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Numerical Modeling of Coupled Heat and Mass Transfer with Moving Boundary during Convective Drying Of Potato Slices

Kuma G. Erko, Addisalem H. Taye and Werner C. Hofacker

Abstract-A numerical model of coupled heat and mass transfer equations of convective drying for cylindrical potato slice with drying parameters of hot air temperature (60°C, 70°C, 80°C) and hot air velocity (1 m/s, 1.2 m/s and 1.5 m/s) at constant relative humidity(20 °C) was developed. The experiment was conducted in the convective drier with controlled air temperature, vision and continued mass measuring by a computer interface were used to collect data of drying process. The developed unsteady-state partial differential equations have been solved by means of the Finite Elements Method coupled to the Arbitrary Lagrangian-Eulerian (ALE) method to trace the moving boundary of product and air interface during the drying process using Comsol Multiphysics® 5.3. The state variables, surface temperature and moisture content of the material, as well as the shrinkage, and drying rate were determined using the formulated model. The numerical model also predicted the effect of fixed and moving boundaries on the drying curve. The relative drying curve, drying rate and surface temperature of the numerical simulation shows good agreement with the experimental data analyzed. In addition, the influence of the drying temperature on the total color difference (TCD) of the dried sample was investigated. The result shows that temperature has significant influence on the TCD. In both, the numerical and the experimental method, increasing the drying parameters has positive effect on the quality of the product and the drying kinetics in the range of chosen for this study.

Keywords: coupled heat and mass transfer, Numerical modeling, Moving boundary, Potato, Total color difference

1 INTRODUCTION

Conventional air-drying is the most frequently used drying method in the food industry. During vegetable drying mass and heat transfer play an important role. Understanding and formulation of well-verified mathematical drying models will make it possible to control the process to produce stable products of high quality. During the drying process, the samples shrink and change their color that has a high effect on the quality of the product.

The goal is to retain the actual nutrients, tastes and color. In vegetables and fruits, the amount of shrinkage is very closely related to the amount of water lost by dehydration or evaporation. However, the effect of shrinkage during drying has often been ignored due to its complexity. In the cases where it was considered though, different authors developed different equations to describe the shrinkage during drying (Mayor and Sereno, 2004). Even the shrinkage itself is not only defined by thickness, area or volume shrinkage, it can also experience other geometric changes during drying such as bending, twisting, and irregular size reduction, producing an evident shape change or deformation (Campos-Mendiola et al., 2007) Color is also an important quality attribute of dried products. It occurs in the interaction of light, observed object and observer (Yam and Papadakis 2004). It was critically evaluated by consumers and is often the basis for their selection or rejection of a product. Color can change during drying due to chemical and biochemical reactions. As reported by (Tsotsas and Mujumda, 2011) the rates of both reactions depend strongly on the processing parameters.

As drying is a complex process, it is good to use numerical modeling to represent the process of a system in a set of mathematical equations, which can effectively characterize the overall process of the system. Those sets of equations developed should predict the coupled heat and mass transfer of the overall process. Therefore, modeling and simulation give the opportunity to have an insight on the process at each specified time.

The main goal of this study was to model and simulate the drying process of vegetables (*potato slices*).The model was developed in an axisymmetric cylinder by using the fundamental models of heat and mass transfer as well as quality parameters such as shrinkage and total color difference (TCD or ΔE) under convective hot-air drying.

The work also tried to evaluate the effect of the shrinkage on moisture diffusivity with the help of simulation. The results from simulation were compared and validated with experimental data obtained. (Sturm et al., 2012) described the lab-scale convective dryer.

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2 EXPERIMENTAL STUDY, MATERIALS AND METHODS

2.1 Experimental Study

The experiments were conducted using a laboratory scale single layer convective dryer. Depending on the arrangement of the tunnel, it can be used as a through-flow or as an overflow system. The air is provided by a fan. The air flow speed was measured by using a hot wire anemometer. The relative humidity was controlled through a data logger controller. Throughout the experimental run, the sample weights were continuously recorded at predetermined time intervals until no noticeable differences between subsequent readings were observed. (Sturm et al., 2012) presented the experimental set-up used.

2.2 Materials and Methods

Potatoes were purchased from a local market in Konstanz, Germany and stored in a fridge at 4 °C. The test trials done were triplicates to obtain accurate drying process data. The theoretical or numerical modeling and simulation was validated by experimental work that was carried out for different drying parameters of hot air temperatures (60°C, 70°C, 80°C) and hot air velocities (1m/s, 1.2 m/s and 1.5 m/s) at a constant relative humidity. Coupled heat and mass transfer of the partial differential equations were solved by means of the Finite Elements Method with Arbitrary Lagrangian-Eulerian (ALE) method to trace the moving boundary of the product and air interface during the drying process using Comsol Multiphysics® 5.3.

3 MATHEMATICAL MODEL FOR HEAT AND MASS TRANSFER

3.1 Governing Equations

The convective heat transfer from the air to the sample interface was assumed to be an external convection process whereas heat transfer from the surface of the product to the body of the product occurred mainly by conduction. In the meantime, moisture was transported within the product via convection and diffusion processes and moved from the inside of the product to its surface. The heat and mass transfer equations used in the model were governed by the following partial differential equation (PDE). The transient drying kinetics can be modeled by the Fickian equation which is exactly in the form of the Fourier equation of heat transfer (I. Dincer & S. Dost, 1995, Md. Rajibul Islam, 2010).

$$\left(\frac{1}{y^m}\right)\left(\frac{\partial}{\partial y}\right)\left[y^m\left(\frac{\partial T}{\partial y}\right)\right]=\left(\frac{1}{\alpha}\right)\left(\frac{\partial T}{\partial t}\right) \quad (1)$$

For moisture (mass) transfer

$$\left(\frac{1}{y^m}\right)\left(\frac{\partial}{\partial y}\right)\left[y^m\left(\frac{\partial M}{\partial y}\right)\right]=\left(\frac{1}{D_{eff}}\right)\left(\frac{\partial M}{\partial t}\right) \quad (2)$$

Where m = 0, 1, and 2 for an infinite slab, infinite cylinder, and a sphere respectively. $y = z$ for an infinite slab, $y = r$ for infinite cylinder and sphere.

Shrinkage of vegetable products during drying is a noticeable physical incident, which occurs due to moisture diffusion.

To simplify the model, the following assumptions were made:

- Heat transfer and moisture movement are one-dimensional;
- No chemical reaction takes place during drying i.e. chemical properties of material and air are constant within the range of the temperatures considered;
- The sample (material) undergoes shrinkage as long as drying takes place;
- The hot-air is uniformly distributed through the dryer.

The theoretical representation of the process during forced convectional drying is shown in Fig.1

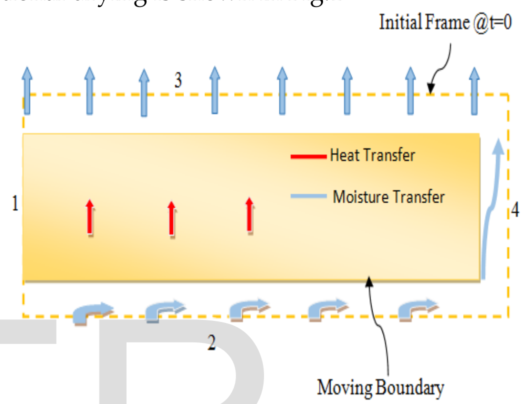

Fig. 1. 1 A schematic representation of heat and mass transfer during drying with shrinkage effect

3.2 Heat and Mass Transfer Boundary Condition

For products subjected to convective hot air drying, the governing equation (1) is solved using the following initial and boundary conditions for heat transfer.

The initial conditions are:

$$M(r,y)\big|_{t=0}=M_o,\ T(r,y)\big|_{t=0}=T_o \quad (3)$$

Also for the products subjected to hot air drying the governing equation was solved with the following boundary conditions in addition to the initial conditions.

The boundary conditions for mass transfer at are:

$$-D\left.\frac{\partial M}{\partial y}\right|_{y=0}+vM\big|_{y=0}=h_m\left(M-M_e\right) \quad (4)$$

$$-D\left.\frac{\partial M}{\partial y}\right|_{y=L}+vM\big|_{y=L}=h_m\left(M-M_e\right) \quad (5)$$

The energy balance at the boundary y=0 can be expressed as:

$$K\frac{\partial T}{\partial y}+\rho C_p vT\big|_{y=0}=h_T\left(T_a-T\right)-h_m\rho\left(M-M_e\right)h_{fg}\big|_{y=0} \quad (6)$$
$$=h_T\left(T_a-T\right)-n.\left(D_{eff}h_{fg}\nabla M\right)$$

The energy balance at the boundary y=L can be expressed as:

$$K\frac{\partial T}{\partial y}+\rho C_p vT\Big|_{y=L}=h(T_a-T)-h_m\rho(M-M_e)h_{fg}\Big|_{y=L}$$
$$=h_T(T_a-T)-n.(D_{eff}h_{fg}\nabla M) \quad (7)$$

The term on the left-hand side of the equations (6 and 7) refers to the heat transferred by conduction and convection from the outer surface to the inside of the potato slice. The first term on the right-hand side is the heat penetrating from the hot air to the potato slice by means of convection, and the second term on the right-hand side denotes the heat dissipation due to moisture evaporation from the sample.

For the sample centerline, an axial symmetry boundary is applied:

$$K\frac{\partial T}{\partial y}+\rho C_p vT\Big|_{r=0}=0; \qquad for\ \ t>0 \quad (8)$$

3.3 Parameters Used in the Model

In the literature, it was shown that physical and transport parameters required for solving the governing equations are assumed to be functions of temperature and moisture content.

Specific Heat

Different authors reported different relations between moisture and temperature and the specific heat that was found experimentally. The specific heat C_p as a function of temperature and moisture that was developed by (N. Wang & J. G. Brennan, 1995) and which depends on the moisture content and the product temperature was used in this study.

$$C_P=4.184\times10^3(0.406+0.00146\theta+0.203M-0.0249M^2) \quad (9)$$

Thermal Conductivity

The thermal conductivity K of potatoes used in this model (Eq. (6, 7 and 8)) was a function of moisture. The relation equation of the thermal conductivity shows that as the moisture content decreases the thermal conductivity of potatoes would also decrease as shown in (Eq. (10)).

$$K=0.05963-\frac{0.1931}{M}+\frac{0.0301}{M^2} \quad (10)$$

Diffusion Coefficient

The effective moisture diffusivity of the potatoes was used as a function of the material moisture content and the temperature (Kiranoudis et al., 1995).

$$D=1.29\times10^{-6}\exp\left(\frac{-0.0725}{M}\right)\exp\left(\frac{-2044}{T}\right) \quad (11)$$

Heat and Mass Transfer Coefficients

The mass transfer coefficient h_m can be determined from the following equation (Azharul Karim, M.N.A. Hawlader, 2005) for laminar flow (Eq.(12)) and for turbulent flow (Eq.(13)), respectively:

$$Sh=\frac{h_mL}{D_{eff}}=0.332\,\mathrm{Re}^{0.5}\,Sc^{0.33} \quad (12)$$

$$Sh=\frac{h_mL}{D_{eff}}=0.0296\,\mathrm{Re}^{4/5}\,Sc^{1/3} \quad (13)$$

Similarly, the heat transfer coefficient is calculated from the following equation (C. Kumar et al. 2012) for laminar (Eq.(14)) and for turbulent flow (Eq.(15)) respectively:

$$Nu=\frac{h_TL}{k}=0.664\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33} \quad (14)$$

$$Nu=\frac{h_TL}{k}=0.0296\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33} \quad (15)$$

4 IMAGE ANALYSIS AND SHRINKAGE EVALUATION

4.1 Image Analysis

The color of the samples was measured every ten minutes using a CCD camera that was integrated into the dryer. For determining changes in the product color the total color difference (TCD or ΔE) calculation was as shown in (Eq. (16)):

$$\Delta E=\sqrt{\Delta L*^2+\Delta a*^2+\Delta b*^2} \quad (16)$$

The parameter *L* refers to the lightness of the samples and ranges from black = 0 to white = 100. A negative value of the parameter *a* indicates green color while a positive one indicates red. A positive value of parameter *b* indicates yellow while a negative value indicates blue color.

4.2 Shrinkage

The methods used to define material shrinkage differ greatly throughout literature (Mayorb and Sereno, 2004).

In this work, the effect of fixed (calculation without shrinkage) and moving boundaries (with shrinkage) on the moisture transfer rate was investigated as well.

To solve the governing equations with the shrinkage effect, it is necessary to determine the shrinkage velocity. In this study, a linear distribution of the shrinkage velocity of fundamental models was used (Mayor and Sereno, 2004).

$$\frac{V}{V_o}=\left(\frac{0.8+M}{0.8+M_o}\right) \quad (16)$$

For linear or isotropic shrinkage (Srikiatden and Roberts, 2006) (Eq. (16)) can be written as:

$$V=V_0\left(\frac{0.8+M}{0.8+M_o}\right)$$

$$V=\pi R_o{}^2Y_o\left(\frac{0.8+M}{0.8+M_o}\right)=\pi R^2Y \quad (17)$$

$$V=\pi R_o{}^2\left(\frac{0.8+M}{0.8+M_o}\right)^{2/3}\times Y_o\left(\frac{0.8+M}{0.8+M_o}\right)^{1/3}=\pi R^2Y$$

From (Eq. (17)) the expression for the radius (R) and the thickness (Z) can be easily be used to calculate the shrinkage velocity along R and the Z.

$$R=R_o\left(\frac{0.8+M}{0.8+M_o}\right)^{1/3} \text{ and } Y=Y_o\left(\frac{0.8+M}{0.8+M_o}\right)^{1/3} \quad (18)$$

By differentiating (Eq. (18)) the interface shrinkage velocity was found and has been used in the numerical model in Comsol Multiphysics® 5.3 with ALE modules.

5 NUMERICAL METHODS

COMSOL Multiphysics® 5.3 solved the coupled heat and mass transfer along with the moving mesh equation using the finite element method. The model was developed and built in COMSOL for a 2-D cylindrical geometry. The partial differential equations were solved using the following COMSOL modules: Chemical Species Transport (Transport of Diluted Species), Heat Transfer (Heat Transfer in Solids) and the moving mesh module Arbitrary Lagrangian-Eulerian (ALE). The Arbitrary Lagrangian-Eulerian (ALE) method was used to trace the moving boundary of the product and the air interface during the drying process.

6 RESULTS AND DISCUSSIONS

The numerical model that was formulated for the convective drying by coupled heat and mass transfer with ALE was validated by experimental data. Experiments were conducted at different air velocities and air temperatures to determine the drying characteristics.

6.1 Temperature and Water Content Distributions

In convective drying, the moisture concentration of the product is an important factor to decide whether it is in equilibrium with its surroundings or not. This knowledge is necessary to be able to produce a stable product.

As shown in Fig.2, the surface directly exposed to the drying air approached the equilibrium moisture content faster than the deeper layers of the materials where the change was slower. The results obtained from numerical simulation could not be validated because of the difficulty to experimentally measured the moisture distribution in the product.

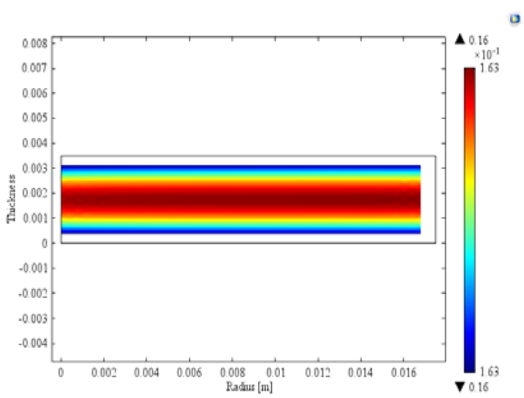

Fig. 2. Dry basis moisture distribution in the 2-D cylindrical geometry of potato slice (T_a=60 °*C*, v_a=1.2 m/s, T_{dp}=20 °C)

6.2 Drying Curve

The drying data for the three temperatures (60°C, 70 °C, 80 °C) and the three air velocities (1 m/s, 1.2 m/s, 1.5) were both experimentally determined and numerically predicted. Drying was continued until the equilibrium moisture content was reached. As shown in Fig.3, an increase in air temperature resulted in a decrease of the drying time due to an increase in the heat transfer rate. An increase in air velocity also resulted in a shorter drying time because of the heat transfer, as well as mass transfer rate, increased. This can be seen in Fig.4. As the air velocity increased, drying time was reduced but the effect was smaller than the one that was obtained by changing the temperature. As it can be seen from these results the proposed model provides helpful indications that can be used to calculate moisture and temperature distributions and to analyze the effect of the drying parameters on both.

The results plotted in Fig.3 and Fig.4 show the numerical simulation with fixed boundaries in comparison to experimentally obtained data. As it can be seen, the values were in good agreement.

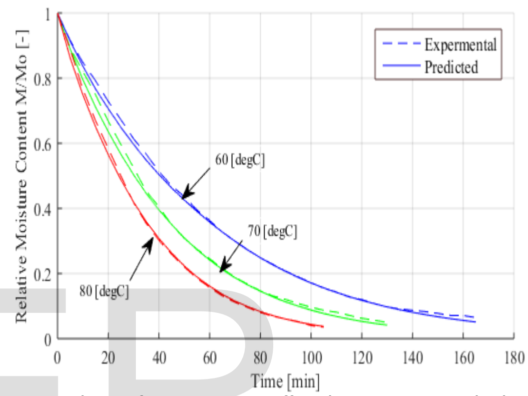

Fig. 3. Comparison of temperature effect between numerical prediction and experimental investigation of moisture profile of potatoes (v_a=1.2 m/s, T_{dp}=20 °C)

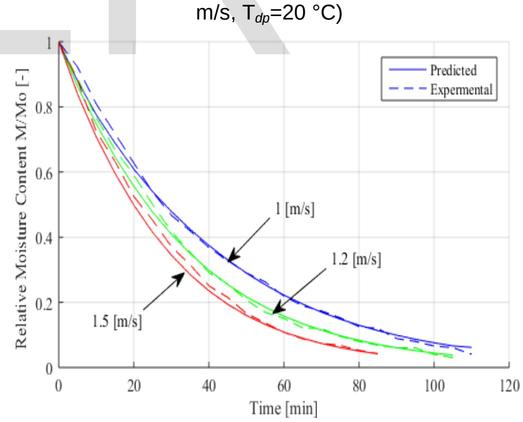

Fig. 4. Comparison of temperature effect between numerical prediction and experimental investigation of moisture profile of potatoes (T_a=80 °C, T_{dp}=20 °C)

6.3 Temperature Distribution in Drying Potatoes

The product surface temperature was recorded online continuously during drying and then compared to the numerically predicted product surface temperature. The two were found to be in good agreement. As it can be seen from Fig. 5 apart from the first 40 minutes of drying the product surface temperatures show some difference. The reasons for this are the initial conditions in the dryer. Over time the simulation and the real temperature started approaching each other and finally agreed more. After the validation of the model, it is possible to predict parameters needed for the process by the parametric sweep analysis option in Comsol shown in Fig.6

The same applies to the product's moisture distribution: the sample temperature distribution was also determined from numerical simulation only since the temperature profile within the sample was too difficult to measure experimentally. The numerically obtained results are shown in Fig.7. The profile seems to support the expected results.

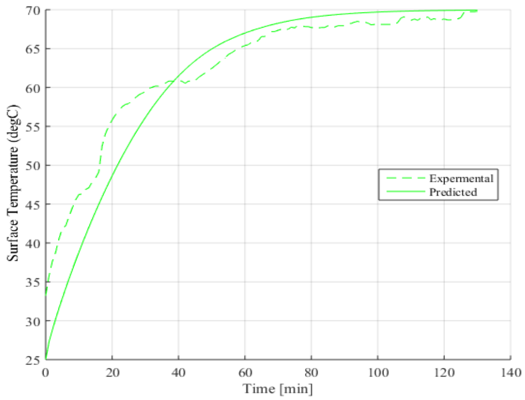

Fig. 5. Comparison of product surface temperature between numerical prediction and experimental investigation at 70 °C (v_a=1.2 m/s, T_{dp}=20 °C)

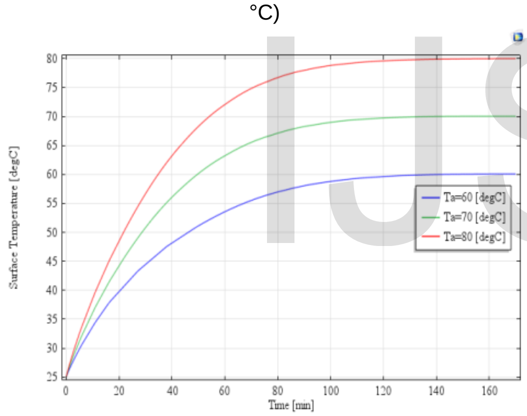

Fig. 6. Swept product surface temperature by Comsol Multiphysics (v_a=1.2 m/s, T_{dp}=20 °C)

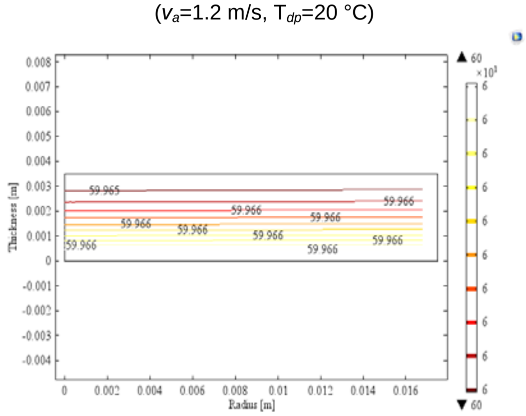

Fig. 7. Temperature distribution of products (Ta=60 °C, v_a=1.2 m/s and T_{dp}=20 °C)

6.4 Drying Rate

The drying rate of the product was high for higher values of the moisture ratio due to high diffusion. Over time, however, it decreased. For the lower moisture ratios, the drying rate was lower. As shown in Fig. 7 the product did not show a constant drying rate for products that were considered dry. Both air temperature and air velocity had a positive effect on the drying rate, i.e. as they increase, the drying rate became also higher.

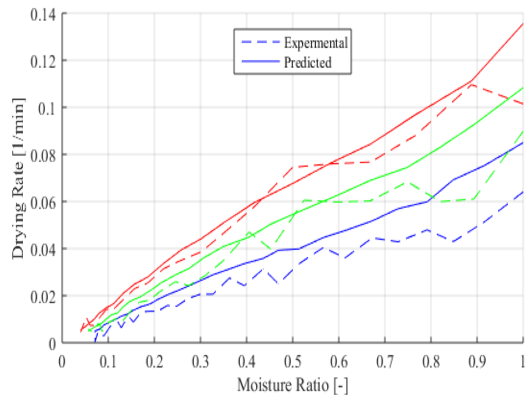

Fig. 8. Drying rate for (T_a=--60 °C, --70 °C, --80 °C and v_a=1.2 m/s at T_{dp}=20°C)

6.5 Image Analysis

To describe the color change of dried potato slices relative to the fresh slices, the total color difference (TCD or ΔE), a combination of the parameters *L, a* and *b,* was determined. The dependency of the total color difference on the moisture ratio of potato slices at different air temperatures is shown in Fig.9. The total color difference increases with a decrease in the air temperature from 60 °C to 80°C. Similar to the results of ΔE for apples (Sturm et al., 2012) and mangoes (Hörsten, & Luecke, 2008), an application of high temperatures to the potato slices resulted in a decrease in the discoloration of the product. The plot of the total color difference at different air velocities is shown in Fig. 10. When keeping a constant air and dew point temperature, the lowest total color change was obtained at an air velocity of 1.5 *m/s* followed by1.2 *m/s* and finally 1 *m/s*. Drying the samples at higher air velocities resulted in a lower color change of the slices (Sturm et al., 2012).

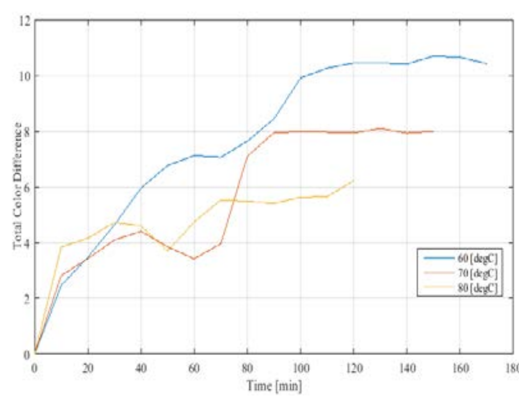

Fig. 9. Effect of air temperatures on product TCD

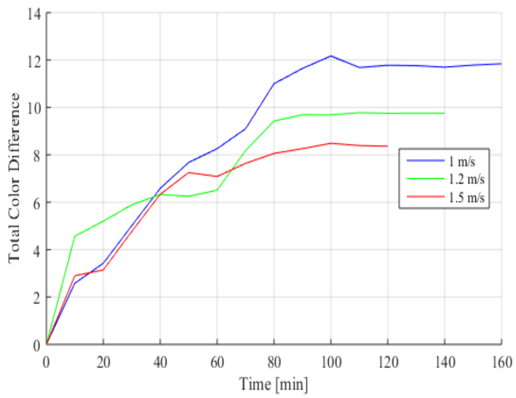

Fig. 10. Effect of air velocity on product TCD

6.6 Effect of Moving Boundaries and Shrinkage

The moisture profiles of fixed and moving boundaries were compared. During the first 30 minutes of the drying process the results of both overlap as shown in Fig. 11. Afterwards, they deviated. The effect was more feasible as drying was continued. From Fig. 12 it can be seen that the relative volume shrinkage occurs after these 30 minutes. When comparing the numerical results of moving boundaries to fixed boundaries the moving boundaries show a shorter drying time and therefore a higher drying rate. One reason for this is the shorter distance the particle has to move to reach the product's surface. On the other hand, shrinkage reduces the capillary gap which decreases diffusion. Therefore, the shrinkage has two opposite effect but the distance effect has a bigger influence on the drying process. The numerically predicted value of relative volume shrinkage was found in the range of 75% to 84% for the considered studied parameters. (L. Hassiniand et al., 2007) have reported the similar result of 77%.

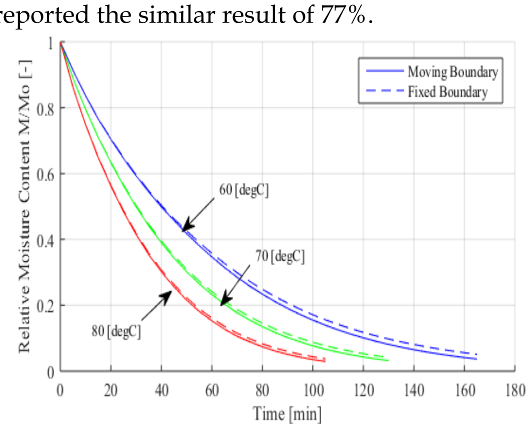

Fig. 11 Effect of fixed and moving boundary on drying curve (v_a=1.2 m/s and T_{dp}=20 °C)

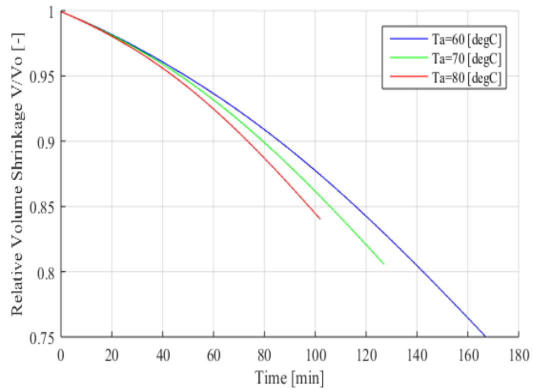

Fig. 12 Product relative volume shrinkage at different temperatures (v_a=1.2 m/s and T_{dp}=20 °C)

7 CONCLUSION

In this work, the mathematical model of coupled heat and mass transfer was studied and then validated with experimentally analyzed data. The two were found to be in good agreement. In the mathematical model developed in Comsol Multiphysics the variables specific heat, thermal conductivity and material diffusivity were a function of both temperature and moisture. The tool was powerful to estimate both moisture and temperature profiles of drying kinetics in the products. The product shrinkage was investigated to be able to compare the real drying process with the simulation and to understand the shrinkage's effect on the moisture diffusion process. The numerical model developed and used along with moving boundaries also gives a chance to see what happens in the drying material at any needed time.

Future work will be conducted to develop continuous batch drying, quality analysis and to study the effect of the shrinkage on the moisture diffusion. The overall goal should be the development of a mass production with the use of the obtained information.

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TABLE.1
SUMMARY OF THERMO-PHYSICAL PROPERTIES OF AIR AND POTATO USED IN MODEL SOLUTIONS

Parameters	Equation/Value
Density of potato (ρp)[9]	$1072\, kg/m^3$
Density of air (ρa) [12]	$1.028\, kg/m^3$
Thermal conductivity of air (k) [12]	$0.0287\, W/m.K$
Specific heat of air (Cpa) [12]	$1007\, J/kg.K$
Dynamic viscosity of air (µa) [12]	$2.052\times10^{-5}\, kg/m.s$

Binary water diffusion (DAB)[11]	$2.56\times10^{-5}\,m^2/s$
Reynolds number (Re) [7]	$\rho_a vL/\mu_a$
Prandtl number (Pr) [7]	$C_{pa}\mu_a/k_a$
Schmidt number(Sc) [7]	$\mu_a/\rho_a D_{AB}$
Vapor saturation pressure (Psat) [13]	$610.78\exp\left[17.2694\,\theta/(\theta+238.3)\right]$
Air moisture concentration (M∞) [13]	$P_{sat}RHM/RT_a$
Effective moisture diffusivity (Deff) [9]	$1.048\times10^{-5}\exp\left(-\frac{25.77}{8.314\times10^{-3}T}\right)$
Latent heat of vaporization (hfg)KJ/kg	$2501.05\times10^{3}\left(\frac{647.3-T}{647.3-273.15}\right)^{0.3298}$

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NOMENCLATURE

Cp	Specific heat (J/kg.K)
D	diffusion coefficient (m^2/s)
hm	external mass transfer coefficient (m/s)
hT	heat transfer coefficient
k	thermal conductivity of air (W/m.K)
K	thermal conductivity potato (W/m.K)
L	sample thickness (m)
M	Moisture content (kg water/kg dry air)
Nu	Nusselt number
Pr	Prandtl number
R , r	coordinate (m)
Re	Reynolds number
Sc	Schmidt number
T	Temperature (K)
t	time (s)
v	shrinkage velocity (m/s)
V	volume (kg/m^3)
Y, y	coordinates (m)
n	unit vector normal to product surface

Greek letters

α	thermal diffusivity (m^2/s)
μ	dynamic viscosity (kg/m.s)
θ	temperature (°C)

Subscript

a	air
e	equilibrium
eff	effective
o	initial condition