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Linear and Nonlinear Drying Behavior in Tuberous Crop Slices

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Understanding drying physics is a complex task because interactions between phases and variations in thermal properties change over time. In this investigation we used two models to simulate the drying of potatoes slices. Drying kinetics were modeled by both the drying characteristic curve (DCC) method and by a mechanistic approach implemented in COMSOL Multiphysics. The DCC was developed on the basis of experimental data and a reference drying rate, which for potatoes is the maximum evaporation rate during the process. The surface thermal evolution was considered to estimate the drying rate curve and the drying stages. The phenomenological model considers both the transport of free water and water vapor by applying a mechanistic approach. In order to simulate free water transport we took into account the capillary diffusivity term, and to simulate water vapor evacuation we considered the desorption isotherm. Two drying conditions were analyzed, 1.0 and 2.2 m/s of air flow with 60°C and 30% relative humidity (RH). The mechanistic model solves the primary unknown's moisture content, temperature, and dry air density. Both models were compared against experimental data. The simulation correctly describes the drying kinetics for the trial at 2.2 m/s and fails to simulate the phenomena at 1.0 m/s. Two different drying behaviors influenced by air flow speed were identified by following the evolution of surface temperature and mass flux. The dependence of mass flux on the difference in temperature (T_air − T_surface) shows that the area of exchange is a very important parameter to be considered in simulations, because both linear and nonlinear behaviors are manifested.

Keywords Drying characteristic curve; Exchange area; Mass flux; Physics-based model; Thermal driving force

INTRODUCTION

Drying is the most frequent operation for food preservation. However, upon drying of foods, important alterations follow, such as shrinkage, degradation of nutrients, browning, etc. Mathematical models are important to gain a deeper understanding of drying physics. Models allow us to optimize the energy consumption and the quality of product and to reduce the operation time. A mathematical model is a mathematical analog of the physical reality, describing the properties and features of a real system in terms of mathematical variables and operations. Mathematical models can predict the moisture evolution and moisture patterns within materials during drying. In this way, models facilitate the understanding of moisture mobility. With theoretical results we can improve practical problems; for example, by tracking the moisture distribution in foods with simulations we can improve the moisture content homogeneity within materials at the end of the drying process. Mathematical models can be classified into physics-based and observation-based models.[1] Drying is a multiphase phenomenon and is of interest for a wide range of materials.[2–6]

Drying of potatoes has been extensively studied; nevertheless, the drying behavior and physics reveal a complex system that must be analyzed by different approaches. May et al.[7] used a central composite design in order to study the interaction of temperature and sample dimension on drying behavior. Both temperature and surface area per unit volume were found to significantly affect drying behavior. However, they found that the presence or absence of a constant rate stage was not dependent on temperature (46–74°C with initial sample dimensions of an area/volume ratio of 2.3 to 0.16 mm^−1). In order to reduce the drying time, either temperature and or area/volume (A/V) can be increased. However, for food products that tend to be sensitive to temperature, increasing the A/V appears to be a better option.[7]

A reduction in the exchange surface area has an effect on the drying rate of foods and porous media; the change in geometrical shape has to be taken into account because these materials undergo large deformations due to shrinkage. Using Transpore software, Perré and May[8] studied the drying of potatoes. The simulation results exhibit dramatic variations in the shape of the sample as water is removed from the product. Due to a reduction in the exchange surface area, the drying rate decreases although free water remains available at the surface. This means that
for such a product, the correct reference for this period should be constant drying flux period (mass per unit of time and surface area) instead of a constant drying rate period; however, the authors do not mention the air flow velocity used or the relative humidity.

Iyota et al. [9] conducted drying experiments on raw potato slices (May Queen) using atmospheric pressure, superheated steam, and hot air as the drying media at 170 and 240°C (a very high temperature for this product). Sample potato slices were prepared from stored potato blocks of 22 mm × 22 mm. The samples were stored from 3 to 5 weeks at room temperature. The applied drying conditions were 170°C and an air flow of 0.159 m/s and 240°C with an air flow of 0.204 m/s. Air drying resulted in no starch granules being observed, excluding those at the surface after 300 s. However, even after air drying was complete, nongelatinized starch granules were found in the area near the surface. Browning rapidly proceeds from \( X = 1 \) after the moisture content reaches 0, and drying at higher temperatures starts the coloring more quickly and reduces lightness. According to this investigation, in the initial stage of superheated steam drying, the moisture content temporarily increases due to steam condensation and there is rapid development of starch gelatinization, whereas in hot air drying, starch gelatinization occurs more slowly than with superheated steam drying. Two important considerations exist when analyzing this research. Firstly, the authors used very low air flow velocities, so a convective effect has been diminished. Secondly, they do not mention the relative humidity used during drying or record the temperatures within the samples.

Rapid drying affects the microstructure of potato tissue (variety Irga). [10] Lewicki and Pawlak [10] applied convection, puff drying, and freeze drying to potatoes. Blanching, which preceded drying, allows for gelatinization of starch and the swelling of cells. Convective drying in hot air was applied at 60°C and air velocity of 1.5 m/s. The tissue was compact, cells were close to each other, and there was no evidence of broken cell walls. Not all of the cells were completely filled with gelatinized starch. Convective drying causes shrinkage of the tissue; however, there was no severe damage to the cell walls. It was estimated that about 12% of cells were broken, and other cells simply shrunk during dehydration but their integrity was preserved. Expanding vapor pressure pulls the cell walls apart and creates a porous structure during puff drying. The authors found that the most devastating effects on the microstructure of plant tissue were observed during freeze drying. The damage to the tissue was so extensive that the structure lost its continuity. A very porous and fragile product was formed. Forces tearing tissue into pieces are dependent on the kind of processed material. Lewicki and Pawlak [10] concluded that drying of potato tissue is more severe than drying of apple tissue.

Nonconventional drying processes have been applied to potatoes. Song et al. [11] published the drying characteristics and kinetics of vacuum–microwave-dried (MVD) potato slices. They used the Page and Henderson models in order to study the effects of drying conditions on the models parameters. Higher drying rates were found under higher microwave power and vacuum pressure levels. However, the effect of vacuum pressure on the drying rate was not as significant as that of microwave power.

Sensory and chemical changes in potatoes were studied by Iciek and Krysiak [12]. Potato cubes were dried at 60 and 90°C with a flow of 1.5 m/s air flow. The authors observed that drying with dry air (relative humidity \( \text{RH} = 3\% \)) at relatively low temperature (60°C) gave rise to products with good sensory properties, light color, and high susceptibility to rehydration but containing high 5-hydroxymethylfurfural concentrations. Drying at higher temperature (90°C) with humid air (RH = 15%) ensured production of dried potatoes with low 5-hydroxymethylfurfural content but worse sensory attributes. However, the authors were interested in chemical changes, but they did not analyze the drying physics of potato cubes.

In order to improve food attributes, we can compare different drying methods. Setiady et al. [13] conducted drying experiments on fresh Russet potatoes (Solanum tuberosum). The potatoes were peeled, washed, and cut into cylinders 3.5 cm in diameter and 3 mm thick and then blanched in 98°C deionized (DI) water for 2 min. For convective drying at 60°C for 360 min they used an air flow of 1.8 m/s. They found that the MVD potatoes remained relatively intact following rehydration and cooking and retained suitable textural, sensory, and color properties. Freeze-dried (FD) potatoes were soft and spread to fall apart during rehydration and darkened the most during cooking. FD potatoes were significantly lighter than hot air–dried (HAD) or MVD potatoes. HAD potatoes browned to a greater extent during dehydration compared to FD and MVD potatoes and cooked HAD were chewier compared to FD and MVD potatoes. FD potatoes had faster rehydration times and higher (almost double) water retention capacity compared to HAD and MVD potatoes; MVD and HAD had similar rehydration properties. At the optimum rehydration time, FD potatoes were significantly softer and less cohesive, gummy, chewy, and resilient compared to HAD and MVD potatoes. The authors did not discuss the drying physics, nor did they mention the relative humidity used or indicate the drying kinetics or drying rate curves.

The biological materials used display a great complexity and heterogeneity; for example, the initial moisture content depends on the material variety, harvest season, etc. The drying characteristic curve (DCC) is a simple mathematical method to simulate the moisture content evolution and drying rate from experimental data. [14] DCC is used to standardize and model drying kinetics independent of
process conditions and is used in the identification of the drying periods of a reduced drying rate curve.

Potato is a homogeneous material that has been widely studied but whose drying physics is poorly understood. There are many models for drying; however, most are based on diffusion mechanisms, which limit the understanding of moisture mobility in the capillary region. Other models have been created to simulate the drying of heterogeneous and complex materials; nevertheless, a deeper comprehension is needed because water removal from foods must be improved.

Water distribution in biological materials is very complex. In order to improve the understanding of the role of water in foods, new tools and paradigms are necessary; for example, Tiburski et al. used differential scanning calorimetry to study the effect of moisture content on the heat resistance of bacterial spores. They found that spore destruction during heating was affected by the amount of water remaining in the spore.

Many approaches have been implemented to study the drying of potatoes; nevertheless, in this experiment we endeavor to explain the two drying behaviors observed in potatoes affected by air flow velocity by comparing experimental data, an empirical model, and a phenomenological model. We also conducted a drying trial under well-established conditions. Experimental data, the DCC method, and a physics-based model are compared for the first time in order to study the drying physics of tuberous samples. A physics-based model was created by coupling equations in COMSOL Multiphysics EDP mode.

MATERIALS AND METHODS

Material and Equipment

Potato variety Alpha (Solanum tuberosum) was obtained from a local supermarket and stored without packaging at 3-4°C for one day. The potatoes were peeled one hour before the drying experiments. Slices (50 mm diameter, 5 mm height) were prepared and placed in two aluminum trays. In order to prevent samples from sticking to the trays, plastic mesh was used during drying (Fig. 1a). A blanching treatment in hot water at 70°C for 1 min was applied in order to inhibit enzymatic reactions. The initial moisture content was determined using the standard oven method.

The trials were performed in a dryer tunnel (Fig. 1b). The dryer was equipped with a Labview data acquisition system. Data were logged every 2 min. Two temperatures were measured with J-type thermocouples (Fig. 2), and the surface temperature was measured with an infrared thermometer (EXTECH model 42560) located on the top of the tunnel.

Process Conditions

A unifactorial design was used with air velocity as the variable measured at two preestablished levels (1.0 and 2.2 m/s). The velocity of the air flow was regulated with a frequency adjuster connected to an Armee Chicago centrifugal fan motor with a size of 12 and a power of ½ Hp. The air flow was controlled by a SAMI o18 MD2 044mD2 frequency converter with a voltage of 220/230/240 V on the main phase. The frequency converter was used to vary the speed of the fan motor to a determined frequency. All experiments were replicated four times. The temperature and humidity inside the dryer were...
constant. Monitoring of the humidity and temperature was performed using a VAISALA HUMICAP HMP234 humidity sensor (2% error, previously calibrated with saline; ASTM E104-85 Drying was controlled at 60°C and 30% RH. The relative humidity was well controlled and the steam was supplied by Anghinetti equipment. Data were standardized by calculating \( W/W_{\text{max}} \) and \( (dW/dt)/W_{\text{max}} \).

**DRYING CHARACTERISTIC CURVE**

Moisture content versus time was calculated from experimental data. The method considers the reduced moisture content \( W_r \), which standardizes \( W \) as:

\[
W_r = \frac{W - W_{\text{eq}}}{W_{\text{crit}} - W_{\text{eq}}},
\]

where \( W_{\text{eq}} \) is the equilibrium moisture content and \( W_{\text{crit}} \) is the critical moisture content, which corresponds to the maximum moisture content for potatoes. \( W_{\text{eq}} \) is calculated from a sorption isotherm and corresponds to the equilibrium moisture content. In this investigation we consider the value of 0.03 kg water/kg dry mass.

The reduced drying rate \( V_r \) considers a reference rate \( (V_{\text{ref}}) \), which for our case (high moisture content) is the maximal drying rate. It also assumes that the transport mechanism is dependent on \( W_r \); therefore, the reduced drying rate \( V_r \) can be obtained from a derivative of time:

\[
V_r = \frac{V - V_{\text{ref}}}{W_{\text{eq}}} = \left( -\frac{dW}{dt} \right)_r = f(W_r).
\]

Because the drying rate is a function of reduced moisture content, it was calculated using mathematical expressions describing the behavior of kinetics as follows:

\[
f(W_r) = 0 \quad \text{if} \quad W_r = 0
\]

\[
0 < f(W_r) < 1 \quad \text{if} \quad 0 < W_r < 1
\]

\[
f(W_r) = 1 \quad \text{if} \quad W_r = 1
\]

Then, we obtained the graph of \( V_r \) as function of \( W_r \). We incorporated the superficial thermal evolution in order to identify the drying periods. By establishing limits for each period, we can identify different behaviors, which can be represented by the following expressions:

\[
\text{If } W_{\text{rm}} < W_r \leq W_{\text{rn}} \quad f(W_r) = a_x W_r + b_x
\]

\[
\text{If } W_{\text{rn}} < W_r \leq W_{\text{eq}} \quad f(W_r) = c_x \exp(d_x W_r).
\]

By substituting (2) into both Eqs. (6) and (7) and applying (1), the differential equations representing the moisture evacuation for both linear and exponential stages was obtained. The expression was solved by the separation of variables; Eq. (7) gives the solution for drying kinetics \( W(t) \) for each stage:

- **Linear**

\[
W(t) = W_{\text{eq}} + (W_0 - W_{\text{eq}}) \left[ \left( W_{\text{ref}} + \frac{b_x}{a_x} \right) \exp \left( -\frac{a_x V_{\text{ref}}}{W_0 - W_{\text{eq}}} (t - t_2) - \frac{b_x}{a_x} \right) \right]
\]

- **Exponential**

\[
W(t) = W_{\text{eq}} - \left[ \frac{1}{d_x} (W_0 - W_{\text{eq}}) \ln \exp \left( \frac{-d_x W_r}{W_0 - W_{\text{eq}}} \right) + \frac{c_x d_x V_{\text{ref}}}{W_0 - W_{\text{eq}}} t \right].
\]

The model parameters \( a, b, c, \) and \( d \) were calculated by minimizing the sums of squared errors using the Solver tool.
in Excel from the expression

\[ SE_i = \left[ \sum_{i=1}^{n} \left( \frac{W_{\text{exp}} - W_{\text{mod}}}{W_{\text{exp}}} \right)^2 \right]_i, \tag{10} \]

where \( n \) is the number of records of each step in the drying kinetics, \( W_{\text{exp}} \) is experimental data, and \( W_{\text{mod}} \) is the model data. The values for each parameter are displayed in Table 1.

**PHYSICS-BASED APPROACH**

Withaker\(^{22}\) proposed the thermodynamic fundamentals to model drying. In this experiment, we consider Whittaker’s approach to the drying model. A representative volume element represents three phases that coexist and are at their thermodynamic equilibrium.

Drying is the extraction of a liquid from a porous solid or from granular materials. A distinction is made between the mechanical drying processes, where the motion of liquid is caused by forces and thermic drying processes and where drying is produced by heat. We have to differentiate between three phenomena concerning thermic drying processes: first, the transport mechanism of heat into the porous medium; second, the transition phase of the liquid water into steam; and third, the transport of water vapor. The transition phase is caused exclusively by heat transfer. It is denoted by evaporation and can occur in two different forms: At relatively low temperatures, the transport of vapor is performed via the surface of the liquid phase as diffusion into the gas phase, and at higher temperatures the gas pressure gradient is the driving force of vapor transport.

During the drying process, the surfaces of the liquid move into the inner part of the porous body. This process can be observed in capillary-porous solids if no reservoir is available. Obviously, no transition phase (liquid into gas) exists in the inner region of the liquid phase.

Drying physics is a complex topic in food systems. In this investigation, a mathematical model was adapted to model drying. In this experiment, we consider Whittaker’s approach to the drying model. A representative volume element represents three phases that coexist and are at their thermodynamic equilibrium.

**Theory**

Continuity equations for each phase by considering the change of phase are as follows:

\[
\text{Liquid water : } \frac{\partial \rho_l}{\partial t} + \nabla \cdot \left( \rho_l \overrightarrow{V_l} \right) = -I \tag{11}
\]

\[
\text{Vapor water : } \frac{\partial \rho_v}{\partial t} + \nabla \cdot \left( \rho_v \overrightarrow{V_v} \right) = I, \tag{12}
\]

where \( I \) is the evaporation rate. Then, the moisture transport equation is the time-dependent equation

\[
\frac{\partial W}{\partial t} + \nabla \cdot \left\{ \frac{1}{\rho_l} \left( \rho_l \overrightarrow{V_l} + \rho_v \overrightarrow{V_v} \right) \right\} = 0, \tag{13}
\]

where \( W \) is the moisture content (kg water/kg dry mass); \( \rho_s \) is solid density (kg/m\(^3\)); \( \rho_l \overrightarrow{V_l} \) represents the liquid water flux; and \( \rho_v \overrightarrow{V_v} \) is the water vapor flux.

The energy balance takes into account the mass flux needed for each phase. This balance is affected by the heat capacity, and it represents the energy transported for each phase; thus, the energy equation is

\[
\rho C_p \frac{\partial T}{\partial t} + \left[ \left( \rho_l \overrightarrow{V_l} C_{p_l} + \rho_v \overrightarrow{V_v} C_{p_v} + \rho_s \overrightarrow{V_s} C_{p_s} \right) \right] \nabla T - \nabla \cdot (\lambda \nabla T) = 0, \tag{14}
\]

where \( C_p \) is the heat capacity (J/kg K) for the liquid phase (l), vapor (v), and air (a), respectively; \( T \) is temperature (K); and \( \lambda \) are thermal conductivity tensors (W/m K; see Table 1). Equations (13) and (14) are a nonlinear partial differential equation system, because material parameters depend on local moisture content and temperature.

During the first minutes of drying, liquid water is mostly evacuated by capillary forces. Free water evacuation is written by using the concept of capillary diffusivity, which involves all phenomena that take place within the
capillarity domain\(^{[4,23]}\):

\[
\rho_l \nabla \dot{V}_l = -D_{\text{c}} \cdot [\nabla W]. \tag{15}
\]

This expression has been used by several authors.\(^{[3-5,23]}\)

For the mobility of water vapor, a pressure gradient is considered; the expression translates the water vapor transport as mass vapor evacuated by both a pressure and concentration gradient:

\[
\rho_v^g \nabla \dot{V}_v = \rho_v^g k_v \cdot \frac{k_{rg}}{\mu_g} \cdot \nabla P_v^g - \rho_v^g D_{\text{eff}} \cdot \nabla C_v^g, \tag{16}
\]

where \( k \) is the intrinsic permeability (m\(^2\)); \( k_{rg} \) represents the relative gas permeability; \( \mu_g \) represents the gas viscosity (Pa s); and \( D_{\text{eff}} \) is the effective diffusion coefficient (m\(^2\)/s). The term \( C_v^g \) is the mass concentration of water vapor in the gaseous phase. An equivalent expression is used for the dry air.

\( \rho_v^g \) is calculated from the ideal gas law, \( PV = nRT \), where \( P_v^g \) is vapor pressure in the gaseous phase, which is a function of both the water activity \( a_w \), and the saturation vapor pressure \( P_{\text{sat}} \):

\[
P_v^g = a_w \cdot P_{\text{sat}}^g. \tag{17}
\]

Water activity is a thermodynamic concept,\(^{[24,25]}\) of the ratio of the fugacity, \( f \), of a substance and its fugacity, \( f_o \), at a given temperature. Water activity is a very useful factor in assessing mobility-controlled processes in foods. Water content (due to the plasticizing action) has a dominating effect on mobility of hydrophilic food components.\(^{[26]}\) In COMSOL we have used the tool “insert table” to interpolate the isotherm, and then the equilibrium moisture content is depicted by this desorption isotherm.

During the first minutes of drying, free water is mainly removed by capillary flow; in the hygroscopic domain bound water is removed principally by diffusion.\(^{[23,25,26]}\)

\( \Phi \) is the ratio between the volume of voids and total volume. Table 2 shows the constitutive equations used in this investigation.

The initial conditions establish that at \( t = 0 \), the initial moisture content and temperature are those measured in the laboratory. Dirichlet conditions were applied to simulate the heat transfer:

\[
T_s = n \cdot (\nabla T), \tag{18}
\]

where \( T_s \) incorporates historical values for the temperature of the material’s surface and is respected in COMSOL Multiphysics. Equation (18) represents the imposed temperature at the surface. A Neumann boundary condition was imposed for mass transfer that includes dry air and water vapor density. Boundary conditions define the interface between the model geometry and its surroundings:

\[
\text{Mass : } -k_m (\rho_{\text{dry}} - \rho_v^g) = -n \cdot (-D \nabla C_v^g) \tag{19}
\]

\[
\text{Air : } k_u (\rho_{\text{dry}} - \rho_v^g) = -n \cdot (-D \nabla C_v^g), \tag{20}
\]

where \( \rho_{\text{dry}} \) and \( \rho_v^g \) are the dry air and water vapor density within the drying medium, respectively.

In simultaneous heat and mass transfer applications we assume that \( -\frac{\partial W}{\partial T} = \frac{h_{\text{ev}}}{\rho_v^g} (T_{\text{surrounding}} - T_{\text{surface}}) \). This equation will be useful for the following discussion.

### Numerical Solution in COMSOL

The mathematical model was solved in COMSOL Multiphysics 3.5a. The equations for moisture content and dry air were written in the PDE general form in COMSOL, and the equation for energy conservation was implemented in the coefficient form. The general form PDE provides a framework for the specification of PDEs that can be nonlinear. The coefficient form can only be used for mildly nonlinear problems. The UMFPACK solver was used because it solves a linear system \( Ax = b \) or \( xA = b \) with a sparse square (say \( n \times n \)) real or complex matrix. A lower
upper (LU) factorization of the matrix is firstly calculated. Second-order Lagrange elements were used and the heat and mass flux were simulated by considering the mobility on the y-axis only (1D transport).

When using UMFPACK as a preconditioner, one can also provide a drop in tolerance in the range 0 to 1. A value of 0.01 means that it drops matrix entries smaller than 1% of the maximum value in each column of the LU factors. Doing so reduces the size of the factors and reduces memory requirements. However, the dropping occurs only when writing the LU factors, and it does not affect the rest of the factorization process. In contrast, in the Incomplete LU preconditioner, the element dropping affects the rest of the factorization process, which leads to a more memory-efficient preconditioner. When an iterative solver is used, COMSOL Multiphysics estimates the error of the solution while solving. Once the error estimate is small enough, as determined by the convergence criterion

\[ \rho |M^{-1}(b - Ax)| < \text{tol} |M^{-1}b|, \]

the software terminates the computations and returns a solution.

For UMFPACK, \( M = LU \), where L and U are the LU factors computed by the solver.

Convergence criteria state that the iterations terminate when the relative (preconditioned) residual time for factor \( \rho \) is less than the tolerance (\( \text{tol} \)). It is possible to set factor \( \rho \) in the Factor in error estimate edit field (default = 400). When using UMFPACK as a preconditioner, one can also provide a drop tolerance in the range 0 to 1. A value of 0.01 means that it drops matrix entries smaller than 1% of the maximum value in each column of the LU factors. Doing so reduces the size of the factors and reduces memory requirements.

A rectangular geometry was created that represents the material slice (5 cm diameter and 0.5 cm height). The simulation domain consisted of 296 triangular elements (Fig. 4). The time step used was 100 s for a simulation time of 30,000 s [0:100:30,000]. The assigned values for the relative and absolute tolerance are 0.1 and 0.01, respectively. The material parameters and properties were incorporated and the EDP model was adapted by the general formulation in COMSOL. The moisture content and dry air density were the primary unknowns.

RESULTS AND DISCUSSION

Figure 5 shows the periods identified from the thermal evolution at the surface (at 1.0 m/s air flow) and from the drying rate. During the first minutes, a short, constant drying rate period is clearly observed (arrow 1 in red) and is described by a linear function in the DCC method.
During the first minutes, capillary forces dominate the process, and the liquid water flows outwards at quasiconstant rate. In order to take this capillary effect into account, we have identified it with the term capillary diffusivity (transport of free water) in our phenomenological model. In the figure we can easily identify a flat temperature profile (arrow 1 in red) due to a constant feed in liquid flow at the surface and a negligible solid shrinkage. Porosity therefore remains constant during the first minutes of the drying process. In the second period, an exponential behavior is identified (arrow 2). The temperature increases as the samples start to shrink, which increases the resistance to water flow and the exchange surface area consequently decreases, thus affecting the mass flux. In the third period, the temperature is relatively constant and the evaporation rate decreases sharply (arrow 3). A very low drying rate is then observed because, at this point, the material has reached equilibrium.

Shrinkage and the presence/absence of liquid water at the surface explain these three steps during drying, because the water content, dry air distribution, and solid skeleton consolidation are the phases responsible for thermal behavior in porous materials. Water evaporation allows for an alteration in porosity and thermal conductivity and finally in shrinkage. The Biot (Bi) theory states that for this kind of physics, a convective/conductive competence is developed at the interface. In this theory, Bi is expressed as \( \frac{h}{k} = \frac{x_l}{x_v} \), where \( x_l \) is the characteristic length and is expressed as \( \frac{\text{volume}}{\text{area}} \). If energy conservation is respected at the boundary layer, then the convective and conductive term must be affected by the \( \frac{\text{volume}}{\text{area}} \) relationship. A strong dependence exists between heat and mass transfer (simultaneous process), so the area of exchange must affect the increase in temperature. The expression \( \text{Mass flux} = \frac{h}{k} \left( T_{\text{surrounding}} - T_{\text{surface}} \right) \) explains this fact; because \( h \) (convective heat transfer coefficient) and the thermal conductivity remain constant in our experimental conditions, \( A \) is the only parameter that can modify the rate of liquid water evaporation.

According to drying physics, the constant rate phase is governed by atmospheric conditions and a falling rate phase is controlled by conditions within the porous media; in period 1 (constant drying rate, arrow 1), the convective heat transfer coefficient limits the temperature evolutions at the surface.

An interesting discussion is presented by Perré and May,\(^8\) who suggested that the dramatic variations in the sample shape as water is removed are explained by the exchange surface area reduction; the drying rate decreases although free water remains available at the surface. They identified this period as the constant drying flux period (mass per unit of time and surface area) instead of the constant drying rate period.

At 2.2 m/s the temperature evolution showed a very different behavior (Fig. 6). Firstly, a constant drying rate was not identified. The heating process was constant and relative humidity was the same as for the trials at 1.0 m/s. At 2.2 m/s the heat transfer coefficient improved but remained constant throughout the experiment. The most interesting fact is the absence of a constant drying rate at 2.2 m/s. Moreover, the three periods observed at low air flow are not observed at 2.2 m/s air flow. This is a very important finding because the apparition of this constant drying rate could be indirect evidence of less intense shrinkage. In addition, the simultaneous relationship between heat and mass transfer at the boundary layer allows us to analyze mass flux evolution and historical temperatures. A continuous increase in temperature is depicted at 2.2 m/s, which must be understood in terms of mass flux.

The moist porous solid contracts during drying and a heterogeneous shrinking causes stress in the food sample. This critical state occurs when the boundary layer dries very quickly and the inner part remains in a moist state. In such a case, large tension stresses arise on the boundary layer and the surface warps and sometimes cracks; this phenomenon can be indirectly analyzed by recording the surface temperature of the material.

After the critical moisture content, water vapor is removed by diffusion (water vapor). The mass transfer to the gas phase ends when the liquid has completely evaporated, but within biological material shrinkage makes it difficult for the moisture to diffuse inside the material because the porosity is diminished. At this point internal conditions control the process.

Temperature and moisture content evolution are displayed in Figs. 7 and 8. The capillary domain exists until \( \approx 0.385 \) kg water/kg dry mass. In Fig. 7 the characteristic drying curve and the physics-based model are depicted. The DCC correctly simulates all of the experimental data. The phenomenological model correctly describes the drying kinetics at 2.2 m/s; nevertheless, the numerical results
for the drying trial at 1.0 m/s deviate from the experimental data. The explanation for this is that at 1.0 m/s important shrinkage occurs, which modifies the evaporation rate, and this was not considered in the model. The capillary network is strongly modified during the second period, where temperature increases considerably.

At 1 m/s the evaporation is slower than it is at 2.2 m/s. At 1 m/s we identify three periods, among them a constant drying rate. We explain this fact using a simultaneous heat and mass transfer expression.

Figure 8 depicts the drying kinetics, history of surface temperature, and the numerical results from both the DCC and the drying physics model. The simulations display good agreement with experimental drying kinetics at 2.2 m/s. However, at 1.0 m/s a deviation is clearly identifiable. Heat transfer fundamentals establish that the driving force behind convective heat transfer is represented by the term $T_{\text{airflow}} - T_{\text{sample surface}}$. Mass flux depends on this driving force. The energy flux across a fluid–solid phase interface is roughly proportional to the difference between the temperature on the surface of the material and the temperature of the surrounding bulk fluid, which is to be assumed to be well mixed. $q \cdot n = h(T_{\text{surface}} - T_{\text{surrounding}})$.

In order to better understand the drying physics, we plot the mass flux versus the thermal driving force. In Fig. 9 we compare the two scenarios studied in this investigation. Figure 9a depicts the mass flux data at 1 m/s air flow, and Fig. 9b shows the mass flux at 2.2 m/s. At higher air flows, a linear relationship can be explained by a less intense shrinkage, because a simultaneous expression for heat and mass transfer is $-\frac{hA}{T} = \frac{hA}{T} (T_{\text{surrounding}} - T_{\text{surface}})$, where $A$ is the exchange surface (area), and it has been considered constant. Therefore, if ($A$) changes during drying, a nonlinear behavior is expected. In reality, area ($A$) changes during drying, but its evolution seems to be more important at low air flows (1.0 m/s), so in Fig. 8a, this nonlinear dependence of mass flux on the thermal driving force is comprehensible.

Transport mechanisms during drying are affected by the microstructure. Drying changes the microstructure of food and alters the exchange area ($A$), thus limiting the mass flux. Because the material is composed of 80% starch when dried, it is the chemical composition and physical changes during drying that modify the tissue’s mechanical properties. At 2.2 m/s it seems that area ($A$) changes are less important due to constant heating and a fast evaporation rate at the surface.
Two drying behaviors were clearly identified from this analysis. Mass flux and thermal driving force show a linear and nonlinear dependence, which according to simultaneous heat and mass transfer theories is affected by the surface exchange area.

With respect to the numerical results, the error for each model was calculated as a minimization of quadratic error. The calculated error for each air flow condition was 0.29 and 0.12 (kg water/kg dry mass) for 1.0 and 2.2 m/s air flow velocities, respectively. The deviation between DCC and experimental curves was 0.05 and 0.07 for 1.0 and 2.2 m/s air flow velocities, respectively.

CONCLUSIONS

We simulated drying kinetics and identified the drying behavior of potato slices at two air flow conditions: the first at low air flow (1.0 m/s) and the second at 2.2 m/s. At 1.0 m/s the experimental data reveal the existence of a nonlinear mass flux dependence on driving force (temperature) and the presence of three surface heating periods. At 2.2 m/s a constant drying rate was not observed, a linear mass flux dependence on energy was observed, and a less intense shrinkage is physically evident.

The DCC method satisfactorily reproduced all of the experimental average drying curves and is suitable to describe and simulate drying kinetics at different drying conditions. The DCC correctly simulated all drying trials and mathematical expressions were derived for potato slices.

The physics-based model correctly described the drying kinetics at 2.2 m/s but failed to simulate the experimental data at 1.0 m/s. By taking simultaneous heat and mass transfer balance into consideration, the failure was explained by a shrinkage phenomenon, because the exchange area was not considered in simulation at lower air flows.

When the mass flux and the thermal driving force \( (T_{\text{airflow}} - T) \) are plotted, two very interesting behaviors are identified. At low air flow (1.0 m/s), a nonlinear relationship is revealed; the alteration of the exchange surface area is the most important because the mass flux was strongly affected. With drying at 2.2 m/s the evaporation rate allows for a constant increase in temperature; therefore, drying is faster and shrinkage is less intense. When shrinkage is less intense, it is possible to explain why thermal driving force is directly proportional to mass flux by means of the conservation equation, so we can expect a linear behavior of mass flux versus thermal driving force \( (T_{\text{airflow}} - T) \), a fact that was proven by this investigation.

Finally, drying simulations must consider the characteristic length (volume/area) of the product. Flux mass and the thermal driving force show a linear and nonlinear relationship depending on air flow speed. The history of the temperature and the exchange surface area must be considered in future investigations, but chiefly experimental and modern tools must be implemented to measure shrinkage in foods. Physics-based models need thermophysical properties, which are a function of temperature and moisture content, and though obtaining these data can prove challenging, modern lab facilities and modeling techniques can offer innovative solutions to drying.

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REFERENCES


