Heat and Mass Transfer in Packed Bed Drying of Shrinking Particles

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1. Introduction

Drying is the most widespread heat and mass transport process with applications in several engineering areas and to a wide range of industrial and agricultural products, including grains and seeds. Wet granular materials are usually dried by forced convection using a hot air flow through a packed bed. Besides the low capital cost and low maintenance cost, packed bed dryers have some advantages in relation to moving bed dryers. For instance, the equipment is of simple operation, requiring no additional energy expense to move the solid particles throughout the bed, and minimizing the mechanical damages to the material. Moreover, investigations into packed bed dryers become increasingly important to obtain information on fluid-particle interactions, because this type of dryer provides the base for better understanding the simultaneous phenomena of heat and mass transfer which occur inside each particle in the bed, and the transfer phenomenon between solid and fluid phases of the packed bed, this being a mixture of dried granulated material and air.

The studies on transport phenomena that occur during drying of different particulate materials are not only of technological interest because of the numerous industrial applications, but also of scientific interest because of the material complexity. Within this context, beds of shrinking particles offer important challenges for the analysis of simultaneous heat and mass transfer during drying. A type of shrinking particle includes basically two separated regions: a gel-based coating, which has a highly deformable porous structure, and a wet core, which consists of liquid and solid. Gel-coated particles undergo significant shrinkage during moisture removal, which leads to changes in both the size and shape of the solid, modifying the structural properties of the particulate bed, thus affecting the fluid-particle interaction. The complexity increases as the extent of shrinkage is also process dependent. That is the result of the moisture gradient in the product, which, in turn, induces stresses and, thus, mechanical deformation (Eichler *et al.*, 1997).

A scientific understanding of heat and mass transfer in drying of deformable porous media and the role of shrinkage phenomenon is required for a more rational design and optimization of drying operating conditions. In this sense, mathematical modelling is very important. A large variety of models has been developed to describe the heat and mass transfer inside deep bed dryers. Comprehensive reviews of these models and simulation methods are available in the literature (Brooker *et al.*, 1992; Cenkowski *et al.*, 1993).

The mathematical models traditionally applied to describe 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 constitutive equations for thermodynamics equilibrium and heat and mass transfer between the phases. Unfortunately, one of the most common oversights in the so-called two-phase models is to neglect the shrinkage phenomenon as well as the changes induced in structural properties of the particulate bed. However, it should be pointed out that the drying of deformable particles is a problem of significant difference from other drying processes involving rigid particulate material, for which the aforementioned assumptions are valid. As a result, efforts have been directed to characterize physical changes in different materials during drying (Koç *et al.*, 2008; Mayor & Sereno, 2004) as well as to adequate models of packed bed dryers to simulate heat and mass transfer in a deformable porous medium (Prado & Sartori, 2008; Bialobrzewski *et al.*, 2008; Mihoubi & Bellagi, 2008; Kowalski *et al.*, 2007), so that particle-fluid interactions can be understood and drying optimized. Such investigations are important for the development of more efficient dryers, once they could lead to reductions in energy consumption when it comes to air flow requirements for materials that present higher bulk porosity upon shrinkage.

One of the most important parameters required in a drying model is the mass transfer coefficient, which expresses the inverse of a resistance to water transfer from the solid to a drying medium (Zanoelo *et al.*, 2007). Although numerous investigations have been performed for measuring and correlating this parameter in packed beds (Geankoplis, 1993; Krokida *et al.* 2002), the changes in shape, dimension and solid structure of deformable particles yield to a particular system where the available coefficients of mass transfer are not suitable to reproduce mass loss during drying of the material. The shrinkage phenomenon affects the length of the diffusion path in dried material, which influences the moisture diffusion coefficient of the material and, as result, influences the drying rate (Bialobrzewski *et al.*, 2008). As a consequence, any attempt to simulate and optimise the operation of drying of shrinking particles requires an experimental investigation that aims to obtain the mass transfer coefficient involved in this operation. Knowledge of the shrinkage mechanism, and of the influence of the process variables on shrinkage, improves the understanding of drying kinetics (Hashemi *et al.*, 2009; Bialobrzewski *et al.*, 2008).

The objective of this chapter is to provide comprehensive information on theoretical-experimental analysis of coupled heat and mass transfer in packed bed drying of shrinking particles. The modelling of the physical problem is first presented and, then the factors that influence its simulation are discussed. The focus is on the shrinkage phenomenon and its effects on the heat and mass transport coefficients. Finally, the validity of the model to predict the bed displacement and the evolution of moisture content and temperature in fluid and solid phases throughout the granular bed during convective drying is confirmed by using sets of data available for the drying of two deformable porous media, a packing of mucilaginous seeds and a packing of seeds having artificial gel coating.

2. Mathematical modelling

The physical problem under consideration is illustrated in Figure 1, in which a drying fluid flowing upward percolates a packed bed of gel-coated seeds. The detail of a volume element extracted from the packed bed shows that part of this 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.

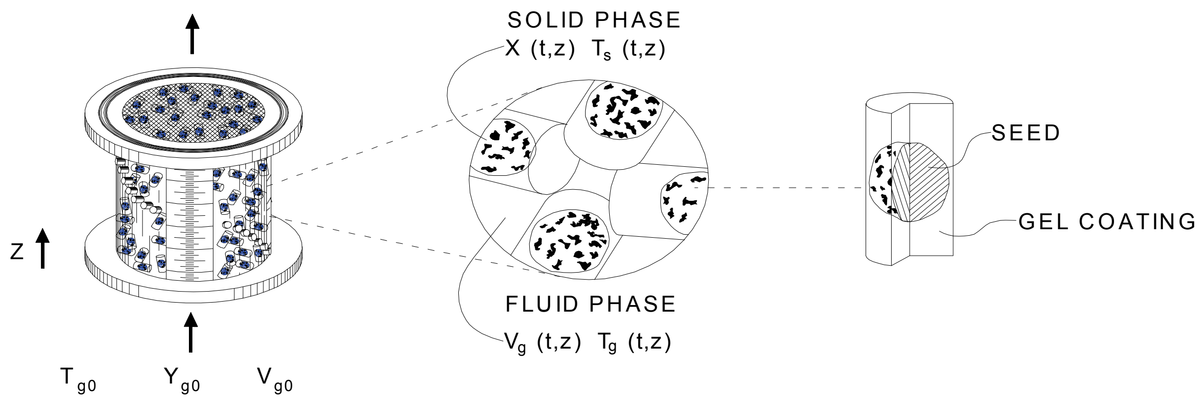


Fig. 1. Sketch of the drying problem

Mass balance in the solid:

$$\frac{\partial X}{\partial t} = f \tag{1}$$

Mass balance in the fluid:

$$\rho_g \left(\frac{v_g}{S_b} \cdot \frac{\partial Y_g}{\partial \xi} + \varepsilon \frac{\partial Y_g}{\partial t} \right) = -\rho_b \cdot \frac{\partial X}{\partial t} \tag{2}$$

Energy balance in the solid:

$$\rho_b \cdot \left(Cp_S + X \cdot Cp_w \right) \frac{\partial T_S}{\partial t} = ha_v \left(T_g - T_S \right) + \rho_b \cdot \left[L_p + \left(Cp_v - Cp_w \right) \cdot T_s \right] \cdot \frac{\partial X}{\partial t} \tag{3}$$

Energy balance in the fluid:

$$\frac{v_g \cdot \rho_g}{S_b} \cdot \left(Cp_g + Y_g Cp_v \right) \frac{\partial T_g}{\partial \xi} + \rho_g \cdot \varepsilon \cdot \left(Cp_g + Y_g Cp_v \right) \frac{\partial T_g}{\partial t} = \left[ha_v - \rho_b \cdot Cp_v \cdot \frac{\partial X}{\partial t} \right] \cdot \left(T_s - T_g \right) \tag{4}$$

Initial and boundary conditions:

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

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

Table 1. Model equations (Partial differential equations system)

For a complete description of the process, a two-phase model taking into account the effects of bed shrinkage and moisture content on the physical properties is applied. Other assumptions adopted include: the air flow 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. The resulting system of coupled differential equations describing the mass and energy conservation balances for the solid phase and the fluid phase are summarized in the Table 1.
The model equations were written in Lagrangian formulation to incorporate the movement of bed contraction. The dimensionless moving coordinate system, ξ, is related to the spatial coordinate, **z**, by the following equation (Ratti & Mujumdar, 1995):

$$dz = \frac{\rho_{b_0}}{\rho_b} d\xi = \frac{V_b}{V_{b0}} d\xi = S_b \, d\xi \qquad (7)$$

The solution of the mathematical model requires knowledge of the shinkage and interphase transport parameters, which are analytically examined in the following sections.

3. Shrinkage

3.1 General aspects

Shrinkage is a physical phenomenon which tends to occur simultaneously with heat and mass transfer in the drying process. In biological materials it occurs when the viscoelastic matrix contracts into the space previously occupied by the water removed from the cells (Aguilera, 2003). Shrinkage is macroscopically characterized by a reduction in volume or area due to evaporation of moisture contained in the solid. According to Mayor & Sereno (2004), heating and water loss cause stresses in the cellular structure of the material and lead to changes in shape and decrease in dimensions.
In deformable porous media, shrinkage or bed displacement can occur as a result of these changes in particles size and shape, and also due to gradients of moisture content generated inside the packed bed.
This phenomenon cannot be ignored for modelling of the drying process, especially for beds of particles with high initial moisture content. Besides the high moisture content, some particles have natural or artificial coating with gel characteristics. Due to the highly deformable polymeric structure of gels, these particles suffer changes in their original dimensions and shape during moisture removal, modifying the thickness and physical properties of the packed bed, as well as the heat and mass exchange area, thus affecting the drying process. However, the influence of shrinkage on heat and mass transfer in the drying of packed beds needs to be better clarified.
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 food such as fruit and vegetables (Chemkhi *et al.*, 2005; Wang & Brennan, 1995). There are few works reported in the literature on shrinkage of particulate food in bulk (Ratti, 1994) and even less on bulk shrinkage of seeds (Lang *et al.*, 1993).
The quantification of the shrinkage phenomenon as well as of the changes induced in structural parameters of the granular bed is essential for accurate simulation and interpretation of heat and mass transfer phenomena during drying.

3.2 Experimental measurement

Volume changes in individual particles have been evaluated by picnometric techniques and geometric measurements using micrometers. Image analysis has also been used to measure the shrinkage of different materials. These techniques are briefly reviewed in the following paragraphs.

The dimensions method has been commonly used (Burmester & Eggers, 2010; Batista *et al.*, 2007; Dissa *et al.*; 2008) to quantify the changes in apparent volume of samples, by averaging a number of dimensions measurements with micrometers or paquimeters, assuming known geometries. Surface area changes can also be evaluated from geometric measurements and by calculating the approximate surface area of the equivalent sphere, i.e., a sphere that has the same volume as the real particle (Suzuki *et al.*, 1976; Ratti, 1994; Ochoa *et al.*, 2007). This method can only be applied if the initial solid geometry was maintained during drying. When the shrinkage is accompanied by deformations, the use of volumetric displacement methods (buoyant forces) is recommended to determine the volume changes of material (Suzuki *et al.*, 1976; Lozano *et al.*, 1983; Ratti, 1994; Arnosti Jr. *et al.*, 2000; Zielinska & Markowski, 2010; Ochoa *et al.*, 2007).

Volumetric displacement methods have been used by many researchers to determine the apparent volume of different solid materials. Among these, the liquid pycnometric technique is the simplest, and it involves the immersion of the sample in a container of known liquid volume (generally water, hexane or toluene). The apparent volume of sample is determined by measuring the liquid volume displacement. In order to avoid absorption of liquid by the sample, thus ensuring measurement of its apparent volume, an impermeable coating is applied to the solid surface (Aviara *et al.*, 1999).

The use of gas stereopycnometer has been widely spread to determine the true solid volume, which excludes open pore volume (Prado, 2004; Zogzas *et al.*, 1994). However, the measured volume includes a portion of pore spaces inside the solid that are inaccessible to the gas (Chang, 1988).

Image analysis has become one of the most common techniques for shrinkage evaluation. It is a non-destructive method that allows continuous measurement of important parameters during drying such as area, perimeter, major and minor axis length, Feret diameter, elongation and roundness (Prado & Sartori, 2008; Yadollahinia & Jahangiri, 2009; Ramos *et al.*, 2010).

The shrinkage of granular beds has been determined from vertical bed displacement, which can be measured with a linear potentiometer (Lang *et al.*, 1993).

3.3 Experimental and theoretical approaches

Different approaches for shrinkage are found in the literature. The theoretical one involves mechanical laws, in which material stresses and deformations during drying are taken into account. In the experimental one, studies aim to quantify the dependence of materials volume as a function of their moisture content.

The theoretical approach was used for some researchers (Shishido *et al.*, 1986; Towner, 1987) in soil and polymers drying. However, its application to foodstuffs is extremely complex, due to the cellular and multiphase nature of the system and to the necessity of knowing the structure and mechanical and viscoelastic properties of each system phase as well as their variations with moisture content and temperature (Crapiste *et al.*, 1988; Ratti, 1994). Therefore, the most widely used approach for studying food shrinkage is the experimental.

In this approach, the shrinkage coefficient (S_b) is obtained from experimental data according to the ratio between the sample volume at a drying time t and the initial volume of the sample. Changes in S_b with respect to the moisture content constitute the shrinkage curve.

Empirical and theoretical models have been developed to describe the shrinkage behavior of individual particles during drying. In both models, shrinkage has been correlated linearly and non-linearly to moisture content.
In theoretical models, the prediction of changes in volume is based on mass and volume conservation laws assuming, in most cases, additivity of the volumes of the different phases in the system (Mayor & Sereno, 2004).
Suzuki *et al*. (1976) measured the shrinkage of root vegetables that occurred during drying. They attempted to correlate the experimental data with three postulated models; uniform drying, core drying and semicore drying. In the uniform drying model, shrinkage is assumed to be equal to the volume of the water lost by evaporation during all stages of drying. This model results in two equations. The first requires equilibrium moisture content and bulk density, while the second requires the initial moisture.
Based on the laws of mixtures, Sokhansanj & Lang (1996) developed the following two equations to describe the contraction of solid volume, excluding the interparticle volume, and the reduction in grain apparent volumes, respectively, as functions of moisture content:

$$\frac{V_s}{V_{s_0}} = \left[\frac{1-X_0}{1+(\eta-1)\cdot X_0}\right]\cdot\left[\frac{1+(\eta-1)\cdot X}{1-X}\right] \tag{8}$$

and

$$\frac{V_b}{V_{b_0}} = \frac{\left[1-(X_0-X)\right]\cdot\left[1+(\eta-1)\cdot X\right]\cdot(1-\varepsilon_0)}{\left[1+(\eta-1)\cdot X_0\right]\cdot(1-\varepsilon)} \tag{9}$$

where, V_s and V_{s0} are the volumes of solid grain matrix, V_b and V_{b0} are the volumes of particles corresponding to wet basis moisture contents at a certain time (X) and initial time (X_0), respectively, and η is the relative specific mass of the dry solid which is considered constant for each grain.
For the solid matrix, Equation 8 is based on the hypothesis of the additivity of volumes of water and solids, assuming that the volume of air in pores is negligible. In other words, the shrinkage is considered to be equal to the volume of the evaporated water at each period of time during drying. This model has been used for grain kernels, fruit, vegetables and gel-like products by several authors (Zogzas *et al.*, 1994, Krokida & Maroulis, 1997; Arrieche & Sartori, 2004). The model developed for individual particles, Equation (9), taking into account variations of the porosity during the drying process, is particularly interesting, as it can be extended to describe shrinkage behavior of packed beds.
Although there are theoretical models providing physical interpretation for the shrinkage phenomenon, most researchers (Zielinska & Markowski, 2010; Ramos *et al.*, 2010; Ochoa *et al.*, 2007; Prado *et al.*, 2006; Arnosti Jr. *et al.*, 2000; Ratti, 1994; Lozano *et al.*, 1983) have used empirical equations to represent the changes in volume and surface area as functions of moisture content. This is because empirical models allow the prediction of shrinkage without requiring the knowledge of physical properties, such as porosity which is not usually available.

3.4 Experimental shrinkage behavior of individual particles and porous media

To obtain an in-depth understanding of porous bed shrinkage during drying, first, it is necessary to begin with a complete characterization of shrinkage of individual particles, not only in terms of reduced dimensional change in volume, area or thickness, but also of the changes induced in porosity, true and apparent densities, which are clearly dependent upon variations in moisture content. Then, the behavior of deformable porous media is evaluated and related to the characteristics of their individual particles. In order to examine this relationship, experimental data available for thin and deep beds of mucilaginous and gel-coated seeds were chosen to be presented to fulfill the necessities of the present section. Besides the arrangement of particles in the dryer, as single or deep beds, other factors such as volume of water removed and drying conditions affect the magnitude of shrinkage. These factors are also examined in the following paragraphs.

3.4.1 Effect of packing on shrinkage

Information on the shrinkage of papaya seeds both in bulk and as individual particles is presented in Figure 2. The magnitude of shrinkage was significantly affected by the packing of particles. More specifically, the shrinkage coefficient during drying of deep bed of papaya seeds was significantly lower than that of individual seeds arranged in a single layer through which air flows in forced convection. Besides the reduction in particle size, the contraction of the bed porous also appears to be affected by the changes observed in particle shape. Such changes cause a rearrangement of particles within the bed, defining a void space between the particles and, thus leading to a stable packing conformation.

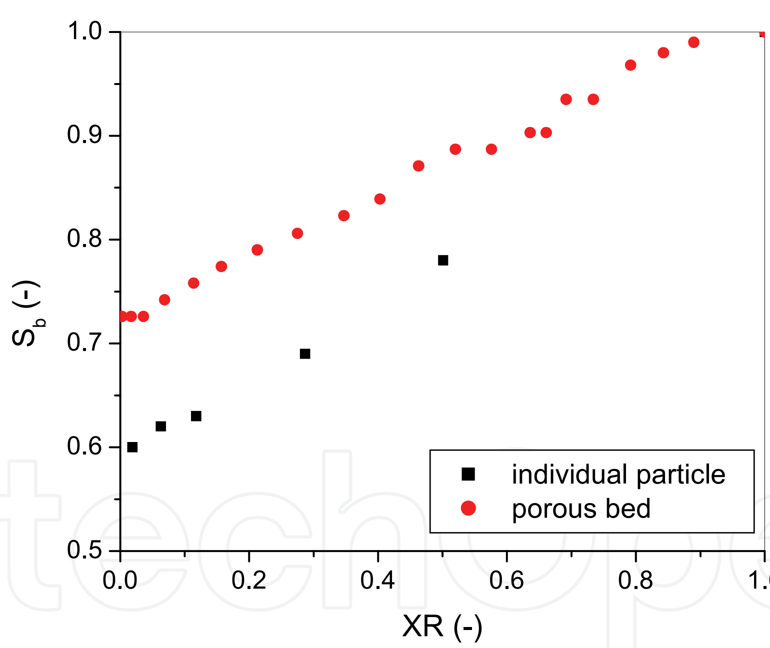


Fig. 2. Volume shrinkage coefficient (S_b) as a function of dimensionless moisture content (XR), for mucilaginous seeds in bulk and as individual particles

3.4.2 Effect of volume of removed water

In the case of deformable media, there is a balance during moisture removal between volume change, density and porosity. In order to know whether the loss in moisture content is converted into volume reduction or into porosity increase, the magnitude of particle shrinkage is usually plotted against normalized volume of water removed (Figure 3). The volume contraction of papaya seeds both in deep bed and as individual particles was lower than the corresponding amount of water removed during drying. According to May & Perré (2002), this behavior reveals that shrinkage of particles and granular bed is accompanied by an increase in porosity, as a result of the reduction in system volume as well as of simultaneous incorporation of gaseous volume.

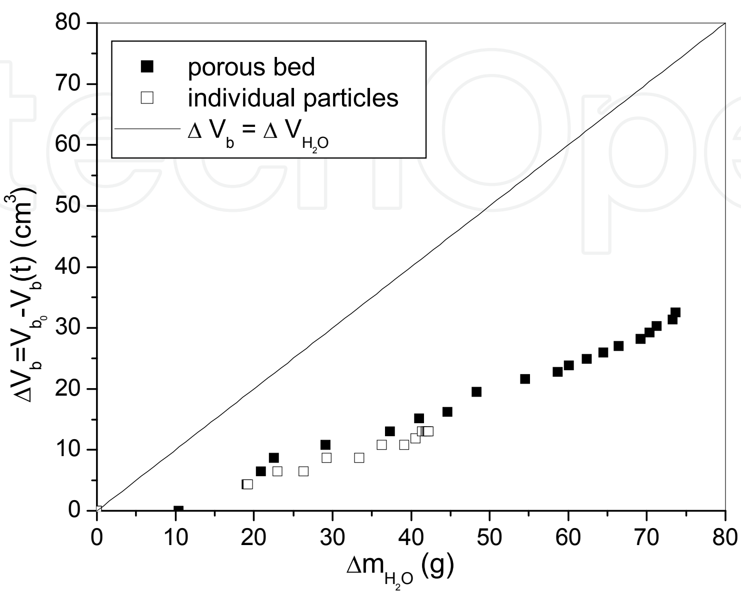


Fig. 3. Relationship between volume reduction and water loss during drying of mucilaginous seeds in bulk and as individual particles, T_{g0} = 50°C, v_{g0}=0.5 m/s

3.4.3 Effect of drying conditions

Volume changes of individual particles and granular deep beds affected by different drying conditions like temperature, air velocity and relative humidity have been investigated by several researchers (Ratti, 1994; Lang *et al.*, 1993). In order to examine this subject, experimental shrinkage data of gel coated millet in bulk and as individual particles are presented in Figures 4 and 5, respectively, as functions of moisture content at different drying conditions.

Shrinkage of individual particles was significantly affected by the operating conditions. This influence is closely related to the rate at which the material is dried, so that the magnitude of volume contraction was higher at lower drying rates. At 30°C and 0.5 m/s, corresponding to low drying rate conditions, external resistance controls the mass transfer, the moisture profiles of the particles are uniform and stresses are minimum (Ratti, 1994). Hence, the particle shrinks uniformly. On contrary, at rapid drying rate conditions, associated with the elevated operating conditions, 50°C and 1.5 m/s, internal resistances control the mass transport and the migration of internal moisture is not uniform, so that it does not compensate the evaporation rate from the particle surface. This induces the formation of a rigid crust in the gel coating, that fixes the volume, hindering subsequent shrinkage.

While for individual particles the volume contraction appears to decrease with an increase in drying rate, no effect of drying conditions on bed shrinkage was found. The deviation within the experimental data obtained under different drying conditions was smaller than the measurement uncertainties. This assures that the bed shrinkage can be correlated with only the bed average moisture content in the experimental range studied.

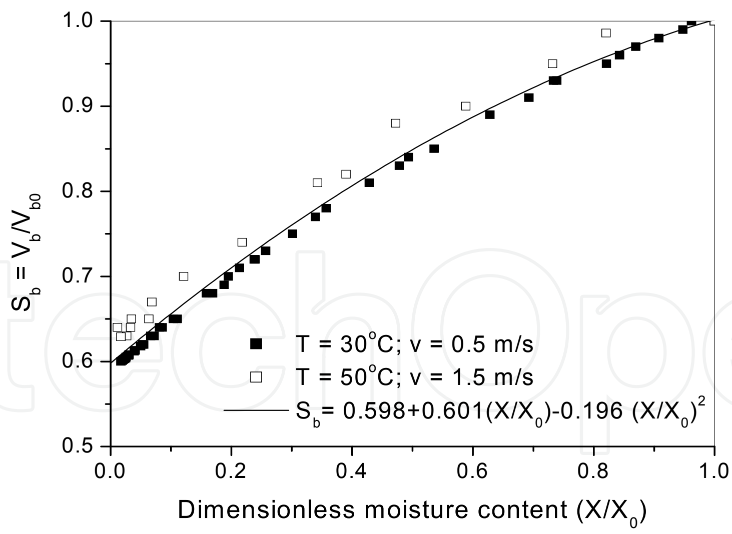


Fig. 4. Bulk shrinkage ratio (S_b) as function of dimensionless bed-averaged moisture content

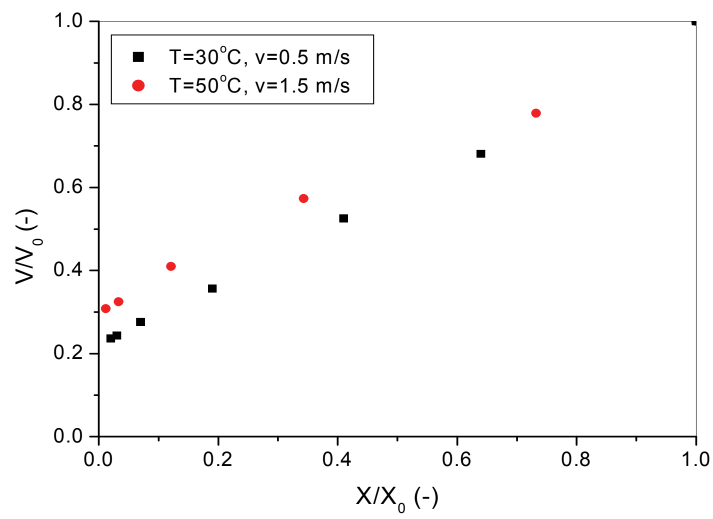
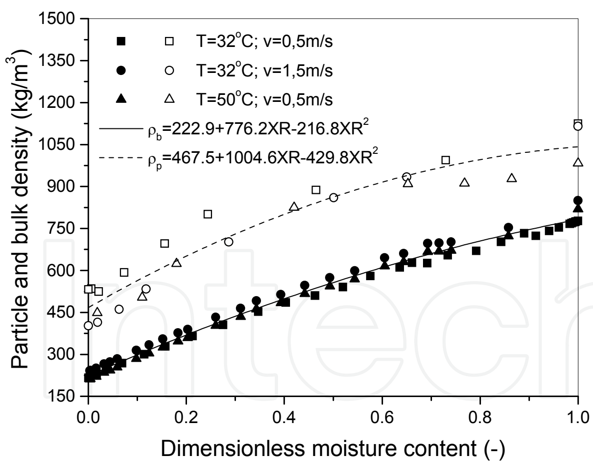


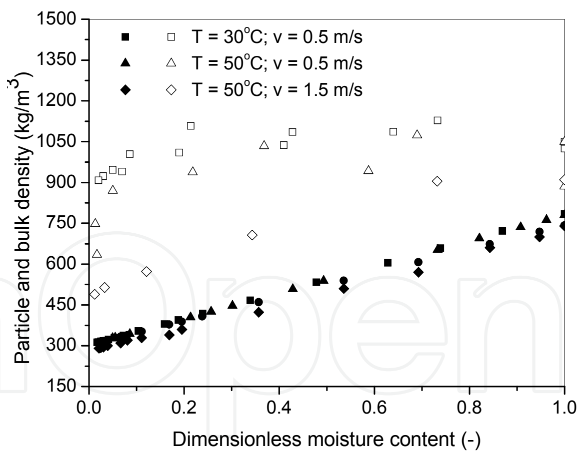
Fig. 5. Shrinkage ratio (S_b) as a function of dimensionless moisture content for artificially coated seeds

3.5 Changes in structural properties during drying

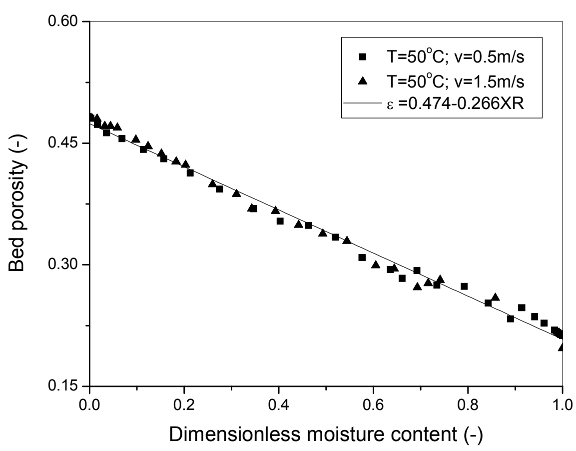
Physical properties of beds composed of very wet particles are clearly dependent upon reduction of both moisture content and volume. Any attempt to raise the shrinkage phenomenon to a higher level of understanding must address the structural properties of the material such as density, porosity and specific area. Moreover, porosity, specific area and bulk density are some of those physical parameters that are required to build drying models; they are particularly relevant in case of porous beds and as such plays an important role in the modelling and understanding of packed bed drying.. Several authors (Ratti, 1994; Wang & Brennan, 1995; Koç *et al.*, 2008) have investigated the changes in structural properties during drying. In what follows, a discussion is directed to changes in physical properties during drying of single and deep bed of skrinking particles. Typical experimental data on changes in structural properties of mucilaginous and gel coated seeds during drying in bulk or as individual particles are presented in Figure 6.



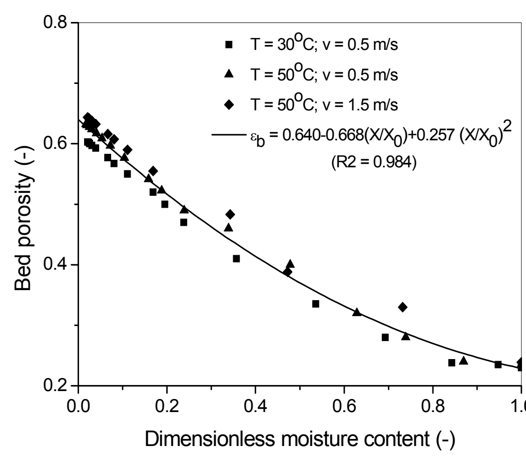
(a) Particle and bulk density versus dimensionless moisture content, for mucilaginous seeds



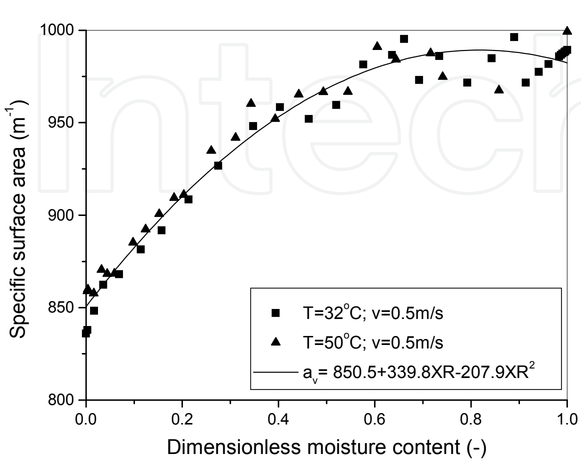
(b) Particle and bulk density versus dimensionless moisture content, for gel coated seeds



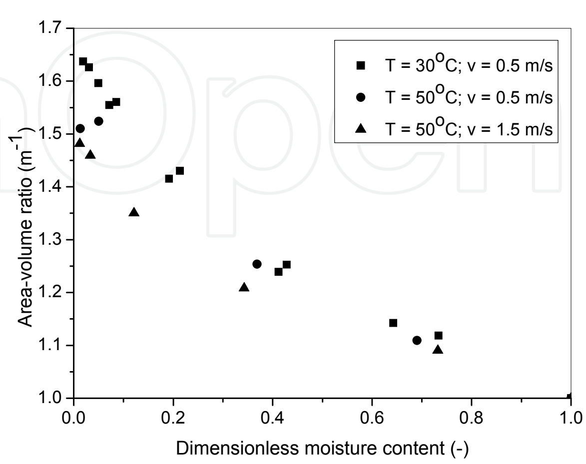
(c) Bed porosity versus dimensionless moisture content, for mucilaginous seeds



(d) bed porosity versus dimensionless moisture content, for gel coated seeds



(e) Specific surface area versus dimensionless moisture content for the packed bed



(f) area to volume ratio versus dimensionles moisture content for individual particles

Fig. 6. Structural properties during packed bed drying of mucilaginous and gel coated seeds

For granular beds, three densities have to be distinguished: true, apparent and bulk density. The true density of a solid is the ratio of mass to the volume of the solid matrix, excluding all pores. The apparent density describes the ratio of mass to the outer volume, including an inner volume as a possible pore volume. The term particle density is also used. The bulk density is the density of a packed bed, including all intra and inter particle pores. These structural properties are determined from measurements of mass, true volume, apparent volume and bulk or bed volume. Mass is determined from weighing of samples, whereas the distinct volumes are measured using the methods described in section 4.2. The bed porosity is calculated from the bulk density and the apparent density of the particle.

In Fig. 6 (a) the apparent and bulk densities are shown as functions of dimensionless moisture content of mucilaginous seeds under different drying conditions. The density of packed beds of mucilaginous seeds 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 both densities may be attributed to higher weight decrease in both individual particle and packed bed in comparison to their volume contraction on moisture removal.

Apparent density behavior of individual particles and its dependency on temperature were found to be dependent on type of coating (natural or artificial). The distinct behavior of apparent density of mucilaginous and gel coated seeds may be ascribed to the distinct characteristics of reduction in mass and volume of each particle during drying. Contrary to the behavior presented by mucilaginous seeds, the apparent density of gel coated seeds, displayed in Figure 6 (b), was almost constant during most of the drying due to reductions of both particle volume and amount of evaporated water in the same proportions. In the latter drying stages, as the particles undergo negligible volume contraction, the density tends to decrease with moisture loss.

It can also be seen from Figures 6(a) and 6 (b) that drying conditions affected only the apparent density of gel coated seeds. Drying at 50^{o}C and 1.5 m/s, which resulted in the higher drying rate, provided coated seeds with the lower apparent density values. This suggests that there is a higher pore formation within the gel-based coating structure during rapid drying rate conditions. High drying rates induce the formation a stiff outer layer in the early drying stages, fixing particle volume, thus contributing for replacement of evaporated water by air.

The difference between the apparent and bulk densities indicates an increase in bed porosity. Porosity of thick bed of mucilaginous seeds ranged from 0.20, for wet porous beds, to 0.50, for dried porous beds (Fig. 6c). However, beds composed of gel coated seeds presented a higher increase in porosity, with this attaining a porosity of about 0.65 (Fig. 6d). 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 among particles within the packed bed, leading to a higher compaction of the porous media and, consequently, to a reduction of porosity.

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

The relationships between the calculated specific surface area of the porous bed as well as of the area volume ratio of the particle with dimensionless moisture content are shown in Figures 6 (e) and 6 (f).

Fig. 6 (f) presents the experimental particle surface area per unit of particle volume made dimensionless using the fresh product value as a function of the dimensionless moisture, for gel-coated seeds. Shrinkage resulted in a significant increase (about 60%) of the area to volume ratio for heat and mass transfer, faciliting the moisture transport, thus increasing the drying rate. This parameter was found to be dependent on drying conditions. The increase in the specific area of the coated particle is reduced as the air drying potential is increased and the shrinkage is limited. On the other hand, the specific surface area of porous bed decreased by about 15 % during drying, Fig. 6 (a). This reduction can be attributed to the significant increase in bed porosity in comparison with the variation in seed shape and size.

The results concerning deep beds indicate that changes in both density, porosity and specific area of the bed are independent of operating conditions in the range tested, and are only related only to the average moisture content of the partially dried bed.

Figure 2 showed a significant contraction of the volume of packed bed composed of mucilaginous particles, of approximately 30%, while Figures 6 (c) and (d) revealed an increase of about 150% in porosity during deep bed drying. Such results corroborate that shrinkage and physical properties such as porosity, bulk density and specific area are important transient parameters in modelling of packed bed drying.

Equations describing the evolution of shrinkage and physical properties as a function of moisture content are implemented in mathematical modeling so as to obtain more realistic results on heat and mass transfer characteristics in drying of deformable media.

4. Drying kinetics

Among the several factors involved in a drying model, a proper prediction of the drying rate in in a volume element of the dryer is required. According to Brooker et al. (1992), the choice of the so-called thin layer equations strongly affects the validity of simulation results for thick-layer bed drying. Several studies related to evaluation of different drying rate equations have been reported in the literature. However, most of works does not deal with the effects of the shrinkage on the drying kinetics although this phenomenon could strongly affect the water diffusion during drying. The influence of shrinkage on drying rates and water diffusion is hence examined in the following paragraphs. To this, experimental kinetic behaviour data of papaya seeds in thin-layer bed are presented. Comparison of the mass transport parameters without and with the shrinkage of gel coated seeds is also presented.

4.1 Experimental determination

Drying kinetics is usually determined by measuring the product moisture content as a function of time, known as the drying curve, for constant air conditions, which are usually obtained from thin layer drying studies Knowledge of the drying kinetics provides useful information on the mechanism of moisture transport, the influence of operating conditions on the drying behaviour as well as for selection of optimal drying conditions for grain quality control. This approach is also widely used for the determination under different drying conditions of the mass transfer parameters, which are required in deep bed drying models (Abalone et al., 2006; Gely and Giner, 2007; Sacilik, 2007; Vega-Gálvez et al, 2008; Saravacos & Maroulis, 2001; Xia and Sun, 2002; Babalis and Belessiotis, 2004).

4.2 Influence of shrinkage on drying behaviour and mass transfer parameters

The theory of drying usually states that the drying behaviour of high moisture materials involves a constant-rate stage followed by one or two falling-rate periods. However, the presence of constant drying rate periods has been rarely reported in food and grain drying studies. A possible explanation for this is that the changes in the mass exchange area during drying are generally not considered (May and Perré, 2002). In order to obtain a better understanding on the subject the discussion is focussed on thin layer drying of shrinking particles, which are characterized by significant area and volume changes upon moisture removal. Experimental drying curves of mucilaginous seeds, obtained under thin-layer drying conditions are presented and examined.
Typical results of water flux density as a function of time with and without consideration of shrinkage are shown in Figure 7.

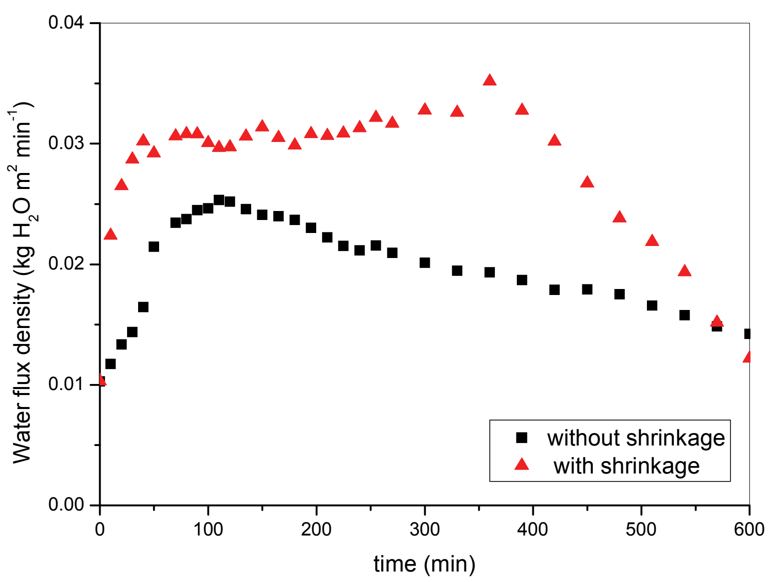


Fig. 7. Water flux density versus moisture content

Because of the initial water content of mucilaginous seeds as well as of their deformable coating structure, the course of drying is accompanied by both shrinking surface area and volume. This results in a large area to volume ratio for heat and mass transfer, faciliting the moisture transport, thus leading to higher values of water flux density. On the other hand, If the exchange surface area reduction is neglected the moisture flux density may decrease even before the completion of the first stage of drying, although free water remains available on the surface (Pabis, 1999). It is evident from Figure 7 that on considering constant mass transfer area the constant-flux period was clearly reduced, providing a critical moisture content which does not reflect the reality.

4.3 Thin-layer drying models

Thin-layer equations are often used for description of drying kinetics for various types of porous materials. Application of these models to experimental data has two purposes: the first is the estimation of mass transfer parameters as the effective diffusion coefficient, mass transfer coefficient, and the second is to provide a proper prediction of drying rates in a volume element of deep bed, in order to be used in dryer simulation program (Brooker et al., 1992.; Gastón et al., 2004).

The thin layer drying models can be classified into three main categories, namely, the theoretical, the semi-theoretical and the empirical ones (Babalis, 2006). Theoretical models are based on energy and mass conservation equations for non-isothermal process or on diffusion equation (Fick's second law) for isothermal drying. Semi-theoretical models are analogous to Newton's law of cooling or derived directly from the general solution of Fick's Law by simplification. They have, thus, some theoretical background. The major differences between the two aforementioned groups is that the theoretical models suggest that the moisture transport is controlled mainly by internal resistance mechanisms, while the other two consider only external resistance. The empirical models are derived from statistical relations and they directly correlate moisture content with time, having no physical fundamental and, therefore, are unable to identify the prevailing mass transfer mechanism. These types of models are valid in the specific operational ranges for which they are developed. In most works on grain drying, semi-empirical thin-layer equations have been used to describe drying kinetics. These equations are useful for quick drying time estimations.

4.3.1 Moisture diffusivity as affected by particle shrinkage

Diffusion in solids during drying is a complex process that may involve molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, surface diffusion and all other factors which affect drying characteristics. Since it is difficult to separate individual mechanism, combination of all these phenomena into one, an effective or apparent diffusivity, D_{ef}, (a lumped value) can be defined from Fick's second law (Crank, 1975).

Reliable values of effective diffusivity are required to accurately interpreting the mass transfer phenomenon during falling-rate period. For shrinking particles the determination of D_{ef} should take into account the reduction in the distance required for the movement of water molecules. However, few works have been carried out on the effects of the shrinkage phenomenon on D_{ef}.

Well-founded theoretical models are required for an in-depth interpretation of mass transfer in drying of individual solid particles or thin-layer drying. However, the estimated parameters are usually affected by the model hypothesis: geometry, boundary conditions, constant or variable physical and transport properties, isothermal or non-isothermal process (Gely & Giner, 2007; Gastón *et al.*, 2004).

Gáston *et al.* (2002) investigated the effect of geometry representation of wheat in the estimation of the effective diffusion coefficient of water from drying kinetics data. Simplified representations of grain geometry as spherical led to a 15% overestimation of effective moisture diffusivity compared to the value obtained for the more realistic ellipsoidal geometry. Gely & Giner (2007) provided comparison between the effective water diffusivity in soybean estimated from drying data using isothermal and non-isothermal models. Results obtained by these authors indicated the an isothermal model was sufficiently accurate to describe thin layer drying of soybeans.

The only way to solve coupled heat and mass transfer model or diffusive model with variable effective moisture diffusivity or for more realistic geometries is by numerical methods of finite differences or finite elements. However, an analytical solution of the diffusive model taking into account moisture-dependent shrinkage and a constant average water diffusivity is available in the literature (Souraki & Mowla, 2008; Arévalo-Pinedo & Murr, 2006)

Experimental drying curves of mucilaginous seeds were then fitted to the diffusional model of Fick's law for sphere with and without consideration of shrinkage to determine effective moisture diffusivities. The calculated values of D_{ef} are presented and discussed. First, the adopted approach is described.

The differential equation based on Fick's second law for the diffusion of water during drying is

$$\frac{\partial(\rho_d X)}{\partial t} = \nabla \cdot \left(D_{ef} \nabla (\rho_d X)\right) \tag{10}$$

where D_{ef} is the effective diffusivity, ρ_d is the local concentration of dry solid (kg dry solid per volume of the moist material) that varies with moisture content, because of shrinkage and X is the local moisture content (dry basis).
Assuming one-dimensional moisture transfer, neglected shrinkage and considering the effective diffusivity to be independent of the moisture content, uniform initial moisture distribution, symmetrical radial diffusion and equilibrium conditions at the gas-solid interface, the solution of the diffusion model, in spherical geometry, if only the first term is considered, can be approximated to the form (López et al., 1998):

$$XR = \frac{X - X_e}{X_0 - X_e} = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 D_{ef}}{R^2} t\right) \tag{11}$$

Where XR is the dimensionless moisture ratio, X_e is the equilibrium moisture content at the operating condition, R is the sphere radius.
In convective drying of solids, this solution is valid only for the falling rate period when the drying process is controlled by internal moisture diffusion for slice moisture content below the critical value. Therefore, the diffusivity must be identified from Eq. (11) by setting the initial moisture content to the critical value X_{cr} and by setting the drying time to zero when the mean moisture content of the sample reaches that critical moisture content.
In order to include the shrinkage effects, substituting the density of dry solid ($\rho_d = m_d/V$), Eq. (11) for constant mass of dry solid could be expressed as (Hashemi et al., 2009; Souraki and Moula, 2008; Arévalo-Pinedo, 2006):

$$\frac{\partial(X/V)}{\partial t} = \nabla \cdot \left(D_{ef} \nabla (X/V)\right) \tag{12}$$

where V is the sample volume. Substituting Y = X/V, the following equation is obtained:

$$\frac{\partial Y}{\partial t} = \nabla \cdot \left(D_{ef}^{*} \nabla Y\right) \tag{13}$$

with the following initial and boundary conditions:

$$t = 0,\ Y = X_0/V_0$$
$$t > 0,\ z = 0,\ \frac{\partial Y}{\partial z} = 0$$
$$t > 0,\ z = L,\ Y = X_{eq}/V_{eq}$$

A solution similar to Eq. 11 is obtained:

$$YR = \frac{Y - Y_e}{Y_0 - Y_e} = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 D_{ef}^{*}}{R^2} t\right) \tag{14}$$

where D_{ef}^* is the effective diffusivity considering the shrinkage, R is the time averaged radius during drying:
The diffusional models without and with shrinkage were used to estimate the effective diffusion coefficient of mucilaginous seeds. It was verified that the values of diffusivity calculated without consideration of the shrinkage were lower than those obtained taking into account the phenomenon. For example, at 50°C the effective diffusivity of papaya seeds without considering the shrinkage (D_{ef} = 7.4 x 10^{-9} m^2/min) was found to be 30% higher than that estimated taking into account the phenomenon (D_{ef}^* = 5.6 x 10^{-9} m^2/min). Neglecting shrinkage of individual particles during thin-layer drying leads, therefore, to a overestimation of the mass transfer by diffusion. This finding agrees with results of previous reports on other products obtained by Souraki & Mowla (2008) and Arévalo-Pinedo and Murr (2006).

4.3.2 Constitutive equation for deep bed models

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). For simulation purpose, models that are fast to run on the computer (do not demand long computing times) are required.
When the constant rate period is considered, it is almost invariably assumed to be an externally-controlled stage, dependent only on air conditions and product geometry and not influenced by product characteristics (Giner, 2009). The mass transfer rate for the evaporated moisture from material surface to the drying air is calculated using heat and mass transfer analogy where the Nusselt and Prandtl number of heat transfer correlation is replaced by Sherwood and Schmidt number, respectively.
With the purpose of describe drying kinetics, when water transport in the solid is the controlling mechanism, many authors have used diffusive models (Gely & Giner, 2007; Ruiz-López & García-Alvarado, 2007; Wang & Brennan, 1995).
When thin-layer drying is a non-isothermal process an energy conservation equation is coupled to diffusion equation. Non-isothermal diffusive models and isothermal models with variable properties do not have an analytical solution; so they must be solved by means of complicated numerical methods. The numerical effort of theoretical models may not compensate the advantages of simplified models for most of the common applications (Ruiz-López & García-Alvarado, 2007). Therefore, simplified models still remain popular in obtaining values for D_{ef}.
Thus, as thin-layer drying behavior of mucilaginous seeds was characterized by occurring in constant and falling rate periods, a two-stage mathematical model (constant rate period and falling rate period) for thin layer drying was developed to be incorporated in the deep bed model, in order to obtain a better prediction of drying rate at each period Prado & Sartori (2008).
The drying rate equation for the constant rate period was described as:

$$\frac{dX}{dt} = -k_c = 1.3 \times 10^{-9} \cdot T_g^{4.112} \cdot v_g^{0.219} \tag{15}$$

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, so that:

$$\frac{dX}{dt} = -K \cdot \left(X - X_{eq}\right) \quad (16)$$

Lewis equation was chosen because combined effects of the transport phenomena and physical changes as the shrinkage are included in the drying constant (Babalis *et al.*, 2006), which is the most suitable parameter for the preliminary design and optimization of the drying process (Sander, 2007).
The relationship between drying constant K and temperature was expressed as:

$$K = 0.011 \exp\left(-201.8/T_g\right) \quad (17)$$

The critical moisture content was found to be independent on drying conditions, in the tested range of air temperature and velocity, equal to (0.99 ± 0.04) d.b.

5. Heat transfer

The convective heat transfer coefficient (h) 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 & 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. Table 2 shows the three main correlations found in the literature to predict h in packed beds.

Correlation	Range of validity	Reference
$Nu_p = \left(0.5 Re_p^{1/2} + 0.2 Re_p^{2/3}\right) Pr^{2/3}$ (18)	$20<Re_p< 80000$ $\varepsilon<0.78$	Whitaker (1972)
$h = 3.26\, Cp\, G_g\, Re^{-0.65}\, Pr^{2/3}$ (19)	$20<Re<1000$	Sokhansanj (1987)
$h = \left(\frac{Cp_g\, G_g}{\varepsilon}\right)\left(\frac{2.876}{Re} + \frac{0.302}{Re^{0.35}}\right) Pr^{-2/3}$ (20)	$10<Re<10000$	Geankoplis (1993)

Table 2. Empirical equations for predicting the fluid-solid heat transfer coefficient for packed bed dryers

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

6. Simultaneous heat and mass transfer in drying of deformable porous media

Drying of deformable porous media as a deep bed of shrinking particles is a complex process due to the strong coupling between the shrinkage and heat and mas transfer phenomena. The degree of shrinkage and the changes in structural properties with the moisture removal influence the heat and mass transport within the porous bed of solid particles. The complexity increases as the extent of bed shrinkage is also dependent on the process as well as on the particle size and shape that compose it.

Theoretical and experimental studies are required for a better understanding of the dynamic drying behavior of these deformable porous systems.

Mathematical modelling and computer simulation are integral parts of the drying phenomena analysis. They are of significance in understanding what happens to the solid particles temperature and moisture content inside the porous bed and in examining the effects of operating conditions on the process without the necessity of extensive time-consuming experiments. Thus, they have proved to be very useful tools for designing new and for optimizing the existing drying systems.

However, experimental studies are very important in any drying research for the physical comprehension of the process. They are essential to determine the physical behavior of the deformable porous system, as a bed composed of shrinking particles, as well as for the credibility and validity of the simulations using theoretical or empirical models.

This section presents the results from a study on the simultaneous heat and mass transfer during deep bed drying of shrinking particles. Two model porous media, composed of particles naturally or artificially coated with a gel layer with highly deformable characteristics, were chosen in order to analyze the influence of the bed shrinkage on the heat and mass transfer during deep bed drying.

First, the numerical method to solve the model equations presented in section 2 is described. The equations implemented in the model to take into account the shrinkage and physical properties as functions of moisture content are also presented. Second, the experimental set up and methodology used to characterize the deep bed drying through the determination of the temperature and moisture distributions of the solid along the dryer are presented. In what follows, the results obtained for the two porous media are presented and compared to the simulated results, in order to verify the numerical solution of the model. A parametric analysis is also conducted to evaluate the effect of different correlations for predicting the heat transfer coefficient in packed beds on the temperature predictions. Lately, simulations with and without consideration of shrinkage and variable physical properties are presented and the question of to what extent heat and mass transfer characteristics are affected by the shrinkage phenomenon is discussed.

6.1 Numerical solution of the model

The numerical solution of the model equations, presented in section 2, 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 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. A computer program in FORTRAN was developed to solve the set of difference equations.
The equations for physical and transport parameters used in model solution are reported in Table 3.

Sorption Properties		
- Equilibrium isotherms	$X_{eq} = \left[\frac{-\exp\left(-1.77\times 10^{-2}\cdot T + 4.25\right)}{\ln(RH)}\right]^{1/1.90}$	(21)
- Moisture desorption heat		
	$L_p = \left(2500.8 + 2.39\cdot T_g\right)\cdot\left[1 + 3.2359\cdot\exp\left(-33.6404\cdot X\right)\right]$	(22)
Drying Kinetics ($0.5 < v_g < 1.5$ m/s $30 < T_g < 50$ °C)		
- constant rate period	$\frac{dX}{dt} = -k_c = 1.3\times 10^{-9}\ {T_g}^{4.112}\ {v_g}^{0.219}$	(15)
- falling rate period	$K = 0.011\exp\left(-201.8/T_g\right)$	(17)
Heat transfer coefficient Equations (18), (19) or (20) from Table 2		
Bulk density	$\rho_b = 240.8 + 546.1\cdot XR$	(23)
Bed porosity	$\varepsilon = 0.474 - 0.266\cdot XR$	(24)
Specific area	$a_v = 850.5 + 339.8\cdot XR - 207.9\cdot X^2$	(25)

Table 3. Physical and transport parameters used in model solution

6.2 Experimental study on deep bed drying

The validity of the model which takes into account the shrinkage of the bed and variable physical properties during drying is verified regarding the packed bed drying of particles coated by natural and artificial polymeric structures.
Deep-bed drying experiments were carried out in a typical packed bed dryer (Prado & Sartori, 2008). The experiments were conducted at air temperatures ranging from 30 to 50°C and air velocities from 0.5 to 1.5 m/s, defined by a 2^3 factorial design. These operating conditions satisfy the validity range of the constitutive equations used in the model.
The instrumentation for the drying tests included the measurement of the following variables: temperature of solid particles with time and along the dryer, moisture content of the material with time and along the dryer, and thickness of the bed with time.
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.
Techniques for measuring solid moisture and temperature are usually adopted and drying tests are conducted to validate the simulation results of these variables.
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 preferential channels, 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.
Temperature distributions were measured using T-type thermocouples located at different heights along the bed.
The overall error in temperature measurements is 0.25^{o}C. In the measurements of airflow, air humidity and solid moisture, the errors are, respectively, equal to 4%, 4% and 1%.
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.

6.3 Experimental verification of the model

The main aim of this section is provide information on the simulation and validation of the drying model by comparison with experimental data of temperature and moisture content distributions of material along the shrinking porous bed and with time. Previously, it is presented a parametric analysis involving the heat transfer coefficient.

6.3.1 Sensitivity analysis of the model

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 (18) to (20) (Table 2), were tested in drying simulation in order to obtain the best reproduction of the experimental data.
Figure 8 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 2). 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 & 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 8 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.

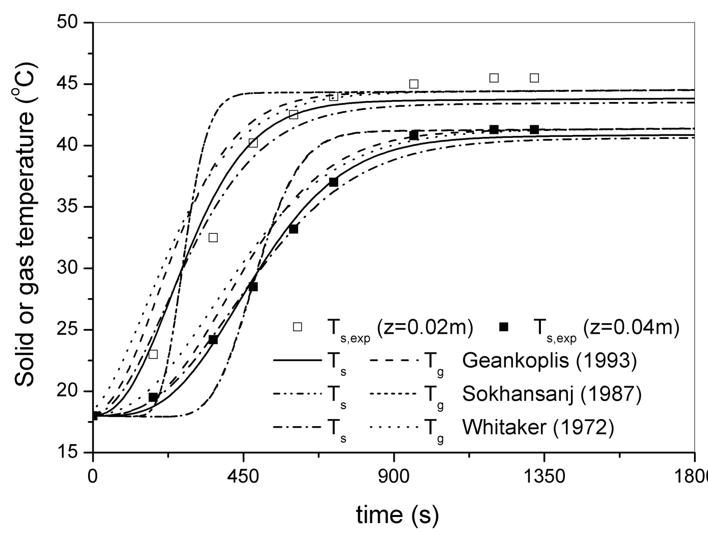


Fig. 8. Dynamic evolution of experimental and simulated temperature profiles obtained from different correlations for h. Drying conditions: v_g = 1.0 m/s, T_{g0} = 50°C, Y_{g0} = 0.01kg/kg, T_{s0} = 18°C and X_0 = 3.9 d.b.

6.3.2 Solid temperature and moisture profiles

In Figures 9 and 10 are presented at different drying times typical experimental and simulated results of moisture and temperature throughout the bed composed of mucilaginous seeds. 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 capability of the model to simulate moisture content and temperature profiles during thick-layer bed drying of mucilaginous seeds. From Figure 9 it can also be verified that he model is capable of predicting the simultaneous reduction in the bed depth taking place during packed bed drying.

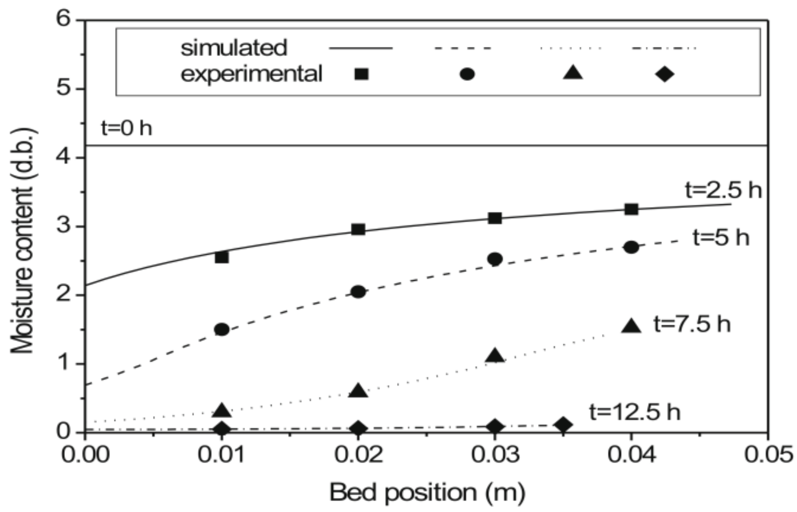


Fig. 9. Experimental and simulated results of moisture of seeds with mucilage throughout the bed, Tgo =50^{0}C, Ygo =0.01 kg/kg and Vgo =1.0 m/s, Ts =20^{0}C and Xo=4.1 d.b.

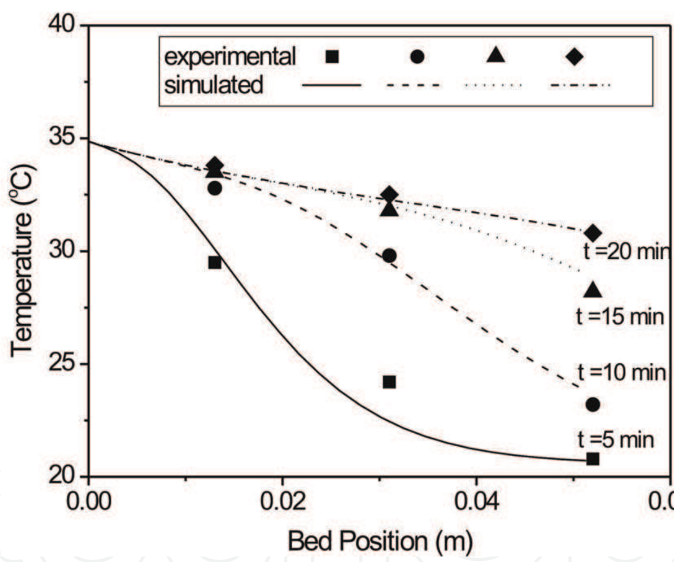


Fig. 10. Experimental and simulated results of temperature of seeds with mucilage along the bed. Tg_0 = 35^{o}C, Y_{g0} =0.0051 kg/kg and v_{g0} = 0.8 m/s. T_s =20.8^{o}C and X_0 =3.5 d.b.

6.3.3 Temporal profiles of solid temperature and moisture simulated with and without consideration of shrinkage and variable physical properties

In order to emphasize the importance of shrinkage for a better interpretation of heat and mass transfer in packed bed drying, Figures 11 and 12 show, respectively, the moisture content and temperature profiles of solid with time simulated with and without incorporating bed shrinkage and variable physical properties in the model. It can be verified that there is a significant difference between the sets of data. 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, predicting higher values of moisture content and lower values of temperature 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 solid 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.

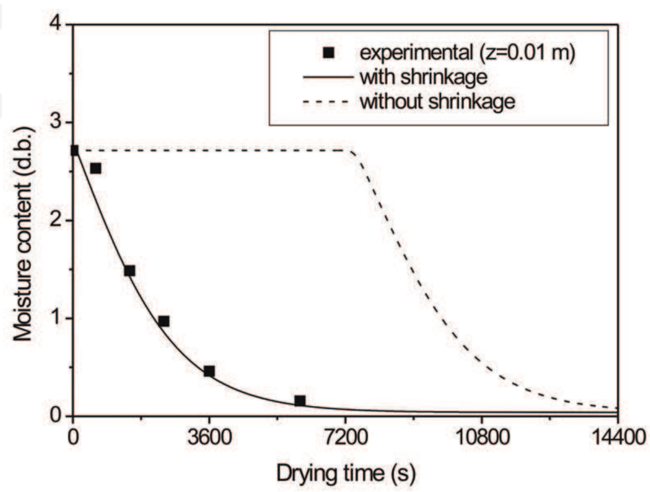


Fig. 11. Moisture content simulated with and without shrinkage. T_{g0}=50°C; v_{g0}=0.5 m/s, Y_{g0} = 0.099 db, Ts_0 = 24°C and X_0 = 2.7 db

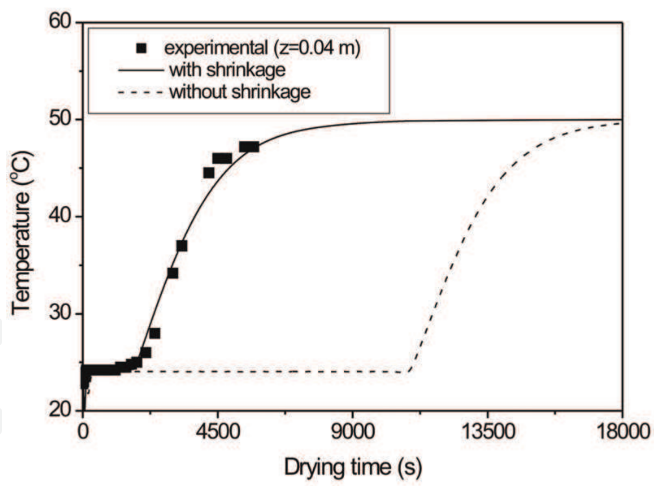


Fig. 12. Seed temperature simulated with and without shrinkage. T_{g0}=50°C; v_{g0}=0.5 m/s, Y_{g0} = 0.099 db,Ts_0 = 24°C and X_0 = 2.7 d.b.

7. Final remarks

This chapter presented a theoretical-experimental analysis of coupled heat and mass transfer in packed bed drying of shrinking particles. Results from two case studies dealing with beds of particles coated by natural and artificial gel structure have demonstrated the importance of considering shrinkage in the mathematical modelling for a more realistic description of drying phenomena. Bed contraction and variation in properties such as bulk density and porosity cannot be ignored from the point of view of the process dynamics.

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 including the effects of changes in structural properties of the packed bed to be taken into account.

In the drying model presented for coated particles, differences in the mass transfer coefficients in the core and external gel layer are not taken into account. This is a limitation of the model that needs to be examined. Moreover, as shrinkage characteristics are directly related to quality attributes, such as density, porosity, sorption characteristics, crust and cracks, the tendency in research is the development of seeds with artificial coating, presenting the best combination of shrinkage and drying characteristics to yield products with higher resistance to deformation and minimal mechanical damages.

8. Nomenclature

a_v	specific surface area, [m^{-1}]
Cp	specific heat, [J/kg ^oC]
D_{ef}	effective mass diffusivity, [m^2/min]
dp	particle diameter, [m]
G_g	air mass flow rate, [kg m^{-2} s^{-1}]
h	heat transfer coefficient, [J/m^2s ^oC]
k	drying constant, [s^{-1}]
K_g	thermal conductivity [J/s m ^oC]
L_p	latent heat of vaporization, [J/kg]
N	number of discretized cells
Pr	Prandtl number, [-]
Re	Reynolds number, [-]
RH	relative humidity, [-]
S_b	shrinkage parameter, [-]
t	time, [s]
T	temperature, [^oC]
v_g	air velocity, [m/s]
V	volume, [m^3]
X	solid moisture, d.b.,[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, [kgm^{-3}]

Abbreviation

d.b.	dry basis
w.b.	wet basis

Subscripts

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

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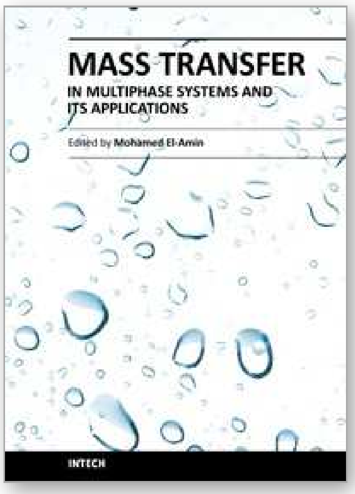

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This book covers a number of developing topics in mass transfer processes in multiphase systems for a variety of applications. The book effectively blends theoretical, numerical, modeling and experimental aspects of mass transfer in multiphase systems that are usually encountered in many research areas such as chemical, reactor, environmental and petroleum engineering. From biological and chemical reactors to paper and wood industry and all the way to thin film, the 31 chapters of this book serve as an important reference for any researcher or engineer working in the field of mass transfer and related topics.

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