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INVERSE APPROACHES TO DRYING OF SLICED FOODS

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ABSTRACT

This paper deals with the application of inverse concepts to the drying of foods that undergo changes in their dimensions. The objective of this paper is an analysis of the possibility of the simultaneous estimation of the moisture diffusivity, together with other thermophysical properties of vegetables and fruits, as well as the heat and mass transfer coefficients. As a representative drying vegetable product, the potato has been chosen and as a representative fruit product the apple has been chosen. For the estimation of the unknown parameters, the transient readings of a single temperature sensor located in the midplane of the slices, exposed to convective drying, have been used. A mathematical model of the drying process of shrinking bodies has been applied. The Levenberg-Marquardt method and a hybrid optimization method of minimization of the least-squares norm were used to solve the present parameter estimation problem.

NOMENCLATURE

a = water activity
c = heat capacity (dry basis), [J K^{-1} kg^{-1} db]
C = concentration of water vapor, [kg m^{-3}]
D = moisture diffusivity, [m^2 s^{-1}]
D_0 = Arrhenius factor, [m^2 s^{-1}]
E_0 = activation energy [J kg^{-1}]
E = ordinary least square norm [(^{0}C)^2]
h = heat transfer coefficient, [W m^{-2} K^{-1}]
h_D = mass transfer coefficient, [m s^{-1}]
ΔH = latent heat of vaporization, [J kg^{-1}]
$\mathbf{I}$ = identity matrix
j_m = mass flux, [kg m^{-2} s^{-1}]
j_q = heat flux, [W m^{-2}]
$\mathbf{J}$ = sensitivity matrix
k = thermal conductivity, [W m^{-1} K^{-1}]
L = flat plate thickness, [m]
m = mass, [kg]
p_s = saturation pressure , [Pa]
$\mathbf{P}$ = vector of unknown parameter
R = absolute gas constant [J K^{-1} mol^{-1}]
R_w = specific gas constant [J K^{-1} kg^{-1}]
t = time, [s]
T = temperature, [^{0}C]
T_k = temperature, [K]
$\mathbf{T}$ = vector of estimated temperature, [^{0}C]
v = specific volume, [m^3 kg^{-1}]
V = volume, [m^3]
x = distance from the mid-plane, [m]
X = moisture content (dry basis), [kg kg^{-1} db]
$\mathbf{Y}$ = vector of measured temperature, [^{0}C]

Greek symbols

β' = shrinkage coefficient [-]
δ = thermo-gradient coefficient, [K^{-1}]
ε = phase conversion factor
μ = damping parameter
ρ = density, [kg m^{-3}]
φ = relative humidity
ψ = dimensionless coordinate

Subscripts

a = drying air
$b0$ = fully dried body

f	=	final
m	=	monolayer
w	=	water
s	=	dry solid

Superscripts

r	=	number of iterations
T	=	transposed

INTRODUCTION

In this paper a mathematical model of the drying process of shrinking bodies has been applied, where the moisture content and temperature fields in the drying body are expressed by a system of two coupled partial differential equations. The system of equations incorporates coefficients that are functions of temperature and moisture content, and must be determined experimentally. All the coefficients, except for the moisture diffusivity, can be relatively easily determined by experiments. The main problem in the moisture diffusivity determination by classical or inverse methods is the difficulty of moisture content measurements. We have recently analyzed a method for moisture diffusivity estimation by the temperature response of a drying body [1-6]. The main idea of this method is to make use of the interrelation between the heat and mass transport processes within the drying body and from its surface to the surroundings. Then, the moisture diffusivity can be estimated on the basis of an accurate and easy to perform single thermocouple temperature measurement by using an inverse approach.

Real experiments have been conducted to investigate the applicability of the method to food processing, when involving drying of thin flat samples. The experiments have been conducted on the experimental setup that is designed to simulate an industrial convective dryer. As a representative drying vegetable product, the potato has been chosen and as a representative fruit product the apple has been chosen.

The Levenberg-Marquardt method and a hybrid optimization method of minimization of the least-squares norm were used to solve the present parameter estimation problem.

An analysis of the influence of the drying air velocity, temperature and relative humidity, drying body dimensions, and drying time on the moisture diffusivity estimation, enables the design of appropriate experiments is conducted as well. In order to realize this analysis, the sensitivity coefficients and the determinant of the information matrix were calculated for the characteristic drying regimes and drying body dimensions.

MATHEMATICAL FORMULATION

The physical problem involves a single slice of a potato of thickness 2*L* initially at uniform temperature and uniform moisture content (Fig. 1). The surfaces of the drying body are in contact with the drying air, thus resulting in a convective boundary condition for both the temperature and the moisture content. The problem is symmetrical relative to the midplane of the slice. The thickness of the body changes during the drying from $2L_0$ to $2L_f$.

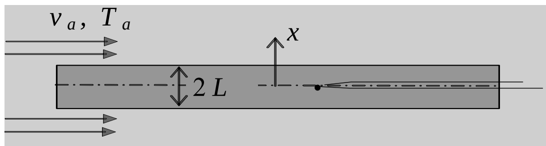

Fig. 1 Scheme of the drying experiment

In the case of an infinite flat plate the unsteady temperature, $T(x, t)$, and moisture content, $X(x, t)$, fields in the drying body are expressed by the following system of coupled nonlinear partial differential equations for energy and moisture transport

$$c\rho_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \varepsilon \Delta H \frac{\partial(\rho_s X)}{\partial t} \qquad (1)$$

$$\frac{\partial(\rho_s X)}{\partial t} = \frac{\partial}{\partial x}\left(D\rho_s \frac{\partial X}{\partial x}\right) \qquad (2)$$

The shrinkage effect of the drying body was incorporated through the changes of the specific volume of the drying body. There are several models for describing the changes of the specific volume of the body during drying. In this paper, linear relationship between the specific volume, v_s, and the moisture content, X, has been used.

$$v_s = \frac{1}{\rho_s} = \frac{V}{m_s} = \frac{1+\beta' X}{\rho_{b0}} \qquad (3)$$

The problem of the moving boundaries due to the changes of the dimensions of the body during the drying was resolved by introducing the dimensionless coordinate

$$\psi = \frac{x}{L(t)} \tag{4}$$

Substituting the above expression for ρ_s ($=1/v_s$) and ψ into Eqs. (1) and (2) and rearranging, the resulting system of equations for the temperature and moisture content prediction becomes

$$\frac{\partial T}{\partial t} = \frac{k}{\rho_s c}\frac{1}{L^2}\frac{\partial^2 T}{\partial \psi^2} + \frac{\psi}{L}\frac{dL}{dt}\frac{\partial T}{\partial \psi} + \frac{\varepsilon \Delta H}{c}\frac{\rho_s}{\rho_{b0}}\left(\frac{\partial X}{\partial t} - \frac{\psi}{L}\frac{dL}{dt}\frac{\partial X}{\partial \psi}\right) \tag{5}$$

$$\frac{\partial X}{\partial t} = D\frac{\rho_{b0}}{\rho_s}\frac{1}{L^2}\frac{\partial^2 X}{\partial \psi^2} + \left[\frac{\rho_{b0}}{\rho_s^2}\frac{1}{L^2}\frac{\partial (D\rho_s)}{\partial \psi} + \frac{\psi}{L}\frac{dL}{dt}\right]\frac{\partial X}{\partial \psi} \tag{6}$$

The initial conditions are

$$t = 0: \quad T(\psi,0) = T_0, \; X(\psi,0) = X_0 . \tag{7}$$

The temperature and the moisture content boundary conditions on the surfaces of the drying body in contact with the drying air are

$$-k\frac{1}{L}\left(\frac{\partial T}{\partial \psi}\right)_{\psi=1} + j_q - \Delta H(1-\varepsilon) j_m = 0 \tag{8}$$

$$D\rho_s \frac{1}{L}\left(\frac{\partial X}{\partial \psi}\right)_{\psi=1} + j_m = 0 \tag{9}$$

The convective heat flux, $j_q(t)$, and mass flux, $j_m(t)$, on these surfaces are

$$j_q = h\left(T_a - T_{x=L}\right) \tag{10}$$

$$j_m = h_D\left(C_{x=L} - C_a\right) \tag{11}$$

The water vapour concentration in the drying air, C_a, is calculated from

$$C_a = \frac{\varphi\, p_s(T_a)}{R_w\, T_{k,a}} \tag{12}$$

where φ is the relative humidity of the drying air and p_s is the saturation pressure. The water vapor concentration of the air in equilibrium with the surface of the body exposed to convection is calculated from

$$C_{x=L} = \frac{a(T_{x=L}, X_{x=L})\, p_s(T_{x=L})}{R_w\, T_{k,x=L}} \tag{13}$$

The water activity, a, or the equilibrium relative humidity of the air in contact with the convection surface at temperature $T_{x=L}$ and moisture content $X_{x=L}$ are calculated from experimental water sorption isotherms.

The boundary conditions on the mid-plane of the drying slice are

$$\left(\frac{\partial T}{\partial \psi}\right)_{\psi=0} = 0, \quad \left(\frac{\partial X}{\partial \psi}\right)_{\psi=0} = 0 . \tag{14}$$

Problem defined by Eqs. (5-14) is referred to as a direct problem when initial and boundary conditions as well as all the parameters appearing in the formulation are known. The objective of the direct problem is to determine the temperature and moisture content fields in the drying body.

In order to approximate the solution of Eqs. (5) and (6), an explicit numerical procedure has been used.

INVERSE APPROACH

For the inverse problem of interest here, the thermophysical properties and the boundary conditions parameters of a drying body are regarded as unknown parameters.

The estimation methodology used is based on the minimization of the ordinary least square norm

$$E(\mathbf{P}) = [\mathbf{Y} - \mathbf{T}(\mathbf{P})]^{\mathrm{T}}[\mathbf{Y} - \mathbf{T}(\mathbf{P})] . \tag{15}$$

Here, $\mathbf{Y}^{\mathrm{T}} = [Y_1, Y_2, \ldots, Y_{\mathrm{imax}}]$ is the vector of measured temperatures, $\mathbf{T}^{\mathrm{T}} = [T_1(\mathbf{P}), T_2(\mathbf{P}), \ldots T_{\mathrm{imax}}(\mathbf{P})]$ is the vector of estimated temperatures at time t_i (i = 1, 2, …, imax), $\mathbf{P}^{\mathrm{T}} = [P_1, P_2, \ldots P_N]$ is the vector of unknown parameters, imax is the total number of measurements, and N is the total number of unknown parameters (imax ≥ N).

A hybrid optimisation algorithm OPTRAN [7] and the Levenberg-Marquardt method [8, 9] have been utilized for the minimization of $E(\mathbf{P})$

representing the solution of the present parameter estimation problem.

The Levenberg-Marquardt method is a quite stable, powerful, and straightforward gradient search minimization algorithm that has been applied to a variety of inverse problems. It belongs to a general class of damped least square methods.

An alternative to the Levenberg-Marquardt algorithm, especially when searching for a global optimum of a function with possible multiple minima, is the hybrid optimization program OPTRAN. OPTRAN incorporates six of the most popular optimization algorithms: the Davidon-Fletcher-Powell gradient search, sequential quadratic programming algorithm, Pshenichny-Danilin quasi-Newtonian algorithm, a modified Nelder-Mead simplex algorithm, a genetic algorithm, and a differential evolution algorithm. Each algorithm provides a unique approach to optimization with varying degrees of convergence, reliability and robustness at different stages during the iterative optimization procedure. The hybrid optimizer OPTRAN includes a set of rules and switching criteria to automatically switch back and forth among the different algorithms as the iterative process proceeds in order to avoid local minima and accelerate convergence towards a global minimum.

THE DRYING BODIES PROPERTIES

In this paper, application of the proposed method for the estimation of the thermophysical properties of foods has been analyzed.

Heat capacity of food materials can be taken as equal to the sum of the heat capacity of solid matter and water absorbed by that solid

$$c = c_s + c_w X \qquad (16)$$

Although the heat capacities of solid matter, c_s, and water, c_w, are functions of the temperature, constant values have been most widely used.

Moisture diffusivity of foods is very often considered as an Arrhenius-type temperature function [10, 11]

$$D = D_0 \exp[-E_0/(R\,T_k)] \qquad (17)$$

with constant values of the Arrhenius factor, D_0, and the activation energy for moisture diffusion, E_0.

From [12] was concluded that for practical calculations the system of the two simultaneous partial differential equations could be used by treating the thermal conductivity, k, and the phase conversion factor, ε, as constants.

The variation in water activity with change in moisture content of samples at a specified temperature is defined by sorption isotherms. In this paper, the most widely accepted and efficient model for sorption isotherms of foods, the Guggenheim-Anderson-de Boer (GAB) model [13] has been used.

PARAMETERS ESTIMATION ANALYSIS

For the inverse problem of interest here, the moisture diffusivity parameters, together with other thermophysical properties of the potato as well as the heat and mass transfer coefficients and the relative humidity of the drying air, are treated as unknown parameters.

Thus, in the inverse problem the analyzed vector of the unknown parameters was

$$\mathbf{P}^T = [D_0, E_0, \rho_s, c_s, k, \varepsilon, h, h_D, \varphi] \qquad (18)$$

For the simultaneous estimation of these unknown parameters, the transient reading of a single temperature sensor located at the position $x = 0$, has been considered.

An analysis of the influence of the drying air velocity, temperature and relative humidity, drying body dimensions, and drying time on the unknown parameters estimation, enables the design of appropriate experiments to be conducted as well. In order to realize this analysis, the sensitivity coefficients and the determinant of the information matrix were calculated.

The sensitivity coefficients analysis has been carried out for an infinite flat plate model of a slices of potato and apple with initial moisture content of $X(x, 0) = 5.00$ kg/kg and 6.00 kg/kg respectively and initial temperature $T(x, 0) = 20.0$ ^oC. The drying air bulk temperature, T_a, was varied between 40 ^oC and 80 ^oC, the convection heat transfer coefficient between 27 and 33 W m^{-2} K^{-1}, and the initial thickness of the slices, $2L_0$, between 2 and 6 mm.

From the sensitivity coefficients analysis the following experimental parameters were chosen: T_a = 60 ^oC, $2L_0$ = 3 mm, h = 30 W m^{-2} K^{-1}, $h_D = 3.36\text{x}10^{-2}$ m s^{-1} and $\varphi = 0.1$. Figure 2 shows the relative sensitivity coefficients $P_j \partial T_i/\partial P_j$, i = 1, 2,…, imax, for temperature with respect to the unknown parameters, for this case, for potato.

The relative sensitivity coefficients for apple are very similar.

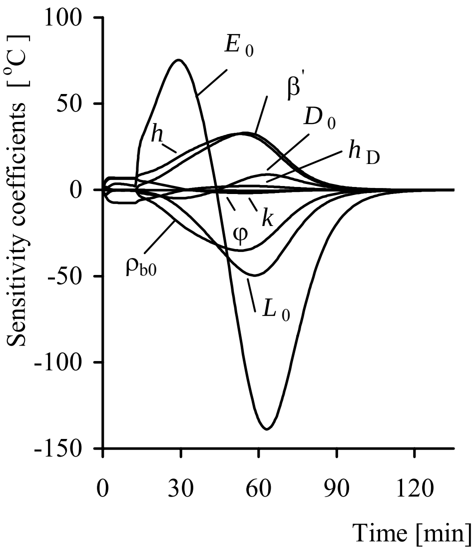

Fig. 2 Relative sensitivity coefficients

It can be seen that the relative sensitivity coefficients with respect to the phase conversion factor, ε, and the thermal conductivity, *k*, are very small. This indicates that ε and *k* cannot be estimated in this case. This also indicates that the influence of the phase conversion factor and the thermal conductivity on the transient moisture content and temperature profiles is very small in this case. This can be explained by the very small heat transfer Biot number and consequently very small temperature gradients inside the body during the drying process. For these reasons, the phase conversion factor and the thermal conductivity were treated as known quantities for the examination described below.

The heat capacity of wet potato was taken as equal to the sum of the heat capacity of solid matter and absorbed water, Eq. (16). Since the heat capacity of the solid matter, c_s, presents only a few percent of the overall heat capacity of the potato, the relative sensitivity coefficients with respect to the heat capacity of solid matter is also very small. Consequently, the value of the heat capacity of the solid matter was also taken as known.

The relative sensitivity coefficients with respect to the density of the fully dried body, ρ_{b0}, and the shrinkage coefficient, β', are relatively high. Despite this, because the shrinkage effect of the drying body was incorporated through the changes of the specific volume of the drying body, these parameters were determined by separate experiments.

The relative sensitivity coefficients with respect to the initial potato slice thickness are high as well, but the initial slice thickness was measured with sufficient accuracy, so it is also taken as a known parameter.

It can be seen that the temperature sensitivity coefficient with respect to the convection mass transfer coefficient h_D is very small relative to the temperature sensitivity coefficient with respect to the convection heat transfer coefficient, *h*. The very high mass transfer Biot number and the very small heat transfer Biot number can explain this. To overcome this problem, in this paper the mass transfer coefficient was related to the heat transfer coefficient through the analogy between the heat and mass transfer processes in the boundary layer over a drying body [2]

$$h_D = 0.95 \frac{D_a}{k_a} h \qquad (19)$$

where D_a and k_a are the moisture diffusivity and thermal conductivity in the air, respectively. The obtained relation is very close to the well-known Lewis relation. By using the above relation between the heat and mass transfer coefficients, they can be estimated simultaneously, so that only the heat transfer coefficient is regarded as an unknown parameter.

Determinant of the information matrix with normalized elements has been calculated in order to define drying time. Elements of this determinant of the information matrix were defined for a large, but fixed number of transient temperature measurements. The duration of the drying experiment corresponding to the maximum determinant value was used for the computation of the unknown parameters. The maximum determinant of the information matrix corresponds to the drying time when nearly equilibrium moisture content and temperature profiles have been reached.

EXPERIMENTAL

Real experiments have been conducted to investigate the applicability of the method to food processing, when involving drying of thin flat samples. The experiments have been conducted on the experimental setup that is designed to simulate an industrial convective dryer.

Drying of approximately three millimeter thick potato or apple slices have been examined. The slices have been in contact with the drying air from the top and the bottom surfaces. Two shelves, (Fig. 3), each holding three moist slices have been introduced into the rectangular experimental channel of dimensions 25 x 200 mm.

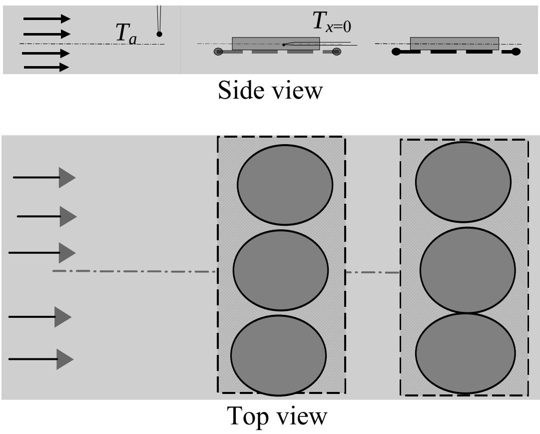

Fig. 3 Scheme of the drying experiment

A micro-thermocouple was inserted in the midplane of each of the three slices on the first shelf. An arithmetical mean of the readings from the three thermocouples was used as a transient temperature reading, for the estimation of the unknown parameters. The slices on the second shelf were weighed every ten minutes in order to obtain the volume-averaged moisture content change during drying. The temperature of the drying air, T_a, has been recorded as well. The initial moisture content, X_0, and the initial slices thickness, $2L_0$, were measured for each of the experiments.

RESULTS AND DISCUSSION

From the above relative sensitivity coefficients analysis it was concluded that in the convective drying experiment it is possible, based on a single thermocouple temperature response, to estimate simultaneously the moisture diffusivity, the convection heat and mass transfer coefficients, and the relative humidity of the drying air. All other quantities appearing in the direct problem formulation were taken as known.

Potato

Our experimental results for the changes of the specific volume of drying potato slices, confirm the expression (3) with ρ_{b0} = 755 kg m^{-3} and the shrinkage coefficient β' = 0.57. The heat capacity was calculated from Eq. (16). The following values, proposed in reference [14] for potatoes, were used: c_s = 1381 J kg^{-1} K^{-1}, and c_w = 4187 J kg^{-1} K^{-1}. A mean value of k = 0.40 W m^{-1} K^{-1} from the results obtained in [15] for the thermal conductivity of potato was utilized in this paper. The influence of the phase conversion factor ($0 \le \varepsilon \le 1$) on the transient moisture content and temperature profiles is very small. A mean value of ε = 0.5 was used in the paper. For the GAB isotherm equation parameters the Gane experimental results for potatoes [13, p. 45] were used in this paper ($C_0 = 6.609\cdot10^{-1}$; ΔH_C = 528.4 kJ kg^{-1}; K_0 = 0.606; ΔH_K = 53.33 kJ kg^{-1}; ΔH_X = 123.6 kJ kg^{-1}), except for X_{m0}. The value of $X_{m0} = 3.8\cdot10^{-2}$ was obtained from our experimental results.

A number of drying experiments with similar experimental conditions, (T_a = 56.6-59.5 ^{O}C, $2L_0$ = 2.36-3.14 mm, X_0 = 3.70-4.83 kg/kg and T_0 = 14.9-17.7 ^{O}C), have been carried out.

Table 1 shows the computationally obtained parameters and RMS-error for potato, for experiment P1: T_a = 58.13 ^{O}C, $2L_0$ = 3.14 mm, X_0 = 4.80 kg/kg and T_0 = 17.53 ^{O}C.

Table 1 Estimated parameters and RMS-error

	Potato	**Apple**
$D_0\cdot10^3$ [m^2 s^{-1}]	7.985	63.905
E_0 [kJ mol^{-1}]	43.3	50.215
h [W m^{-2} K^{-1}]	31.08	24.137
$h_D\cdot10^2$ [m s^{-1}]	3.48	2.70
φ [-]	0.0899	0.1011
RMS [^{O}C]	0.55	0.64

In Fig. 4 the estimated moisture diffusivities are compared with the results published by other authors [16]. Estimated moisture diffusivities compare well with the values obtained by other authors who utilized different methods.

In Fig. 5 the experimental transient temperature reading, $T_{x=0}$, and the experimental volume-averaged moisture content change during drying are compared with numerical solutions for the estimated parameters. Very good agreements were obtained.

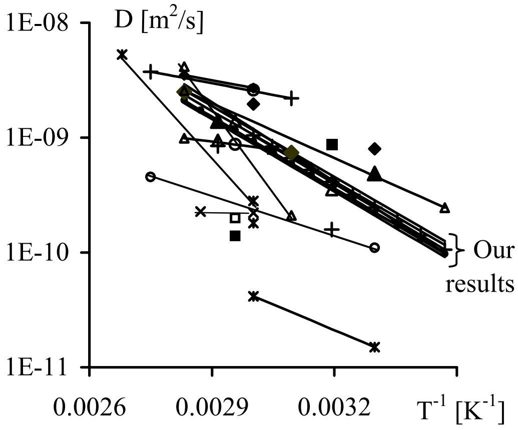

Fig. 4 Moisture diffusivity of potatoes

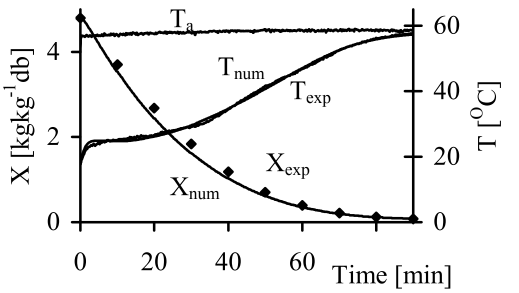

Fig. 5 The mid-plane temperature, T, the temperature of the drying air, T_a, and the volume-averaged moisture content, X, changes during the drying of a potato slice

Apple

In the case of apple the values of the appropriate thermophysical parameters used are:

ρ_{b0} = 768 kg m^{-3}; β' = 0.75, [16],
c_s = 1415 J kg^{-1} K^{-1}; c_w = 4187 J kg^{-1} K^{-1}, [14],
k = 0.35 W m^{-1} K^{-1}, [15],
ε = 0.5, [12]
C_0 = 0.013; ΔH_C = 12.32 kJ mol^{-1};
K_0 = 1.38; ΔH_K = -0.92 kJ mol^{-1};
ΔH_X = 1.47 kJ mol^{-1}, [13]
X_{m0} = 6.21·10^{-2} kg kg^{-1} db, [16].

Table 1 shows the computationally obtained parameters and RMS-error for apple, for experiment A1: T_a = 60.17 ^{O}C, $2L_0$ = 2.96 mm, X_0 = 6.46 kg/kg and T_0 = 16.91 ^{O}C.

In Fig. 6 the estimated moisture diffusivities for apples are compared with the results published by other authors [16].

In Fig. 7 the experimental transient temperature reading, $T_{x=0}$, and the experimental volume-averaged moisture content change during the convective drying of a apple slice are compared with numerical solutions. Very good agreement between the experimental and numerical temperature and moisture content changes during the drying has been obtained as well.

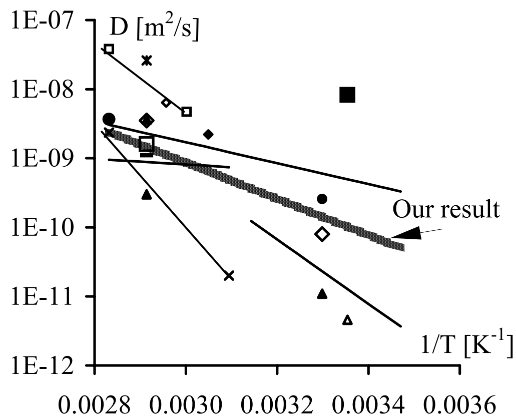

Fig. 6 Moisture diffusivity of apples

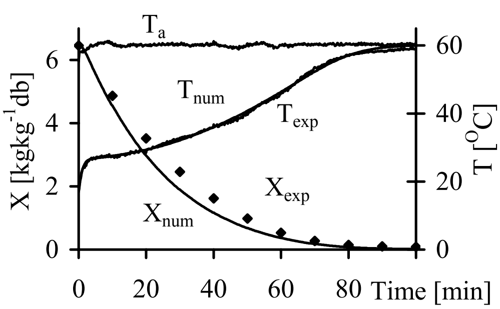

Fig. 7 Time-variations during drying of apple: The mid-plane temperature, T, the temperature of the drying air, T_a, and the volume-averaged moisture content, X

CONCLUSIONS

The inverse problem of simultaneous estimation of thermophysical properties and the boundary condition parameters of drying foods by using only temperature measurements has been analyzed in this paper. For this, a mathematical model of drying of shrinking bodies has been developed. As a representative drying vegetable product, the potato has been chosen and as a representative fruit product the apple has been chosen.

For the estimation of the unknown parameters, the transient readings of a single temperature sensor located in the midplane of the slice exposed to convective drying have been used. The Levenberg-Marquardt and the hybrid optimization method OPTRAN were applied for evaluation of the unknown parameters.

It can be concluded that in the convective drying experiments of apples and potatoes it is possible, based on a single thermocouple temperature response, to estimate simultaneously the two moisture diffusivity parameters, the convection heat and mass transfer coefficients, and the relative humidity of the drying air.

Estimated moisture diffusivities compare well with the values obtained by other authors who utilized different methods.

Very good agreement between the experimental and numerical temperature and volume-averaged moisture content changes during drying has been obtained.

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