop.

Hukill and Ives equation were used to estimate pressure drops in grain bulks by many designers [Kumar and Muir 1986, Sokhansanj et al. 1990, Jayas et al. 1991a, Alagusundaram et al. 1992, Sinicio et al. 1992, Nalladurai et al. 2002, Agullo and Marenya 2005]. Kenghe et al. [2011, 2012] examined the Shedd, Hukill and Ives equations for pressure drop prediction. Resistance of bulk lathyrus and bulk soybean was accurately described by Shedd equation followed by Hukill and Ives equation and Ergun equation.

The amount and size distribution of foreign material affect the resistance to airflow therefore researchers modified Hukill and Ives empirical equation to include foreign material as follows:

– for bulk canola [Jayas and Sokhansanj 1989]

$$\Delta P' = \Delta P(1 + 1.75 f_m) \tag{15}$$

(equation valid for fines from 0 to 0.25 by mass fraction and airflow from 0.0243 to 0.2633 $m^3/(m^2 \cdot s)$),

– for bulk flax seed [Jayas et al. 1991a]

$$\Delta P' = \Delta P[1 + (A + Bv_0)CHAF + (C + Dv_0)FINF] \tag{16}$$

(equation valid for chaff from 0 to 0.15 by mass fraction, fines from 0 to 0.15 by mass fraction and airflow from 0.036 to 0.25 $m^3/(m^2 \cdot s)$),

– for bulk lentils [Sokhansanj et al. 1990]

$$\Delta P' = \Delta P[1 + (a' - b' v_o) f_m] \tag{17}$$

(a' = 6.3435 and b' = 5.7218 for fines from 0 to 0.25 by mass fraction and airflow from 0.003 to 0.6 $m^3/(m^2 \cdot s)$),

where:

ΔP – pressure drop across clean grain bed [Pa/m];

$\Delta P'$ – pressure drop across grain bed mixed with fines or fines and chaff [Pa/m].

The constants A, B, C and D in equation (16) for vertical airflow direction were 0.0081, –0.0049, 0.0638 and –0.0870, respectively and for horizontal direction were –0.0056, 0.0309, 0.0686 and –0.0334, respectively [Jayas et al. 1991a].

Kay et al. [1989] measured the airflow resistance of shelled corn in both horizontal and vertical directions at eight airflow rates between 0.0126 and 0.4767 $m^3/(m^2 \cdot s)$ and at three bulk densities between 765.5 and 802.7 kg/m^3. They found that ratio between the horizontal and vertical resistances can be represented by equation of the following form:

$$H / V = C_1 + C_2 \ln v_0 + C_3 (\ln v_0)^2 + C_4 (\ln v_0)^3 \qquad (18)$$

where:
H / V – ratio of horizontal and vertical airflow resistance;
C_1, C_2, C_3, C_4 – constants for equation.

Chuma et al. [1983] determined the effect of the depth of the bed and airflow rate on statistic pressure using Ramsin equation [Bakker-Arkema et al. 1969]:

$$\Delta P_1 = a v_0^n H^m \qquad (19)$$

where:
ΔP_1 – pressure drop [Pa];
H – depth of packed bed [m];
n, m – constants.

For the constant n the values of 1.46, 1.55, and 1.64 for rough rice, wheat, and corn, respectively, were obtained. Constant m was found to be 1.1. Chuma et al. [1983] stated that constant a depends linearly on the moisture content and increases with increasing the moisture content.

To describe the empirical relationship between pressure drop across bulk grain and the experimental variables such as airflow rate, moisture content, bulk density and fines content, statistical model was often used. Model was developed using standard stepwise non-linear regression techniques. The result relationship takes the following general form:

$$\Delta P = b_1 v_0^2 + b_2 M v_0 + b_3 \rho_b v_0 + b_4 f_m v_0 \qquad (20)$$

where: b_1, b_2, b_3, b_4 – regression coefficients.
This form of equation allows relative comparison of each of the variable effects.

Equation (20) was used by Siebenmorgen and Jindal [1987] on rough rice, Dairo and Ajibola [1994] on sesame seeds, and Chung et al. [2001] on grain sorghum and rough rice. Sacilik [2004] used the equation to describe the pressure drop of poppy seeds, Agullo and Marenya [2005] to describe the pressure drop of parchment coffee, and Kenghe et al. [2011, 2012] to predict the pressure drop of lathyrus and soybean.

There are some attempts in the literature to describe the airflow in grain bulks using mathematical models other than Ergun model. Khatchatourian et al. [2009] developed a mathematical model, algorithm, and software, to calculate the static pressure, streamlines, and airflow velocity distribution in two- and three-dimensions under anisotropic conditions.

CONCLUSIONS

For long-term safe storage of grains, they must be kept cool and dry. Drying or cooling is done by forcing air through the grains to remove high moisture and temperature gradients within the bulk. When air is forced through a layer of bulk agricultural materials, resistance to the flow, the so-called pressure drop, develops as a result of energy lost through friction and turbulence. The prediction to airflow resistance is fundamental to the design of efficient drying and aeration systems. Fan selection for these systems requires knowledge of how much airflow resistance will be developed in a particular bed of grain. The airflow – pressure drop relationship are useful in the mathematical modelling of airflow pressure patterns and airflow distribution in stored agricultural materials masses.

The resistance to airflow through agricultural materials has been studied for many years. Several theoretical, semi--theoretical, and empirical models have been developed relating pressure drop to airflow, among others Ergun model, modified Ergun equations, Shedd model, Hukill and Ives model, and statistical models. The theoretical Ergun model has been originally developed for packed beds of uniformly sized spheres. The equation contains a linear and quadratic velocity term, which depends on bed porosity, particle diameter and fluid properties. An alternative expressions are the models of Shedd, Hukill and Ives, and statistical model. The constants in these equations have a purely empirical nature without physical meaning. The models found however to fit many experimental data sets.

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Streszczenie: *Opory przepływu powietrza przez warstwę ziarna – przegląd. Część I: Równania oporów przepływu*. Aby bezpiecznie przechowywać ziarno przez długi czas, musi być ono schłodzone i wysuszone. Suszenie i wietrzenie ziarna wykonuje się, przetłaczając powietrze przez warstwę ziarna, co powoduje zmniejszenie gradientów temperatury i zawartości wody w warstwie. Dobre dobranie wentylatora wymaga umiejętności wyznaczenia oporów przepływu powietrza przez badaną warstwę. W artykule dokonano przeglądu teoretycznych, półteoretycznych i empirycznych modeli do wyznaczania omawianych oporów. Omówiono m.in. model Erguna, zmodyfikowany model Erguna, model Shedda, model Hukilla i Ivesa oraz modele statystyczne. Model Erguna jest modelem teoretycznym. Pierwszy człon tego modelu zależy liniowo od prędkości, drugi zaś zależy od kwadratu prędkości. Oba człony zależą również od porowatości złoża, średnicy ziaren i parametrów przetłaczanego płynu. Stałe w modelach empirycznych są wielkościami jedynie empirycznymi bez znaczenia fizycznego. Modele te ze względu na swoją prostotę są bardzo często stosowane w praktyce.

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