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Research paper

Simultaneous heat and mass transfer in a fixed bed dryer

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HIGHLIGHTS

- The drying of soybean seeds in a fixed-bed dryer was studied.
- The soybean seed drying can be successfully predicted by a two-phase model.
- The used model was able to predict the heterogeneity of the process.
- The simulated results were in a good agreement with the experimental data.

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ABSTRACT

This study evaluated the simultaneous heat and mass transfer between the air and soybean seeds in a fixed bed dryer in thick layer, using a two-phase model, with an adequate set of constitutive equations. The proposed model was solved numerically using the method of lines. The experimental data for seed moisture and temperature, and those of the drying air, obtained in a pilot unit at different positions along the bed, were compared to simulated results, indicating good agreement. Process heterogeneity along the fixed bed dryer was also analyzed.

1. Introduction

Drying is a fundamental process in productions and technology of high quality seeds, since it aids in obtaining a product with quality and moisture adequate for commerce, besides favoring longer conservation of seeds [1,2]. An effective drying process is one that, besides reducing water contents of the product, increases its post-harvest conservation potential, preserving its physical characteristics and technological properties [3].

Artificial drying of soybean seeds involves a series of peculiarities [4–7]. Literature reports on seed quality changes during drying, either in moving beds [8–10] or fixed ones [11,12]. Due to the caution demanded in any system that involves moving the seeds, which can lead to mechanical damages, it is recommended to use fixed bed dryers. In this type of dryer, seed remains static and the drying air is forced through the interstitial space of the seed mass. It also should be considered that seeds must be dried to a moisture content below 15% (db), for safe storage without serious losses in their physiological quality [13].

Accurate prediction of seed temperature and seed moisture during drying is necessary to find the best dryer configuration and the most suitable operating conditions, in order to preserve seed quality. Mathematical models in the literature, for grain drying, can also be used for predicting seed drying. Thus, proper modeling and computer simulation of temperature and moisture profiles in the dryer, once validated by experimental data, allow, for example, examination and interpretation of the effect of operating conditions on the drying process without the need of incurring in an extensive set of experimental tests. Moreover, greater understanding of heat and mass transfer between a solid and a fluid contributes for the project and control of new dryers, as well as for the optimization of extant ones, securing a final product in adequate conditions of processing and storage [14]. However, it must be highlighted that experimentation is of uttermost importance, since it contributes for the development of more realistic mathematical models and for the verification of precision and credibility of simulations.

The so-called two-phase model can be used to model the grain (or seed) drying in fixed and moving beds [14–19]. This model comprises the mass and energy balance equations applied to both

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fluid and solid phases and requires constitutive equations for the coefficient of heat transfer between these two phases, drying kinetics and equilibrium sorption.

The major objective of this study was to analyze the heat and mass transfer during drying of soybean seeds in fixed bed, considering the heterogeneity of the process along the bed as a function of drying variables. The experimental validation of the used methodology allows the determination of more adequate conditions for seed quality after drying in fixed bed.

2. Mathematical model

Some considerations were assumed for the development of the model [13]:

a) convection in the solid surface is the predominant mechanism of heat transfer;
b) internal diffusion is the predominant mechanism of mass transfer;
c) the biological heat of respiration of the seed has been considered negligible;
d) fluid flows have a flat velocity profile;
e) convection in the solid surface is the predominant mechanism in the thermal exchange process;
f) heat loss through the walls of the system is negligible;
g) heat transfer in the normal direction of flow is negligible compared to heat transfer towards the flow;
h) unidirectional fluid flow;
i) constant physical—chemical properties along the bed.

Considering the moisture range of the soybean seeds used in this work, as well as the residence time of the seeds in the dryer, the biological heat of respiration of the seed has been considered negligible compared to the other contributions. It is also worth noting that, for the conditions of the present work the Biot number for the heat transfer is less than 0.1, hence the conductive resistance to heat transfer can be neglected relative to the convective one. The Biot number for the mass transfer is larger than 100, during all drying process, which suggests that the internal diffusion resistance is the controlling mechanism of mass transfer. The others assumptions are valid for analyses of nearly all grain dryers.

The energy and mass balances applied on a differential volume ($S.dy$) of the fixed bed dryer, considering the aforementioned assumptions, result in the following differential equations:

a) Mass conservation

⇨ Fluid

$$\frac{\partial W}{\partial t} = \frac{1}{\varepsilon \rho_f}\left(f - G_f \frac{\partial W}{\partial y}\right) \tag{1}$$

⇨ Solid

$$\frac{\partial M}{\partial t} = \frac{-f}{(1-\varepsilon)\rho_s} \tag{2}$$

b) Energy Conservation

⇨ Fluid

$$\frac{\partial T_f}{\partial t} = \frac{-ha\left(T_f - T_s\right) - Gf\left(Cp_f + WCp_v\right)\frac{\partial T_f}{\partial y}}{\varepsilon p_f\left(Cp_f + WCp_v\right)} \tag{3}$$

⇨ Solid

$$\frac{\partial T_s}{\partial t} = \frac{ha\left(T_f - T_s\right) - f\left(\lambda + Cp_v\left(T_f - T_s\right)\right)}{(1-\varepsilon)\rho_s(Cp_s + MCp_l)} \tag{4}$$

Initial conditions of moisture and temperature of seeds, and the boundary conditions of the inlet air humidity and temperature are:

⇨ Initial conditions:

$$M = M(y,0) = M_0$$

$$T_s = T_s(y,0) = T_{s0}$$

⇨ Contour Conditions:

$$W = W(0,t) = W_0$$

$$T_f = T_f(0,t) = T_{f0}$$

2.1. Constitutive equations

2.1.1. Sorption isotherms

Halsey modified equation [20], Eq. (5), has been successfully used in literature to predict the equilibrium moisture content (M_{eq}) of soybean seeds [21].

$$M_{eq} = \frac{\left[\left(\frac{-\exp(-0.00672 * T_s + 3.02)}{\ln(\mathrm{RH})}\right)^{1/1.508}\right]}{100} \tag{5}$$

for M_{eq} in db, RH decimal and T_s in °C.

2.1.2. Drying kinetics

Knowledge of the drying kinetics equation is essential for grain or seed modeling. A thin-layer modeling approach is adequate to describe the change in moisture content as a function of time and known air conditions. In thin layer drying experiments, air at constant humidity, temperature and mass flow rate is passed through a thin layer of moist material. The drying behavior of the material under these constant external conditions is then monitored over a period of time. The average properties of the seeds are assumed to be valid throughout the thin layer bed or the volume element of a thick layer bed.