

Diffusivity of Potato and Apple

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ABSTRACT: Drying is a classic example of heat and mass transfer and is a very important method for food preservation. In this case, diffusivity is an important parameter in mass transfer. Although we distinguish between different internal transfer mechanisms, such as: pure diffusion, surface diffusion, Knudsen diffusion, capillary flow, evaporation and condensation, thermal diffusion, however the most common term used is effective diffusivity. In this paper, the diffusivity of Carrera type potato and Golden Delicious type apple was determined, by drying samples in an experimental setup that simulates a far infrared-vacuum dryer, and the two parameters of diffusion model are determined using the DirInSens software package and the Levenberg-Marquardt method. The results of this research were compared with the results of other research presented in the scientific and professional literature which show good agreement.

KEYWORDS: Heat and mass transfer, experimental research, drying, diffusivity, inverse approach.

I. INTRODUCTION

The heat and mass transfer in a capillary porous body is essentially a simultaneous process. Namely, heat is transferred by conduction, convection, and radiation, while mass transfer by diffusion, based on the second Fick's law and it defines a second important transport property, mass diffusivity^{1,2}. A classic example of heat and mass transfer is drying. Drying is one of the most exploited methods for preserving food products³.

For heat to transfer from one body to another there must be a temperature gradient. Diffusivity defines several internal mass transfer mechanisms, such as: pure diffusion, surface diffusion, Knudsen diffusion, capillary flow, evaporation and condensation, thermal diffusion, etc., but the most common term used is effective diffusivity.

Pure diffusion is considered as the spontaneous, random thermal movement of particles from an area of high concentration to an area of low concentration without any external driving forces or bulk fluid motion.

Surface diffusion generally can be thought as the jumping of particles between adjacent adsorption sites on a surface, whereby this movement is typically a thermally driven process with rates that increase with increasing temperature⁴.

Knudsen diffusion occurs when the scale length of a system is comparable to or smaller than the mean free path of the particles involved. In that case, the molecules collide with the walls of the long and narrow capillary pore, leading to Knudsen diffusion⁵.

Capillary flow is the process of a liquid flowing in a narrow space without the assistance of external forces like gravity. It occurs due to intermolecular forces between the liquid and the surrounding solid surfaces, and if the diameter of the capillary is small enough, then the combination of surface tension and adhesive forces between the liquid and the capillary wall act to move the liquid⁶.

Evaporation and condensation are opposite phase changes in porous body where matter shifts between a liquid and a gas based on heating or cooling⁷.

Thermal diffusion is the movement of different components in a fluid or gas mixture in porous body driven by a temperature gradient⁸.

II. MATERIAL AND METHODS

In this paper, the diffusivity of potato and apple was determined. For this purpose, samples of potatoes of the Carrera type and apples of the Golden Delicious type were used. The samples were cylindrical in shape with a thickness of 3 mm and a diameter of 43 ± 10^{-1} mm.

The samples were dried in an experimental setup that simulates a far infrared-vacuum dryer, during which mass changes and temperature changes in the center of the samples were measured (fig. 1).

To determine the diffusivity, the inverse approach was used where the parameters of the diffusion equation were optimized⁹.

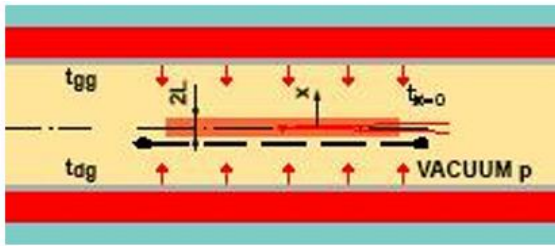


Fig. 1. Scheme of the far infrared-vacuum drying experiment

III. EXPERIMENTAL RESEARCH

On figure 2 is presented experimental setup for far infrared vacuum drying research of 3 mm thick apple and potato samples and is designed to simulate real dryer.

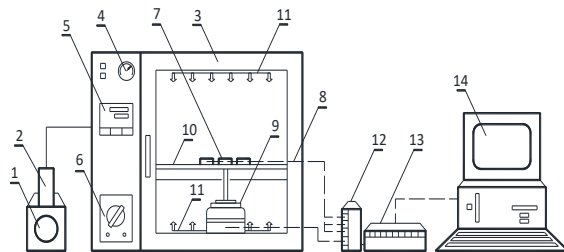


Fig. 2. Experimental far infrared-vacuum drying setup

1 - vacuum pump, 2 - separator, 3 - vacuum chamber, 4 - vacuum-meter, 5 - temperature controller, 6 - vacuum regulator, 7 - samples, 8 - micro thermocouples, 9 - load cell, 10 - tray, 11 - heaters, 12 -computer interface, 13 - A/D converter, 14 - personal computer

The temperature in the vacuum chamber was achieved by infrared heaters, while the vacuum pressure was achieved by a single-stage rotary vacuum pump (type EQ-2XZ, MTI Korea, Korea). The transition temperatures of the samples were measured by three micro-thermocouples type K, which were connected to a data acquisition system consisting of a computer interface (type IDR-N-ST, Omega, USA) and a 24-bit A/D converter (type OMB-DAQ-2408, Omega, USA). The measurement of the changes in the mass of the samples over time was achieved by a load cell (type OMEGA LCL 040, Omega, USA), which was connected to the data acquisition system.

The results of the measured temperatures in the center of the samples and the average moisture for potato and apple are given in Fig. 3 and Fig. 4 respectively.

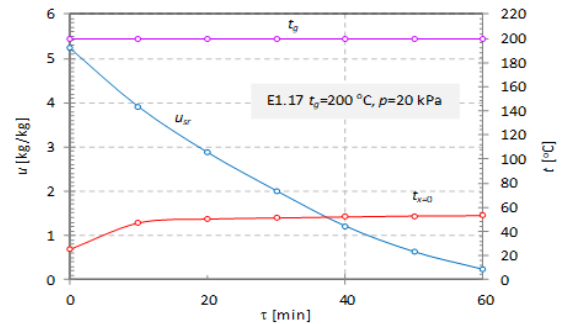


Fig. 3. Change in temperature at the center of the sample and average moisture for potato slices

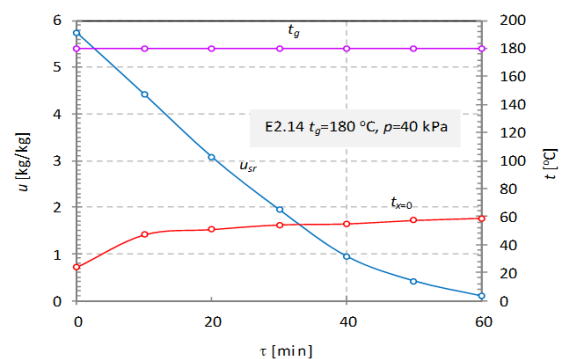


Fig. 4. Change in temperature at the center of the sample and average moisture for apple slices

IV. DETERMINATION OF DIFFUSIVITY OF POTATO AND APPLE SLICES USING AN INVERSE APPROACH

Considering the fact that drying is a simultaneous transfer of heat and mass, the two second-order partial differential equations are set up^{10,11}:

$$c_s \rho_s \frac{\partial t}{\partial \tau} = \lambda \frac{\partial^2 t}{\partial x^2} + \varepsilon r \frac{\partial(\rho_s u)}{\partial \tau}$$

$$\frac{\partial(\rho_s u)}{\partial \tau} = \frac{\partial}{\partial x} (a_m \rho_s \frac{\partial u}{\partial x})$$

u - moisture content, [kgkg⁻¹ d.b.], t - temperature, [°C], c_s - heat capacity (dry basis), [JK⁻¹kg⁻¹ d.b.], ρ_s - density, [kgm⁻³], τ - time, [s], λ - thermal conductivity, [Wm⁻¹K⁻¹], x - distance from the mid-plane, [m], ε - phase conversion factor, [-], r - latent heat of vaporization, [Jkg⁻¹], a_m - moisture diffusivity, [m²s⁻¹].

Given the fact that the drying body shrinks, the density can be expressed as follows:

$$\rho_s = \frac{\rho_{\beta 0}}{1 + \beta_{\rho} u}$$

ρ_{β0} is the density of the fully dried body and β_ρ is the shrinkage coefficient.

Moisture diffusivity of potato and apple is expressed as an Arrhenius-type temperature function:

$$a_m(T_k) = a_{m0} \exp\left(-\frac{E_0}{RT_k}\right)$$

a_{m0} is the Arrhenius factor, [m^2s^{-1}], E_0 is activation energy, [Jmol^{-1}], R is absolute gas constant, [$\text{JK}^{-1}\text{mol}^{-1}$], and T_k is the sample temperature, [K].

As can be seen, there are eight unknown parameters, including value of the sample half-thickness L_0 [m], which can be determined through an inverse approach:

$$\mathbf{P}^T = [a_{m0}, E_0, \lambda, c_s, \rho_{\beta 0}, \beta_{\rho}, \varepsilon, L_0]$$

In this research, the unknown parameters are determined using the DirInSens software package and the Levenberg-Marquardt method:

$$E(\mathbf{P}) = [\mathbf{Y} - \mathbf{T}(\mathbf{P})]^T [\mathbf{Y} - \mathbf{T}(\mathbf{P})]$$

Since the aim of this research is to determine moisture diffusivity, the analysis will focus on determine the two diffusion model parameters, a_{m0} , and E_0 , along with the half-thickness of the sample, L_0 , and remaining parameters will be taken from previous research.

The diagrams in Fig. 5 and 6 show the change in the root mean square deviation, RMS, of the measured from the calculated temperatures and the convergence of the determined parameters for the conducted experiments.

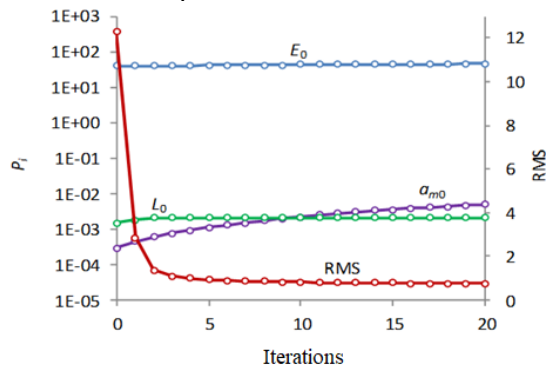


Fig. 5. Convergence of the calculated parameters and the RMS function for potato

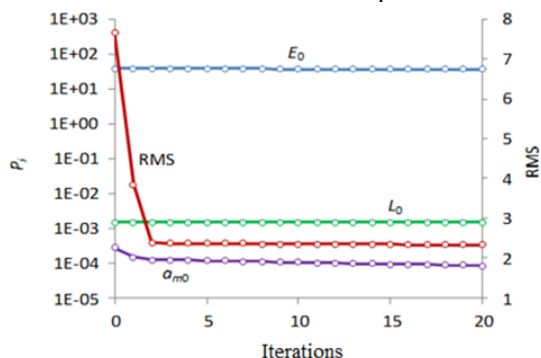


Fig. 6. Convergence of the calculated parameters and the RMS function for apple

From the diagrams in Fig. 5 and 6, it can be observed that the solutions converge stably and that the objective functions monotonically decrease to their minimum.

The values of the determined parameters for diffusivity of potato and apple and mean square deviation are given in Tables 1 and 2.

Table 1 Calculated parameters and RMS deviation for potato

	$a_{m0} \cdot 10^3$ [m^2/s]	E_0 [kJ/mol]	$L_0 \cdot 10^{-3}$ [m]	RMS [$^{\circ}\text{C}$]
Initial values	0.294	39.50	1.500	12.28
Calcul. values	4.801	45.02	2.102	0.760

Table 2 Calculated parameters and RMS deviation for apple

	$a_{m0} \cdot 10^3$ [m^2/s]	E_0 [kJ/mol]	$L_0 \cdot 10^{-3}$ [m]	RMS [$^{\circ}\text{C}$]
Initial values	0.274	38.50	1.500	7.660
Calcul. values	0.085	36.40	1.472	1.330

In order to verify the results for the diffusivity of potato and apple obtained in this paper, they were compared with other diffusivities given in the scientific and professional literature by various authors (Fig. 7 and 8).

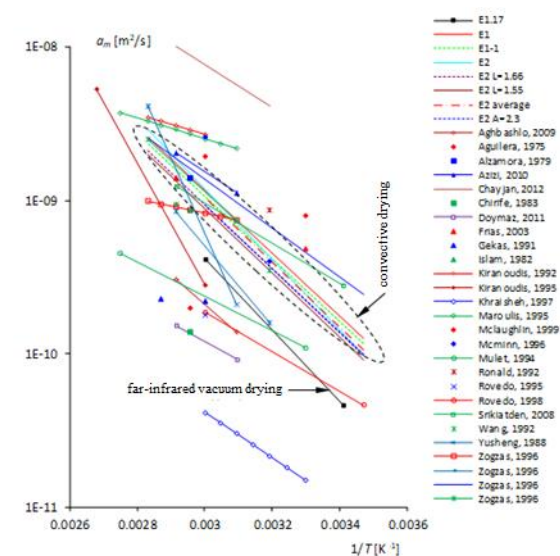


Fig. 7. Potato diffusivity values

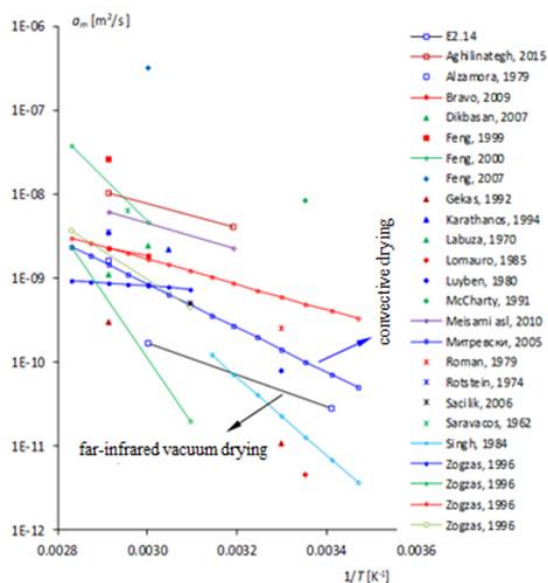


Fig. 8 Apple diffusivity values

V. CONCLUSION

The heat and mass transfer is essentially a simultaneous process, where heat is transferred by conduction, convection, and radiation, while mass transfer by diffusion, based on the second Fick's law. Drying is classic example of heat and mass transfer and one of the most exploited methods for preserving food products.

Effective diffusivity defines several internal mass transfer mechanisms, such as: pure diffusion, surface diffusion, Knudsen diffusion, capillary flow, evaporation and condensation, thermal diffusion, etc.

In this research, the diffusivity of Carrera type potato and Golden Delicious type apple was determined, by drying samples in an experimental setup that simulates a far infrared-vacuum dryer.

The unknown parameters of diffusion model are determined using the DirInSens software package and the Levenberg-Marquardt method.

The results of the research show good agreement with the results of other research presented in the scientific and professional literature.

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