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Comparison of equilibrium models for grain aeration

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ABSTRACT

Mathematical modeling has played a significant role in the post-harvest system of cereals, fruits and other food commodities. More specifically, simulations have increasingly been used for the optimal design, planning and operation of grain aeration systems. Many models have been proposed to simulate this process, and others have been adapted to this purpose. Among them, there are two equilibrium models which do not require expensive solution techniques and can be used to evaluate the process time, grain temperature and grain moisture content variations. This study deals with the evaluation of these models by comparing the simulation results with experimental data. Results showed that both models had good correlations with experimental data and presented a very similar performance. The two evaluated models can be easily implemented in computer programs, contributing to improvements in this process control and guaranteeing the management of grain quality during the storage period.

1. Introduction

The quality of grain is related to appearance, nutrition, sanitary conditions and industrial characteristics. Damage caused by insects and fungi are the main cause of quality and quantity losses in grain storage, including mycotoxin contamination (Dawlal et al., 2012).

Grain aeration is a process of great relevance to post-harvest engineering and cereal storage control. The most important benefits from reducing grain temperature, either by using ambient or refrigerated air, are the maintenance of quality and the control of moisture migration. Lower temperatures will also have a considerable impact on the population parameters of insects and mites (Beckett, 2011; Hagstrum et al., 2012; Paraginski et al., 2014).

Considering the general concern over the use of chemical products in the post-harvest sector, the use of grain aeration may increase. With further research and development in this area, efforts can be made to improve the use of this technology in tropical and subtropical countries, as well as to optimize the process in regions where it is naturally feasible. Mathematical modeling to produce reliable simulations can result in a better interpretation of aeration behavior, enabling effective training in this area, lowering costs and reducing fan running times. Simulation studies allow the isolating of effects of specific parameters that directly influence the grain aeration, such as airflow, grain properties and climate conditions (Khatchatourian and Oliveira, 2006; Lopes et al., 2008a; Nawi et al., 2010; Silva et al., 2012).

Another important field of study by using mathematical modeling is the impact of different aeration control strategies on grain quality. The aeration control can turn the fan on or off based on different options such as time, grain temperature, air temperature and relative humidity (r.h.), and combinations of these options. As showed by Kaliyan et al. (2007), Lopes et al. (2008b, 2010), the decision about an aeration control strategy depends on the availability of money and technical knowledge to achieve the planned aeration objectives. Aeration time, energy consumption, grain deterioration, final grain temperature and moisture content will depend on the control used for aerating.

Grain aeration models are basically classified as equilibrium or non-equilibrium. Equilibrium models assume that equilibrium conditions exist between the product and the incoming air in each grain layer during a discrete period of time (Brooker et al., 1992). Non-equilibrium models are based on the assumption that, in a deep bed, there is no equilibrium between the incoming air and the grain. Thus, a set of partial differential equations are derived from the laws of heat and mass transfer and the mathematical theory of single solid bodies (Srivastava and John, 2002).

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An equilibrium model was proposed by Thompson et al. (1968), based on heat and mass balances taken over a thin layer of grain and considering a process dominated by the external mass transfer. This model has been widely used to study and optimize different drying applications (Arinse et al., 1993; Tirawanichakul et al., 2004; Lecorvaisier et al., 2010), but it can be easily adapted for simulating grain aeration process.

Another equilibrium model, governed by partial differential equations and based on mass and energy balances, was formulated by Thorpe (1997) and presented in more detail in Thorpe (2001). This model has been used to simulate the aeration process, enabling suitable estimates of grain temperatures and moisture contents. Lopes et al. (2006) validated the Thorpe model with data from aerated maize and reported some changes in the original equations in order to simplify and decrease computational time, without decreasing accuracy.

The two above mentioned models are useful because they highlight the physical processes of heat and mass transfer in grain over time. Lopes et al. (2014) have already compared the Thompson and Thorpe models, evaluating grain drying, but there is still a gap when comparing the models regarding the aeration process. This is mainly due to the diversity of aeration strategies and the way the process modifies the grain ecosystem. When grain is dried the primary objective is to reduce its moisture content, but when aeration is applied, the main objective is to maintain the grain under low and uniform temperature.

Motivated by the simplicity and flexibility of the Thompson and Thorpe models, the purpose of this study was to evaluate them, comparing the simulation results with experimental data. Results should facilitate the selection of the most appropriated model for different aeration applications.

2. The models

2.1. Thorpe

According to the Thorpe model, the differential equations that describe the heat and mass transfer in beds of ventilated grains can be expressed as:

$$\frac{\partial\theta}{\partial t}\left\{\rho_b\left[c_g + c_w U_p\right] + \varepsilon\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T}\right)\right]\right\} = \rho_b h_s \frac{\partial U_p}{\partial t} - u_a\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T}\right)\right]\frac{\partial\theta}{\partial y} + \rho_b\frac{dm_s}{dt}\left(Q_r - 0.6h_v\right) \quad (1)$$

$$\frac{\partial U_p}{\partial t} = -\frac{\rho_a u_a}{\rho_b}\frac{\partial R}{\partial y} + 0.6\frac{dm_s}{dt}\left(1 + 1.66U_p\right) \quad (2)$$

The above equations are coupled and solved by using the finite difference numerical method. As the solution of one equation affects the solution of the other and there are non-linear terms, it is impossible to obtain closed form solutions so that the grain conditions can be expressed directly as a function of distance along the grain bed and time from the start of the aeration (Navarro and Noyes, 2001; Lopes et al., 2014).

The grain bulk is divided into layers in the direction of the airflow and at the start of simulations, the distribution of grain moisture content and temperature within the bed of grain are known. The layer limits are called nodes and at the first node it is assumed that the mass and temperature conditions are at equilibrium with the blown air and the surface of the grain bulk. The temperature and moisture content of each other node are calculated by approximations to the first and second derivatives that appear in the model equations, as:

$$\theta_i^{m+1} = \theta_i^m + \frac{\Delta t(A+B)}{\left\{\rho_b\left[c_g + c_w U_{p_i}^m\right] + \varepsilon\rho_a\left[c_a + R_i^m\left(c_w + D_v\right)\right]\right\}} \quad (3)$$

$$A = \rho_b h_{si}\left(-\frac{\rho_a u_a}{\rho_b}\frac{R_i^m - R_{i-1}^m}{\Delta y} + 0.6M_{s_i}^m\left(1 + 1.66U_{p_i}^m\right)\right) \quad (4)$$

$$B = -u_a\rho_a\left[c_a + R_i^n\left(c_w + D_v\right)\right]\frac{\theta_i^m - \theta_{i-1}^m}{\Delta y} + \rho_b M_{s_i}^m\left(Q_r - 0.6h_{v_i}^m\right) \quad (5)$$

$$U_{p_i}^{m+1} = U_{p_i}^m + \Delta t\left(-\frac{\rho_a u_a}{\rho_b}\frac{R_i^m - R_{i-1}^m}{\Delta y} + 0.6M_{s_i}^m\left(1 + 1.66U_{p_i}^m\right)\right) \quad (6)$$

Therefore, the temperature and the moisture content of each layer are the mean of its boundary node conditions. The first layer values are estimated by applying Lagrange interpolation over the five first nodes. During the simulation process, the grain moisture contents and temperatures are calculated after each time interval for each layer in an iterative way. The iterations are carried out until the grain average temperature reaches a preset value or specific criteria of an aeration control strategy.

The specific heat of water and air are well-established quantities and can be considered as constant values (4186 and 1000 J °C kg^{-1}, respectively) as suggested by Navarro and Noyes (2001). The specific heat of grain changes according to the grain moisture content variation and can be calculated in each time interval for each grain layer by using empirical equations (Brooker et al., 1992; Lopes et al., 2008a).

As suggested by Thorpe (2001), the differential heat of sorption is estimated in each iteration step by applying Eq. (7). This method is based on the Clapeyron equation and compares the vapor pressures of water in equilibrium with moist grain and free water.

$$h_s = h_v\left(1 + \frac{De^{-EU}}{(\theta + C)^2}(\theta + 273.15)\left(-5 + \frac{6800}{\theta + 273.15}\right)\right) \quad (7)$$

The value of the differential of latent heat of vaporization with relation to temperature (D_v) should be considered equal to −2363 from Eq. (8), presented by Cengel and Boles (1998), according to Thorpe (2001). This equation was obtained by fitting a linear equation to thermodynamic data given in standard textbooks giving values of latent heat from vaporisation of water within a maximum error of 0.02% in the temperature range from 0 to 50 °C.

$$h_v = 2501330 - 2363T \quad (8)$$

The heat from oxidation of grain is considered equal to 15,778 kJ s^{-1} m^{-3} since the oxidation of 1 kg of grain substrate liberates 15,778 kJ of heat and forms 1.47 kg of carbon dioxide and 0.6 kg of water (Thorpe, 2001).

The grain bulk porosity can also be considered a constant value (40%), since the intergranular void volume is 35–55% of the grain bulk volume for most product types (Brooker et al., 1992). The velocity of the air depends on the bin dimensions and on the required airflow rate (Lopes et al., 2014).

The method developed by Thompson (1972) is used to determine the rate of dry matter loss (Eq. (9)). Thus, an empirical equation is applied considering that the dry matter loss is time dependent: