Modeling on Heat and Mass Transfer in Stored Wheat during Forced Cooling Ventilation

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A mathematical model based on the theory of heat and mass transfer in porous media was developed to simulate the evolution of grain temperature and moisture content in a wheat storage bin during ventilation with cooling air at the constant temperature and humidity. Unlike the previous works on this aspect, the present work was not focused on cooling the stored grain by ventilation with ambient air, but with the refrigerated air. Validation was performed by comparing between predicted and measured grain temperature and grain moisture content for two cases. Predicted data were in reasonable good agreement with measured ones. The model and the parameter values used in the model are applicable for predicting temperature and moisture of stored grains under ventilation conditions.

Keywords: Heat and moisture transfer; Numerical simulation; Aeration; Stored grains

Introduction

High temperature and high moisture are the main reason for grain deterioration during storage. One method to reduce the deterioration of the stored grains is to cool it to reach a safe temperature and moisture level using an aeration system [1]. The cooling of grain during storage by ventilation with air has received increasing attention in recent years as it offers the possibility of controlling insects with reduced levels of pesticide application [2]. Accurate prediction of grain moisture and temperature during storage is needed in order to develop and evaluate aeration strategies. Many mathematical models have been developed to simulate the heat and the moisture transfer in aerated bulk stored grains. The partial differential equation (p.d.e.) models for wheat storage with aeration were developed by Metzger [3] and Wilson [4]. The models simulated forced convective heat and moisture transfer in vertical direction, but the model was not validated. Chang et al. [5-6] and Sinicio et al. [7] developed a rigorous model to predict the temperature and moisture content of wheat during storage with aeration, and found that prediction result is in reasonable agreement with observed data. Sun and Woods [8], Jia et al. [9], Andrade [10] and Devilla [11] simulated the temperature changes in a wheat storage bin respectively, and however, the moisture changes were not done. Iguaz et al. [12] developed a model for the storage of rough rice during periods with aeration. Daniela de Carvalho Lopes et al. [13] presented the methodology employed in the development of a software program, called AERO, that simulates the grain aeration process based on a one-dimensional model by using time variant ambient data, which enables the effects of hot spots to be considered.

In above studies, most of these models only deal with cooling grain with ambient air, relatively few models deal with temperature and moisture content changes with cooling grain with refrigerated air. Because of the higher temperature and relative humidity of ambient air in summertime, it is not fit for the ventilation to the stored...
grain, which was harvested usually in summertime. Cooling with refrigerated air can decrease quickly the temperature of the grain in a storage bin, so that the deterioration processes of grain will cease or be reduced to an acceptable rate. In this work, the model was developed according to the standard laws of heat and mass, and investigated the heat transfer and moisture loss during cooling aeration, whereby the governing equations were solved based on a finite volume approach to obtain the temperature profiles and moisture within the bulk of grain during cooling with a refrigerated air, and the simulation model was validated with experimental data.

**Governing equation**

The mathematical model used in this work is based on the theory of mass, energy balances and fluid dynamics in porous medium. The following set of equations governed the moisture, heat and momentum transfer in an aerated bulk of grain. The governing equations were formulated based on the following assumptions: (1) the bulk grain was considered as a continuous porous media; (2) within a stack of grain, the moisture and heat between the air and grain was transferred by convection and diffusion; (3) thermo-physical properties of the porous medium were constant in the range of temperature encountered; (4) the effect of hysteresis in the sorption process is neglected; (5) no change in the grain dry matter and internal heat generation take place. The moisture, heat and momentum transfer in an aerated bulk of grain are written as follows:

\[
\frac{\partial (\rho_a w)}{\partial t} + \nabla \cdot (\rho_a \vec{u} w) = \nabla \cdot (\rho_a D_{eff} \nabla w) + S_w \quad (1)
\]

\[
\left( \rho_a c_a + \rho_g (1 - \varepsilon) \right) \frac{\partial \vec{u}}{\partial t} + \rho_a c_a \nabla (\rho_a \vec{v}) = k_{eff} \nabla^2 T + S_h \quad (2)
\]

\[
\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} = -\nabla P + \nabla \left( \frac{\mu}{\rho_a} \nabla \vec{u} \right) + S_i \quad (3)
\]

in which \( w \) is the moisture content of air, \( t \) is time, \( a \) is superficial or Darcian velocity of air through grains. \( \mu \) is the viscosity of air. The void fraction of the bed of grains, \( \varepsilon \), is 0.4. \( \nabla \) is the del operator. The density of the intergranular air, \( \rho_a \), is 1.225 kg/m\(^3\). The effective diffusion coefficient, \( D_{eff} \), of water vapour through bulk grains is \( 5.73 \times 10^{-6} \) m\(^2\)/s at 20\(^\circ\)C reported by Thorpe [14]. The moisture source term, \( S_w \), that arises as a result of the grain kernels absorbing or desorbing moisture can be expressed as \( S_w = -(1 - \varepsilon) \rho_g \frac{\partial W}{\partial t} \), in which the density of durum wheat on a dry basis, \( \rho_g \), is 639 kg/m\(^3\). \( W \) is the moisture content of grains, \( c_s \) is the specific heat of air, \( c_t \) is the specific heat of grain, \( T \) is the temperature of bulk grain. The rate at which the kernels gain or lose moisture is given by the expression of

\[
\frac{\partial W}{\partial t} = -k(W - W_e), \quad \text{in which } k \text{ is the drying constant, given by O’Callaghan et al. [15] as } k = 2000 \exp \left( -\frac{5094}{T + 273.15} \right), \quad W_e \text{ is the moisture content of the outer surface of the grain kernels in equilibrium with the intergranular air conditions. It is expressed as } W_e = -\frac{1}{B} \log \left( \frac{T + C}{A} \log r \right), \quad \text{where } A, B \text{ and } C \text{ are empirical constants that in the case of durum wheat is assumed the values of 921.69}^{\circ}\text{C}^{-1}, 18.077 \text{ and } 112.35 \text{ }^{\circ}\text{C}, \text{respectively, as proposed by Chung and Pfost [16]. The relative humidity, } r, \text{ of the intergranular air is defined as } r = \frac{P}{p_{sat}}. \quad \text{Hunter [17] has provided the following empirical relationship between the saturation vapour pressure of water and temperature as } p_{sat} = \frac{6 \times 10^{22}}{(T + 273.15)^{6800}} \exp(-\frac{6800}{T + 273.15}) + 0.662 \frac{w}{T^{0.5}}. \quad \text{The effective bulk thermal conductivity in eq. (2), } k_{eff}, \text{ is 0.157 gleaned from the work of Gray [18]. The source term, } S_h, \text{ takes the form by Thorpe [19] as } S_h = -h_s (1 - \varepsilon) \rho_a \frac{\partial W}{\partial t}, \quad \text{where } h_s \text{ is the heat of sorption of water on the grains. Hunter [20] demonstrates that the ratio of the heat of sorption to the latent heat of vaporization, } h_s, \text{ of free water is given by } h_s = 1 + \frac{p_{sat}}{p} \frac{dT}{dr} \frac{dr}{dT}, \quad \text{in which } \frac{dT}{dp} = \left( \frac{T + 273.15}{p_{sat}} \right)^{0.5} \left( \frac{6800}{T + 273.15} \right)^{-5} \quad \text{and } \frac{dr}{dT} = \frac{Ar}{(T + C)^2} \exp(-BW_e). \quad P \text{ is the pressure of air in eq. (3).}

One can picture the momentum source \( S_i \) as the pressure gradient along a bed of grain uniformly aerated in the i-th direction with a velocity \( u_i \). It takes the form

\[
S_i = -\left( \sum_{j=1}^{3} D_{ij} u_{ij} + \sum_{j=1}^{3} C_i \frac{\partial}{\partial z_j} [u_j] \right), \text{ in which two orthogonal horizontal directions are designated by the indices 1 and 2, and the vertical direction has the index 3. According to the report presented by Thorpe [21], in this work the values of } D_{ij} \text{ and } C_i \text{ are } D_{11} = D_{22} = 1.833 \times 10^{-5}, \quad D_{33} = 2.037 \times 10^{-6}, \quad C_{11} = 18371, \quad C_{22} = 26767.

**Materials and methods**

A 10 m diameter reinforced concrete cylindrical grain