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SIMULTANEOUS HEAT AND MASS TRANSFER IN PACKED BED DRYING OF SEEDS HAVING A MUCILAGE COATING

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Abstract - The simultaneous heat and mass transfer between fluid phase and seeds having a mucilaginous coating was studied during packed bed drying. To describe the process, a two-phase model approach was employed, in which the effects of bed shrinkage and nonconstant physical properties were considered. The model took into account bed contraction by employing moving coordinates. Equations relating shrinkage and structural parameters of the packed bed with moisture content, required in the drying model, were developed from experimental results in thick-layer bed drying. The model verification was based on a comparison between experimental and predicted data on moisture content and temperature along the bed. Parametric studies showed that the application of correlations capable of incorporating changes in bed properties gives better data simulation. By experimental-theoretical analysis, the importance of shrinkage for a more accurate interpretation of heat and mass transfer phenomena in the drying of porous media composed of mucilaginous seeds is corroborated.

Keywords: Heat and mass transfer; Shrinkage; Drying; Mucilaginous seeds; Physical properties.

INTRODUCTION

Fixed bed drying of moist particles is a solid-fluid contact technique widely applied in agricultural and chemical engineering in the form of thick-layer bed drying or thin-layer drying. Grains, seeds, coffee, wood chips, coal and many chemical products are usually dried this way (Resio *et al*., 2005; Faria and Rocha, 2000; Saastamoinen and Impola, 1997).

From a scientific point of view, drying of particulate solids is a complex process characterized by interactions of heat and mass transfer occurring simultaneously between the particles and the drying medium during circulation through the porous bed. Because of its great technological relevance, thick-layer bed drying has been studied for many years (Wang and Chen, 1999). A large variety of models has been developed for describing the heat and mass transfer inside thick-layer bed dryers. Comprehensive reviews of these models and simulation methods are available in the literature (Brooker *et al*., 1992; Cenkowski *et al*., 1993).

The most rigorous mathematical models for packed-bed drying of solid particles are based on principles of mass and energy conservation for the gaseous and solid phases in a controlled volume in conjunction with empirical equations for thermodynamic equilibrium and heat and mass transfer between phases. Unfortunately, the so-called two-phase models have been developed considering that the shrinkage and the changes in structural properties of the particulate bed are negligible during removal of moisture. Under these assumptions, such modeling is valid only for thick-layer bed drying of

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*To whom correspondence should be addressed rigid inorganic particles or seeds with a relatively low initial moisture content, where changes in volume can be neglected.

Recent experimental and theoretical studies have demonstrated the importance of considering shrinkage for a more realistic analysis of drying phenomena, but most of these studies are concentrated on single particles of foods such as fruits and vegetables (Chemkhi *et al*., 2005; Wang and Brennan, 1995). There are few works on shrinkage of particulate food in bulk (Ratti, 1995) and even less on bulk shrinkage of seeds (Lang *et al*., 1993). Hence, the influence of shrinkage on heat and mass transfer in the drying of packed beds is not yet well understood.

A type of thick-layer bed that offers important challenges for a combined analysis of heat and mass transfer and shrinkage in drying, but that has received relatively little attention in modeling, is that formed by gel-coated particles. These particles are produced mainly by coating the core particles with polymeric matrices containing gelling binders. Particles with an artificial coating are widely applied in, for example, chemical, pharmaceutical, agricultural and food industries. Particles naturally coated by a mucilaginous outer layer with highly deformable gel characteristics can also be found in, for example, papaya seeds. Besides acting as a physical protection and contributing to extend seed germination, the mucilage found in the seed coat is also rich in pectin.

Gel-coated seeds are not generally dried in moving beds due to the mechanical damage that can occur in this type of dryer. By avoiding friction between the seeds, which can induce undesirable fissures to form in the outer layer and loss of seed quality, fixed bed drying is viewed as a feasible technique to reduce the high moisture content of papaya seeds to appropriate levels for safe storage or further processing.

Mathematical modeling of fixed bed dryers applied to this type of particle is thus essential to achieve a better understanding of the fluid-solid heat and mass transfer in deformable porous media as well as for the study of their optimum operation and process design.

Besides an understanding of shrinkage, other fundamental information required in a two-phase model is the knowledge of equations for heat and mass transfer and for thermodynamic equilibrium between phases. According to Brooker *et al*. (1992), the choice of these equations strongly affects the validity of simulation results for thick-layer bed drying. Several studies related to evaluation of drying rate equations have been reported in the literature, but references to evaluation of equations for predicting the convective heat transfer coefficient (h) are relatively scarce (Krokida *et al*., 2002).

The convective heat transfer coefficient is one of the most critical parameters in air drying simulation, since the temperature difference between the air and solid varies with this coefficient (Akpinar, 2004). Reliable values of h are, thus, needed to obtain accurate predictions of temperature during drying. The use of empirical equations for predicting h is a common practice in drying, since the heat transfer coefficient depends theoretically on the geometry of the solid, physical properties of the fluid and characteristics of the physical system under consideration, regardless of the product being processed (Ratti and Crapiste, 1995). In spite of the large number of existent equations for estimating h in a fixed bed, the validity of these, for the case of the thick-layer bed drying of shrinking particles has still not been completely established.

Within this context, the objective of the present work is to analyze the processes of heat and mass transfer between fluid phase and particles coated by a deformable mucilaginous coating in a fixed bed dryer. For a complete description of the process, the two-phase model proposed should take into account the effects of bed shrinkage and moisture on the porous bed properties. The introduction of these effects in the mathematical description, their importance and the adequacy of the two-phase model thus obtained are discussed in regard to the drying of papaya seeds. Before turning to a more elaborate model, changes in thickness and structural parameters of the packed bed composed of these seeds are characterized experimentally. In what follows, a method for solving the resulting partial equations system is presented. Next, to verify the validity of the model, predicted results are compared to experimental data on temperature and moisture content throughout the bed. Different empirical equations for predicting the heat transfer coefficient in packed beds are also evaluated for use in drying simulation in order to obtain the best reproduction of the experimental data. Finally, the question of to what extent heat and mass transfer characteristics are affected by the shrinkage phenomenon is discussed.

MATHEMATICAL MODELING

The physical problem under consideration is illustrated in Figure 1, in which a packed bed of mucilage-coated seeds is percolated by a drying fluid flowing upward. The detail of a volume element extracted from the packed bed shows that part of this volume element is composed of solid particulate material, whereas the remaining void space is occupied by the fluid phase. Interactions between the solid and fluid phases by heat and mass transfer occur simultaneously during drying.

Due to the highly deformable polymeric structure of mucilage coating, the particles (detail in Figure 1) tend to be susceptible to changes in size and shape during moisture removal that modify both the thickness and structural properties of the packed bed in the dryer and, consequently, the fluid-solid heat and mass transport. Shrinkage and variable physical properties such as bulk density, porosity and specific area, are thus important transient parameters in the modeling of drying.

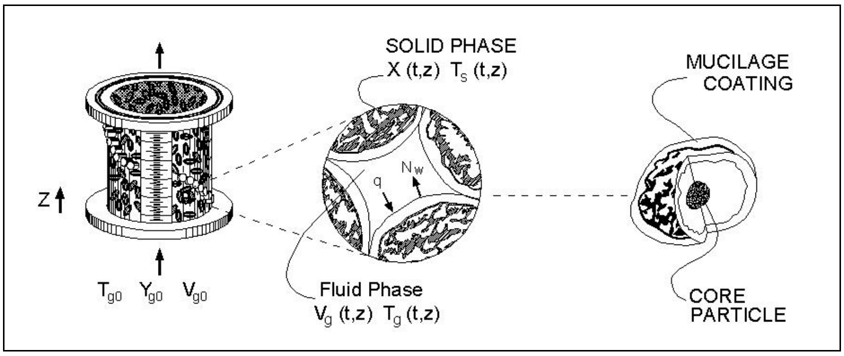


Figure 1: Sketch of the drying problem.

For a complete description of the process, the two-phase model proposed should take into account the effects of bed shrinkage and moisture content on the physical properties. Other assumptions adopted in the model formulation were as follows: the airflow is one-dimensional with uniform distributions of velocity, humidity and temperature in the cross section of the bed; heat losses through dryer walls are negligible; the fluid-solid heat transfer in the packed bed is predominantly convective; and heat and mass transport is one-dimensional.

Under the assumptions outlined above, the resulting system of coupled differential equations describing the mass and energy conservation balances for the solid phase and the fluid phase are summarized below.

Mass conservation

$$\rho_g \left(\frac{v_g}{S_b} \frac{\partial Y_g}{\partial \xi} + \varepsilon \frac{\partial Y_g}{\partial t} \right) = -\rho_b \frac{\partial X}{\partial t} \tag{1}$$

Energy conservation for the solid phase

$$\begin{aligned} &\rho_b \left(Cp_S + XCp_w \right) \frac{\partial T_S}{\partial t} = ha_v \left(T_g - T_S \right) + \\ &\rho_b \left[L_p + \left(Cp_v - Cp_w \right) T_s \right] \frac{\partial X}{\partial t} \end{aligned} \tag{2}$$

Energy conservation for the solid fluid

$$\begin{aligned} &\frac{v_g \ \rho_g}{S_b} \left(Cp_g + Y_g Cp_v \right) \frac{\partial T_g}{\partial \xi} + \\ &\rho_g \varepsilon \ \left(Cp_g + Y_g Cp_v \right) \frac{\partial T_g}{\partial t} = \\ &\left[ha - \rho_b \ Cp_v \ \frac{\partial X}{\partial t} \right] \left(T_s - T_g \right) \end{aligned} \tag{3}$$

Thin-layer drying equation

$$\frac{\partial X}{\partial t} = f\left(X, v_g, Y_g, T_g \right) \tag{4}$$

Boundary and initial conditions
Initial profile (t =0)

$$\begin{aligned} &z = 0 \begin{cases} X = X_0 ; T_s = T_{s0} \\ Y_g = Y_{g0;} T_g = T_{g0} \end{cases} \\ &z \neq 0 \begin{cases} X = X_0 ; T_s = T_{s0} \\ Y_g = Y_{sat} \left(T_{s0} \right) ; T_g = T_{s0} \end{cases} \end{aligned} \tag{5}$$

Boundary condition

$$z = 0 \ \forall \ t, \ Y_g = Y_{g0} \, \text{and} \, T_g = T_{g0} \tag{6}$$

To incorporate the movement of bed contraction, the model equations were written in Lagrangian formulation. The dimensionless moving coordinate system, ξ, is related to the spatial coordinate by the following equation (Ratti and Mujumdar, 1995):

$$dz = \frac{\rho_{b_0}}{\rho_b}\ d\xi = \frac{V_b}{V_{b0}}\ d\xi = S_b\ \ d\xi \tag{7}$$

The adequacy of the two-phase model thus obtained is verified in the present work with regard to the packed bed drying of papaya seeds, which are selected as model mucilaginous particles.

Numerical Solution

The numerical solution of the model equations provides predictions of the following four drying state variables: solid moisture (X), solid temperature (T_s), fluid temperature (T_g) and air humidity (Y_g) as functions of time (t) and bed height (z).

The model equations were solved numerically using the finite-difference method. From the discretization of spatial differential terms, the initial set of partial differential equations was transformed into a set of ordinary differential equations. The resulting vector of 4 (N+1) temporal derivatives was solved using the DASSL package (Petzold, 1989), which is based on the integration method of backwards differential formulation.

Solution of the mathematical model requires knowledge of the thermodynamic equilibrium and interphase transport parameters. A summary of these parameters, whose equations were obtained from previous studies, is given below. The development of the equations for predicting the shrinkage parameter (S_b) and structural properties of the packed bed as a function of moisture content, required in the approach used, was based on experimental results of the present work.

Model Parameters

a) Sorption Equilibrium Properties

The modified Halsey equations developed for predicting the equilibrium moisture content (X_{eq}) of papaya seeds with mucilage (Prado and Sartori, 2000) was used in the thick-layer bed drying simulation:

$$X_{eq} = \left[\frac{-\exp\left(-1.77\times10^{-2}\ \ T + 4.25\right)}{\ln\left(RH\right)}\right]^{1/1.90} \tag{8}$$

In addition, the desorption isotherms were analyzed according to principles of thermodynamics to obtain the following equations representing the latent heat of vaporization of water in mucilaginous seeds:

$$L_p = \left(2500.8 + 2.39\ \ T_g\right)$$
$$\left[1 + 3.2359\ \ \exp\left(-33.6404\ \ X\right)\right] \tag{9}$$

b) Drying-Rate Equation

The equation which gives the evolution of moisture content in a volume element of the bed with time, also known as thin-layer equation, strongly affects the predicted results of deep-bed drying models (Brooker, 1992). According to Prado and Sartori (2000), because of the high moisture content of papaya seeds, two equations are needed to cover the entire drying period: one for the constant rate period and the other for the decreasing rate period. The drying rate equation for the constant rate period is described as

$$\frac{dX}{dt} = -k_c\ k_c = 1.3\times10^{-9}\ \ {T_g}^{4.112}\ \ {v_g}^{0.219} \tag{10}$$

valid for $0.5 < v_g < 1.5$ m/s $30 < T_g < 50$ °C

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 as

$$\frac{dX}{dt} = -K\ \left(X - X_{eq}\right) \tag{11}$$

where the relationship between drying constant K and temperature is expressed as

$$K = 0.011\exp\left(-201.8/T_g\right) \tag{12}$$

c) Convective Heat Transfer Coefficient

Due to the limited number of reports dealing with external heat transfer in through-flow drying of beds consisting of particles with a high moisture content and susceptible to shrinkage, three correlations found in the literature to predict h in packed beds, Equations (13) to (15) (Table 1), were tested in drying simulation in order to obtain the best reproduction of the experimental data.

Table 1: Empirical equations for predicting the fluid-solid heat transfer coefficient for packed bed dryers.

Correlation	Range of validity	Reference
$Nu_p = \left(0.5\, Re_p^{1/2} + 0.2\, Re_p^{2/3}\right)\ Pr^{2/3}$ (13)	$20 < Re_p < 80000$ $\varepsilon < 0.78$	Whitaker (1972)
$h = 3.26\ Cp\ G_g\ Re^{-0.65}\ Pr^{2/3}$ (14)	$20 < Re < 1000$	Sokhansanj (1987)
$h = \left(\frac{Cp_g\ G_g}{\varepsilon}\right)\left(\frac{2.876}{Re} + \frac{0.302}{Re^{0.35}}\right)\ Pr^{-2/3}$ (15)	$10 < Re < 10000$	Geankoplis (1993)

where $Re = \frac{\rho_g\ v_g\ dp}{\mu}$, $Re_p = \left(\frac{\rho_g\ v_g\ dp}{\mu}\right)(1-\varepsilon)$, $Nu = \frac{h\ dp}{K_g}$, $Nu_p = \frac{h \cdot dp \cdot \phi \cdot \varepsilon}{K_g \cdot (1-\varepsilon)}$ and $Pr = \frac{Cp_g\ \mu}{K_g}$

EXPERIMENTAL STUDY

In this study, two groups of deep-bed drying experiments were carried out. The objective of the first group was to determine the physical characteristics of porous media composed of papaya seeds during drying and to develop equations relating shrinkage and properties of the packed bed with moisture content in order to incorporate them into the mathematical model. The objective of the second group was to evaluate the numerical solution of the two-phase model by comparison with experimental measurements of moisture content and temperature along the bed.

Preparation of Material

Papaya seeds were extracted from ripe fruits, using the wet procedure. The fruits were cut into two longitudinal halves and the seeds removed by hand. After manual extraction of the seeds, significant amounts of fibrous pulp and sugar residual were removed by washing with repeated soakings in water. After the last soaking, the suspension of seeds was passed through a set of wire meshes to drain off the excess water and to separate the seeds by size, thus avoiding the effect of seed size variability on the phenomena under study. Whole seeds were then allowed to stand for one hour at room temperature prior to each drying test. The moisture content of papaya seeds used in these tests ranged from 80 to 83% (wet basis).

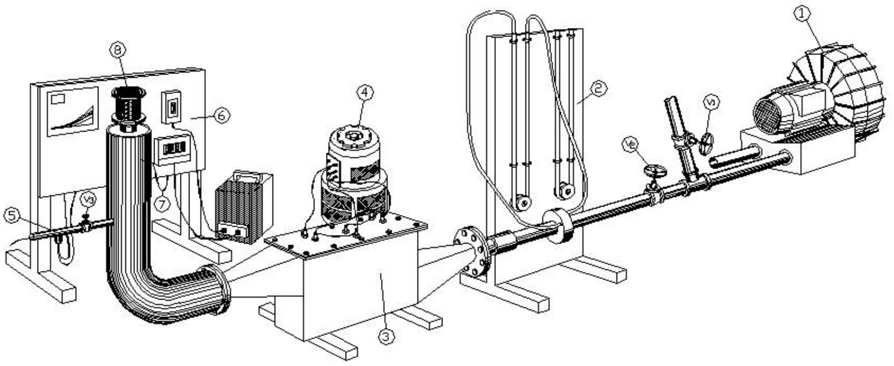
Experimental Setup

A scheme of the thick-layer bed dryer used to conduct the experiments is shown in Fig. 2. In this unit, airflow is supplied by a 0.75 HP blower (1). Flow-regulating valves (V1, V2) control the airflow, which is measured indirectly in terms of pressure drop over an orifice plate (2). The drying air is heated in an electrical heater (3) attached to a 2500 W voltage regulator. The vertical duct has a flow-homogenizing section containing perforated steel plates that assure that temperature and humidity are uniform and distributions enter the packed bed (8) at about 92% of the cross section. The cylindrical wall of the whole unit is thermally insulated with fiber glass to minimize heat loss, thus assuring no radial temperature gradients inside the packed bed.

A psychrometer (5) is placed at the inlet of the dryer to determine the absolute humidity of the drying air by measurements of wet and dry bulb temperatures. The inlet air dry bulb temperature is measured using a copper-constantan thermocouple (7). The temperature sensors are connected to a set of selector key and digital milivoltimeter (6).

The experiments were conducted at air temperatures ranging from 30 to 50^{o}C and air velocities from 0.5 to 1.5 m/s, defined by a 2^3 factorial design. These operational conditions satisfy the quality standard for papaya seeds as well as the validity range of the equations used in the model.

According to Prado and Sartori (2000), the thin-layer drying conditions for papaya seeds are satisfied by using a bed depth of 0.01m. Thus, in the studies of shrinkage and transfer phenomena involved in thick-layer bed drying, in which gradients of temperature and moisture content exist, an initial bed height of 0.05 m was used.



1. Blower
2. Flowmeter
3. Electrical Heater
4. Voltage Regulator
5. Phychrometer
6. Selector Key and Miuvoltimeter
7. Thermocouples
8. Drying Cells

V1, V2, V3. Gate Valves

Figure 2: Experimental apparatus of the fixed bed dryer (Silva, 1997).

Physical Properties and Bed Shrinkage Measurements

The shrinkage of the packed beds during drying was determined from measurement of its height at three angular positions. From the weighing and vertical displacement of the packed porous bed with time, the parameter of shrinkage (S_b) was obtained as a function of bed-averaged moisture content. The mass of the packed porous bed was measured using a balance with a 0.001 g accuracy and a scale range of 400 g and its dry mass was determined at the end of each experiment by the oven method at $(105 \pm 3)^{o}$C for 24 hours. From packed bed volume and mass measurements the bulk density was also determined, while seed density was measured with an air comparison pycnometer. Bed porosity was then calculated from the ratios of the aforementioned densities.

Since in the present work a packed bed is regarded as an ensemble of deformable particles, shrinkage of individual particles was also characterized. The size and shape of individual particles as a function of moisture content were determined by image analysis.

Measurements of Moisture Content and Temperature

Although a two-phase model is more realistic for considering interaction between solid and fluid phases by heat and mass transfer, describing each phase with a conservation equation, it is not simple to use. In addition to the complexity of it solution, there is an additional difficulty, with regards to its experimental validation, more precisely with the measurement of moisture content and temperature within both the solid phase and the drying air phase.

To assure the accuracy of model predictions, techniques for measuring solid moisture and temperature were adopted in this study.

a) Moisture Distribution

To avoid one of the major problems during experimentation on the fixed bed, associated with determination of solid moisture content distribution by continuously taking seed samples from each layer of the deep bed, which can modify the porous structure, possibly causing a preferential channel, a stratification method was used. To this, a measuring cell with a height of 0.05 m was constructed with subdivisions of 0.01 m to allow periodical bed fragmentation and measurement of the local moisture by the oven method at $(105 \pm 3)^{o}$C for 24 hours. Afterwards the measuring cell was refilled with a nearly equal mass of seeds and reinstalled in its dryer position. By adjusting the intervals of bed fragmentation appropriately, a moisture distribution history was produced for the packed bed.

Although it is a method that requires a large number of experiments and the use of a packing technique to assure the homogeneity and reproducibility of the refilled beds (Zotin, 1985), stratification provides experimental guarantees for model validation.

b) Temperature Distributions

Unprotected thermocouples were inserted into the center of the packed bed at the top to determine the solid temperature distribution and its dynamic behavior during drying. A helical arrangement of the temperature sensors, as detailed in Figure 1, attempted to minimize their interference with the airflow inside the porous bed.

The overall error in temperature measurements was 0.25°C. For airflow, air humidity and solid moisture measurements, the estimated uncertainties were 4%, 4% and 1%, respectively.

RESULTS AND DISCUSSION

The assumptions used in the model formulation were that the shrinkage and changes in physical properties of the packed bed were not negligible. The validity of these assumptions can be proved by the results shown in Figures 3 and 4, which illustrate significant variation in bed depth, bulk density, porosity and specific area with moisture content.

The deviation within the experimental data obtained under different drying conditions was smaller than the measurement uncertainties. This assures that in the experimental range studied the structural properties can be correlated with only the average moisture content.

Figure 3 shows the dynamics of bed shrinkage associated with the loss of moisture during the drying of papaya seeds. The contraction of the packed bed was exponential with respect to time, similar to the drying kinetics. Bed shrinkage occurred mainly in the constant rate period.

Contraction of the volume of the porous media composed of mucilaginous seeds was associated with changes in size and the seed shape factor ($\phi = dp/dl$) of the seed as verified in Figure 4 (a). However, the magnitude of volumetric shrinkage of the packed beds, of about 30%, was not directly proportional to that of individual particles, nearly 50%. This is due to the rearrangement of particles within the bed, defining a void space between the particles and, consequently, the packing conformation. The relationship between the Vl/Vl_0 ratio and the bed-averaged dimensionless moisture content, $XR = (X - X_{eq})/(X_0 - X_{eq})$, was represented by a second-order polynomial, expressed as

$$S_b = V_b / V_{b0} = 0.713 + 0.347XR - 0.056XR^2 \quad (16)$$

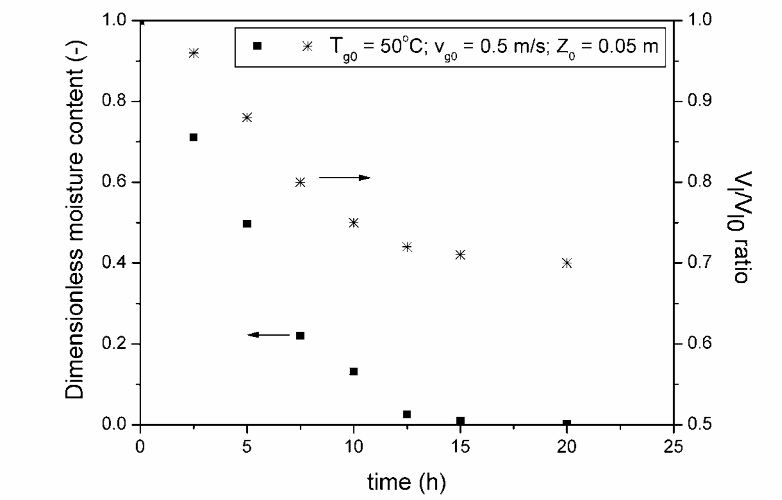


Figure 3: Dimensionless moisture content and bulk shrinkage ratio (S_b) as functions of time.

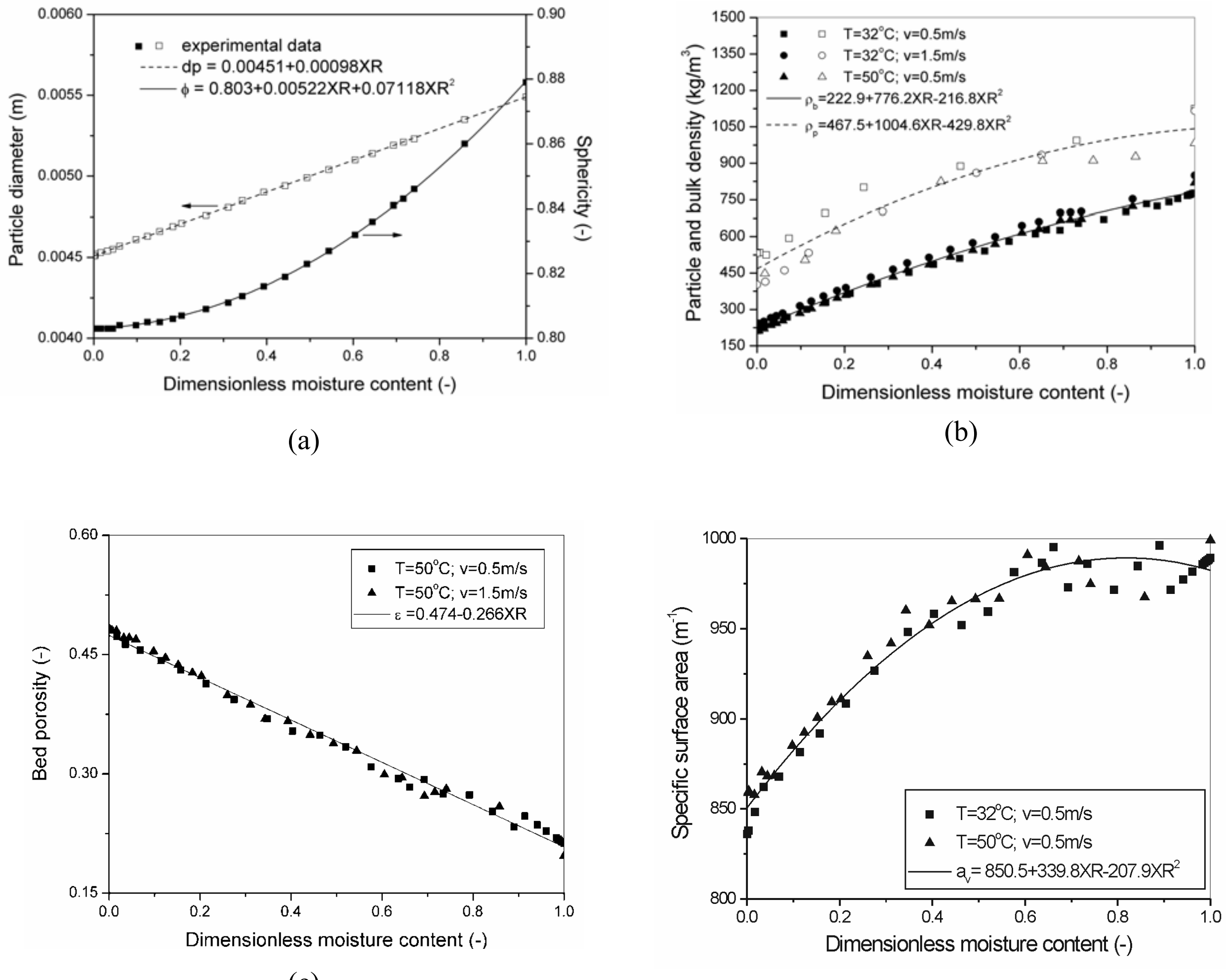
Figure 4 (b) contains typical results for the particle and bulk densities as a function of dimensionless moisture content under different drying conditions. The density of packed beds was found to vary from 777 to 218 kg/m^3, while the particle density varied from 1124 to 400 kg/m^3 as drying proceeded. The decrease in densities may be attributed to the greater decrease in weight for both individual particle and packed bed in comparison to the contraction of their volume on removal of moisture.

Typical experimental data on porosity during packed bed drying of papaya seeds are plotted against bed-averaged moisture content in Figure 4 (c). As can be observed, there was a significant increase in porosity in the packed bed of mucilaginous seeds, which varied between 0.20 for wet porous beds and 0.50 for dried porous beds. The low porosity of the wet packed beds can be explained in terms of the agglomerating tendency of the particles at high moisture contents. In addition, highly deformable and smooth seed coat facilitates contact between particles within the packed bed, resulting in a higher compaction of the porous media and, consequently, in a reduction in porosity.

The increase in bed porosity during drying is due firstly to deformation of the mucilage coating, which modifies seed shape and size, resulting in larger interparticle air voids inside the packed bed. Secondly, packed bed and particle shrinkage behaviors are not the same, so the space taken by the evaporated water is filled with air. The variation of about 150% in porosity is extremely high in comparison with other seed beds (Deshpande *et al.*, 1993).

The relationship between the calculated specific surface area and dimensionless moisture content is shown in Figure 4 (d). The specific surface area decreased by about 15% during drying. This reduction can be attributed to the significant increase in bed porosity in comparison with the variation in seed shape and size.

The equations developed to characterize the effects of moisture content on the shrinkage and structural parameters were then implemented in mathematical modeling so as to obtain more realistic results on heat and mass transfer characteristics in the packed bed drying of papaya seeds.



(a) (b)

(c) (d)

Figure 4: Structural properties during packed bed drying of mucilaginous seeds.

Figure 5 shows typical experimental and simulated temperature profiles throughout the packed bed with time, employing in the drying model different empirical equations for predicting the convective heat transfer coefficient (Table 1). Different predictions were obtained, showing the significant effect of h on the numerical solutions. These results are counter to findings for the modeling of thick-layer bed drying of other grains and seeds, specifically rigid particles (Calçada, 1994). In these findings a low sensitivity of the two-phase model to h is generally reported.

When the correlation of Sokhansanj (1987) is used, both the solid and fluid temperatures increase rapidly towards the drying temperature set. However, when the correlations given by Whitaker (1972) and Geankoplis (1993) are applied, the increase in temperature is gradual and thermal equilibrium between the fluid and solid phases is not reached, so there is a temperature difference between them.

Based on the differences in model predictions, the effects of shrinkage on the estimation of h during drying can be discussed. It should be noted that the Sokhansanj equation is based on the physical properties of air and the diameter of the particle. Thus, it is capable of taking into account only the deformation of individual particles during drying, which produces turbulence at the boundary layer, increasing the fluid-solid convective transport and resulting in an overpredicted rate of heat transfer within the bed (Ratti and Crapiste, 1995). Experiments show that, in the drying of shrinkable porous media, application of correlations capable of incorporating the effects of changes in structural properties, such as Whitaker (1972) and Geankoplis (1993) equations, gives better prediction of the temperature profile. Of these two equations, the Geankoplis equation was chosen, based on a mean relative deviation (MRD) of less than 5%, to be included as an auxiliary equation in drying simulation.

From Figure 5 it can also be verified that during the process of heat transfer, from the increase in saturation temperature up to a temperature approaching equilibrium, the predicted values for the solid phase were closest to the experimental data. This corroborates the interpretation adopted that the temperature measured with the unprotected thermocouple is the seed temperature.

In Tables 2 and 3 experimental and simulated values of moisture content and temperature and their respective mean relative deviations are presented for two typical drying runs. The mean relative deviations are less that 7% and the maximum absolute error is less than 12% for all the data tested. These results demonstrate the reliability of the two-phase model to simulate moisture content and temperature profiles during thick-layer bed drying of mucilaginous seeds.

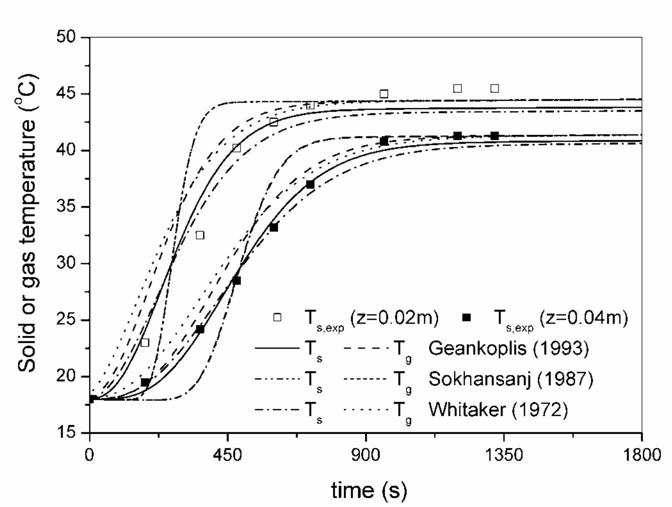


Figure 5: Dynamic evolution of experimental and simulated temperature profiles obtained from different correlations for h. Drying conditions: $v_g = 1.0$ m/s, $T_{g0} = 50^oC$, $Y_{g0} = 0.01$kg/kg, $T_{s0} = 18^oC$ and $X_0 = 3.9$ d.b.

Table 2: Experimental and predicted moisture content at various positions in the bed. Drying conditions: $Tg_0 = 50^oC$, $Y_{g0} = 0.01$ kg/kg, $v_{g0} = 1.0$ m/s, $T_s = 20^oC$ and $X_0 = 4.1$db.

t = 2.5 h				t = 7.5 h				t = 12.5 h			
z (m)	X_{exp} (db)	X_{sim} (db)	Error (%)	z (m)	X_{exp} (db)	X_{sim} (db)	Error (%)	z (m)	X_{exp} (db)	X_{sim} (db)	Error (%)
0.010	2.55	2.62	2.82	0.010	0.30	0.31	3.67	0.010	0.05	0.052	5.52
0.020	3.01	2.92	1.32	0.020	0.59	0.61	2.54	0.020	0.06	0.065	10.70
0.030	3.17	3.12	0.26	0.030	1.10	1.08	8.70	0.030	0.08	0.092	8.24
0.040	3.30	3.25	0.55	0.037	1.54	1.35	12.10	0.035	0.12	0.130	4.24
0.047	3.37	3.32	1.36	-	-	-	-	-	-	-	-
MRD = 0.92 %				MRD = 6.75%				MRD = 7.11%			

Table 3: Experimental and predicted temperature at various positions in the bed. Drying conditions: $Tg_0 = 35^oC$, $Y_{g0} = 0.005$ kg/kg, $v_{g0} = 0.8$ m/s, $T_s = 20.8^oC$ and $X_0 = 3.5$ d.b.

t = 5 min				t = 15 min				t = 60 min			
z (m)	T_{exp} (°C)	T_{sim} (°C)	Error (%)	z (m)	T_{exp} (°C)	T_{sim} (°C)	Error (%)	Z (m)	T_{exp} (°C)	T_{sim} (°C)	Error (%)
0.013	29.5	30.8	4.41	0.013	33.5	33.7	0.60	0.013	34.0	33.6	1.18
0.031	24.2	22.8	5.78	0.031	31.8	32.1	0.94	0.031	33.2	32.3	2.71
0.050	20.8	20.7	0.48	0.050	28.2	29.0	2.84	0.050	32.5	31.3	3.69
MRD = 3.56%				MRD = 1.46%				MRD = 2.53%			

Figure 6 shows a comparison of seed temperature profiles within the packed bed for various drying times predicted with and without incorporating the effects of bed shrinkage and moisture content on the physical properties in the model. When these effects are ignored the predicted values of seed temperature at a specific bed height are lower than those simulated under the assumption of shrinkage. It should be noted that there is no difference in the region close to the bed inlet (z = 0.01 m), where drying occurs under constant drying conditions. In the upper layers of the porous media, where heat transfer is an important step in controlling the drying dynamics, differences between the predictions become evident as the rate of heat transfer is increased because of the contraction of bed volume.

A typical simulation for moisture content along the bed is presented in Figure 7. The model that does not take into account variable physical properties and shrinkage tends to describe a slower drying process than that accompanied by bed contraction and to predict higher values of moisture content at all times. From a practical point of view this would result in higher energy costs and undesirable losses of product quality.

These results suggest that the assumptions of the modelling are essential to simulate adequately seed temperature and moisture content during drying, which have to be perfectly controlled at all times in order to keep the losses in quality to a minimum.

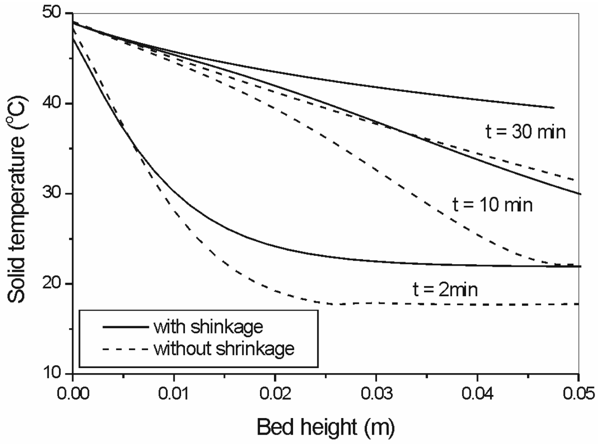


Figure 6: Simulated solid temperature profiles along the packed bed of mucilaginous seeds with and without consideration of shrinkage. $T_{g0} = 50^oC$, $v_{g0} = 1.0$ m/s, $Y_{g0} = 0.01$ kg/kg, $Ts_0 = 18^oC$ and $X_0 = 3.9$ d.b.

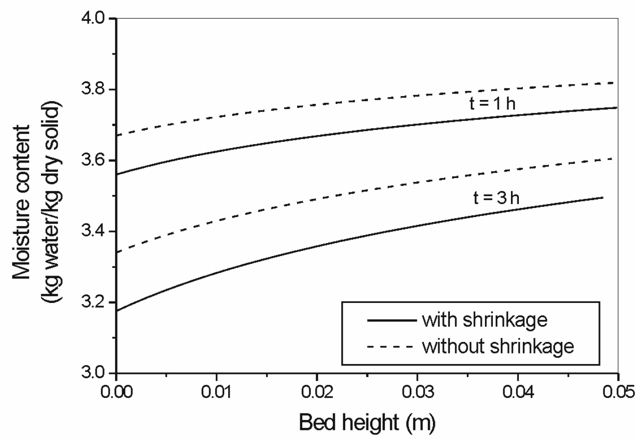


Figure 7: Simulated moisture content profiles along the packed bed of mucilaginous seeds with and without consideration of shrinkage. $T_{g0} = 40^oC$, $v_{g0} = 1.5$ m/s, $Y_{g0} = 0.011$ kg/kg, $Ts_0 = 20^oC$ and $X_0 = 4.0$ d.b.

CONCLUSIONS

It is concluded from the experimental-theoretical study that, for packed bed drying of seeds having a mucilage coating, such as papaya seeds, shrinkage and changes in structural properties can not be ignored from the viewpoint of the process dynamics. Bed contraction and variable properties such as bulk density, porosity and specific area must be implemented in modeling in order to obtain more realistic results.

The suitability of the two-phase model approach to describe the heat and mass transport phenomena associated with drying of shrinkable porous media is proven by well-predicted results compared with experimental measurements for both moisture content and temperature throughout the packed bed.

Parametric studies showed that the effect of h on the numerical solutions is significant. The best reproduction of the experimental data is obtained when h is calculated using the empirical equation of Geankoplis (1993), which has terms that allow the effects of changes in structural properties of the packed bed to be taken into account.

NOMENCLATURE

a_v	specific surface area	m^{-1}
Cp	specific heat	J/kg °C
dp	particle diameter	m
dl	maximum linear length	m
G_g	air mass flow rate	$kg\ m^{-2}\ s^{-1}$
h	heat transfer coefficient	J/m^2s °C
K	drying constant	s^{-1}
K_g	thermal conductivity	J/s m °C
L_p	latent heat of vaporization	J/kg
N	number of discretized cells	(-)
Nu	Nusselt number	(-)
Pr	Prandtl number	(-)
Re	Reynolds number	(-)
RH	relative humidity	(-)
S_b	shrinkage parameter	(-)
t	time	s
T	temperature	°C
v_g	air velocity	m/s
V	volume,	m^3
X	solid moisture content,	kg/kg
XR	dimensionless moisture,	(-)
Y_g	air humidity, d.b.,	kg/kg
z	spatial coordinate,	m

Greek Symbols

ε	porosity	(-)
ϕ	sphericity	(-)
ξ	dimensionless moving coordinate	(-)
ρ	density	$kg\ m^{-3}$

Subscripts

0	initial	(-)
b	bulk	(-)
exp	experimental	(-)
eq	equilibrium	(-)
g	gaseous, fluid	(-)
p	particle	(-)
s	solid	(-)
sat	saturation	(-)
sim	simulated	(-)
v	vapor	(-)
w	liquid water	(-)
sat	saturation	(-)

Abbreviation

d.b.	dry basis	(-)
MRD	mean relative deviation	(-)
w.b.	wet basis	(-)
sim	simulated	(-)
v	vapor	(-)
w	liquid water	(-)

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