Evolution of the driving forces during convective drying of carrot slices

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Abstract. To explore the drying characteristics, a model combining the Fick’s second law of diffusion with a convective boundary condition on the material surface is solved numerically. And the evolutions of the moisture gradient within the sample (internal driving force) and the relative humidity difference between the bulk air and the material surface (external driving force) with drying time are obtained. These obtained results show that the relative humidity difference remains its maximum for some period at the beginning of drying, and then falls progressively to zero for samples with high initial moisture content. However, it falls from its maximum to zero without constant period for samples with low initial moisture content. And the moisture gradient in the outer is always greater than that in the inner within the sample. Correspondingly, the moisture migration flux in the outer is always greater than that in the inner within the sample. These observations indicate that both the external and the internal driving force simultaneously control the whole drying process, and the transferring rate of internal moisture cannot be equal to or higher than that of surface moisture. Thus, the magnitude of drying rate is directly dominated by the external driving force.

1. Introduction

Moisture transfer in porous materials during the drying process is usually considered to take place in two successive steps: (1) from the interior to the surface and (2) evaporation from the surface to the air. It is said that the drying process occurred at a constant drying rate period if the transferring rate of internal moisture was equal to or higher than that of surface moisture. And the drying process was at falling drying rate period if the internal moisture transferring rate was lower than that of surface moisture [1]. As proposed by Debase et al. [2], a two-stage drying process model proposed was based on two hypotheses: (1) the resistance to the solid-gas mass transfer of water was assumed to be located near the external surface of the solid particles, in the gas phase and the solid water content was assumed uniform during the constant rate period; (2) in the falling rate period, an internal resistance to mass transfer, corresponding to the moisture diffusion in the solid particle, must be taken into account. Up to now, there have been many researches on both mathematical modeling and experimental studies about the drying behavior of various materials based on the view of moisture diffusion resistances of the external and internal samples, such as wheat [3], cheese [4], and fruit pectin gels [5], mate leaves [6] and paper [7]. However, the studies on the hot-air drying behaviors of materials from the point of
driving forces are scarce in the literature. In this work, such an effort was made: the evolution of the driving forces of moisture diffusion, i.e. the internal moisture gradient and the humidity difference between the surface and the bulk air during the drying process were estimated and the drying characteristics of high initial moisture content and low initial moisture content product in view of the drying driving forces was also further analyzed.

2. Mass transfer model

One-dimensional transient mass transfer for an infinite slab and for a homogeneous product with constant moisture diffusivity, and a boundary condition considering convective mass transfer, can be described by the following equations:

\[
\frac{\partial m}{\partial t} = D \frac{\partial^2 m}{\partial x^2} \quad \text{For } 0 < x < L ; \ t > 0
\]  

Where \( m \) is the moisture content at time \( t \) at point \( x \), and \( D \) stands for the diffusion coefficient of water through the carrot samples.

The following initial condition is accepted:

\[
m(x,0) = m_0 \quad \text{For } 0 \leq x \leq L ; \ t = 0
\]  

Which means that the moisture content in the samples before drying is uniform and equal to \( m_0 \).

The mass flux of water from the carrot slice surface [8], \( J \), is proportional to the external driving force, i.e., the difference between the humidity in the bulk air, \( y_{am} \), and the gas humidity just above the surface of the carrot slice, \( y_{in} \).

\[
J = h_m (y_{in} - y_{am}) \rho_a \quad \text{For } x = 0 ; \ t > 0
\]  

The humidity of bulk air, \( y_{am} \), can be calculated from the relation between absolute and relative humidity [9]. In addition, the surface humidity, \( y_{in} \), is a function of the local moisture content at the surface of carrot slice, \( m_{ms} \), proposed by Aversa et al [10].

Food bottom:

\[
\frac{\partial m}{\partial x} = 0 \quad \text{For } x = L ; \ t > 0
\]  

The local moisture content change obeys the conventional diffusion equation (1) with initial condition (2) and boundary conditions (3) and (4). This initial boundary problem (2), (3), (4) and (1) are solved numerically by the finite difference method with an explicit algorithm. The sample is divided into 10 subintervals by points’ \( x_i = (i-1/2) \Delta x \) (\( i = 1, 2, 3, \cdots, 9 \)) with \( \Delta x = L/10 \) along the thickness; introduce discrete time \( T_N = kn \); and replace equations (1), (2), (3), and (4) by their finite difference approximation:

\[
m(t_{n+1}, x_i) = m(t_n, x_i) + D \frac{\Delta t}{\Delta x^2} \left[ m(t_n, x_{i+1}) - 2m(t_n, x_i) + m(t_n, x_{i-1}) \right] \quad i = 2, 10
\]  

\[
m(0, x_i) = m_0 \quad i = 1, 11
\]
\[ D \rho_a \frac{m(t_{n+1}, x_{i+1}) - m(t_n, x_i)}{\Delta x} = h_m \left( y_m(t_n) - y_a(t_n) \right) \rho_a \quad i = 1 \] (7)

\[ \frac{m(t_{n+1}, x_{i+1}) - m(t_n, x_i)}{\Delta t} = 2D \frac{m(t_n, x_{i-1}) - m(t_n, x_i)}{\Delta x} \quad i = 11 \] (8)

3. Results and discussion

Figure 1 compared the experimental data of moisture content vs. drying time with that predicted results by the proposed model with an initial moisture content of 9.21 kg water/kg dry matter [8]. Obviously, the theoretical values well superimposed on the experimental values, indicating that the proposed model based on a convective boundary condition on the material surface was adequate for predicting the drying process of carrot slice.

Figure 1. The plot of experimental (star) and calculated (line) moisture content as function of time for carrot slice natural convective drying with air temperature 60°C and relative humidity 15%.

Figure 2. The evolution external driving forces of moisture diffusion for the carrot slices drying process simulation with \( m_0 = 9.21 \) kg water/kg dry matter, \( L = 0.004 \) m, \( r = 0.007 \) m, \( T_a = 60°C \), \( V_A = 0.269 \) m/s, \( \psi = 15\% \).
Figures 2 and 3 show the external and internal driving forces of moisture diffusion for the carrot slices drying process simulation with $m_0=9.21$ kg water/ kg dry matter, $L=0.004$m, $r=0.007$m, $T_a=60^\circ$C, $v=0.269$m/s, $\psi=15\%$. As expected in the Figure 2 the external driving force i.e. difference between moisture content of air at the sample surface and bulk air was the maximum and almost constant for the material with high moisture content in the initial phase of drying. The reason is under a certain drying condition, the external driving force is only associated with the water activity of the sample surface. And if the local moisture content of the sample surface is equal to or greater than its critical moisture content, the water activity of the sample surface will remain constant and is equal to 1. With the water vapor removed away from the sample surface, when the local moisture content reached its critical moisture content, the water activity would decrease with moisture content of sample surface. Correspondingly, the external driving force decreased with increase in drying time as shown in Figure 2. These observation are in agreement with convective drying of saturated porous media (clay samples) [12, 13].

From Figure 3, the initial internal driving force of moisture diffusion was null in the sample. At the beginning of drying, the evaporation of liquid water at the surface resulted in a moisture gradient between the surface and its neighbour. This moisture gradient drove the moisture diffusing from the neighbour to the surface. In turn, the neighbour local moisture decreasing formed the gradient between the neighbour and the next neighbour, and the moisture gradient drove the next neighbour local moisture diffusing to the neighbour. In this manner, the internal driving forces were formed progressively in the whole sample, the moisture diffused from the inner to the surface and with these driving forces. It is worth noting that the driving forces increased from zero to their maximum, and remained a period, then decreased and approached to zero with increase in drying time. And the inner driving force was less than the outer during the whole drying process. These observations gave the dynamic nature of internal driving forces during mass transport in porous materials with initially high moisture content. In addition, these observations provided validation to driving force rather than resistance on the change of drying rate.

![Figure 3](image-url)

Figure 3. The evolution of the internal driving forces of moisture diffusion for the carrot slices drying process simulation with $m_0=9.21$ kg water/ kg dry matter, $L=0.004$m, $r=0.007$m, $T_a=60^\circ$C, $v=0.269$m/s, $\psi=15\%$.

The external and internal driving forces as function of drying time for carrot slice with $m_0=2.21$ kg water/ kg dry matter, $L=0.004$m, $r=0.007$m, $T_a=60^\circ$C, $v=0.269$m/s, $\psi=15\%$, were shown in Figures 4 and 5. The driving forces appeared significantly different from the driving force curve with highly initial moisture content (Figures 2 and 3). Upon examining the results shown in Figures 4 and 5, it was
immediately apparent that the external driving force decreased with drying time. The internal driving force increased with drying time firstly, and then it fell progressively. Unlike the highly initial moisture content, the transition phase of increasing to falling for the internal driving force was sharp. For all initial moisture contents, the flux of water migrating from the inner to the outer neighbour were less than the flux of water migrating from the outer to the outer adjacent, and the rate of moisture migration to the surface of an carrot slice was less than that of moisture diffusion from the particle surface to the bulk air. Contrary to the view of Devlet et al. [1] and Perez-Alonso et al. [14], Drying rate only depended on the relative humidity difference between the bulk air and the sample surface. If the local moisture content of the sample surface was equal or greater than its critical moisture content, the water activity of sample surface will remained constant and was equal to 1. Corresponding to the drying characteristic diagram, this phase was the constant drying rate period. When the local moisture content of the sample surface was less than the critical moisture content, the water activity of the sample surface will decrease with the local moisture content of the sample surface. And the drying process was in the falling rate period. With the analysis of the driving force of the moisture diffusion, it was apparent that the whole drying processes were simultaneously controlled by the external and internal driving forces. And the magnitude of the drying rate was dominated by the external drying force.

![Figure 4](image1.png)

**Figure 4.** The variations of external driving force as function of drying time for carrot slice with $m_0=2.21 \text{ kg water/ kg dry matter, } L=0.004\text{m, } r=0.007\text{m, } Ta=60^\circ\text{C, } v_{an}=0.269\text{m/s.}$

![Figure 5](image2.png)

**Figure 5.** The variations of internal driving force as function of drying time for carrot slice with $m_0=2.21 \text{ kg water/ kg dry matter, } L=0.004\text{m, } r=0.007\text{m, } Ta=60^\circ\text{C, } v_{an}=0.269\text{m/s.}$
4. Conclusion
A model combining the Fick’s second law of diffusion with a convective boundary condition on the material surface was solved numerically and compared with experimental data. The obtained evolutions of the moisture gradient within the sample (internal driving force) and the relative humidity difference between the bulk air and the material surface (external driving force) indicated that both the external and the internal driving force simultaneously controlled the whole drying process. And the magnitude of drying rate was directly dominated by the external driving force.

Acknowledgments
This work was financially supported by the fund of National Science Foundation of China (No.51566006).

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