SIMULTANEOUS HEAT AND MASS TRANSFER IN PACKED BED DRYING OF SHRINKING PARTICLES

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Abstract. *The purpose of this paper was develop a mathematical model of simultaneous heat and mass transfer for the prediction of moisture and temperature profiles in packed bed dryer of shrinking granular materials. The model consists of a set of four non-linear PDE's resulting from mass and energy balances for the solid and gaseous phases and of empirical relations for heat and mass transfer and for thermodynamic equilibrium between phases.* In order to incorporate the effect of shrinkage, a moving coordinate system that follows the movement of bed contraction was used. C*hanges in physical properties during drying were also taken into account.* The model equations were solved using the finite difference method. *The model was applied to packed bed drying of solid particles with and without natural coat, which are highly susceptible to deformation. Temperature and moisture content profiles predicted with and without consideration of shrinkage were compared with those obtained from the experimental study. A more reasonable prediction was obtained when the shrinkage effect was considered.*

Keywords. *heat and mass transfer, drying, packed bed, shrinkage, simulation.*

1. Introduction

Drying is one the most widespread heat and mass transport processes, with applications in several engineering areas. Packed bed dryers are widely used to dry granular materials in the form of deep bed. Grains, wood chips, coal and many products chemical products are usually dried by this way (Sun and Woods, 1997; Sheikholeslami and Watkinson, 1991; Saastamoinen and Impola, 1997). Besides the low capital cost and low cost of maintenance, this type of dryer has some advantages in relation to others dryers as the moving beds for example: it is a equipment of simple operation, it does not require additional energy expense to move the solid particles throughout the bed and minimizes the mechanical damages to the material.

Packed bed drying has been investigated for many years. Several mathematical models have been proposed to describe the heat and mass transfer involved in this process. Comprehensive reviews of these models and simulation methods are available in the literature (Brooker et all, 1992; Cenkowski et all, 1993).

Models traditionally employed for describing heat and mass transfer in packed bed drying of solid particles are formulated according to the principles of mass and energy conservation for the gaseous and solid phases in a controlled volume in conjunction with empirical relations for thermodynamics equilibrium and heat and mass transfer between the phases. However, most of these so-called two-phase models, do not take the shrinkage phenomenon and the changes in physical properties of the system into account. These assumptions make the model equations simpler and thus easier to solve, but they also make these models applicable only for drying process of granular materials with relatively low initial moisture content.

In the case of particles with high moisture content, the shrinkage could not be ignored from the point of view of process dynamic. Changes in particle shape and size during drying induce significant bed shrinkage, altering physical properties and affecting heat and mass transport between fluid and solid. However, the role of shrinkage on heat and mass transfer equations is not well understood. Such investigation is important to develop more efficient dryers because it could lead to reductions in energy for airflow requirements for materials that exhibit higher bulk porosity upon shrinkage.

In attempting to improve the design of convective dryers for deformable particles and having the fixed bed as the base for better understand the fundamental phenomena in different particulate beds, this work has as objective the theoretical-experimental study of simultaneous heat and mass transfer between air and a shrinking particulate material during convective drying in a packed bed. In the present study a mathematical model that takes into account the effect of the shrinkage on heat and mass transfer is formulated. The resulting equations and the corresponding initial and boundary conditions are solved numerically. The model is validated by the comparison of the predicted temperature and moisture profiles with the experimental data obtained in a packed bed dryer at bench scale.

2. Mathematical modelling

The problem under investigation, the forced convection of heated air through a vertical cylindrical packed bed of particles having high moisture content and a structure susceptible to deformation, is sketched in Fig. (1).

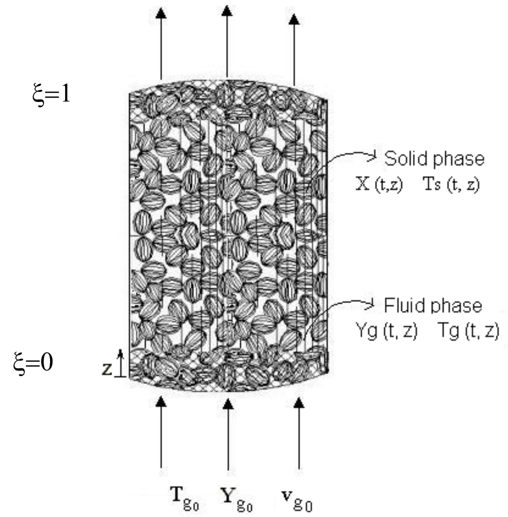


Figure 1. Sketch of the packed bed

The physical-mathematical analysis of simultaneous heat and mass transfer was based on two-phase model, which was extended to incorporate the bed shrinkage. The principal assumptions adopted in the model development were:

– Bed shrinkage is not negligible during drying;
– physical properties are assumed to be functions of local moisture content and temperature;
– one-dimensional airflow, with uniform air velocity, humidity and temperature in the dryer;
– heat losses through the wall of the dryer are negligible;
– convective mechanism is predominant in the heat transfer process, and
– one-dimensional transport of heat and mass.

2.1. Energy and mass balance equations

A set of four partial differential equations (PDE's) was obtained from mass and energy balances for the solid and fluid phases in an elemental layer of the packed bed. It allows to predict the following four drying state variables: solid moisture (X), solid temperature (T_s), fluid temperature (T_g) and air humidity (Y_g) as function of time (t) and bed height (z). In order to take into account the shrinkage phenomenon, a moving coordinate system that follows the movement of bed contraction was used, taking basically a differential control volume that contains always the same amount of dry mass as that at the initial time. The moving coordinate system is related to the spatial coordinate by the following equation:

$$dz = \frac{\rho_{b_0}}{\rho_b} \cdot d\xi = \frac{V_l}{V_{l0}} \cdot d\xi = S_b \cdot d\xi \tag{1}$$

where ρ_b is the bulk density at any time and ρ_{b0} is the initial bulk density; V_l is the bed volume at any time and V_{l0} is the initial bed volume; S_b is the shrinkage parameter of the bed; z is the dimensionless spatial coordinate and ξ is dimensionless moving coordinate.

<u>Mass balance</u>

- Solid phase:

$$\frac{\partial X}{\partial t} = f \tag{2}$$

where f is the expression for drying rate.

- Fluid phase:

$$\rho_g \left(\frac{v_g}{S_b} \cdot \frac{\partial Y_g}{\partial \xi} + \varepsilon \frac{\partial Y_g}{\partial t} \right) = -\rho_b \cdot \frac{\partial X}{\partial t} \tag{3}$$

where v_g, ρ_g, and ε are, respectively, air velocity, air density and porosity of the packed bed.

Energy balance

- Solid phase:

$$\rho_b \cdot (Cp_S + X \cdot Cp_w)\frac{\partial T_S}{\partial t} = ha_v(T_g - T_S) + \rho_b \cdot [L_p + (Cp_v - Cp_w) \cdot T_s] \cdot \frac{\partial X}{\partial t} \tag{4}$$

where Cp_s is the solid specific heat, Cp_w is the liquid water specific heat, ha_v is the heat transfer coefficient between fluid and solid, L_p is the latent heat of vaporization of water adsorbed in solid and Cp_v is the specific heat of vapor.

- Fluid phase:

$$\frac{v_g \cdot \rho_g}{S_b} \cdot (Cp_g + Y_g Cp_v)\frac{\partial T_g}{\partial \xi} + \rho_g \cdot \varepsilon \cdot (Cp_g + Y_g Cp_v)\frac{\partial T_g}{\partial t} = \left[ha_v - \rho_b \cdot Cp_v \cdot \frac{\partial X}{\partial t}\right] \cdot (T_s - T_g) \tag{5}$$

where Cp_g is the specific heat of air.

Initial and boundary conditions

Initially, temperature and moisture content of solid throughout the bed is constant, as well as the temperature and humidity of air at the inlet of the bed.

$$X(0, \xi) = X_0 \tag{6}$$

$$T_S(0, \xi) = T_{S0} \tag{7}$$

$$Y_g(0, \xi) = Y_g(t,0) = Y_{g0} \tag{8}$$

$$T_g(0, \xi) = T_g(t,0) = T_{g0} \tag{9}$$

The application of these equations to the packed bed drying of papaya seeds, which were selected as typical shrinking particles, was examined in this study.

2.2. Model parameters

The solution of the above mathematical model requires knowledge of the thermodynamics equilibrium and transport parameters. The knowledge of the physical properties of air and particulate material is also needed. A summary of these properties that were experimentally determined from specific studies is given below. Also, other values or relationships that were found in the literature are cited when used.

2.2.1. Drying rate equation

The equation for the drying rate of individual particles or thin layer equation, which gives the evolution of moisture content with time, strongly affects the predicted results of deep bed drying models. Due to high moisture content of papaya seeds two equations are needed to cover the entire drying period: one for the constant rate period and other for the decreasing rate period. The drying rate for the constant rate period is described by the following equation:

$$\frac{dX}{dt} = -k_c \tag{10}$$

Equations (11) and (12) describe the dependence of k_c on air velocity and temperature for operational ranges from 0,5 to 1,5 m/s and from 30 to 50°C, for seeds with and without mucilage, respectively (Prado and Sartori, 2002):

$$k_c = 1.3 \times 10^{-9} \cdot T^{4.112} \cdot v^{0.219}, \ [1/s] \tag{11}$$

$$k_c = 5.1 \times 10^{-5} \cdot T^{2.114} \cdot v^{0.630}, \ [1/s] \tag{12}$$

For the decreasing rate period, a thin-layer equation similar to Newton's law for convective heat transfer is used, with the driving force or transfer potential defined in terms of free moisture, so that:

$$f = -K \cdot (X - X_{eq}) \tag{13}$$

The drying constant K is assumed to vary only with air temperature. For drying temperatures range from 30 to 50°C, the equations experimentally determined for K of papaya seeds with and without mucilage are written, respectively, as (Prado and Sartori, 2000):

$$K = 0.011\exp\left(-201.8/T_g\right) \tag{14}$$

$$K = 0.018\exp\left(-46.1/T_g\right) \tag{15}$$

2.2.2. Sorptional properties

The Modified Halsey equations developed for predicting the equilibrium moisture of solid particles (X_{eq}) with and without natural coat (Prado and sartori, 2000) were used in the packed bed drying simulation.

- Solid particles with natural coat:

$$X_{eq} = \left[\frac{-\exp\left(-1.99\times10^{-2}\cdot T_g + 4.92\right)}{\ln(RH)}\right]^{1/2.29}, \quad (\%\ kg/kg) \tag{16}$$

- Solid particles without natural coat:

$$X_{eq} = \left[\frac{-\exp\left(-1.77\times10^{-2}\cdot T_g + 4.25\right)}{\ln(RH)}\right]^{1/1.90}, \quad (\%\ kg/kg) \tag{17}$$

The parameters of the Eqs. (16) and (17) were estimated by non-linear regression of the experimental moisture desorption data obtained using the static gravimetric method in a temperature range from 30 to 50°C and relative humidities (RH) ranging from 0,111 to 0,842 (Prado and Sartori, 2000). In addition, the desorption isotherms given by the Eqs. (16) and (17) were analyzed according to the thermodynamics principles to obtain the following equations representing the latent heat of vaporization of water in particles (L_p):

- Solid particles with natural coat:

$$L_p = \left(2500.8 + 2.39\cdot T_g\right)\cdot\left[1 + 3.2359\cdot\exp\left(-33.6404\cdot X\right)\right],\ kJ/kg \tag{18}$$

- Solid particles without natural coat:

$$L_p = \left(2500.8 + 2.39\cdot T_g\right)\cdot\left[1 + 5.1754\cdot\exp\left(-41.0629\cdot X\right)\right],\ kJ/kg \tag{19}$$

2.2.3. Equation for predicting the heat transfer coefficient

There is limited number of reports dealing with heat external transfer in an air flow through packed beds of particles with high moisture content and susceptible to shrinkage. Thus, different correlations found in the literature to predict heat transfer coefficient in fixed bed, presented in Tab. (1), were employed in order to obtain the best reproduction of the experimental data obtained in a packed bed dryer for two cases of superficial layer of the solid.

Table 1. Empirical correlations used for predicting the heat transfer coefficient (h) between fluid and solid in fixed bed.

Equation	Validity range	Reference
$ha_v = 4286.5\cdot\left[\frac{\rho_g\cdot v_g\cdot\left(T_g+273\right)}{101325}\right]^{0.6011}$ (20)	$0.01 < v_g < 0.25\ m\ s^{-1}$	Boyce (1965)
$N_{up} = \frac{h\cdot D_p\cdot\phi\cdot\varepsilon}{K_g\cdot(1-\varepsilon)} = \left(0.5\cdot Re_p^{1/2} + 0.2\cdot Re_p^{2/3}\right)\cdot Pr^{1/3}$ (21)	$20 < Re_p < 80000$ $\varepsilon < 0.78$	Whitaker (1972)
$Nu = 0.664\cdot(8/3\pi)\cdot Re^{0.5}\cdot Pr^{1/3}$ (22)	$Re < 2x10^5$	Welty et all (1984)
$Nu = 0.249\cdot Re^{0.64}$ (23)	$300 < Re < 3000$	Ratti and Capriste (1995)

where h [$J/m^2.s.^oC$], ha_v [$J/m^3.s.^oC$] and Nu, Re and Pr are Nusselt, Reynold and Prandtl numbers. Re_p is the Reynolds number based on the particle diameter.

2.2.4. Bed shrinkage equation

The shrinkage parameter of the bed (S_b) was obtained from experimental data for the packed beds of particles with different superficial characteristics (Prado and Sartori, 2002a). Both solid particles with and without natural coat showed non-linear relationship between the bed shrinkage and the moisture content. The relationship for particles with mucilage was expressed as:

$$S_b = \frac{V_l}{V_{l0}} = 0.706 + 0.092 \cdot X - 0.005 \cdot X^2 \qquad (24)$$

and for particles without mucilage:

$$S_b = \frac{V_l}{V_{l0}} = 0.893 + 0.078 \cdot X - 0.014 \cdot X^2 \qquad (25)$$

2.2.5. Particle and bed properties

- Density, porosity and specific area of the bed

Previous experimental study (Prado and Sartori, 2002b) showed that there are changes in bulk density (ρ_b), porosity (ε) and specific area (a_v) due to bed shrinkage during packed bed drying of papaya seeds. These bed properties were represented as function of local moisture content (X) using the equations presented in Tab. (2) for solid particles with and without mucilage coating.

Table 2. Bed physical properties equations.

Bed Properties			
Particles with mucilage		**Particles with mucilage**	
$\rho_b = 232.9 + 133.5 \cdot X$	(26)	$\rho_b = 163.4 + 138.2 \cdot X$	(29)
$\varepsilon = 0.524 - 0.063 \cdot X$	(27)	$\varepsilon = 0.500 - 0.054 \cdot X$	(30)
$a_v = 777.3 + 87.4 \cdot X - 12.7 \cdot X^2$	(28)	$a_v = 799.3 + 53.9 \cdot X$	(31)

where ρ_b [kg/m^3], ε [-] and a_v [m^2/m^3].

- Specific heat of particle (Cp_s)

The specific heat at constant pressure is usually used for heat transfer problem during drying and it may be considered as a constant physical property at temperature ranges which are not to great (López et all, 1998). The values of specific heat at constant pressure for papaya seeds with and without mucilage used for simulation are respectively equal to 1100 and 1300 J/(kg ^{o}C).

2.2.6. Air and water properties

Air and water physical properties are also required in the model solution. The values or equations used for their determination are as follows (Giner et all, 1996).

- Air density (ρ_g)

$$\rho_g = P_{atm} \cdot M_g / R_g \cdot (T + 273), \text{ kg/m}^3 \qquad (32)$$

- Specific heats of air (Cp_g), water vapor (Cp_v) and liquid water (Cp_w)

$$Cp_g = 1005 \text{ J/(kg }^oC); \; Cp_v = 1883 \text{ J/(kg }^oC); \; Cp_w = 4187 \text{ J/(kg }^oC)$$

- Saturation vapor pressure (P_{sat})

$$P_{sat} = \exp\left(54.119 - 6547.1/(T_g + 273) - 4.23 \ln(T_g + 273)\right), \text{ Pa} \qquad (33)$$

- Partial vapor pressure in humid air (P_v)

$$P_v = P_{atm}\left[Y_g / (0.622 + Y_g)\right], \text{ Pa} \qquad (34)$$

- Relative humidity (RH)

$$RH = P_v / P_{sat}, \text{ decimal} \qquad (35)$$

2.3. Numerical solution of the model

The numerical method employed to solve the system of four coupled non-linear differential equations, Eqs. (2) to (5), subjected to the initial and boundary conditions specified by the Eqs.(6) to (9), was the finite difference technique.

From the discretization of spatial differential terms the initial PDE system of the proposed model is transformed into ODE system. Eqs. (2) to (5) become:

$$\frac{dY_g{}^n}{dt} = -\frac{\rho_b}{\rho_g \cdot \varepsilon}\frac{dX^n}{dt} + \cdot \frac{v_g}{\varepsilon \cdot S_b \cdot \Delta\xi} \cdot \left(Y_g{}^{n-1} - Y_g{}^n\right) \tag{36}$$

$$\frac{dT_s{}^n}{dt} = \frac{1}{\rho_b \cdot \left(Cp_s + X^n \cdot Cp_w\right)} \cdot \left[ha_v \cdot \left(T_g{}^n - T_s{}^n\right) + \rho_b \cdot \left[\lambda + \left(Cp_v - Cp_w\right) \cdot T_s{}^n\right]\frac{dX^n}{dt}\right] \tag{37}$$

$$\frac{dT_g{}^n}{dt} = \frac{1}{\rho_g \cdot \varepsilon \cdot \left(Cp_g + Y_g{}^n \cdot Cp_v\right)}\left[ha_v - \rho_b \cdot Cp_v \frac{dX^n}{dt}\right] \cdot \left(T_s{}^n - T_g{}^n\right) + + \frac{v_g}{\varepsilon \cdot S_b \cdot \Delta\xi} \cdot \left(T_g{}^{n-1} - T_g{}^n\right) \tag{38}$$

$$\frac{dX^n}{dt} = f\left(X^n, Y_g{}^n, T_g{}^n\right) \tag{39}$$

(n=1, 2, ..., N)

where $\Delta\xi = 1/N$, N is the number of discretized cells into which the total height of the bed is divided.

The resulting vector of 4 (N+1) temporal derivatives was solved using the DASSL package (Petzold, 1989), which is based on integration method of Backwords Differential Formuling (BDF).

3. Experimental

The experimental work was carried out to determine the temperature and moisture distributions in a packed bed dryer, which were used to validate the model.

3.1. Experimental set-up

A scheme of a typical packed bed dryer used to conduct the experiments is presented in Fig. (2).

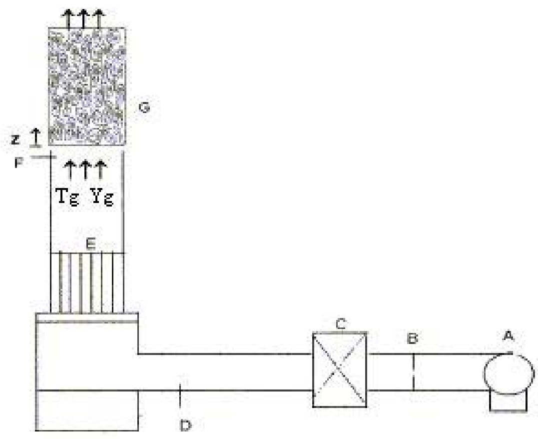


Figure 2. Scheme of the experimental drying set-up used.

In this unit, airflow is supplied by a blower of 0.75 HP (A), passing through a double plate orifice flowmeter (B), which is connected to a manometer. Drying air is heated up by an electrical heater (C), attached to a voltage regulator of 2500 W, passing through an airflow stabilization tube (E), reaching the measuring cell (G) with uniform velocity, humidity and temperature distributions, at about 92% of cross area (Prado, 1999) and percolating the bed of seeds with exaustion to the atmosphere. Air temperature and humidity measurements were carried out by copper-constantan thermocouple (F) and psychrometer (D) via dry and wet bulb temperatures, respectively.

The whole unit was thermally isolated, in order to minimize heat losses through the wall of the system and to ensure uniform distribution of temperature at the inlet of the measuring cell.

The experiments were conducted at air temperatures of 32, 41 and 50°C and air velocity of 0.5, 1.5 and 2.5 m/s usually used for this type of particle and defined on 2^3 factorial design that attend to validity range of the parameters equations of the model. According Prado (1999), thin-layer drying condition in this range is satisfied with bed thickness equal or lower than 1,0 cm. Thus, to study the transfer phenomena involved in drying of deep beds, in which gradients of temperature and moisture content exist, an initial packing height of 0,05 m was used.

3.2. Packed porous bed

Papaya seeds were used as typical shrinking particles. In order to evaluate the influence of superficial characteristics of particles on heat and mass phenomena, the beds were formed by randomly packing particles with and without mucilage coat. Seed samples with uniform distribution of size were used to avoid the effect of variability of particles size, what was obtained using the methodology proposed by Prado and Sartori (2002a) for obtaining the material. Homogeneity and reproducibility of packing was ensured using the packing technique presented by Zotin (1985).

3.3. Experimental procedure

In order to avoid one of the great problems of the experimentation in fixed bed, which is associated to the determination of the moisture content of the solid through sampling during drying, that leads to changes of the porous structure of the bed and the formation of possible preferential coarse, it was used the stratification method for the obtaining of the moisture distribution data throughout the bed.

A measuring cell, made of PVC with diameter 5.25×10^{-2} m and height of 5.00×10^{-2} m with subdivisions of 1.0×10^{-2} m, was constructed. These subdivisions allow the bed fragmentation and the local moisture measurements. A scheme of the drying cell is showed in Fig. (3).

Material moisture contents were determined by the standard oven method of drying at (105 + 3)°C for 24 hours. Air humidity measurement was carried out using psychrometers located at the inlet and exit of the bed, by means dry and wet bulb temperatures.

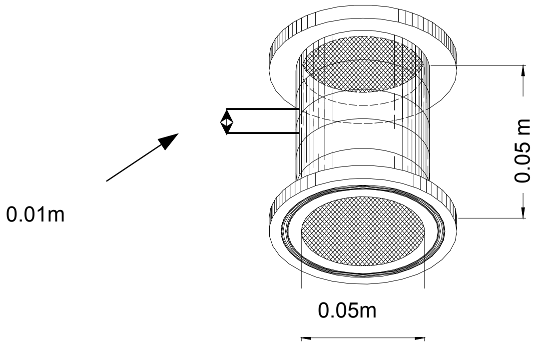


Figure 3. Scheme of the drying cell used for obtaining moisture distribution throughout the bed.

In Fig. (4) is presented a scheme of the drying cell, which was constructed for measurements of temperature distribution and for determination of shrinkage of the particulate bed. The cell consists of a cylindrical tube of transparent acrylic, in order to allow the visualization and the measure of the contraction of volume of the porous bed, with the same dimensions of the cell used for the determination of the moisture distribution (Fig. 3). The helical disposition for the placement of the thermocouples along the bed seeks to minimize the interference of the thermal sensors on the airflow inside the bed.

Thermocouples with and without protection were used for the measurements of air and solid temperatures, respectively. The probable error of measure is of 0,25°C.

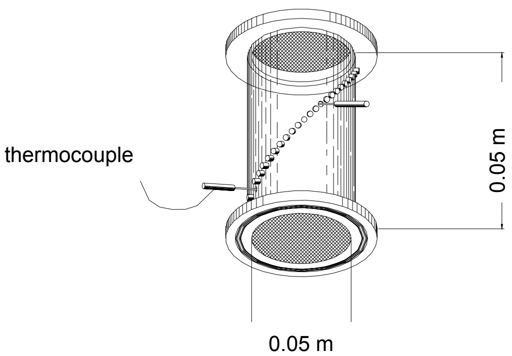


Figure 4. Scheme of the drying cell constructed for obtaining of temperature distribution and shrinkage measurements.

4. Results and Discussion

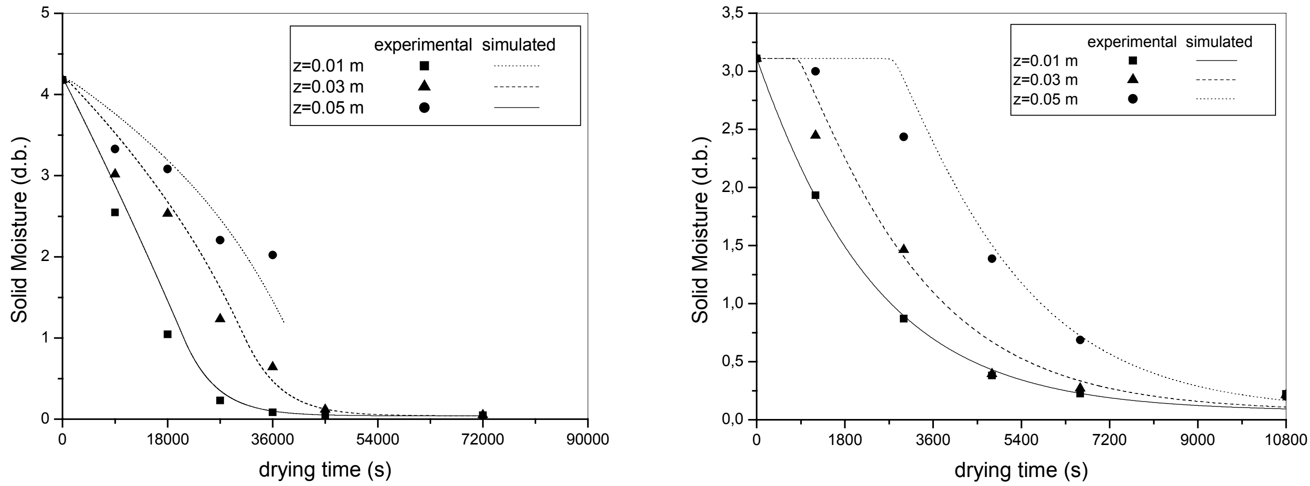
It was possible determine experimentally the temperature and moisture content throughout the packed bed and ensure the initial and boundary conditions at the inlet of the bed, Eqs. (6) to (9).

The simulated profiles of the drying state variables were obtained by numerical solution of the model.

Figures (5.a) and (5.b) show typical results of experimental and predicted moisture contents as function of drying time at three bed heights for packed beds of solid particles with different superficial characteristics (with and without natural coat). It was found that there was a good agreement between experimental and predicted values when shrinkage is considered. The verified trend in these figures is valid for the other analysed conditions.

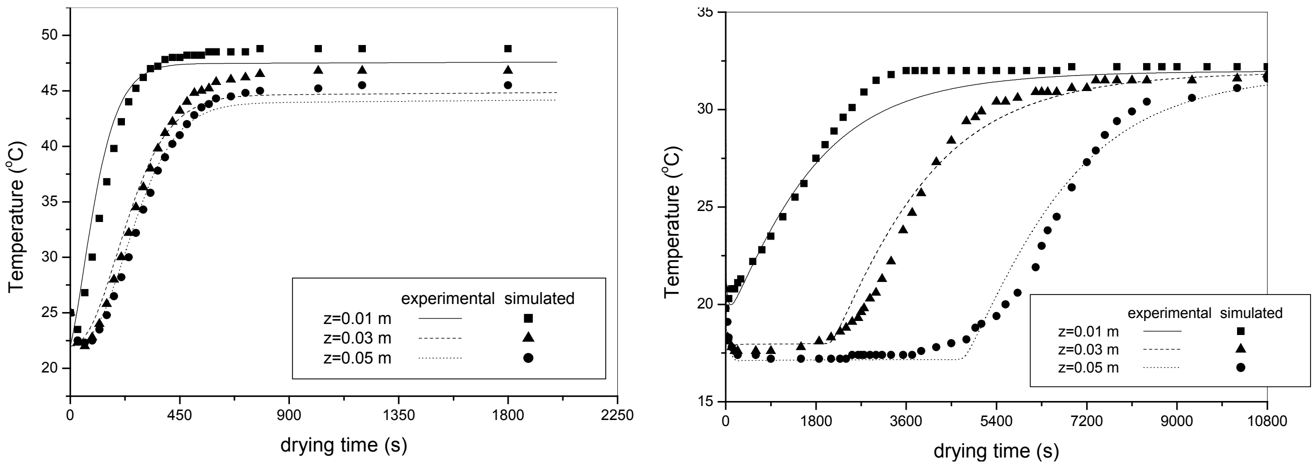
In initial drying stage it can be observed that the prediction accuracy of the model decreased as the drying location moved from the bottom to the bed top. This result can be attributed to the condensation of drying air over the product. When re-wetting of material occurs, the thin layer equation used might not be appropriate.

Figures (6.a) and (6.b) show typical results of a comparison between experimental data and the simulated responses for temperature in air drying at 50°C for beds of particles with mucilage and at 32°C for beds of particles without mucilage, respectively. Best reproduction of the experimental data was obtained using the equation from Whitaker (1972) for the heat transfer coefficient. This equation reproduced better experimental results because it had incorporated a term that takes into account the effect of the packed bed.



(a) (b).

Figure 5. Experimental e predicted moisture content as a function of time at three bed heights during drying at T_{g0}=50°C and v_g=0,5 m/s. (a) for particles with natural coat, (b) for particles without natural coat.

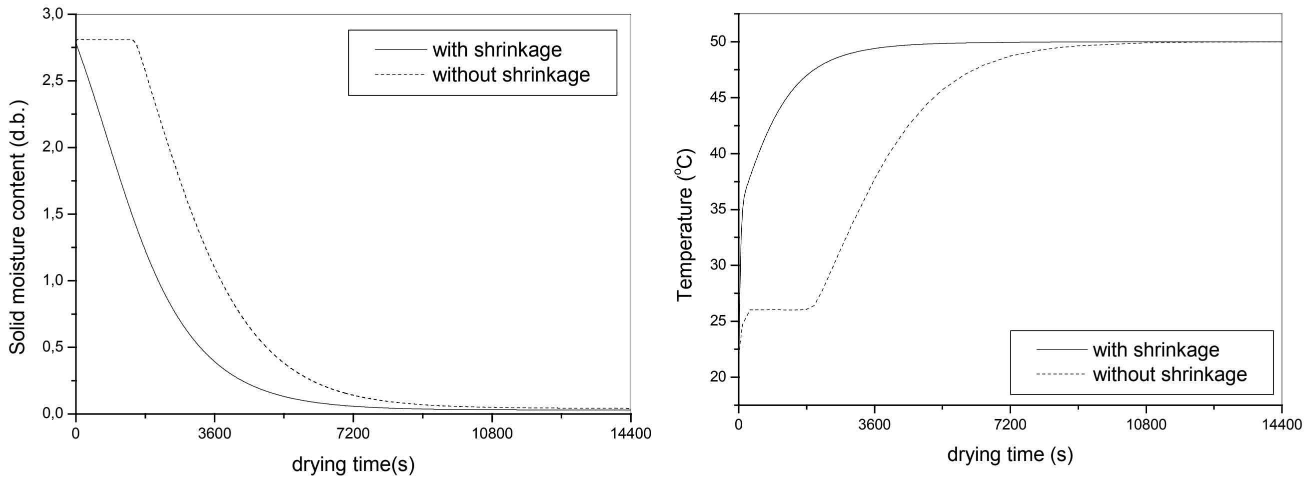


(a) (b)

Figure 6. Experimental and predicted temperature values versus time at three bed heights during drying at v_g=0,5 m/s. (a) for particles with natural coat and T_{g0}=50°C; (b) for particles without natural coat and T_{g0}=32°C.

Figure (7.a) shows the comparison of predicted moisture content values at a bed height of 0.01 m during drying at 50°C with and without incorporating the shrinkage effect in the model. It can be verified that there is a significant difference between the two sets of data. This result was confirmed by F test at 5% level. It was found a less advanced drying when the shrinkage is not taken into account in the model.

In Fig. (7.b) is presented the comparison of simulated temperature evolution with and without the shrinkage effect included in the model. Again, it can be seen that the difference between the two sets of data is significant as drying progresses. The model without the shrinkage predicts lower temperature values at a specific bed height at any given time when compared with model that includes this effect. In this case, the rate of heat transfer is increased because of the of bed volume contraction.

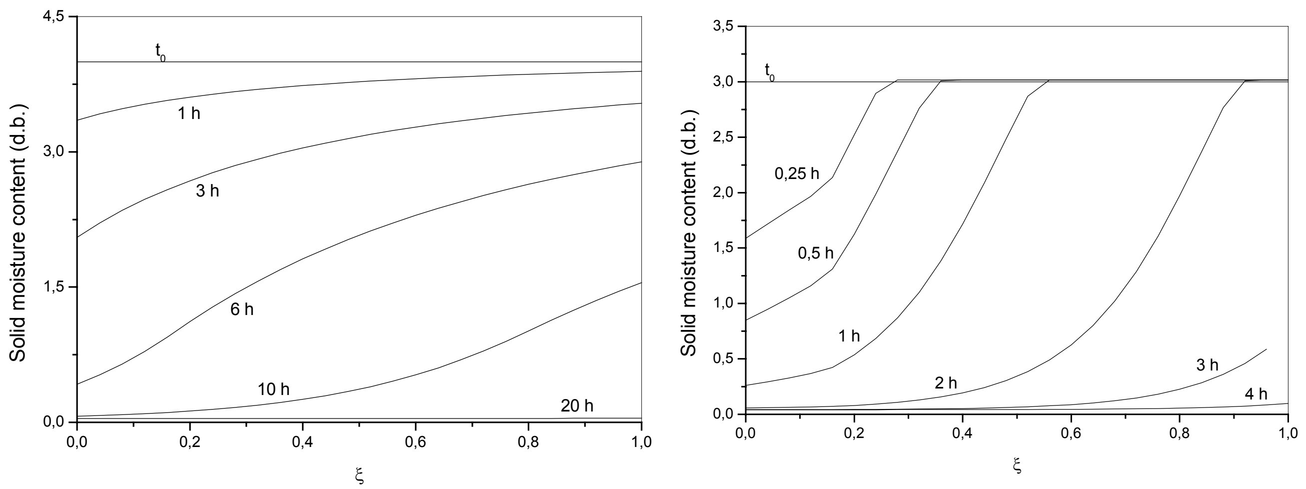


(a) (b)

Figure 7. Predicted results as function of drying time at z=0.01 m; T=50^{o}C; v_g=0.5 m/s, for particles without mucilage, with and without consideration of shrinkage effect. (a) Moisture content, (b) Temperature of the solid.

In order to evaluate the influence of surface characteristics of the particles (presence or no of mucilage coating) on heat and mass transfer, Fig. (8.a) and (8.b) show how well defined moisture content gradients were developed throughout the packed beds of these particles. The difference of drying behavior between the beds was evident. The gradients were greater for beds formed by particles without mucilage coat. On the other hand, beds of coated particles developed moisture gradients during more than ten hours.

When mucilage is removed, the particles lose moisture more easily. The high velocity of the evaporation front throughout the bed can be attributed to superficial structure of the particle having protuberances that provide a high specific area. In the case of coated particles, mucilaginous covering forms a hard impermeable skin during drying, becoming an extra resistance to mass transfer. As result, evaporation front has a more gradual evolution throughout the bed. The proposed model predicted a homogeneous bed at specified conditions after 20 hours for particles with mucilage and after 4 hours for particles without natural coat.



(a) (b)

Figure 8. Simulated moisture content profiles throughout the packed bed during drying at T_{g0}=50^{o}C and v_g=0,5 m/s. (a) for particles with mucilage and (b) for particles without mucilage.

5. Conclusions

The following conclusions can be drawn from the results obtained in this study.

The applied experimental methodology is suitable to determine the temperature and moisture distributions with sufficient accuracy for purposes of model validation.

It is corroborated that bed shrinkage has influence on simultaneous heat and mass transfer in packed bed drying of solid particles with high moisture content so that it should be taken into account in the mathematical models. A more reasonable prediction of temperature and moisture content profiles is obtained when the shrinkage was considered.

Besides a better understanding of heat and mass transfer phenomena during packed bed drying of shrinking particles, the model described in this work also allows the analysis of the effects of particles superficial characteristics on the temperature and moisture content within the bed.

This model could be extended to incorporate the condensation of drying air over the product and to take into account the dependence of the material specific heat on temperature and moisture content. In addition, a two-dimensional transport of heat and mass could be considered.

The drying model presented, which is based on energy and mass balances in conjunction with relationships for equilibrium thermodynamic, heat and mass between the phases and physical properties of the bed of particles, obtained from specific studies, provides good results when applied to study the simultaneous heat and mass transfer. The accomplished theoretical-experimental analysis can be used as a guide in similar studies involving different categories of materials.

6. Acknowledgement

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7. References

Boyce, D.S., 1965, “Grain Moisture and Temperature Changes With Position and Time during Through Drying”, J. Agric. Eng. Res., Vol. 10, pp. 333-341.

Brooker, D.B.; Bakker-Arkema, F.W. and Hall, C.W., 1992, “Drying and Storage of Grains and Oilseeds”, An AVI Book published by van Nostran Reinhold, New York, 450 p.

Cenkowski, S., Jayas, D. S. and Pabis, S., 1993, “Deep-Bed Grain Drying – A Review of Particular Theories”, Drying Technology, Vol. 11, No. 7, pp. 1553-1581.

Giner, S.A., Mascheroni, R.H. and Nellist, M.E., 1996, “Cross-flow Drying of Wheat: a Simulation Program With a Diffusion-based Deep-Bed Model and Kinetic Equation for Viability Loss Estimation”, Drying Technology, Vol. 14, No.10, pp. 2255-2292.

López, A., Piqué, M.T. and Romero, A., 1998, “Simulation of Deep Bed Drying of Halzenuts”, Drying Technology, Vol. 16, No. 3-5, pp. 651-665.

Petzold, L.R., 1989, “DASSL: A Differential Algebraic System Solver”, Computer and Mathematical Research Division, Lawrence Livermore National Laboratory, Livermore, CA, USA.

Prado, M.M., 1999, Drying of Papaya Seeds, M. Sc. Thesis, Federal University of São Carlos, São Carlos, Brazil, 108 p. (in portuguese).

Prado, M.M. and Sartori, D. J. M., 2000, “Quality, Sorption Isotherms and Drying Kinetics of Papaya Seeds”, Proceedings of the 12th International Drying Symposium, Vol. 1, Noordwijkerhout, The Netherlands, pp.14001-14010.

Prado, M.M. and Sartori, D.J.M., 2002a, “Study of the Shrinkage Phenomenon during Drying of Seeds With Different Superficial Characteristics”, Rural University Journal, Earth and Exact Sciences Series, Vol. 21, No.1, pp. 11-20 (in portuguese).

Prado, M.M. and Sartori, D.J.M., 2002b, “Experimental Determination of Changes in Bulk Density, Porosity and Specific Area Associated to Shrinkage during Fixed Bed Drying of Seeds With Different Superficial Structures”, Proceedings of the 13th Brazilian Congress of Chemical Engineering, Natal/RN, Brazil (in Portuguese).

Ratti, C. and Crapiste, G.H., 1995, “Determination of Heat Transfer Coefficients during Drying of Foodstuffs”, J. Food Proc. Eng., Vol. 18, pp. 41-53.

Saastamoinen, J. and Impola, R., 1997, “Drying of Biomass Particles in Fixed and Moving Beds”, Drying Technology, Vol. 15, pp. 1919-1929.

Sheikholeslami, R. and Watkinson, A.P., 1991, “Drying of Wood Residues in a Fixed Bed”, In S.Kakac, B. Kilkis, F.A. Kulack and F. Arinc, Convective Heat and Mass Transfer in Porous Media, pp. 673-693, Dordrecht: Kluwer Academic Publishers.

Sun, D. W. and Woods, J. L., 1997, “Simulation of the Heat and Moisture Transfer Process during Drying in Deep Grain Beds”, Drying Technology, Vol. 15, No. 10, pp. 2479-2508.

Welty, J.R., Wicks, C.E. and Wilson, R.E., 1984, “Fundamentals of Momentum, Heat and Mass Transfer”, 3rd Ed., John Wiley Sons: New York, 655p.

Whitaker, S., 1972, “Forced Convection Heat Transfer for Flow in Past Flat Plates, Single Cylinders, and for Flow in Packed Bed and Tube Bundles”, AIChE J., Vol. 8, pp.361-371.

Zotin, F.M.Z., 1985, The Effect of Wall in Packed Towers, M. Sc. Thesis, Federal University of São Carlos, São Carlos, Brazil, 85 p. (in portuguese).