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Research Paper

A pore-scale model for predicting resistance to airflow in bulk grain

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A pore-scale model was developed to predict airflow resistance through grain bulks. The model consisted of two components: simulation of pore structures and prediction of pressure drop through connected pores that formed airflow paths in the grain bulk. The discrete element method (DEM) was used to simulate the spatial arrangement (pore structure) of grain kernels in a grain bulk. The grain kernels were approximated as spherical particles in the DEM model. Based on the DEM simulations, a collection of tetrahedron units was constructed to represent local airflow paths (individual pores) and these local paths were then connected to form global airflow paths. A flow branching model was developed to predict pressure drop within each local flow path, and the total pressure drop through the grain bulk was then calculated as the sum of resistances of all local paths associated with the global path. An experiment was conducted to validate the proposed model. The results showed that the model predictions were in reasonable agreement with the experimental data. The predicted pressure drop was 12% higher than the experimental value at a low superficial air velocity of 0.013 m s^{-1} when the inertial effect was negligible, and 17% lower than the measured value at a high air velocity of 0.027 m s^{-1} when some inertial effect existed.

1. Introduction

A common practice of preserving the quality of stored grain is drying or aeration, in which fans are used to move air through grain bulks to remove grain moisture or lower grain temperature and prevent spoilage. Many factors influence the effectiveness and energy efficiency of grain drying/aeration systems, such as air temperature and relative humidity, grain moisture content, grain type, and airflow resistance (Aviara, Ajibola, & Oni, 2004; Gunasekaran & Thompson, 1986; Hellevang, 2013; Jokiniemi, 2016; Morey, Cloud, & Lueschen, 1976; Tiusanen, Jokiniemi, & Hautala, 2013; Zuritz & Singh, 1985). Understanding airflow through bulk grain is important for designing grain drying and aeration systems. Airflow resistance (or air pressure drop) of agricultural products has been studied since 1930s. Most of studies involve the measurement of pressure drop along a column of the material being tested at different flow rates, and then the experimental data are fitted to some empirical equations or models (Ergun, 1952; Hukill & Ives, 1955; Shedd, 1953). The ASABE Standard D272.3 (2011) summarises the pressure drops for airflow through various grains, seeds and other agricultural products

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Nomenclature

a_1, a_2	Empirical constants in multiplier function $f(\theta_i)$
A_f	Available cross-sectional area (ACSA) for air to flow through a tetrahedron (m^2)
At	Area of triangle (m^2)
A_1, A_2, A_3	Areas occupied by three particles in a triangle (m^2)
ACSA	Available cross-sectional area (m^2)
AEP	Air entry point
C_0	Centroid of the air inlet triangle in a tetrahedron unit
C_1, C_2, C_3	Centroids of the three air outlet triangles in a tetrahedron unit
C_t	Centroid of tetrahedron
d_f	Equivalent local flow path diameter (width) (m)
d_p	Particle diameter (mm)
D	Hydraulic diameter of the pipe (m)
D_0	Diameter of the mother tube (m)
D_i	Diameters of daughter tubes (m), i = 1, 2, 3
F_i	Proportional coefficient
f_D	Dimensionless coefficient (the Darcy friction factor)
$f(\theta_i)$	Multiplier function
g_1, g_2	Constants in ASABE airflow resistance equation for a particular grain
HSV	High superficial air velocity ($m\ s^{-1}$)
k_n	Normal stiffness of wall ($N\ m^{-1}$)
k_s	Shear stiffness of wall ($N\ m^{-1}$)
k_{pn}	Normal stiffness of particle ($N\ m^{-1}$)
k_{ps}	Shear stiffness of particle ($N\ m^{-1}$)
L_0	Length of the mother tube (m)
L_i	Lengths of daughter tubes (m), i = 1, 2, 3
LFPW	Local flow path width (m)
LSV	Low superficial air velocity ($m\ s^{-1}$)
MF	Multiplier function
p	Half of the perimeter of a triangle (m)
Q_0	Volumetric flow rate in the mother tube ($m^3\ s^{-1}$)
Q	Airflow superficial velocity ($m\ s^{-1}$)
r_A, r_B, r_C	Radii of particles A, B, C, respectively (m)
Re_i	Reynolds number
S_1, S_2, S_3	Lengths of three sides of a triangle (m)
V_0	Velocity of airflow in the mother tube ($m\ s^{-1}$)
V_i	Velocity airflow in daughter tubes ($m\ s^{-1}$), i = 1, 2, 3
Ø	Porosity (%)
ΔL	Bed depth (m)
ΔP	Pressure drop (Pa)
ΔP_t	Total pressure drop of airflow through a tetrahedron unit (Pa)
ΔP_S	Pressure drop of airflow through the inlet (straight) section (in mother tube) (Pa)
$\Delta P_{b1,\ 2\ or\ 3}$	Pressure drop due to branching in daughter tubes (Pa)
μ_p	Friction coefficient between particles
μ_w	Friction coefficient between particle and wall (clear acrylic)
ρ_p	Particle density ($kg\ m^{-3}$)
ρ_b	Bulk density ($kg\ m^{-3}$)
ρ	Density of air ($kg\ m^{-3}$)
θ_i	Branching angle (°)
θ_1, θ_2, θ_3	Branching angles from the mother flow to the three branching flows (°)

as curves relating the superficial air velocity ($m\ s^{-1}$) to the pressure drop per unit depth ($Pa\ m^{-1}$). These models are simple and easy to use, but they are limited in directly capturing the effects of some of the fundamental characteristics of porous materials, such as pore structure.

Much research has shown that airflow resistance through a grain bulk is affected by many factors, including airflow velocity, flow direction, and bulk density (Amanlou & Zomorodian, 2011; Hood & Thorpe, 1992; Jayas & Muir, 1991; Nalladurai et al., 2002). The effect of these factors on airflow resistance may be related to the pore structure of grain bulk. Given the complexity and variability of pore structure in grain bulks, it is challenging to develop mechanistic airflow resistance models. In the realm of flow through porous media, researchers have attempted to develop mechanistic pore-scale models. For example, Du Pless and Woudberg (2008) proposed a concept of representative unit cell (RUC) to simplify the pore structures of porous media, based on which the resistance to airflow was predicted. Wu, Yu, and Yun (2008) developed a model to predict the resistance of flow through granular media based on the average hydraulic radius model and the contracting-expanding channel model with the average pore diameter. A common approach/simplification in the existing pore-scale models is to idealise the pore structure as a series of geometrically uniform structures, ignoring the true characteristics of pore structures, such as pore size, shape, topology, and connectivity.

Quantifying pore structures in grain bulks is difficult. Researchers have attempted to use experimental methods to study pore structures of bulk grains. For example, Neethirajan and Jayas (2008) used the X-ray computed tomography to reconstruct the pore structures of bulk grains (wheat, barley and flax seed). But few theoretical models can be found in the literature. The discrete element method (DEM) has been shown to have the potential of predicting pore structures of porous media. Gonzalez-Montellano et al. (2011) developed 3D discrete element models to simulate the pore structure of glass beads and maize. In their research, the glass beads were simulated as spheres in a size distribution determined by a given mean diameter and standard deviation, and the maize kernels were simulated as composing of six spheres representing the irregular shape of the real grains. Sobieski et al. (2012) used DEM to simulate the pore structure of porous beds and developed a numerical algorithm to construct the