TWO-DIMENSIONAL MATHEMATICAL MODEL FOR SIMULATION OF THE DRYING PROCESS OF THICK LAYERS OF NATURAL MATERIALS IN A CONVEYOR-BELT DRYER

by

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This paper presents the mathematical model and numerical analysis of the convective drying process of thick slices of colloidal capillary-porous materials slowly moving through conveyor-belt dryer. A flow of hot moist air was used as drying agent. The drying process has been analyzed in the form of a 2-D mathematical model, in two directions: along the conveyor and perpendicular on it. The mathematical model consists of two non-linear differential equations and one equation with a transcendent character and it is based on the mathematical model developed for drying process in a form of a 1-D thin layer. The appropriate boundary conditions were introduced. The presented model is suitable for the automated control of conveyor-belt dryers. The obtained results with analysis could be useful in predicting the drying kinetics of potato slices and similar natural products.

Key words: *drying, thick layer, conveyor-belt dryer, modeling,
              automatic control, simulation*

Introduction

Drying as a method for the preservation of food has been used for centuries. Dried food retains its biological and nutritional values and is resistant to the influence of mold and bacteria.

The drying process of the group of colloidal capillary-porous materials, where natural materials belong, is one of the most complex processes to study. Natural agricultural products are dried by using different types of drying technologies. The transfer of humidity from some substance into drying agent, usually hot moist air, is a complex process of heat necessary for that process and mass transfer.

Many studies have been done on the transfer of heat and moisture during the drying process of natural materials like wood, vegetables, fruits, medical herbs, *etc.* The review of the generally used 1-D analytical models of drying agriculture products based on a thin-layer has been presented in [1-4]. A non-linear partial differential equation was solved numerically [5, 6], and a linear correlation was considered between the thickness of the material and its moisture content. In [7, 8] the importance of internal and external heat transfers in a contact dryer was highlighted.

The 2-D models were introduced in a case where the thickness of the dried materials could not be neglected. In [9, 10] the finite-volume method was used to solve the numerical

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model of a conveyor-dryer. In [11] the drying process of a packed bed of porous particles by using superheated steam and humid air is modeled by 1-D mathematical model of heat and mass transfer. The governing partial differential equations, which were transformed into a non-similar form by using a special transformation is presented in [12]. The resulting partial differential equations were solved numerically by using an implicit finite difference method. In [13] the industrial dryer used for the moisture removal from wet raisins was investigated and gave suggestion for the controller according to drying model. A method of lines and without involving any adjustable parameter or numerically solving the dynamic 2-D model for drying of mate leaves (*Ilex paraguariensis*) is presented in [14]. In [15] drying of corn grains in conveyor dryer was analyzed and numerical solution using finite-volume method were presented.

In this paper an original 2-D mathematical model for defining the essential drying parameters of a movable layer of thick slices of colloidal capillary-porous materials in a conveyor-belt dryer, using hot moist air as the drying agent, is presented. The background of this model is presented in [1] where the drying process was analyzed in the form of a 1-D *thin layer*. It could be used for defining the drying kinetics of potatoes and similar natural products. Obtained mathematical equations could be used for the automated control of the drying process.

Methodology and material

Previously presented models have structure which is not applicable for the automated control of a convective drying process in industrial conveyor dryers. They are developed for drying material which does not move through the steam of a drying agent. Also, determination of drying kinetics curves of the whole layer by experiments and defining dependences using the average values of the number of particles of the material and moisture content in the layer is insufficient to study the drying process of the thick layer of the natural materials. The main reason is that changes of parameters values along the height of the thick layer have non-linear variation.

The here presented method and model for the determination of drying kinetics curves is based on the experimental results obtained in the Vinča Institute of Nuclear Science, Belgrade, and have been presented in [16-19]. The main improvement of the model is made by introducing the corrective coefficient in balance equations of moisture and heat for the thick layer of drying material which is moving through stream of drying agent in the industrial conveyor dryers.

The method of a *thick layer* of natural materials is based on the model and results obtained in the previous study of drying kinetics of a *thin layer*, presented in [1]. The *thin layer* height is small enough and all the changes of the drying parameter values along its height are linear and differentially small. The *thick layer* is divided into a number of *thin layers* which influence each other. The previously defined model [1] is now used for defining the changes of drying parameters inside the *thick layer* by numerically solving partial differential equations, obtained on the basis of material and heat balance of each of the *thin layers*.

The following types of resistance are typical during the convective drying process:
– external resistance of moist convection from the material surface to the drying agent, and
– internal resistance of moist conduction from the inside of the material up to its surface.

The theory of heat and mass transfer explained the first process in detail. The second one is much more complex and it depends on many factors and requires a lot of experimental work for each natural product separately. Some of results were presented in [16-18, 20-24].

The presented algorithm was used for modeling the drying process of thick layers consists of small potato cubes. Potato (*Solanum tuberosum*) was chosen because dried potato

has widespread use in the food industry. According to [25] approximately 75% of all dried food in Russia belongs to dried potato products. In Serbia 80% of all annual production belongs to *Desiree* potato varieties. That potato variety was used for the experiments in [16-18] and all necessary input data for here presented numerical simulation are used from those references.

The mathematical model

The conveyor-belt dryer for natural products (vegetables, fruits, medical herbs, *etc.*), which is used for this analyze, consists of several segments. The schematic view of the first segment is presented on fig. 1 [1, 19].
It consists of a belt conveyor which moves small particles of moist material slowly through the flow of the drying agent. Small particles of moist material have the approximate shape as cubes with average thickness of $h = 48$ mm. They make porous thick layer of moisture material. The drying agent is preheated moist air with exactly defined characteristics. The drying agent flows through the belt conveyor and through the gaps between slices of the moist material up from the bottom, perpendicularly to the moving direction of the moist material. Each segment has its own belt conveyor, 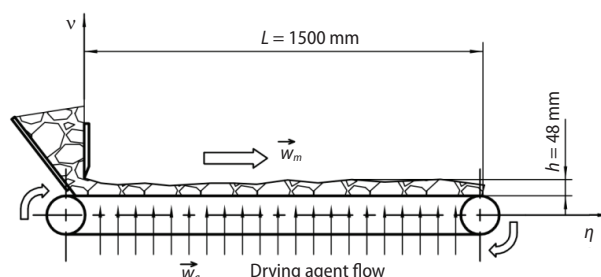fan and heater for the drying agent. The velocity of the belt conveyor in each segment is different, as well as the flow velocity and temperature of the drying agent.

Figure 1. Simplified scheme of the convective conveyor-belt dryer [19]

The mathematical model of the convective drying process of thick movable layer of moist material has the form of four non-linear partial differential equations with constant coefficients and with an algebraic equation of a transcendent character, additionally included.

In accordance with [1] the following assumptions were accepted:
– the velocity of the drying agent in the direction of co-ordinate axes η is negligibly small,
– the velocity of the drying agent in the direction of co-ordinate axes ν has a constant value,
– the total pressure of drying agent has a constant value,
– the moist material velocity in the moving direction (axes η) depends only on time, which means that the material moves along the conveyor without slipping,
– the velocity of the moist material in the moving direction (axes η) is negligibly small, and
– the heat transfer (α) and moisture transfer (β) coefficients have constant values.

The mathematical model is presented as:

$$\frac{\partial x_a}{\partial \nu} = \frac{\beta S_m}{w_a \rho_{da}} \left[p_{wvs} - \mathrm{R}_{wv} \rho_{da} x_a (\theta_a + \theta_0) \right] \tag{1}$$

$$\frac{\partial \theta_a}{\partial \nu} = -\frac{\alpha S_m}{w_a \rho_{da} (c_{pda} + x_a c_{pwv})} (\theta_a - \theta_m) \tag{2}$$

$$\frac{\partial x_m}{\partial \eta} = -\frac{\beta S_m}{w_m \rho_{dm}} \left[p_{wvs} - \mathrm{R}_{wv} \rho_{da} x_a (\theta_a + \theta_0) \right] \tag{3}$$

$$\frac{\partial \theta_m}{\partial \eta} = \frac{\alpha S_m}{w_m \rho_{dm} (c_{dm} + x_m c_w)} (\theta_a - \theta_m) - \frac{\beta S_m}{w_m \rho_{dm} (c_{dm} + x_m c_w)} \left[p_{wvs} - \mathrm{R}_{wv} \rho_{da} x_a (\theta_a + \theta_0) \right] (r_0 - K_r \theta_m) \tag{4}$$

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$$A\left(\frac{x_m}{x_{m0}}\right)^{a_1}\left(\frac{\theta_m}{\theta_{m0}}\right)^{a_2}\left\{x_m - \left[\frac{-\ln\left(1 - \frac{p_{wvs}}{p_1 \cdot 10^{\frac{p_2\theta_m}{p_3+\theta_m}}}\right)}{k_1\left(\theta_m + \theta_0\right)^{k_2}}\right]^{\frac{1}{k_3(\theta_m+\theta_0)+k_4}}\right\} = \frac{\beta S_m}{\rho_{dm}}[p_{wvs} - R_{wv}\rho_{da}x_a(\theta_a + \theta_0)]$$

(5)

The system of eqs. (1)-(5) defines the changes of humidity, x_a, and the temperature of the drying agent – moist air, θ_a, as well as of the moisture, x_m, and temperature of the moisture material, θ_m, and the values of partial pressure of water vapor on the moisture material surface, p_{wvs}, in dependence of two space co-ordinates, horizontal, η, and vertical, v.

For this system of equations the boundary conditions are:

$$x_a(\eta,v)\big|_{v=0} = x_a(\eta,0) = x_{a0} \tag{6}$$

$$\theta_a(\eta,v)\big|_{v=0} = \theta_a(\eta,0) = \theta_{a0} \tag{7}$$

$$x_m(\eta,v)\big|_{\eta=0} = x_m(0,v) = x_{m0} \tag{8}$$

$$\theta_m(\eta,v)\big|_{\eta=0} = \theta_m(0,v) = \theta_{m0} \tag{9}$$

$$p_{wvs}(\eta,v)\big|_{\eta=0,v=0} = p_{wvs}(0,0) = p_{wvs0} \tag{10}$$
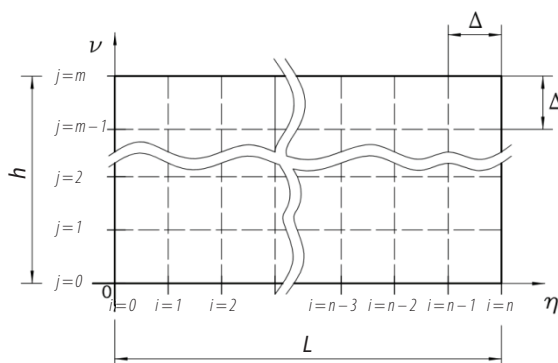
Figure 2. Boundary contour for the system of eqs. (1)-(5)

On fig. 2. the boundary contours presented. It is a rectangle with the length, L, equal to the length of the convey-or segment, and height, h, equal to the height of the *thick layer* on the conveyor ($h = 48$ mm). The boundary contour is valued for the system of eqs. (1)-(5), with boundary conditions (6)-(10).

The complete formulation of the mathematical model, presented in this paper, with detailed clarification of physical meaning of all values given in eqs. (1)-(5), is given in details in [1]. The expressions used for heat transfer coefficient α [Wm^{-2}K^{-1}] and mass (moisture) transfer coefficient β [kgm^{-2}Pa^{-1}s^{-1}] are taken from literature [26, 27].

The system of eqs. (1)-(5), with boundary conditions (6)-(10) can not be solved analytically. For that reason numerical analysis was chosen as the method for solving the presented system of equations. The following auxiliary values are introduced for the partially transformation of the system of eqs. (1)-(5):

$$m_1 = \frac{\beta S_m}{w_a \rho_{da}} \tag{11}$$

$$m_2 = \frac{\alpha S_m}{w_a \rho_{da}} \tag{12}$$

$$m_3 = \frac{\beta S_m}{w_m \rho_{dm}} \tag{13}$$

$$m_4 = \frac{\alpha S_m}{w_m \rho_{dm}} \tag{14}$$

Numerical algorithm for solving the mathematical model

The complete algorithm of numerical solution of the system of eqs. (1)-(4), with boundary conditions (6)-(10) and boundary contour given on fig. 2 is developed by using the Euler method of simple definite differences. For additional algebraic eq. (5) the Newton method of tangent is applied.

In the process of numerical integration the correct selection of the value for integration step, Δ, is extremely important since the *stability* of a solution depends on it significantly. As a natural and logical solution for the value of the integration step, the mean equivalent diameter of a particle, d_e, has been accepted, $\Delta = d_e$.

The first step of the algorithm of numerical integration is to define the *network* by dividing the boundary contour, fig. 2, into equal segments with same width and height as the adopted integration step, Δ. Now, it is possible to define the complete algorithm for numerical solution of system of equations with boundary contour given on fig. 2.

Before solving equations of the complete boundary contour it is necessary to solve the equations in the nodes on the very edges of the boundary contour.

The values of x_a and θ_a are defined by boundary conditions (6) and (7), while the values of x_m and θ_m are calculated by means of algorithm having in mind eqs. (3) and (4) and auxiliary values (13) and (14). It is obtained:

$$x_{a_{i,0}} = x_{a_0} \tag{15}$$

$$\theta_{a_{i,0}} = \theta_{a_0} \tag{16}$$

$$x_{m_{i,0}} = x_{m_{i-1,0}} - \Delta m_3 [p_{wvs_{i-1,0}} - R_{wv} \rho_{da} x_{a_0}(\theta_{a_0} + \theta_0)] \tag{17}$$

$$\theta_{m_{i,0}} = \theta_{m_{i-1,0}} + \frac{\Delta m_4}{c_{dm} + x_{m_{i-1,0}} c_w}(\theta_{a0} - \theta_{m_{i-1,0}}) -$$

$$- \frac{\Delta m_3}{c_{dm} + x_{m_{i-1,0}} c_w}[p_{wvs_{i-1,0}} - R_{wv} \rho_{da} x_{a_0}(\theta_{a_0} + \theta_0)](r_0 - K_r \theta_{m_{i-1,0}}) \tag{18}$$

This algorithm is valid for $i = 0$-p, $j = 0$.

The values of x_a and θ_a are calculated by means of algorithm having in mind the eqs. (1) and (2), and auxiliary values (11) and (12). The values x_m and θ_m are defined by the boundary conditions (8) and (9), as:

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$$x_{a_{0,j}} = x_{a_{0,j-1}} + \Delta m_1 [p_{wvs_{0,j-1}} - \mathrm{R}_{wv} \rho_{da} x_{a_{0,j-1}} (\theta_{a_{0,j-1}} + \theta_0)] \tag{19}$$

$$\theta_{a_{0,j}} = \theta_{a_{0,j-1}} - \frac{\Delta m_2}{c_{pda} + x_{a_{0,j-1}} c_{pwv}} (\theta_{a_{0,j-1}} - \theta_{m_0}) \tag{20}$$

$$x_{m_{0,j}} = x_{m_0} \tag{21}$$

$$\theta_{m_{0,j}} = \theta_{m_0} \tag{22}$$

This algorithm is valid for $i = 0$, $j = 0\text{-}q$.

After solving those equations it is possible to start solving of the equations in nodes within the boundary contour. For all points for which the next conditions are valid:

$$i = 1 - p, \qquad j = 1 - q \tag{23}$$

the values of x_a, θ_a, x_m, θ_m, and p_{wvs}, are obtained by the following algorithm:

$$x_{a_{i,j}} = x_{a_{i,j-1}} + \Delta m_1 [p_{wvs_{i,j-1}} - \mathrm{R}_{wv} \rho_{da} x_{a_{i,j-1}} (\theta_{a_{i,j-1}} + \theta_0)] \tag{24}$$

$$\theta_{a_{i,j}} = \theta_{a_{i,j-1}} - \frac{\Delta m_2}{c_{pda} + x_{a_{i,j-1}} c_{pwv}} (\theta_{a_{i,j-1}} - \theta_{m_{i,j-1}}) \tag{25}$$

$$x_{m_{i,j}} = x_{m_{i-1,j}} - \Delta m_3 [p_{wvs_{i-1,j}} - \mathrm{R}_{wv} \rho_{da} x_{a_{i-1,j}} (\theta_{a_{i-1,j}} + \theta_0)] \tag{26}$$

$$\theta_{m_{i,j}} = \theta_{m_{i-1,j}} + \frac{\Delta m_4}{c_{dm} + x_{m_{i-1,j}} c_w} (\theta_{a_{i-1,j}} + \theta_{m_{i-1,j}}) -$$
$$- \frac{\Delta m_3}{c_{dm} + x_{m_{i-1,j}} c_w} [p_{wvs_{i-1,j}} - \mathrm{R}_{wv} \rho_{da} x_{a_{i-1,j}} (\theta_{a_{i-1,j}} + \theta_0)](r_0 - K_r \theta_{m_{i-1,j}}) \tag{27}$$

Discussion of the results of the numerical simulation

In order to examine the stability of the numerical solution of the system of four non-linear partial differential equations of the convective drying process of natural materials, the boundary conditions have been varied. The boundary conditions in essence are the input parameters of the mathematical model. Initial values for humidity of drying agent, x_a, and its temperature, θ_a, were adopted in accordance with [1, 16, 17] and there are in the zone above the line of saturation. The influence of the drying agent humidity was analyzed for values between $x_a = \{0.06 \text{ and } 0.08\}$ kg$_{wv}$/kg$_{da}$ and temperature in interval between $\theta_a = \{100 \text{ and } 120\}$ ºC. Presented results are obtained using values for initial moisture content and mass (moisture) transfer coefficient obtained experimentally for potato (*Solanum tuberosum*) as drying material, given in [16, 17].

The belt conveyor length was $L = 1.5$ m and the velocity of the conveyor was $w_m = 0.002$ m/s. The potato pieces had the form of a cube, with the edge $d_e = 6$ mm. The length of the edge of the potato cube, $\Delta = d_e$, was chosen for the step of numeric integration, forming 2-D net with 2259 nodes at the boundary contour, 251 steps in the direction of the η-axes and 9 steps in the direction of the v-axes, fig. 2. The product layer on the belt conveyor had the height of $h = 48$ mm and it was porous with the gaps between the cubes. The value of initial humidity and temperature for moist potato cubes were: $x_{m0} = 4.882$ kg$_w$/kg$_{dm}$, $\theta_{m0} = 20$ ºC. All calculations were made in EXCEL.

The obtained results, presented on the following figures, clearly show that the here present-ed mathematical model is very stable without any noticeable elements of the divergence of numerical results. On figs. 3 and 4 changes of the absolute humidity of the drying agent are presented for the two different starting values of drying agent temperature, θ_a, and the drying agent humidity, x_a.

In the beginning of the drying process, the drying agent becomes saturated just after it passed the first layer of the cubes because of the intensive heat transfer to potato cubes, which is presented on figs. 5 and 6. The drying agent temperature drop down is presented on fig. 7. At the same time the high initial humidity of drying agent and the difference between the tempera-tures of potatoes cubes and drying agent is enough to cause condensation on layers of the cubes. Condensation has a positive effect because the water vapor from the drying agent, during the condensation, releases the latent heat of the phase change and heats the drying material. Those two reasons caused that in the beginning the potato cubes did not lose any moisture from their boundary layer – surface at all, which is presented on fig. 8.

By the time, the temperature of the potato cubes rises, fig. 9, the heat transfer from the drying agent becomes less, which causes the drop of drying agent temperature to become smaller, as well as the temperature difference between potato cube and the drying agent. The drying agent becomes unsaturated and the process of moisture transfer trough the boundary lay-
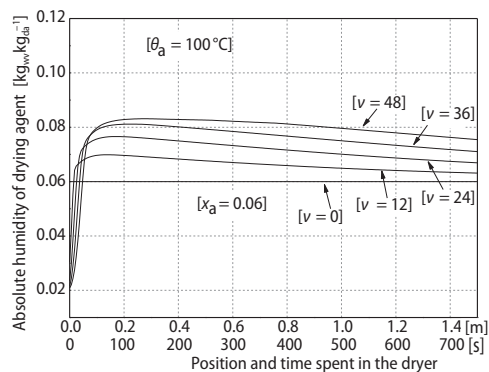

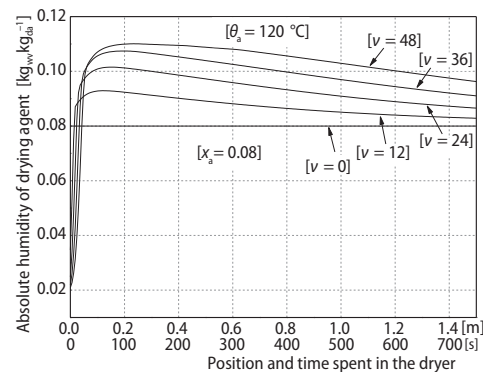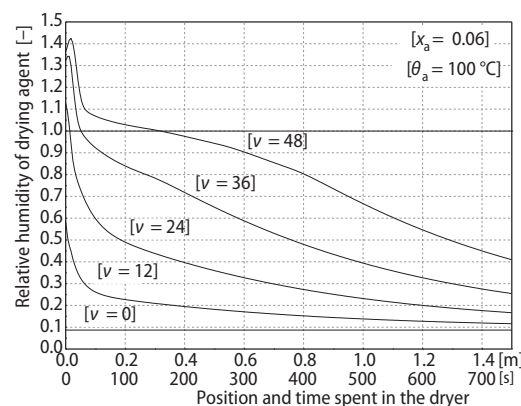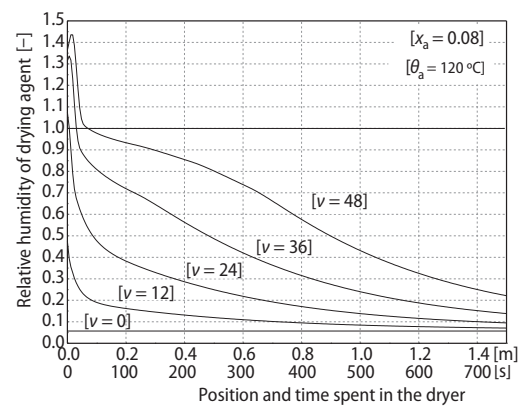Figure 3. Changes of the relative humidity of the drying agent x_a = 0.06 kg$_{wv}$/kg$_{da}$, θ_a = 100 °C

Figure 4. Changes of the relative humidity of the drying agent x_a = 0.08 kg$_{wv}$/kg$_{da}$, θ_a = 120 °C

Figure 5. Changes of the relative humidity of the drying agent x_a = 0.06 kg$_{wv}$/kg$_{da}$, θ_a = 100 °C

Figure 6. Changes of the relative humidity of the drying agent x_a = 0.08 kg$_{wv}$/kg$_{da}$, θ_a = 120 °C

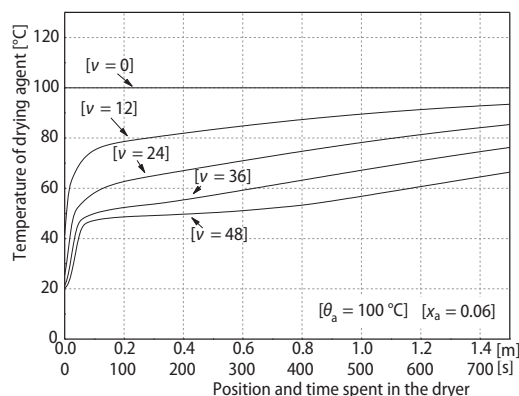**Figure 7. Changes of the temperature of the drying agent $x_a = 0.06$ kg$_{wv}$/kg$_{da}$, $\theta_a = 100$ °C**
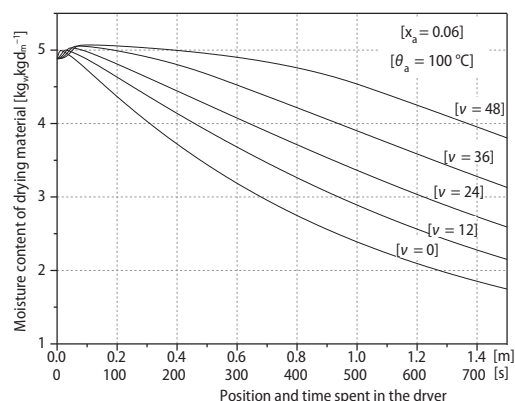

Figure 8. Changes of the moisture content of drying material
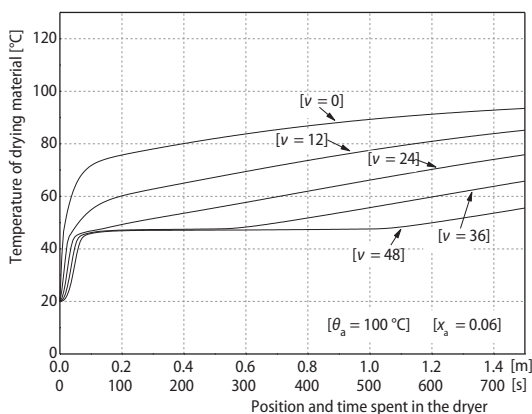
Figure 9. Changes of the temperature of drying material

er of potato cubes begins, firstly on the lower layers of potato cubes and in time in the middle and upper layers. For the top most layer, fig. 5, $v = 48$ mm, $\theta_a = 100$ ºC, and $x_a = 0.06$ kg$_{wv}$/kg$_{da}$, the period when the drying agent is saturated lasts 159 seconds. It becomes shorter for the higher drying agent temperatures and the drying agent humidity. For the same layer, it lasts 36 seconds for $\theta_a = 120$ ºC, and $x_a = 0.08$ kg$_{wv}$/kg$_{da}$, fig. 6.

It is also obvious that the moisture transfer is higher at the beginning of the process and on the layers which first have contact with drying agent, fig. 7. The main reason is that transfer of moisture from the boundary layer − surface, of the wet material to the drying agent needs much less energy and time than the transfer of moisture from the inside of the drying material to the surface.

The obtained results of numerical simulation clearly showed good agreement with experimental results presented in [16, 17].

Conclusions

The presented original mathematical model describes changes in *thick layers* of natural materials and it treats heat and mass transfer on the surface and inside the material as one continuum, but with specific differences. It is suitable for the simulation of the drying process of thick materials and for application in automated control of belt conveyer dryers.

The presented results, obtained using potato cubes as drying material, show the differences of the drying kinetic on different layers of the thick drying material, following the changes of the drying agent moisture and temperature as well as the moisture and temperature of drying material. The numerical solution of the mathematical model gives very stable results. It is clearly shown that the increase of enthalpy of the drying agent caused increase of the dry-

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ing agent absorbing capacity of moisture from drying material. With the increase of enthalpy the heat transfer on to drying material becomes more intensive and the period during which the drying agent is saturated, becomes shorter.

Acknowledgment

Nomenclature

A – constants, [–]
c_{dm} – specific heat capacity of dry material, [Jkg^{-1}K^{-1}]
c_{pda} – specific heat of dry air, [Jkg^{-1}K^{-1}]
c_{pwv} – specific heat of water vapor, [Jkg^{-1}K^{-1}]
c_w – specific heat capacity of water, [Jkg^{-1}K^{-1}]
d_e – equivalent diameter of a particle, [m]
h – height of moist material on belt transporter, [m]
K_r – constant, [–]
k_1, k_2 – constants, [–]
k_3, k_4 – constants, [–]
L – length of belt conveyor, [m]
m_1, m_2 – constants, [–]
m_3, m_4 – constants, [–]
p_{wv} – partial pressure of water vapor of drying agent, [Pa]
p_{wvs} – partial pressure of water vapor on surface of moist material, [Pa]
p_1, p_2 – constants, [–]
p_3 – constants, [–]
R_{wv} – gas constant of water vapor, [Jkg^{-1}K^{-1}]

r_0 – latent heat of evaporation of water at 0 °C, [Jkg^{-1}]
S_m – specific surface of layer of moist material, [m^{2}m^{-3}]
w_a – velocity of draying agent, [ms^{-1}]
w_m – velocity of moist material, [ms^{-1}]
x_a – absolute humidity of drying agent – moist air, [kg$_{wv}$kg$_{da}^{-1}$]
x_m – moisture content of drying material, [kg$_w$kg$_{dm}^{-1}$]

Greek symbols

α – heat transfer coefficient, [Wm^{-2}K^{-1}]
β – mass (moisture) transfer coefficient, [kgm^{-2}Pa^{-1}s^{-1}]
Δ – step of numerical integration, [–]
η, ν – space co-ordinate, [m]
θ_a – temperature of drying agent – moist air, [°C]
θ_m – temperature of drying material, [°C]
θ_0 – constant ($\theta_0 = 273.15$), [K]
ρ_{da} – partial density of dry air, [kg$_{da}$m$^{-3}_a$]
ρ_{dm} – partial density of dry material, [kg$_{dm}$m$^{-3}_m$]

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