Intermittent Drying: Fundamentals, Modeling and Applications

A.G. Barbosa de Lima, J.M.P.Q. Delgado, S.R.F. Neto and C.M.R. Franco

Abstract This chapter focuses on the intermittent drying of wet porous bodies. Drying process was simulated assuming liquid diffusion as the sole mass transport mechanism and constant mass diffusion coefficient. Application has been done to ellipsoidal solids. The transient mass diffusion equation in a prolate spheroidal coordinate system was used to study the process in two-dimensional cases. Results are presented, changing the dimensionless tempering time, aspect ratio of the body and number of drying passes, by using the continuous drying process, drying rate, energy cost, drying time and quality of the product post-drying as comparison parameters.

Keywords Tempering · Simulation · Mass · Quality · Ellipsoid

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1 Basic Concepts in Drying

Hygroscopic materials undergo changes in its water content according to the conditions of the ambient air surrounding it. In the case of agricultural products, control the moisture content is crucial for the preservation of their quality and to avoid waste. In this context, the drying is one of the most widely used methods for this purpose.

Since antiquity, dehydration has been used in food preservation and grain drying. Technical processes were passed from generation to generation through the knowledge acquired with the ancestors, and gradually improved. Dehydration or drying operations are important processes in the chemical and food industries, as well as the storage of grain and other biological products. Reduce the moisture content of agricultural products to a safe level for storage is an usual practical postharvest.

Drying is a process involving heat and mass transfer (moisture) between a hygroscopic product and drying air. In the drying process of a wet porous solid, the air supply heat to the solid and absorbs water of it in vapor phase. In general, drying is conducted with higher air temperatures than the boiling point of the liquid to be eliminated. The heating of the drying air, in order, to reduce the relative humidity and increase its enthalpy and evaporative capacity, must be properly controlled to avoid physical, chemical and biological damage that can cause to the product.

The water vapor present into the product tends to occupy all intercellular space available generating pressure, including the interface between the product and the air surrounding it. This pressure is called the partial pressure of water vapor at the surface (P_s) of product. On the other hand, water vapor in air performs a partial pressure so called as partial pressure of water vapor in the air (P_{air}).

If the moisture content of the product is very low, so that the partial pressure of water vapor at the surface is lower than the partial pressure of water vapor in the ambient air, the product will gain moisture, which may cause the emergence of fungi and damage it. In the drying process, the moisture removal is achieved by water movement, due to a difference in partial pressure of water vapor between the surface of the product to be dried and the air that surrounds it. Then, drying of the product will occur if ($P_s > P_{air}$) (see Fig. 1).

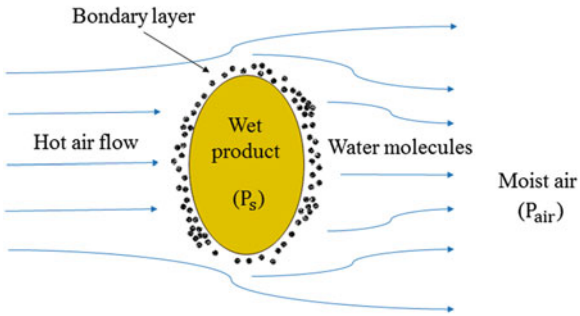

Fig. 1 Representation of the movement of water during drying

Unsaturated air in contact with product causes evaporation of water peripheral which generates a moisture gradient in the layers of the product. Through diffusion, the internal water moves to the periphery, where evaporates, creating new moisture gradients, making the process to continue. In drying with heated air, beyond of the peripheral evaporation, the temperature increase causing an increase in the internal pressure, creating pressure gradients that are added with the water gradient effect. Then, diffusion occurs in presence of the two effects and progress with high intensity. The heated air and with low relative humidity has its evaporative capacity and energy exchange increased by increasing its enthalpy. When the heating happens in the product also increases liquid evaporation and internal pressures [1].

Hygroscopic products during drying have moisture contents commonly defined as: initial, critical and equilibrium moisture content. The initial moisture content is the amount of water into the product when starting the drying process. This water can be strongly bounded to the dry mass of the product, which is difficult to be removed, or in the form of free water which can be removed easily depending on the conditions of the environment in which the product is placed. The moisture content is which occurs changes in the drying rate from constant for decreasing is called critical moisture content. The equilibrium moisture content is reached when the wet product is in equilibrium with the drying air, for a given thermodynamic state of the air. In this case, there is no moisture flux between them. According to Fioreze [2], this does not mean that the product moisture and air are equal, but that the vapor pressures at the product surface and air are equal. When this equilibrium is reached, the moisture inside the product becomes almost uniform.

Drying process presents three classical steps as pictured in the Fig. 2. Early of the drying occurs rising of the temperature of the product and pressure of water vapor (warm-up period). At this moment, the drying rate $d\bar{M}/dt$ is increasing, due to the relative humidity in the boundary layer is less than 100 %, happening what is usually called accommodation period [3]. The increases in drying rate continue to

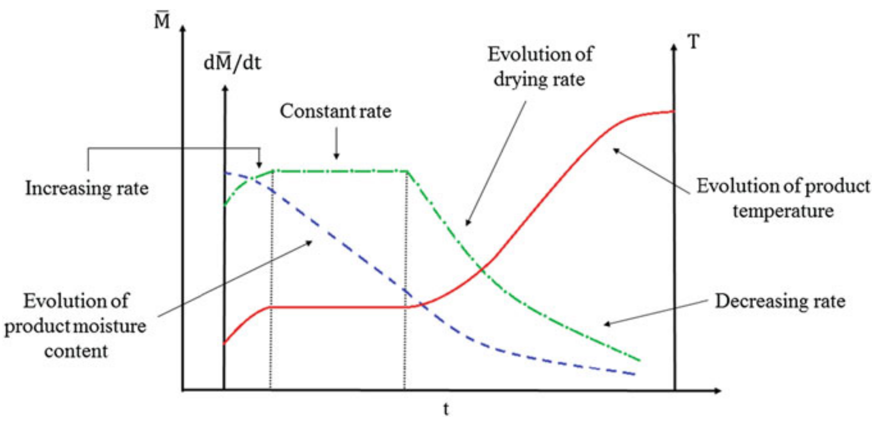

Fig. 2 Typical drying curve

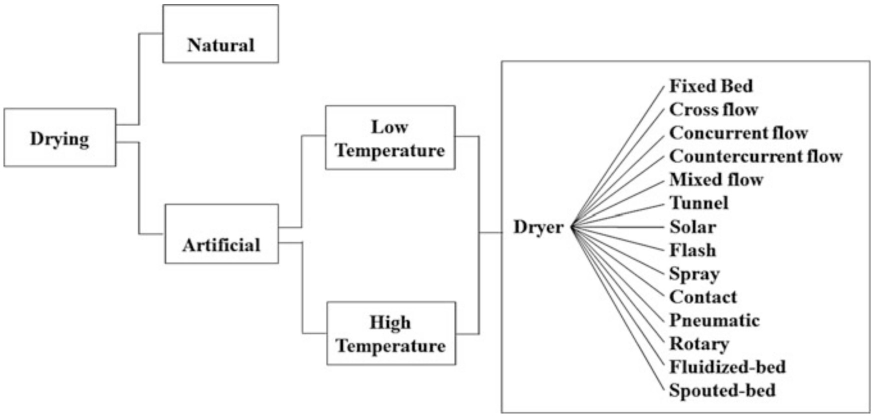

Fig. 3 Drying methods and dryer types

happen until the point where equivalence between heat and mass (water) transfer, occurs that is, the constant rate period. At the start of drying, the product is completely wet and the water flows in liquid phase under a hydraulic gradient, and under this condition, the product temperature equals the wet bulb temperature. While there is surface moisture to progress the evaporation process, the drying rate remains constant. The ending point of the constant rate period is called the point of critical moisture (moisture content at which water ceases to behave as free water).

As drying proceeds, and had passed of the point of critical moisture, the moisture content continue to decrease and the water in the liquid phase forms liquid bridges inside the porous solid. From this point begins the period of decreasing drying rate. During this period, occurs a reduction in moisture migration from the interior to the surface of the product and the heat transfer is not equivalent to the mass transfer. The product temperature exceeds the wet bulb temperature until to the drying air temperature or dry bulb temperature. Finally, the drying occurs within the product until that equilibrium moisture content is reached, i.e., when the amount of evaporated water equals the amount condensed water at the surface of the solid [1, 4, 5].

Drying can be realized of natural or artificial manner (Fig. 3). In natural drying, air movement is made by the wind and the energy for moisture evaporation comes of air drying potential and direct incidence of sun energy. Artificial drying is characterized by the use of manual or mechanical processes both in product handling and in air passage through the product. In drying with forced ventilation we can employ low or high temperature, combined drying, and other techniques. Details about this topic can be found at [1, 2, 4–9].

On operation, the dryers can be classified in two types [1, 2, 4, 5]:

(a) **Continuous dryers** The product is constantly under the action of heat, until that its moisture content reaches a desired value. For this, the product passes through flow regulation mechanism that will determine the time of exposure to drying air, also called residence time.

(b) **Intermittent dryers** Product passes several times through the dryer prior to complete drying. Thus, the product undergoes the action of heat during short time intervals, interspersed with rest periods, i.e., the product do not come into contact with the heated air during this period. In general, these dryers consist of two drying towers and a tank placed above these columns.

During drying, there is a difference between moisture located at the surface and inside the product. The surface that is in direct contact with the air tends to dry more than the central part. Thus, the product undergoes transformations and therefore, several studies have been made in order to determine the best way to accomplish such a process. The analysis in this case is made from experiments and/or simulations using a given mathematical model.

Severe drying with low air relative humidity and high air temperature may damage the product and make it unsuitable for consumption and processing. For example, when the grain loses water it has reduced its size by external compression; this effect increases as it dries. When the grain is heated increases its internal pressure and the more central layers of the grain tend to expand. The grain surface has no elastic plasticity and capability to withstand very high hydro-thermo-mechanical stresses and in this case can suffer cracking or even breakage. As the more unbalanced are the evaporation and diffusion phenomena, the greater the damage.

Thus, it can be said that the main advantage of drying with heated air is in the decreasing in drying time and the disadvantages are the cost of energy required to heat the air and the damage that it can cause to the product due to higher temperature and lower relative humidity mainly in heat-sensitive materials, such as: fruit, vegetables and grains.

Various drying techniques are reported in literature to improve the final product quality and reduce consumption of energy used. First, however, we will present the basic concepts of drying that are important for a better understanding of the physical phenomena involved in the process. Now, we discuss the technique of intermittent drying presenting its main features and a mathematical model to simulate this process.

2 Intermittent Drying

2.1 Fundamentals, Energy Efficiency and Product Quality Aspects

In present day, the concept of multi-stage drying has been well accepted for researchers. Several drying techniques have been proposed in order to rationalize the use of energy, as well as to reduce other problems during the drying process, such as crack, fissure, loss of germination power and vigor of the grain and seeds, non-enzymatic browning of fruits and vegetables. One of these techniques is the intermittent drying.

The intermittent drying is a process that alternates drying periods with of rest or relaxation periods. The product is subjected to the action of hot air in drying chamber at regular time intervals, i.e., heat is supplied discontinuously. In the rest period (non drying, tempering), the product goes through part of the system which does not get heated air, allowing homogenization of moisture and cooling [10, 11]. Each rest period between two other continuous drying is called pass [12]. The aim for determination of the duration and number of cycles (or tempering) in the intermittent drying process is to minimize costs (energy) and get a better final product quality [13–15]. Applies the intermittent drying only in period when the drying rate is decreasing [13, 16].

For certain materials, much of the resistance to drying process lies inside it, so, maintain certain drying air conditions applied only the surface of the material results in high gradients at the product surface, causing possible damage (cracks and deformations) and reducing process efficiency. In these cases, intermittent drying is recommended.

The intermittent drying technique is commonly used for the drying of heat-sensitive material such as: grains (wheat, soya, rice, corn, coffee), vegetables (potato), fruits (guava, banana, mango) and various kinds of herbs [16–25] and non food material such as ceramic and wood [26–30], and provides advantages over the continuous drying. In this method, the speed and uniformity of drying are the most relevant characteristics. The amount of water removed by unit drying time is considerably higher than when the drying is restarted. During the rest period (tempering period), due to moisture gradient established inside the product, there is moisture migration from the interior to the surface, until the moisture in the entire product is almost uniform. This moisture redistribution, beyond of facilitate drying when the heat application is restarted, reduces the water and temperature gradients and, as result, reduces thermal and hydric stresses and physical damage (cracks) to the product, not violating the material structure [31]. This phenomenon is namely cited as the "refreshing effect" by Nishiyama et al. [32].

Due to intermittency, it is possible to use the temperature of the heated air reaching up to 70–80 °C, without causing excessive heating of the product, in general, do not reach temperatures above from 40 to 43 °C [33, 34].

According to Shei and Chen [35] less than 2 % (dry basis) of the moisture is removed from the product after each rest period as using re-circulating rice dryer.

The effect of tempering time on the amount of moisture removed after drying, during the cooling of shelled corn, was studied by Sabbah et al. [36] and Tolaba et al. [37] and the tempering of rice by Steffe et al. [38], Walker and Bakker-Arkema [39], Fioreze [40] and Elbert et al. [41].

Knowledge of the ideal tempering time is very important because of the reduction in energy utilized in the drying to avoid over heating of the product, and mainly, the preservation of product quality. According to Steffe and Singh [42], if the tempering time is too short, cracking may occur and the quality of the grain can be affected. But with the use of a short tempering time, some advantage, such as the minimization of damage produced by chemical changes and insect and microbial activity, as well an increase in drying capacity and drier flexibility, do exist because total drying time is reduced.

Chua et al. [13] show some ways to implement the intermittent drying process:

(a) Intermittent drying whereby heat flux is supplied intermittently rather than continuously. This can be done by interrupting the air flow to provide the material a "rest" or "tempering" period, by a continuous air flow periodically heated, or by periodic variation of air flow or by combination of both;
(b) Aeration which is a drying process involving a combination of high temperature short drying period, tempering, and slow cooling followed by drying;
(c) Air reversal drying which is reversing the direction of the airflow for a period of time and then returns it to its original direction. This procedure is applied to deep bed drying of particulates to minimize temperature and moisture gradients inside the bed;
(d) Cyclic drying which is a drying process whereby the temperature, humidity or velocity of the air undergoes a specified cyclic pattern variation such as sinusoidal, square-wave or saw-tooth patterns. The operating pressure can also be cycled.

Experimental evidence of the potential benefits of intermittent temperature variation on product quality and energy saving has been demonstrated by many researchers [20, 30, 32, 43, 44]. Thus, this technique has been realized in different dryers, such as batch, fluidized bed, spouted bed, microwave and heat pump dryers [33, 45–48].

Chua et al. [49] have demonstrated that employing intermittent drying air temperature could reduce the overall color change of potato, guava and banana samples by 87, 75 and 67 %, respectively. Improvement in retention of ascorbic acid up to 20 % and β-carotene were verified by Chua et al. [49] and Chua et al. [13], respectively.

Nishiyama et al. [32] have demonstrated that the tempering temperature had a significant effect on the rate of internal moisture equilibration and the drying rate was improved subsequent to tempering, showing the benefit of allowing moisture redistribution for wheat and rough rice. Further, they author have concluded that long-grain rough rice required more tempering than short-grain rough rice.

The results of the drying studies presented for Kowalski and Pawłowski [30] allows to state that the intermittent drying can be recommended above all to drying of materials, which have a tendency to cracking during drying as, for example, ceramics and wood. Through changes of drying conditions in the pre-established instants one can avoid material fracture and thus preserve a good quality of dried products. The authors have stated that intermittent drying positively influences the quality of the dried materials without significant extension of the drying time. The best quality of the tested samples was achieved, unfortunately, in the most energy consuming process, that is, during intermittent drying with the variable air humidity. The intermittent drying with variable air temperature gives better product quality than drying in stationary conditions at similar drying times and, what is very important, by the lowest energy consumption in all the tested processes. The best product quality obtained in intermittent drying with variable air humidity and the lowest energy consumption in intermittent drying with variable air temperature suggests the advantageous combination of both these drying techniques to optimize the drying process with respect to the energy consumption and the quality of dried products. Thus, the combination of those techniques would increase the effectiveness of the drying process.

Mabrouk et al. [43] studied intermittent drying of the apple thin slice. Variations in the air temperature and air velocity values permitted to find the most economic velocities for the drying process. The numerical simulations in the intermittent tests, give more information about the behavior of the product during the periods of interruption. This study shows the considerable advantages of the intermittent drying of agricultural products and confirms the preservation of their qualities, the reduction in the drying time and in energy consumption.

Silva et al. [44] has studied the continuous and discontinuous pear drying. Experimental results were compared with the Fick's diffusion model assuming a convective boundary condition enabling the determination of an effective diffusion coefficient and convective mass transfer coefficient at the surface of the product. A good agreement was observed between modeling and experimental data. In the intermittent drying the hot airflow was turned off during night periods, for 13.5 h with velocity and temperature of the air flow 1.2 m/s and 40 °C, respectively. According to the authors, total duration of the pauses (during which the drying installation was turned off, and consequently no energy was spent), was in about 50 % of total test duration. This result points out towards a possible energy saving strategy in the intermittent process. In particular, it is demonstrated that an increase of the number of pauses can lead to significant energy savings and that drying with solar energy, which is inherently discontinuous is an effective method for this type of process.

2.2 *Mathematical Modelling*

Prediction of continuous and intermittent drying by the reliable numerical and analytical approaches is very important to help in the design, energy consumption computation of dryer, and to predict drying rate and moisture and temperature gradients inside the product, and to maintain quality during and post-drying.

To model continuous and intermittent drying process in solid with prolate spheroidal shape, the following assumptions were considered:

- The solid is homogeneous, isotropic and composed of water in liquid phase and solid material;
- The continuous drying process occurs under falling rate;
- The heat conduction through the prolate spheroid is neglected;
- The moisture content profile is symmetric around z-axis;
- The thermophysical properties are constants during the drying process;

- The process occurs under convective condition at the surface of the solid;
- Shrinkage of the solid is neglected.

Based on these assumptions, the following models were developed to simulate the intermittent and continuous drying process.

(a) **Continuous drying modeling**

In many drying problems the internal resistance of the solid to mass transfer is greater than its resistance to heat transfer. In these cases moisture diffusion is the mechanism that controls the process during the falling drying rate period, and the pure diffusion model can be used to predict drying process. During the falling rate period, the drying rate decays with time and continuous heating has little effect on moisture removal so, methods to improve the utilization of energy during the drying process in this period, are very important and must be studied.

The Fick's second law has been used to predict moisture content distribution inside the solid during drying process. It is given as follows:

$$\frac{\partial M}{\partial t} = \nabla \cdot (D \nabla M) \tag{1}$$

where M is the moisture content (dry basis) and D is the effective mass diffusion coefficient of the material.

To predict the diffusion phenomenon in prolate spheroids, it is necessary to write Eq. (1) for an appropriate coordinate system, in this case, in prolate spheroidal coordinates. Figure 4 shows a body with prolate spheroidal geometry.

The relationships between the Cartesian (x, y, z) and prolate spheroidal coordinate systems (μ, φ, ω) are given by Stratton et al. [50], Flammer [51] and Abramowitz and Stegun [52]:

$$x = L\sqrt{\left(1 - \xi^2\right)\left(\eta^2 - 1\right)}\,\zeta \tag{2a}$$

$$y = L\,\sqrt{\left(1 - \xi^2\right)\left(\eta^2 - 1\right)}\,\sqrt{\left(1 - \zeta^2\right)} \tag{2b}$$

$$z = L\,\xi\,\eta \tag{2c}$$

where L_1 and L_2 are the solids dimensions, $L = \left(L_2^2 - L_1^2\right)^{1/2}$, $\xi = \cosh\mu$, $\eta = \cos\phi$ and $\zeta = \cos\omega$. The intervals of the variables ξ, η e ζ (in terms of ω) are: $0 \le \xi \le L_2/L$; $0 \le \eta \le 1$; $0 \le \omega \le 2\pi$.

By calculating the metric coefficients and the Laplacian in the new coordinate system, it can be obtained the following 3-D transient diffusion equation:

$$\frac{\partial M}{\partial t} = \left[\frac{1}{L^2(\xi^2-\eta^2)}\frac{\partial}{\partial \xi}\left((\xi^2-1)D\frac{\partial M}{\partial \xi}\right)\right] + \left[\frac{1}{L^2(\xi^2-\eta^2)}\frac{\partial}{\partial \eta}\left((1-\eta^2)D\frac{\partial M}{\partial \eta}\right)\right]$$
$$+\left[\frac{\sqrt{1-\varsigma^2}}{L^2(\xi^2-1)(1-\eta^2)}\frac{\partial}{\partial \varsigma}\left(\left(\sqrt{1-\varsigma^2}\right)D\frac{\partial M}{\partial \varsigma}\right)\right] \quad (3)$$

Using the symmetry of the body around the z-axis, Eq. (3) can be written as follows:

$$\frac{\partial M}{\partial t} = \left[\frac{1}{L^2(\xi^2-\eta^2)}\frac{\partial}{\partial \xi}\left(D(\xi^2-1)\frac{\partial M}{\partial \xi}\right)\right]$$
$$+\left[\frac{1}{L^2(\xi^2-\eta^2)}\frac{\partial}{\partial \eta}\left(D(1-\eta^2)\frac{\partial M}{\partial \eta}\right)\right] \quad (4)$$

The following boundary conditions during continuous drying periods are used:

- Free surface: Diffusive mass transfer is equal to convective mass transfer at the surface of the solid.

$$-\frac{D}{L}\sqrt{\frac{(\xi^2-1)}{(\xi^2-\eta^2)}}\frac{\partial M}{\partial \xi}\bigg|_{\xi=\xi_f} = h_m[M(\xi=\xi_f,\eta,t)-M_e], \quad (5)$$
$$\xi_f = L_2/L \text{ at the surface}$$

- Planes of symmetry: the angular and radial gradients of moisture content are equal to zero at the planes of symmetry. Then, we can write:

$$\frac{\partial M(\xi;\ 1;\ t)}{\partial \eta} = 0 \quad (6)$$

$$\frac{\partial M(\xi;\ 0;\ t)}{\partial \eta} = 0 \quad (7)$$

$$\frac{\partial M(1;\ \eta;\ t)}{\partial \xi} = 0 \quad (8)$$

- Initial conditions inside solid: the moisture content is constant and uniform.

$$M(\xi;\eta;t=0) = M_o \quad (9)$$

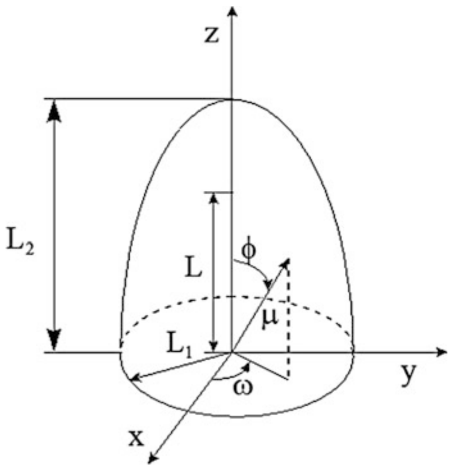

Fig. 4 Characteristics of a prolate spheroid

From the solution of Eq. (4) it can be calculated the average moisture content of the body during drying process as follows [53]:

$$\bar{M} = \frac{1}{V}\int_{V} M dV \quad (10)$$

where

$$dV = \frac{L^3(\xi^2 - \eta^2)}{\sqrt{(1-\zeta^2)}} d\xi d\eta d\zeta \quad (11)$$

is the infinitesimal volume within the solid. Integration of the Eq. (11) over the solid (Fig. 4) gives as result:

$$V = \frac{2}{3}\pi L_1^2 L_2 \quad (12)$$

(b) **Tempering model (Intermittent drying)**

The main difference between the continuous and intermittent drying (tempering) processes is in the initial and boundary conditions used in the model. During tempering, the moisture content profile is calculated through time, assuming the surface of the solid to be impermeable. This last assumption requires the development of a new mathematical modeling to describe mass transfer inside the solid. Under these new conditions, variations in the average moisture content of the solid are negligible during rest period, and only a change in the moisture distribution inside the solid occurs. During tempering period, the moisture content inside the product will be equalized through moisture diffusion. The ideal tempering time can be obtained by considering a final flat moisture distribution. To simulate intermittent drying, the moisture content profile inside the solid at the end of the continuous drying period must be known. Thus, the mathematical modeling that describes the tempering process is given by Eqs. (4) and (6) and the new following initial and boundary conditions:

$$\frac{\partial M(L_2/L;\eta;\ t)}{\partial \xi} = 0 \tag{13}$$

$$M(\xi;\eta;\ t = 0) = f(\xi;\eta) \tag{14}$$

Function f(ξ; η) in the initial period of tempering corresponds to the moisture content profile within the solid at the end of the continuous drying period. It obeys variation with the radial and angular coordinates. Because of the impermeability condition, the drying rate in the solid must be equal to zero. In this case, the rate of moisture storage in the solid must be equal to the change in moisture content inside it, during tempering period. Numerically, the condition given by Eq. (13) corresponds to the situation in which the moisture content at the nodal points on the surface is equal to this value at the nodal points immediately near to the surface. From a mathematical standpoint, this is the same treatment as that used under the symmetry condition. Then, we can express this condition as follows:

$$\left(\frac{\partial M}{\partial t}\right)_P dV = \frac{D}{L}\left(\sqrt{\frac{\xi_s^2 - 1}{\xi_s^2 - \eta_P^2}}\right)\frac{\partial M}{\partial \xi}\bigg|_s dS_\xi \tag{15}$$

being

$$dS_\xi = \frac{L^2\sqrt{(\xi^2 - \eta^2)}\sqrt{(\xi^2 - 1)}}{\sqrt{(1 - \zeta^2)}} d\eta d\zeta \tag{16}$$

The parameter dS_ξ represent mass flow area of an infinitesimal element in the prolate spheroidal coordinate system, as indicated in Fig. 4.

2.3 Numerical Solution Procedure

Several numerical methods (finite-difference, finite-element, finite-volume, etc.) are used to solve the physical problem of mass transfer during drying process in solid with different geometries. Herein, it was used the finite-volume method. The numerical solution of the problem utilizing the finite-volume technique is obtained by integrating Eq. (4) with over a volume and time. For a fully implicit formulation and practice B, the discretized equation is given by [54–56]:

$$A_P M_P = A_E M_E + A_W M_W + A_N M_N + A_S M_S + A_P^0 M_P^0 \quad (17)$$

Application of the Eq. (17) over the computational domain derives a system of linear algebraic equation, which was solved using the Gauss-Seidel iterative algorithm. A 20 × 20 central-volume grid was used in the simulations.

The calculation started with the given initial condition and stopped when the following convergence criterion was satisfied at each point of the computational domain:

$$\left|M^{k-1} - M^k\right| \leq 10^{-8} \quad (18)$$

where k represent k-th iteration.

More details about numerical procedure can be found in the reported literature [12, 57–62].

To determine the tempering Fourier required equalizing the moisture content inside the solid, it is necessary to adopt a stop criterion, which is dependent on the accuracy of the model; in this work $\left|M^{*o} - M^*\right| \leq 10^{-7}$ was adopted as the stop criterion at all the nodal points. The superscript o represents the old time and M^* is the dimensionless moisture content.

3 General Application

Herein, results are presented in term of dimensionless variables moisture content, time, and angular and radial coordinates, as follows:

$$M^* = \frac{M - M_e}{M_o - M_e} \quad (19)$$

$$\eta^* = \eta \quad (20)$$

$$\xi^* = \xi \quad (21)$$

$$t_m^* = \frac{Dt}{L_1^2} \quad (22)$$

The ideal tempering time was obtained for spheroidal bodies with aspect ratios L_2/L_1 = 1.1, 2.0 and 5.0 for an initial dimensionless tempering time corresponding to $t_m^* = Dt/L_1^2 = 0.01098$. For L_2/L_1 = 1.1, 2.0 and 5.0 the ideal tempering Fourier were 0.42700, was 0.73200 and 0.79300, respectively. Differences in tempering

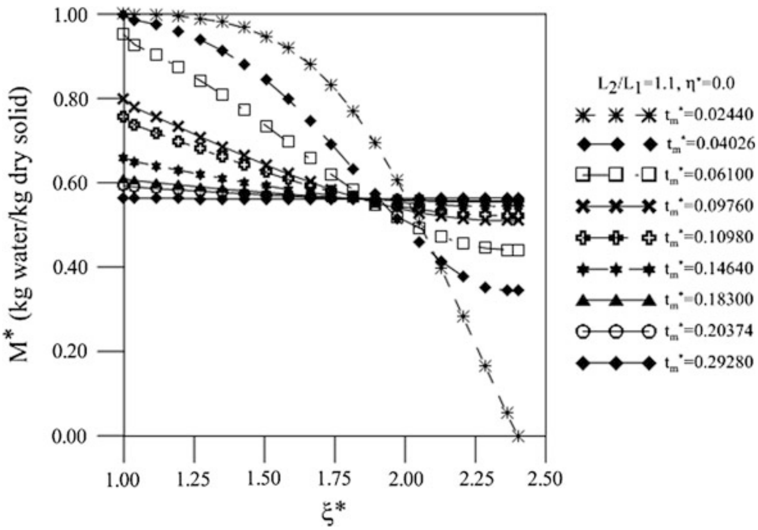

Fig. 5 Radial distribution of the moisture content inside a prolate spheroidal solid (L_2/L_1 = 1.1) during tempering period (r* = 0.0)

time among these cases, mainly between the first and the second cases, are due to the dimensions of the bodies and the moisture content gradients inside the solid at the beginning of the tempering period.

Figure 5 illustrates the moisture content inside the prolate spheroidal solid as a function of the dimensionless radial coordinate, during the tempering period, for aspect ratio L_2/L_1 = 1.1. In this case, tempering period began at $t_m^* = 0.02440$. It can be see that by increasing the dimensionless tempering time, the moisture content profile asymptotically approximated to the average value established at the begin of the tempering period. Variations in the moisture content are more intense in the first instants of drying.

Figure 6 shows the behavior of the moisture content at the center and solid surface of the body (z = 0; y = L_1) during the tempering period. The tempering period started at $t_m^* = 0.02440$. Since loss of moisture at the surface does not occur, the moisture content at this point increases with tempering time due to the decrease in moisture content in the central region of the body. This process will increase the drying rate during the post-tempering period because the difference between moisture content at the surface of the solid and equilibrium moisture content is increased.

Using the tempering mathematical model, two cases were analyzed: (a) variation in the dimensionless tempering time, and (b) number of pass of drying. Figure 7 shows the effect of the tempering time on the drying rate for a prolate spheroid with

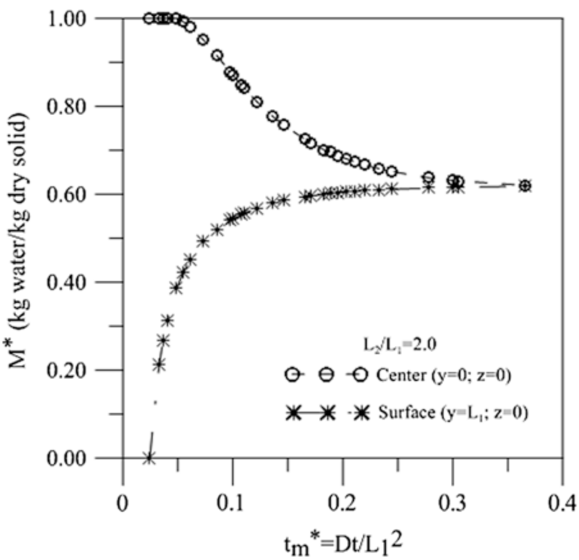

Fig. 6 Moisture content as a function of the dimensionless time for a prolate spheroidal solid with the aspect ratio $L_2/L_1 = 2.0$ during the tempering period

aspect ratio $L_2/L_1 = 2.0$. Tempering started at $t^*_m = 0.01098$ and one pass of drying was used. As compared with continuous drying process, the drying rate increased by increasing the dimensionless tempering time. The drying rate slightly changed as aspect ratio has changed from 1.1 to 5.0. The curves show that the final average moisture content was approximately equal in all cases for the same aspect ratio.

Figure 8 present plots of the average moisture content versus dimensionless time for aspect ratio $L_2/L_1 = 2.0$. In this case the start of tempering is longer than the former case. We can see that occurred an increase in drying rate, greater than that the former cases. Comparing the cases in Figs. 7 and 8, it can be observed that the drying rate increased with the increases in tempering period. This behavior has occurred for increased aspect ratio too. This effect is greater for smaller average moisture content, ranging from 0.40 to 0.10. In all cases, the drying rate is larger than that found in continuous drying, thus energy saving and improving product quality due to reduced stress inside the product is obtained.

Figure 9 shows the effect of an increase in dimensionless tempering time and the use of two passes of drying on the drying rate of prolate spheroid bodies with aspect ratio $L_2/L_1 = 2.0$. It can be seen that an increase in drying rate exists, as compared with the continuous drying process. As tempering time increases, both total amount and drying rate are increased. Thus, the dimensionless time required to complete drying of the wet porous solid is reduced. Practically no effect on drying rate is seen for dimensionless average moisture content lower than 0.15 kg/kg dry basis.

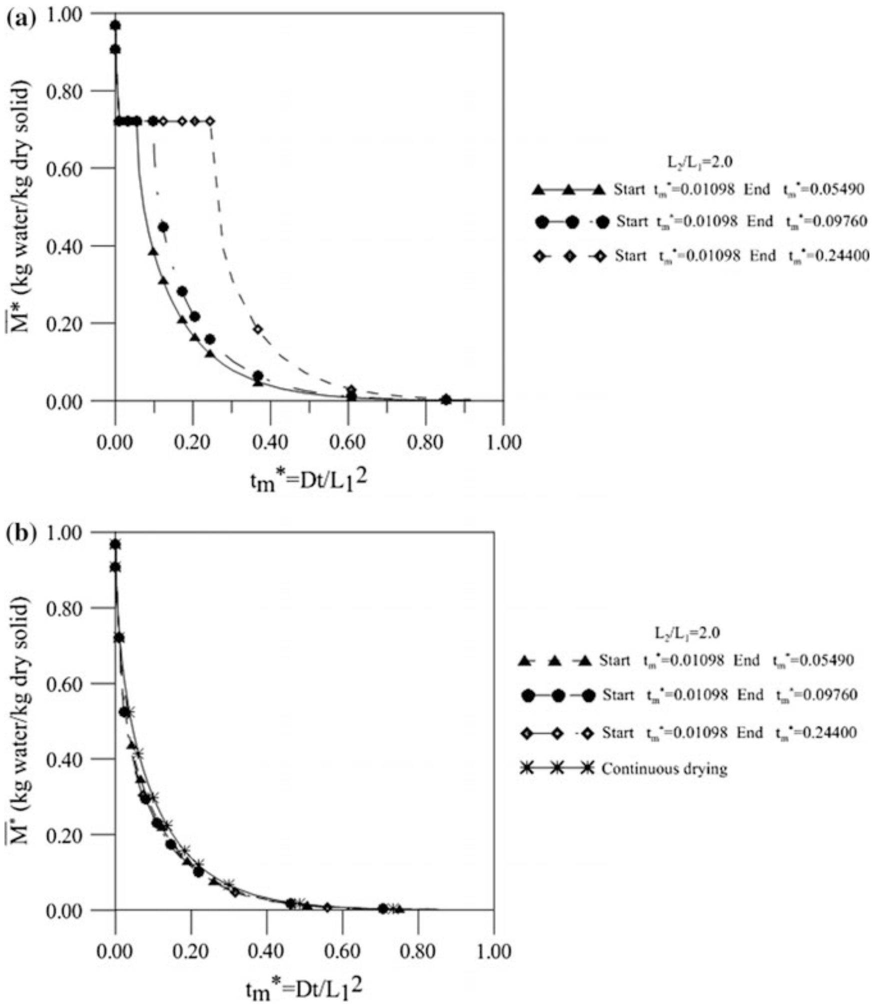

Fig. 7 Dimensionless average moisture content as a function of dimensionless time for a prolate spheroid with aspect ratio 2.0 and different tempering period (one-pass drying). Tempering period has started in 0.01098. **a** Including tempering period, **b** excluding tempering period

Figure 10 illustrates the effect of the use of multipass drying on the drying rate for case $L_2/L_1 = 2.0$, as a function of dimensionless time. The analysis of the curves shows that drying in four passes increases the drying rate more than other cases. However, the use of two passes of drying presented better results, mainly in the

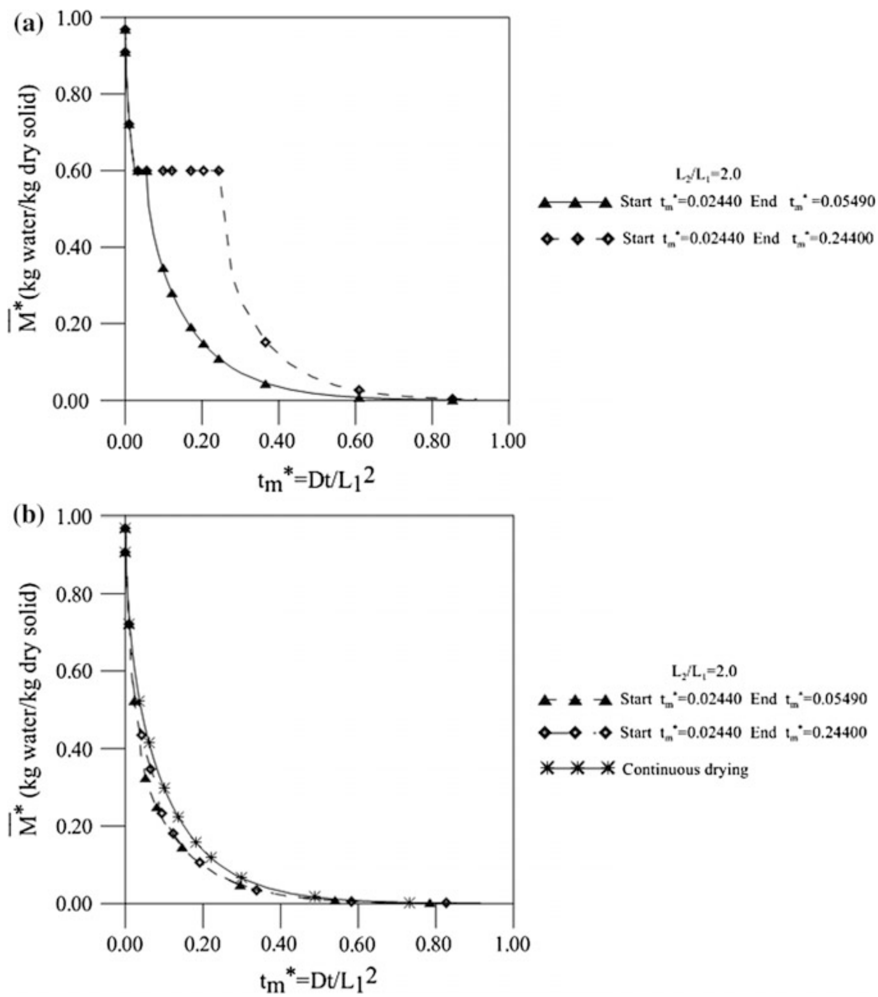

Fig. 8 Dimensionless average moisture content as a function of dimensionless time for a prolate spheroid with aspect ratio 2.0 and different tempering period (one-pass drying). Tempering period has started in 0.02440. **a** Including tempering period, **b** excluding tempering period

second stage of drying. Having a reduced drying time with a lower drying rate is very important in increasing the energy efficiency of the dryer and in reducing internal thermo-hydro-mechanical stresses in the dried material. The multipass drying, with four passes or more can be useful when the product is very sensitive to high temperatures.

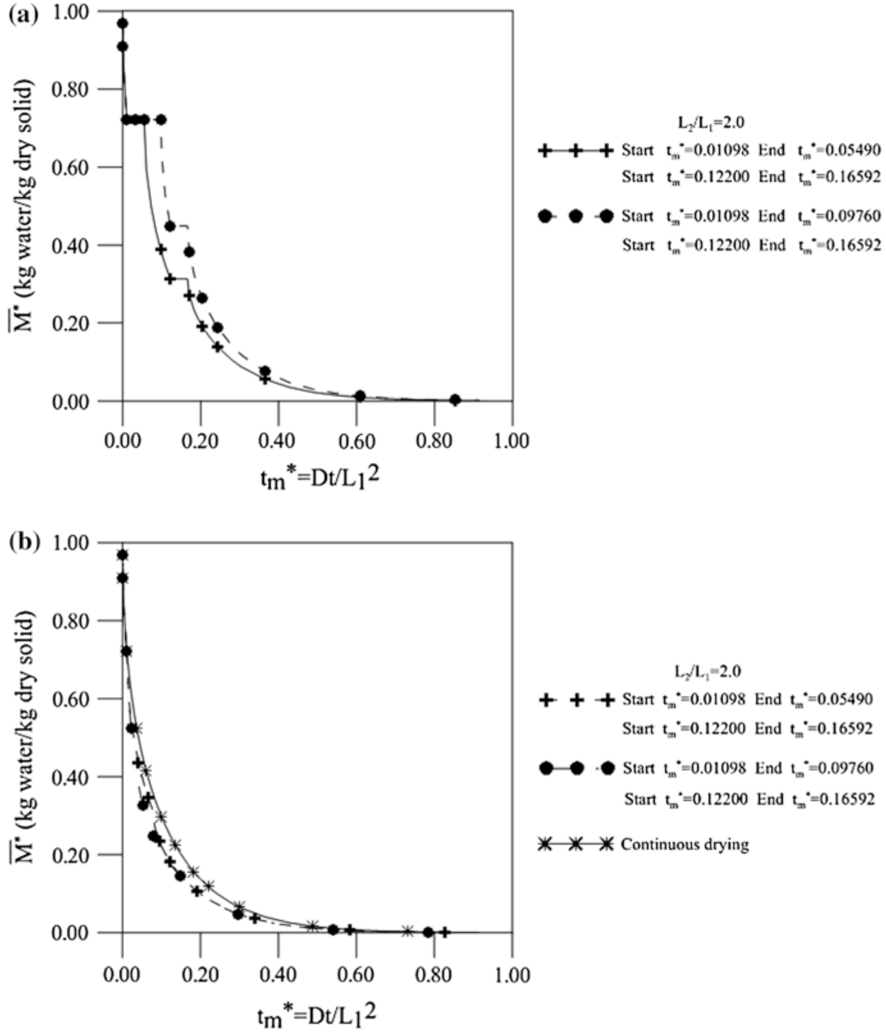

Fig. 9 Dimensionless average moisture content as a function of dimensionless time for a prolate spheroid with aspect ratio 2.0 and different tempering period (two-pass drying). Tempering period has started in 0.02440. **a** Including dimensionless tempering period, **b** excluding dimensionless tempering period

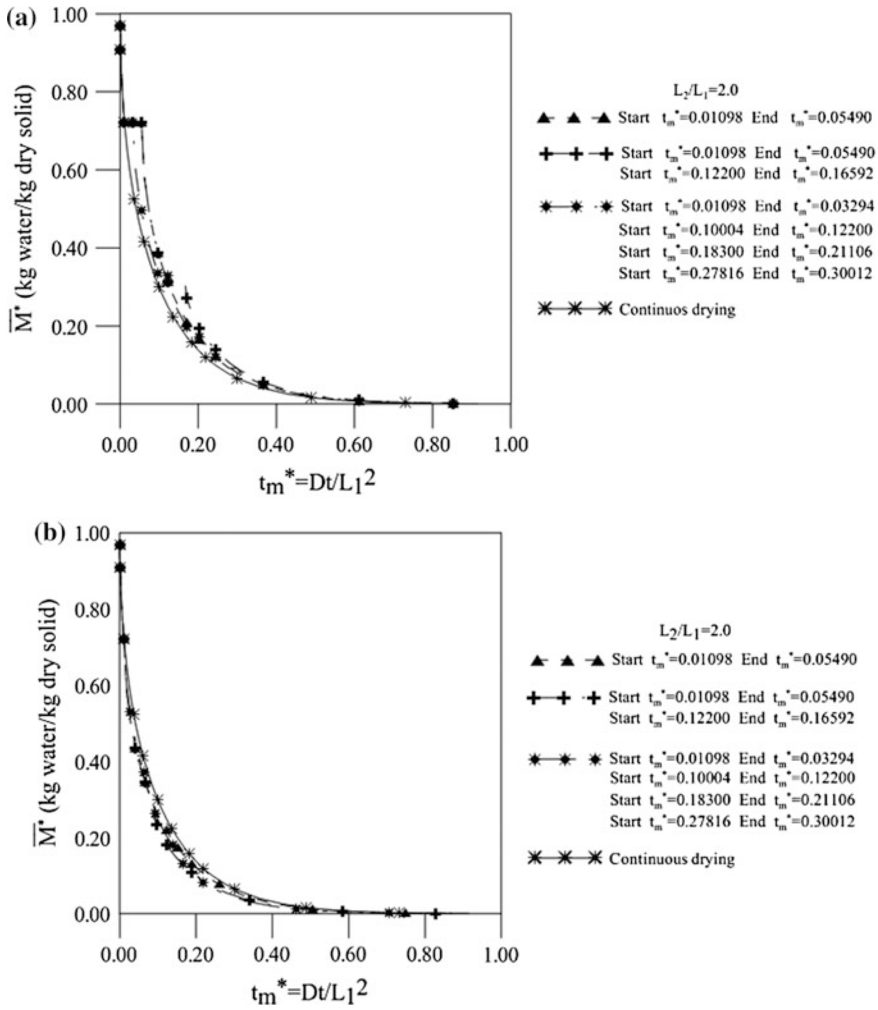

Fig. 10 Predicted drying curves for multi-pass and continuous drying of a prolate spheroidal solid with aspect ratio 2.0. **a** Including dimensionless tempering period, **b** excluding dimensionless tempering period

4 Concluding Remarks

In this chapter, a mathematical modeling to predict continuous and intermittent moisture migration in bodies with prolate spheroidal shape was developed. Numerical procedure using the finite-volume technique was applied to solve the governing equation.

Analysis of the results permits us to conclude that the intermittent drying process (tempering) is an important method to minimize energy utilization in the drying process, and it can be applied in industrial dryers to increase drying efficiency, to reduce energy costs, and maintaining product quality post-drying. In all cases studied, the drying rate after tempering was higher than the in a continuous process. The drying rate of prolate spheroids in processes with two tempering periods was higher than the other cases studied. It was verified that, both, the instant in which tempering period has started and the period of tempering affect the drying rate of the product after tempering.

Further, this work shows that the methodology presented herein has great potential and can be applied for different spheroidal shape ranging from sphere to infinite cylinder by changing the aspect ratio only. Variations in the unsteady-state diffusion equation are unnecessary.

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