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INVERSE APPROACHES TO DRYING WITH AND WITHOUT SHRINKAGE

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Abstract: This paper deals with the application of inverse concepts in drying of bodies with and without significant shrinkage effects. The inverse problem is analyzed for simultaneous estimation of thermophysical properties and the boundary conditions parameters of a drying body. For the estimation of the unknown parameters, the transient readings of a single temperature sensor located in the mid-plane of the slice exposed to convective drying have been used. A mixture of bentonite and quartz sand was chosen as a representative body with negligible shrinkage effect during drying, and a potato as a representative drying body with significant shrinkage effect.

Keywords: inverse approach, drying, thermophysical properties, potato, shrinkage

INTRODUCTION

An inverse approach to parameter estimation in the last few decades has become widely used in various scientific disciplines. Kanevce, Kanevce and Dulikravich (2000, 2000a, 2002, 2004, 2005, 2005a) and Dantas, Orlande and Cotta (2000, 2001, 2002) recently analysed application of inverse approaches to estimation of drying body parameters.

In this paper the drying body moisture content and temperature field 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.

The main idea of the present method is to make use of the interrelation between the heat and mass (moisture) transport processes within the drying body and from its surface to the surroundings. Then, the drying body properties can be estimated on the basis of accurate and easy to perform single thermocouple temperature measurements by using an inverse approach.

This paper deals with the application of inverse concepts in drying of bodies with and without significant shrinkage effects.

The inverse problem is analyzed for simultaneous estimation of thermophysical properties and the boundary conditions parameters of a drying body by using only temperature measurements. For estimation of the unknown parameters, the transient readings of a single temperature sensor located in the mid-plane of the slice exposed to convective drying have been used.

A potato slice was chosen as a representative drying body with significant shrinkage effect. A model material, made of a mixture of bentonite and quartz sand, was chosen as a representative body with negligible shrinkage effect during drying.

An analysis of the influence of the drying air velocity, drying air temperature, drying body dimension, and drying time that enables the design of the proper experiments by using the so-called D-optimum criterion is conducted as well. In order to perform this analysis, sensitivity coefficients and determinant of the information matrix were calculated.

A MATHEMATICAL MODEL OF DRYING

The physical problem involves a single slice of a potato of thickness 2L 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 mid-plane of the slice. The thickness of the body changes during drying from $2L_0$ to $2L_f$.

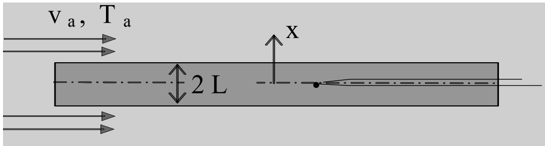

Fig. 1. Scheme of the drying experiment

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

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

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

Here, t, x, c, k, ΔH, ε, D, ρ_s are time, normal distance from the mid-plane of the plate, specific heat, thermal conductivity, latent heat of vaporization, ratio of water evaporation rate to the reduction rate of the moisture content, moisture diffusivity, and density of dry solid, respectively.

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

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

where m_s is the mass of the dry material of the drying body, V is the volume of the drying body, ρ_{b0} is the density of a fully dried body and β' is the shrinkage coefficient.

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

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

The resulting system of equations for the temperature and moisture content prediction becomes

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

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

The initial conditions are

$$t = 0 \quad T(\psi, 0) = T_0, \; X(\psi, 0) = X_0. \qquad (7)$$

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

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

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

$$j_q = h\left(T_a - T_{\psi=1}\right)$$
$$j_m = h_D\left(C_{\psi=1} - C_a\right) \qquad (9)$$

where h is the heat transfer, and h_D is the mass transfer coefficient, T_a is the temperature of the drying air and $T_{\psi=1}$ is the temperature on the surfaces of the drying body. The water vapour concentration in the drying air, C_a, is calculated from

$$C_a = \frac{\varphi \, p_s(T_a)}{R_w \, T_{k,a}} \qquad (10)$$

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

$$C_{x=L} = \frac{a(T_{\psi=1}, X_{\psi=1}) \, p_s(T_{\psi=1})}{R_w \, T_{k,\psi=1}}. \qquad (11)$$

The water activity, a, or the equilibrium relative humidity of the air in contact with the convection surface at temperature $T_{\psi=1}$ and moisture content $X_{\psi=1}$ are calculated from experimental water sorption isotherms.

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

$$\left(\frac{\partial T}{\partial \psi}\right)_{\psi=0} = 0, \quad \left(\frac{\partial X}{\partial \psi}\right)_{\psi=0} = 0. \qquad (12)$$

Problem defined by equations (5-12) is referred to as a direct problem when initial and boundary conditions as well as all 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 equations (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

$$E(\mathbf{P}) = [\mathbf{Y} - \mathbf{T}(\mathbf{P})]^T [\mathbf{Y} - \mathbf{T}(\mathbf{P})] . \qquad (13)$$

Here, $\mathbf{Y}^T = [Y_1, Y_2, \ldots, Y_{imax}]$ is the vector of measured temperatures, $\mathbf{T}^T = [T_1(\mathbf{P}), T_2(\mathbf{P}), \ldots T_{imax}(\mathbf{P})]$ is the vector of estimated temperatures at time t_i (i = 1, 2, …, imax), $\mathbf{P}^T = [P_1, P_2, \ldots P_N]$ 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 (Dulikravich et al., 1999) and the Levenberg-Marquardt method (Marquardt, 1963, Ozisik and Orlande, 2000) have been utilized for the minimization of E(**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 optimisation program OPTRAN. OPTRAN incorporates six of the most popular optimisation algorithms: the Davidon-Fletcher-Powell gradient search, sequential quadratic programming (SQP) algorithm, Pshenichny-Danilin quasi-Newtonian algorithm, a modified Nelder-Mead (NM) simplex algorithm, a genetic algorithm (GA), and a differential evolution (DE) algorithm. Each algorithm provides a unique approach to optimisation with varying degrees of convergence, reliability and robustness at different stages during the iterative optimisation procedure. The hybrid optimiser 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.

RESULTS AND DISCUSSIONS

The proposed method of simultaneous estimation of the thermophysical properties of a drying body as well as the heat and mass transfer coefficients, by using only temperature measurements, was tested for a model material and a potato.

Model material

A model material made of a mixture of bentonite and quartz sand was chosen as a representative body with negligible shrinkage effect during the drying (β'= 0).

From the experimental and numerical examinations of the transient moisture and temperature profiles (Kanevce, 1998) it was concluded that in this case, the system of two partial differential equations (5) and (6) can be used by treating all the coefficients except for the moisture diffusivity as constants. The appropriate mean values are (Kanevce, 1998):

density of the dry solid , ρ_s = 1738 kgm^{-3},
heat capacity, c = 1550 JK^{-1}kg^{-1}db,
thermal conductivity, k = 2.06 Wm^{-1}K^{-1},
latent heat of vaporization, $\Delta H = 2.31 \cdot 10^6$ Jkg^{-1},
phase conversion factor, ε = 0.5.

The following expression can describe the experimentally obtained relationship for the moisture diffusivity

$$D = 9.0 \cdot 10^{-12} X^{-2} \left(\frac{T_k}{303} \right)^{10} . \qquad (14)$$

The experimentally obtained desorption isotherms of the model material are presented by the empirical equation

$$a = 1 - \exp(-1.5 \cdot 10^6 T_k{}^{-0.91} X^{-0.005\,(T+273)+3.91}) . \qquad (15)$$

For the inverse problem investigated here, values of the moisture diffusivity, D, density of the dry solid, ρ_s, heat capacity, c, thermal conductivity, k, phase conversion factor, ε, heat transfer coefficient, h and mass transfer coefficient, h_D are regarded as unknown.

Here the moisture diffusivity of the model material has been represented by the following function of temperature and moisture content

$$D = D_X X^{-2} \left(\frac{T_k}{303} \right)^{D_T} . \qquad (16)$$

where D_X and D_T are constants.

Thus, we analysed the following vector of unknown parameters

$$\mathbf{P}^T = [D_X, D_T, \rho_s, c, k, \varepsilon, h, h_D] . \qquad (17)$$

For the estimation of these unknown parameters, the transient readings of a single temperature sensor located in the mid-plane of the sample was considered (Fig. 1).

The relative sensitivity coefficient, $P_m \partial T_i / \partial P_m$, i = 1 , 2,…, imax, m = 1, 2, …, N, analysis was carried out in order to define the influence of the drying air velocity and temperature and drying body dimension (Kanevce et al., 2000b, 2002, 2005a). Following the conclusions of these previous works the selected drying air bulk temperature, speed, and relative humidity were $T_a = 80\ ^{O}C$, $v_a = 10\ ms^{-1}$ and $\varphi = 0.12$, respectively, and the plate thickness, 2L = 4 mm. The initial moisture content was $X(x, 0) = 0.20\ kgkg^{-1}$ and initial temperature $T(x, 0) = 20\ ^{O}C$. Fig. 2 shows the relative sensitivity coefficients for temperature with respect to all unknown parameters, m = 1, 2,…,8.

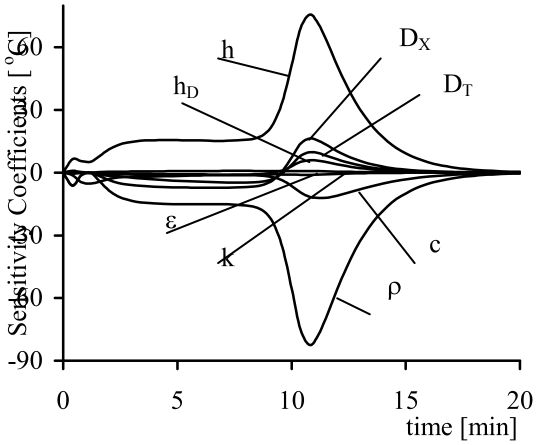

Fig. 2. Relative sensitivity coefficients

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 ($Bi = hL/k \leq hL_0/k = 0.08$) and consequently very small temperature gradients inside the body during drying. For these reasons, the phase conversion factor and the thermal conductivity were treated as known quantities for the examination described below.

The relative sensitivity coefficients with respect to the dry material density, ρ_s, and the convection heat transfer coefficient, h, are linearly-dependent. This makes it impossible to simultaneously estimate ρ_s and h. Due to these reasons and to the fact that the density of the dry material can be relatively easily determined by a separate experiment, the density of the dry material was assumed as known for the inverse analysis.

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 the drying body (Kanevce et al., 2003)

$$h_D = 0.95 \frac{D_a}{k_a} h \qquad (18)$$

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.

Thus, it appears to be possible to estimate simultaneously the moisture diffusivity parameters, D_X and D_T, the heat capacity, c, the convection heat transfer coefficient, h, and the mass transfer coefficient, h_D, by a single thermocouple temperature response in a thin drying plate.

Determinant of the information matrix $\mathbf{J}^T\mathbf{J}$ with normalized elements

$$[\mathbf{J}^T\mathbf{J}]_{m,n} = \sum_{i=1}^{i\,max} \left(P_m \frac{\partial T_i}{\partial P_m} \right) \left(P_n \frac{\partial T_i}{\partial P_n} \right),\ m, n = 1,N \qquad (19)$$

has been calculated in order to define drying time. Fig. 3 presents transient variations of the determinant of the information matrix if D_X, D_T, c, and h, are simultaneously considered as unknown parameters. Elements of this determinant of the information matrix were defined for a large, but fixed number of transient temperature measurements (101 in this case).

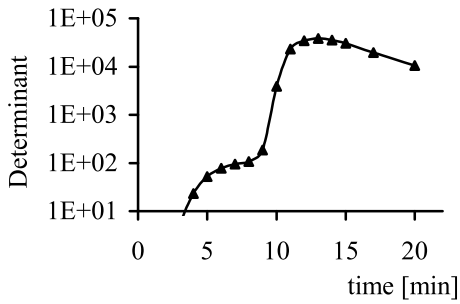

Fig. 3. Determinant of the information matrix

The duration of the drying experiment (the drying time) 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.

The transient readings of the single temperature sensor located in the mid-plane of the sample were obtained by simulated experiments. The experimental data were obtained from the numerical solution of the direct problem presented above, by treating the values and expressions for the material properties as known. In order to simulate real measurements, a normally distributed error with zero mean and standard deviation, σ of 1.0 and 1.5 ^{O}C was added to the numerical temperature response (Fig. 4).

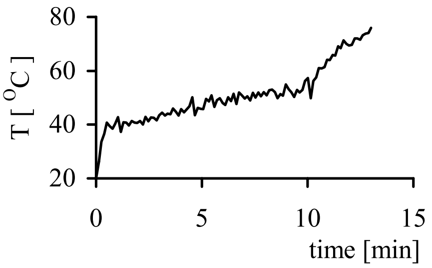

Fig. 4. Temperature response with a noise σ = 1.5 ^{O}C

Table 1 shows the estimated parameters for σ = 1.0, (Case A1.0), and 1.5 ^{O}C, (Cases A1.5 and B1.5). For comparison, the values of exact parameters and the values estimated with errorless, σ =0, (Case A0) temperature data are shown in this table.

Table 1. Estimated parameters and relative errors

Case	$D_X \cdot 10^{12}$ [$m^2 s^{-1}$]	D_T [-]	c [$Jkg^{-1}K^{-1}$]	h [$Wm^{-2} K^{-1}$]	$h_D \cdot 10^2$ [ms^{-1}]
A0 |ε| [%]	8.99 0.1	10.00 0.0	1551 0.1	83.1 0.0	9.29 0.0
A1.0 |ε| [%]	8.83 1.9	10.20 2.0	1600 3.2	83.4 0.4	9.33 0.4
A1.5 |ε| [%]	8.82 2.0	10.17 1.7	1620 4.5	83.5 0.5	9.34 0.5
B1.5 |ε| [%]	8.89 1.2	10.02 0.2		83.0 0.1	9.28 0.1
Exact values	9.00	10.0	1550	83.1	9.29

Table 1 also shows the relative errors of the estimated parameters, ε. They are within 5%, and depend on the noise, σ, (cases A0 to A1.5).

In the case B1.5 the heat capacity, c, was assumed as known. From the obtained results in this case, it appears to be possible to estimate simultaneously with very high accuracy, the moisture diffusivity parameters, D_X and D_T, and the heat and mass transfer coefficients, h and h_D, by a single thermocouple temperature response even in the case with the relatively high noise of 1.5 ^{O}C.

Potato

A potato was chosen as a representative drying body with significant shrinkage effect.

Real experiments have been conducted to investigate the applicability of the method in this case. The experiments have been conducted on the experimental setup that is designed to imitate an industrial convective dryer.

Drying of potato slices approximately three millimetres thick have been examined. The slices have been in contact with the drying air from the top and the bottom surfaces. Two shelves, (Fig. 5), each holding three moist potato slices, have been introduced into the rectangular experimental channel of dimension 25 x 200 mm. A micro-thermocouple was inserted in the mid-plane, (x = 0), 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, ($T_{x=0}$), for the estimation of the unknown parameters. The potato 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 potato slices thickness, $2L_0$, was measured for each of the experiments.

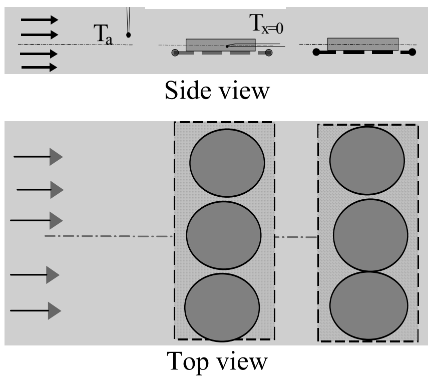

Fig. 5. Scheme of the experimental arrangement

From the sensitivity coefficients analysis the following experimental parameters were chosen: T_a = 60 ^{O}C, $2L_0$ = 3 mm, h = 30 $Wm^{-2}K^{-1}$, h_D = 3.36x10^{-2} ms^{-1} and φ = 0.09.

From the relative sensitivity coefficients analysis it was also concluded that the moisture diffusivity, the convection heat and mass transfer coefficients, and the relative humidity of the drying air, can be estimated simultaneously in this case. All other quantities appearing in the direct problem formulation were taken as known.

The relation (18) was used for simultaneous estimation of the heat and mass transfer coefficients, though only the heat transfer coefficient is regarded as an unknown parameter.

Our experimental results for the changes of the specific volume of drying potato slices, (Fig. 6), confirm the expression (3) with ρ_{b0} = 755 kgm^{-3} and the shrinkage coefficient β' = 0.57.

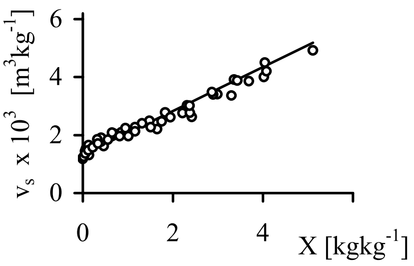

Fig. 6. Change of the specific volume of potato slices

The heat capacity was calculated as equal to the sum of the heat capacity of solid matter and water absorbed by that solid

$$c = c_s + c_w.X \ . \qquad (20)$$

The following values, proposed by Niesteruk (1996) for potatoes, were used: c_s = 1381 J kg^{-1}K^{-1}, and c_w = 4187 Jkg^{-1}K^{-1}.

A mean value from the results obtained by Donsi et al. (1996), for the thermal conductivity of potato, k = 0.40 Wm^{-1}K^{-1} was utilized in this paper.

The influence of the phase conversion factor on the transient moisture content and temperature profiles is very small. A mean value, ε = 0.5 was used in the paper.

The GAB sorption isotherm equation with the Gane experimental parameters for potatoes (Rahman, 1995) were used in this paper ($C_0 = 6.609\cdot10^{-1}$; ΔH_c = 528.4 kJkg^{-1}; K_0 = 0.606 ; ΔH_k = 53.33 kJkg^{-1}; ΔH_x = 123.6 kJkg^{-1}), except for the X_{m0}. The value of X_{m0} = $3.8\cdot10^{-2}$ was obtained from our experimental results.

The moisture diffusivity is considered as an Arrhenius-type temperature function

$$D = D_0 \ \exp[-E_0/(R\ T_k)] \qquad (23)$$

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

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 kgkg^{-1} and T_0 = 14.9-17.7 ^{O}C), have been carried out. The experimental drying time was estimated from the determinant of the information matrix. The maximum determinant value corresponds to the drying time when nearly equilibrium moisture content and temperature profiles have been reached.

Table 2 shows the computationally obtained parameters and RMS-error for the experiment E1: T_a = 58.13 ^{O}C, $2L_0$ = 3.14 mm, X_0 = 4.80 kgkg^{-1} and T_0 = 17.53 ^{O}C.

Table 2. Estimated parameters and RMS-error

	Estimated	Initial guess
$D_0\cdot10^3$ [m^{2}s^{-1}]	7.985	0.25
E_0 [kJmol^{-1}]	43.3	35
h [Wm^{-2}K^{-1}]	31.08	25
$h_D\cdot10^2$ [ms^{-1}]	3.48	2.8
φ [-]	0.0899	0.125
RMS [^{O}C]	0.55	4.93

In Fig. 7 the estimated moisture diffusivities are compared with the results published by other authors that used different methods.

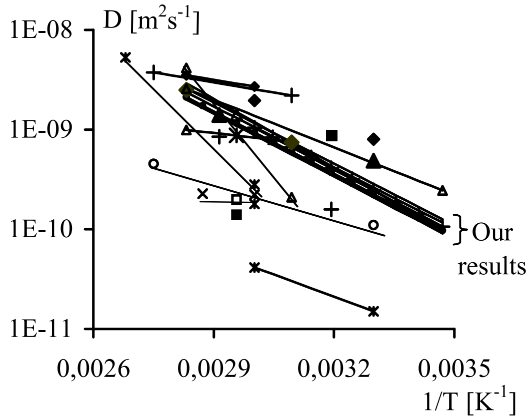

Fig. 7. Moisture diffusivity of potatoes

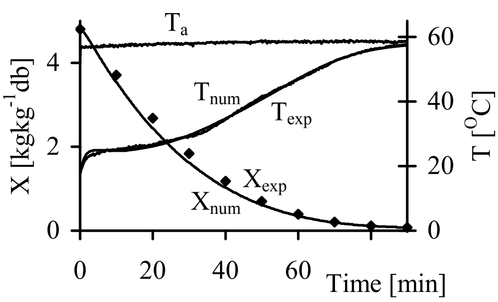

Fig. 8. The mid-plane temperature, T, the temperature of the drying air, T_a, and the volume-averaged moisture content, X, changes during the drying of a potato slice

In Fig. 8 the experimental transient temperature reading, $T_{x=0}$, and the experimental volume-averaged moisture content change during the convective drying of a potato 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.

CONCLUSIONS

The inverse problem of simultaneous estimation of thermophysical properties and the boundary condition parameters of drying bodies with and without significant shrinkage effects by using only temperature measurements has been analysed in this paper. For the estimation of the unknown parameters, the transient readings of a single temperature sensor located in the mid-plane of the slice exposed to convective drying have been used.

A model material, made of a mixture of bentonite and quartz sand, was chosen as a representative body with negligible shrinkage effect during the drying and, a potato was chosen as a representative drying body with significant shrinkage effect. To do that, a mathematical model of drying of shrinking bodies has been developed.

The Levenberg-Marquardt and the hybrid optimisation method OPTRAN were applied for evaluation of the unknown parameters.

It can be concluded that in the case of the model material the two moisture diffusivity parameters and the heat capacity of the drying body together with the heat and mass transfer coefficients can be simultaneously estimated.

In the case of a potato slice it can be concluded that in the convective drying experiment 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.

Other material as well as other models for describing the moisture content and temperature-dependent moisture diffusivity could be analysed in the future.

NOMENCLATURE

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

Greek letters

β'	shrinkage coefficient	-
δ	thermo-gradient coefficient	K^{-1}
ε	phase conversion factor	-
μ	damping parameter	-
ρ	density	kgm^{-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

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