Bulgarian Chemical Communications, Volume 46, Number 4 (pp. 903– 910) 2014

Effect of thermophysical properties on forced convective hot air drying of multi-layered porous materials

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Submitted April 13, 2014

The convective drying kinetics of porous medium was investigated numerically. A mathematical model for forced convective drying was established to estimate the evolution of moisture content and temperature inside multi-layered porous medium. The set of coupled partial differential equations with the specified boundary and initial conditions were solved numerically using a MATLAB code. An experimental set-up of convective drying had been constructed and validated the theoretical model. The temperature and moisture content of the potato samples were dynamic measured and recorded during the drying process. Results indicate that thermal diffusion coefficient has significant positive impact on temperature distribution and mass diffusion coefficient might directly affect on the moisture content distribution. Soret effect has a significant impact on heat flux and temperature distribution in the presence of large temperature gradient.

Key words: porous materials; heat and mass transfer; thermophysical properties; convective drying

INTRODUCTION

Drying is one of the basic techniques for preserving wide variety of products, from raw materials to finished goods, from cereals to fruits. It is a highly complex transient process involving conjugated transfer phenomena of water content and heat. Drying controls to a large extent the final quality of the dried products and consumes a comparatively large amount of latent heat to eliminate the water content within the various perishable products [1-2]. In order to make the better dried products, improve dryer efficiency, reduce the operating expenses and time, the mathematical modelling tools have been one of the most important areas in modern drying technology [3].

In recent years, many investigators like Mujumdar, Tsotsas and Rahman, have devoted their research to drying mathematical model of conjugated transport of moisture content and heat flux through porous medium [4-7]. Bennamouna *et al*. developed a transient model to evaluate the convective drying curve and the product temperature with introduction of shrinkage [8]. Ranjan *et al.* reported a two-dimensional diffusion model describing the heat and mass, momentum transfer to predict the drying rate of bananas. They reported that the experimental results were in good agreement with predicted results [9]. Morais *et al.* investigated the diffusion coefficient and drying curves of cowpea grains based on diffenent mathematical models [10]. Although numerous studies have been published concerning heat and moisture transfer model under different dimensions, mostly in mathematical analysis of the drying rate, and the dynamic characteristic of temperature and water content distribution within different porous

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materials, little literature is available on the effect of thermophysical properties of porous medium on the convective drying kinetics by taking the thermal-diffusion and diffusion-thermo effects into account [11-14].

In this work, a dynamic model with the third boundary condition for describing the transient heat and mass diffusion process inside the moist porous medium during forced hot air drying was proposed. An experimental method for forced convective drying was investigated and fresh potato was used as the sample. The measured values in different running conditions were compared with the calculated results to validate the effectiveness of the theoretical model developed. Effects of using different thermophysical properties of potato samples on the convective drying rate by taking into account the thermal-diffusion and diffusion-thermo effects were then investigated with numerical method.

MATHEMATICAL MODEL

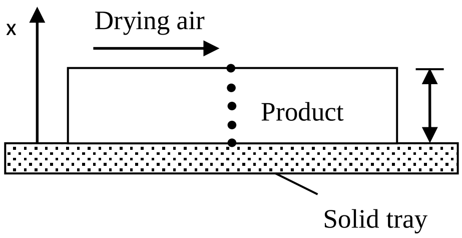


Fig. 1. Physical model of porous medium subjected to drying

A physical model that explains the sliced porous material is exposed to the hot air drying process used is shown in Fig. 1. The physical mechanisms of heat and mass transfer involved in the convective drying as follows: conductive heat transfer from the high-temperature region to the low-temperature region; forced convection takes place between the external surface of porous medium and the drying air surrounding it; mass transfer in the product is one dimensional process, which takes place only at the surface level of the sliced porous solid; the gradients of temperature and relative moisture content are considered as the driving force of mass diffusion.

The physical model that involves the simultaneous heat and mass transfer process, as a consequence, is a very complicatedly model [15]. In order to simplify the model, the hypotheses listed below have been made:

- The flat porous slab is unsaturated, homogeneous and isotropic.
- At time zero, the products are assumed to be at uniform temperature and moisture content distributions.
- The side and bottom surfaces of the product had been insulted, and dimensions in the other directions are sufficiently large that heat transfer and moisture diffusion may be considered as one-dimensional only through x axis.
- The porous bodies are continuous slab during the drying period and compressibility effects are negligible.

According to Luikov's theory and the non-equilibrium thermodynamics using the above assumptions [16], the one-dimensional governing equations with coupled energy transfer and mass diffusion within moist medium subjected to hot air drying can be given as follows:

$$\frac{\partial T(x,\tau)}{\partial \tau} = a_q \frac{\partial^2 T(x,\tau)}{\partial x^2} + a_q \xi \frac{\partial^2 M(x,\tau)}{\partial x^2} \quad (1)$$

$$\frac{\partial M(x,\tau)}{\partial \tau} = a_m \delta \frac{\partial^2 T(x,\tau)}{\partial x^2} + a_m \frac{\partial^2 M(x,\tau)}{\partial x^2} \quad (2)$$

Where T is the local temperature of different thickness within the porous medium (°C); M is the materials moisture content (kg water/kg solid, dry basis); a_q and a_m are the thermal diffusivity (m^2s^{-1}) and effective moisture diffusion coefficient (m^2s^{-1}), respectively; δ and ξ are the thermogradient coefficient (K^{-1}) and moisture gradient coefficient of the material (K); τ is the drying time (s).

Initially, the moisture content and temperature are assumed to be homogeneous within the porous material.

$$T(x,0) = T_0 \quad (3)$$

$$M(x,0) = M_0 \quad (4)$$

The boundary conditions of partial differential equations are given as follows:

$$\frac{\delta T}{\delta x}=0,\quad \frac{\delta M}{\delta x}=0 \text{ at } x=0 \tag{5}$$

$$-\lambda\frac{\delta \mathrm{T}(x,\tau)}{\delta x}\Big|_{x=l}=h_t[T(l,\tau)-T_a] \tag{6}$$

$$-D\frac{\delta M(x,\tau)}{\delta x}\Big|_{x=l}=h_m[M(l,\tau)-M_a] \tag{7}$$

Where λ, D, h_t and h_m are the heat-transfer coefficient ($Wm^{-2}K^{-1}$), mass-transfer coefficient (ms^{-1}), convective heat and mass transfer coefficient, respectively; l is the thickness of the multi-layered porous materials (m), x is the vector dimension in the direction of the thickness (m).

The coupled partial differential equations were discredited with the specified boundary and initial conditions. Equations (1) ~ (7) were integrated numerically by using a LU decomposition scheme, and a MATLAB 7.0 procedure code was developed to solve the system of partial equations. Fig. 2 is the flow chart of the detailed solution procedure.

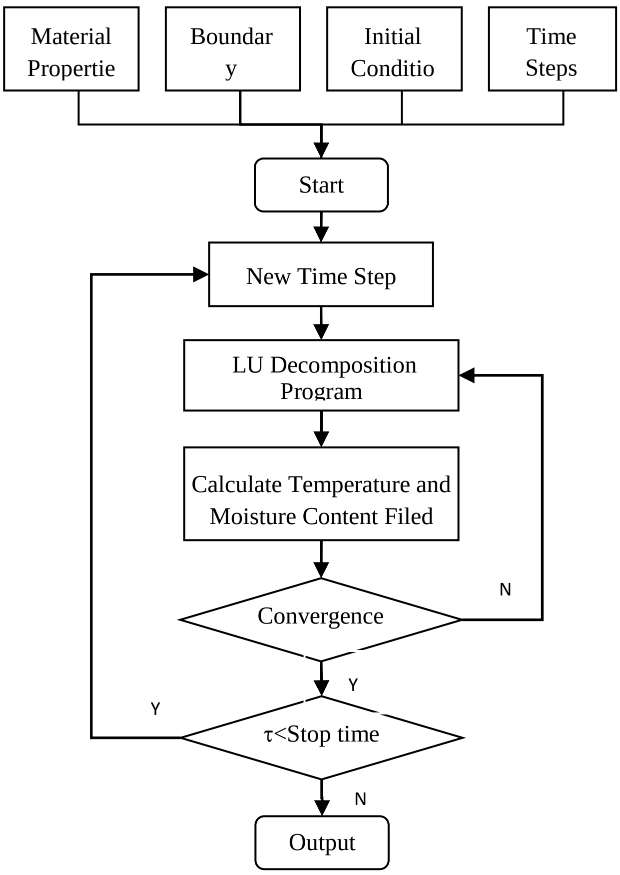


Fig. 2. Flow chart of the numerical calculation.

EXPERIMENTAL PROCEDURES

In order to validate the theoretical model, drying tests were carried out to investigate the coupled heat and mass transport in moist materials. Fig. 3 shows the convective drying experimental set-up scheme. A whole include a hot air drying chamber, a humidifier, an air heater, an analytical balance and a hygrometer and a fan. Before each new test, the drying apparatus is set to the experiment conditions required and then is left running for 90 min to ensure and maintain the steady-state operating conditions.

Fresh potato, which was used as the sample, was obtained from a market under the same brand. At the beginning of each drying test, the drying samples were stabilized at ambient air temperature, then peeled and cut into slices approximately 8 mm thick. The samples were put in the drier, where air was circulated through the top surface of drying material. As Fig.1 shows, the local temperatures of different thickness within the potato samples were measured by five T-type thermocouples, then recorded and stored in a dig ital data logger at an interval of 30 s. To obtain the drying rate, the weight change of the potato specimen during drying was dynamic measured and recorded with an electronic balance (Fig.3). At the end of each drying test, the potato specimens were put in a hot air circulation oven at 120°C for 24 h and weight again to determine the bone-dry weight.

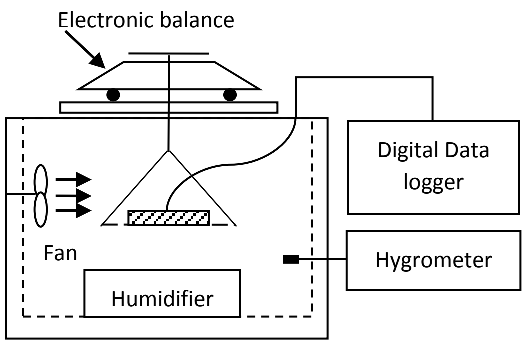


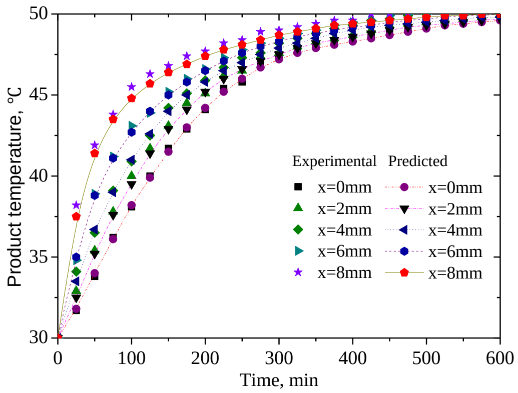
Fig. 3. Overall sketch of the experimental apparatus

To investigate the force convective drying process, a number of drying experiments were conducted using the same samples under different conditions, as Table 1 shows. By inverse problem method [17-18], the thermophysical parameters were estimated, the heat and mass transfer coefficients were a_q =2.54×10^{-7} m^2s^{-1}, a_m =6.95×10^{-8} m^2s^{-1}, δ =0.0124 K^{-1} and ξ =0.0185 K.

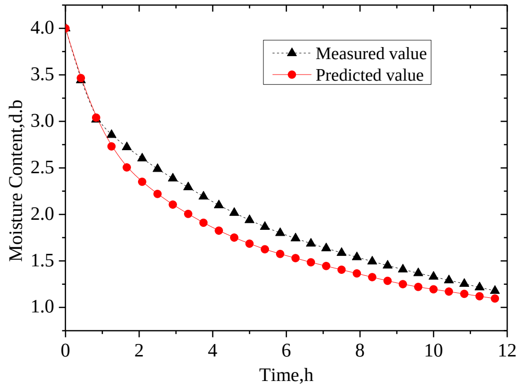
Table 1. Estimated parameters of the contact drying experiment

Temp., ℃	RH, %	Vel., m/s	$\frac{\partial T}{\partial \tau}$, ×10^4℃/s	$\frac{\partial M}{\partial \tau}$, ×10^4%/s	$\left.\frac{\partial T}{\partial x}\right\|_{x=l}$, ℃/s	$\left.\frac{\partial M}{\partial x}\right\|_{x=l}$, %/s
55	40.0	0.276	6.94	-3.375	175.3	-290.9
60	40.0	0.276	8.61	-4.785	218.3	-145.6
60	58.6	0.276	4.19	-2.146	103.9	-187.7
55	58.6	0.192	5.79	-2.548	145.0	-220.7

Figure 4 shows the comparison of the simulated and experimental values of temperature and average moisture content within the potato sample during forced convective drying.



(a) temperature distribution



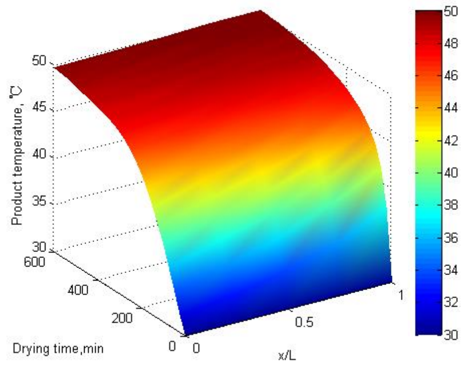
(b) average moisture content

Fig. 4. Comparison of simulative and experimental values with drying time.

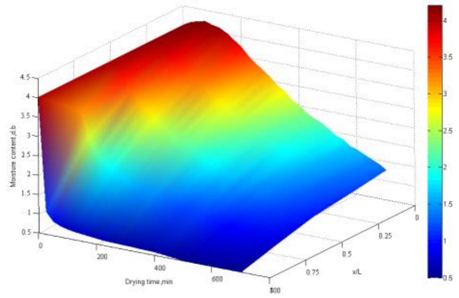
Fig. 4(a) illustrates the local temperature of every layer of the sample will become higher as drying time goes by. The temperature difference between the top and bottom surfaces of the sample is become decrease with the drying time. There were no significant differences between the predicted and experimental temperature values at about 5% level. The drying rates are compared in Fig. 4(b). It is observed that the higher temperature and lower water content in the top surface of the sample than those in the bottom surface. This model could predict the temperature and moisture content variations in close agreement with the experimental data.

RESULTS AND DISCUSSION

Different phenomena linked to local temperature variation and moisture content loss with drying time are observed in the course of modern drying technology [19-20]. Fig. 5 shows local temperature and moisture content distributions profile in the sample under real parameters.



(a) temperature distribution

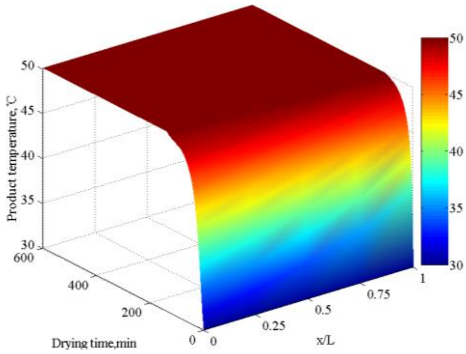


(b) moisture content distribution

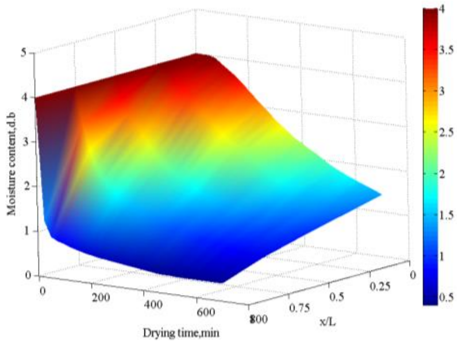
Fig. 5. Temperature and moisture content distributions in the product under real condition.

As shown in Fig. 5(a), the transient temperature of the upper part of the sample was increased rapidly and close to the hot air temperature near the end of drying. As shown in Fig. 5(b), the water content of the upper exposed surface layer of the product gradually decreased with the drying process, and the accumulation phenomenon of local humidity was found in deeper part of the product. As time goes on, the increased range of local moisture content of the deep layer would decrease, and the value would rise steadily. Subsequently the water content of the product was gradually diminished and nearly equal to the hot air humidity as the drying running toward the end. This is attributed to the fact that the mass flux migrate along the temperature gradient under Soret effect.

In order to describe heat and moisture transfer within potato product due to thermal diffusion, the simulation was repeated with thermogradient coefficient a_q=2.54×10^{-6} m^{2}s^{-1} and the numerical simulation results are presented in Fig. 6.



(a) temperature distribution

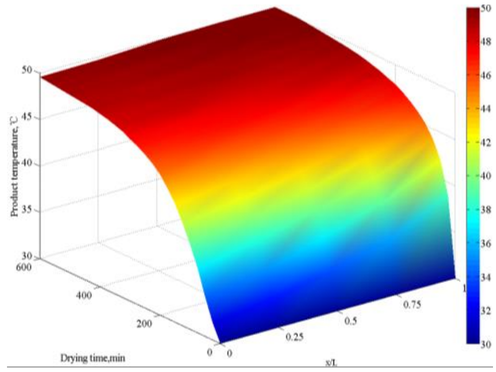


(b) moisture content distribution

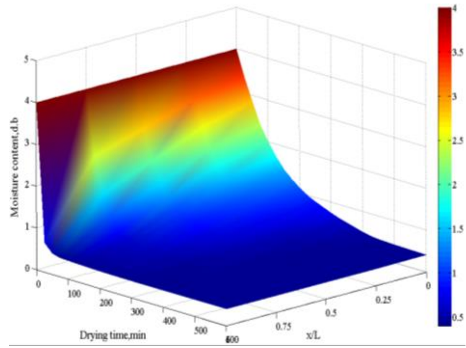
Fig. 6. Effect of heat diffusion coefficient on temperature and moisture content distribution in the product

Fig. 6(a) shows that heat flow from hot air to the porous product is a process of energy transfer tending to equalize temperature in a very short time. These findings confirm that thermal diffusion coefficienthas significant positive impact on heat flux and temperature distribution. However, there is no obvious difference between Fig. 5(b) with Fig. 6(b). One reason for this could be that the thermal diffusion behaviour has no significantly affect on moisture content distribution and dehydration in the product during conventional drying process.

Fig. 7 shows the local water content and temperature distributions profile within the moist product as the effective mass diffusion coefficient increasing by 10 times.



(a) temperature distribution

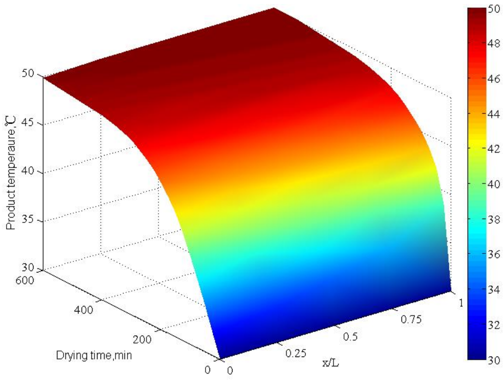


(b) moisture content distribution

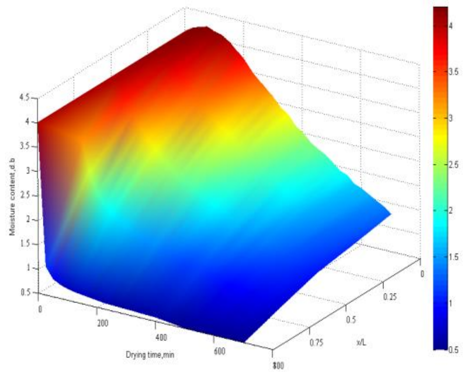
Fig. 7. Effect of mass diffusion coefficient on temperature and moisture content distribution in the product

Compared Fig. 5(a) with Fig. 7(a), one can easily find that it is no obvious difference, this may be due to the effective water vapour diffusion coefficient is very small and its influence on the temperature gradient and heat flow is less weak. It can be found in Fig. 7(b) that the humidity of the product is rapidly decreasing, the bulk of the water vapour migrate much easily through the upper exposed surface of the material and then quickly evaporated into the atmosphere. These findings imply that diffusion coefficient affects mass transfer and moisture content distribution.

As the thermogradient coefficient of the material increasing by ten times, the local temperature and moisture content distribution profiles are Fig.8 shows. It can be concluded from Fig. 8(a) that the thermogradient coefficient of the moist material has relatively less affect on the heat flux. As shown in Fig. 8(b), the accumulation phenomena of moisture content in that deep part of the product will be become more marked, this is due to the fact that water content diffuse towards the lower part of the product under Soret effect to the maximum extent.



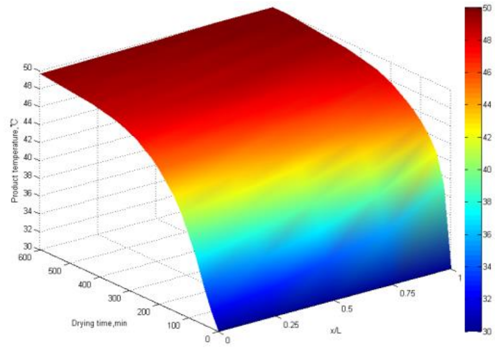
(a) temperature distribution



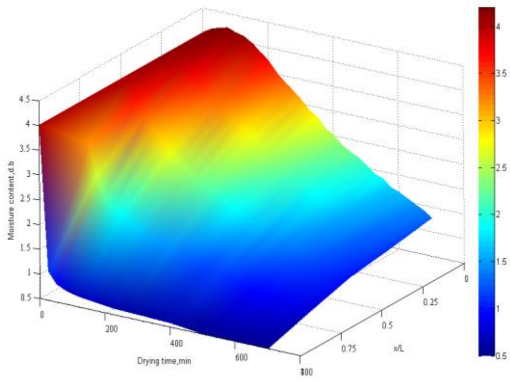
(b) moisture content distribution

Fig. 8. Effect of thermogradient coefficient on temperature and moisture content distribution in the product

Also note that the growth of local moisture content of the deep part of the product reduces constantly and the humidity amount would reach a maximum.Variation of moisture content coefficient inside the product with drying time is shown in Fig. 9. It can be seen that moisture content coefficient has no obvious influence on the temperature distribution in the product. This shows that Duffour effect has relatively weak effect on temperature distribution in convective drying. The results indicate that the effect of mass transfer on heat transfer is very week in conventional drying.



(a) temperature distribution



(b) moisture content distribution

Fig. 9. Effect of moisture gradient coefficient on temperature and moisture content distribution in the product.

CONCLUSIONS

This paper proposes a theoretical model of coupled heat and moisture transport to evaluate the effects of thermophysical properties on the moisture content and temperature distributions within the porous materials during convective drying. An experimental system for analyzing the convective drying characteristic was developed to investigate the coupled heat and mass transport in the moist materials. The predicted temperature and moisture content were compared with the experimental data. Effects of using different thermophysical properties of potato samples on the convective drying rate by taking into account the thermal-diffusion and diffusion-thermo effects were investigated. The predicted results show that thermophysical parameters of the product has significant influence on the combined moisture content and heat transport inside the potatoes subjected to forced convective dried, and the accumulation phenomena of moisture content is found in the deep part of the moist product.

Thermal diffusion coefficient has significant positive impact on heat transfer, and effective mass diffusion coefficient might directly affect on the moisture content distribution and convective drying rate. Soret effect has a significant impact on heat transfer in the presence of large temperature gradient during convective drying.

For further work, it would be desirable to estimate the thermophysical parameters of different porous materials and extend the modelling to multi-dimensional heat and moisture transfer process within moist media during forced convective drying.

Acknowledgements: *Programs Supported by Ningbo Natural Science Foundation under Grant No. 2011A610073 and Beilun Science and Technology Innovation Foundation, Ningbo University of Technology. This material was also funded by National Undergraduate Innovation and Entrepreneurship Training Program (201311058005) and Wang Weimin Innovation Foundation (2013014).*

REFERENCES

1. S.M.A. Rahman, M.R. Islam, A.S. Mujumdar, *Drying Technology*, **25**, 1359 (2007).
2. L. Sun, M.R. Islam, J.C. Ho, A.S. Mujumdar, *Bioresource Technology*, **96**, 1551(2005).
3. C. Lamnatou, E. Papanicolaou, V. Belessiotis, N. Kyriakis, *Numerical Heat Transfer Part A-Applications*, **56,** 379 (2009).
4. V.P.C. Mohan, P. Talukdar, *Int. J. Heat Mass Transfer*, **53**, 4638 (2010).
5. T. Defraeye, B. Blocken, J. Carmelietc, *Int. J. Heat Mass Transfer*, **53**, 112 (2012).
6. R. Prommas, *Int. Commun. Heat Mass Transfer*, **38**, 900 (2011).
7. B. Zecchi, L Clavijo., J.M. Garreiro, P. Gerla, *J. Food Eng.*, **104**, 49 (2011).
8. L. Bennamouna, L. Fraikina, A. Leonarda, *Drying Technol.*, **32**, 13 (2014).
9. R. Ranjan, J. Irudayaraj, J.N. Reddy, A.S. Mujumdar, *Numerical Heat Transfer Part A-Applications*, 45, 997 (2004).
10. 1S.J.D. Morais, I.A. Devilla, D.A. Ferreira, I.R. Teixeira, *Revista Ciencia Agronomica*, **44**, 455 (2013).
11. T.W. Wong, W.H.N.S. Ashikin, C.L. Law, Drying Technol., **32,** 117 (2014).
12. T. Defraeye, B. Blocken, J. Carmeliet, *Int. J. Heat Mass Transfer*, **55**, 112 (2012).
13. C.A. Perussello, V.C. Mariani, A.C.C. do Amarante, *Int. J. Food Properties*, **17**, 891(2014).
14. B.K. Jha, U. Mohammed, A.O. Ajibade, J. Appl. Math, 2013 (2013).
15. I. Bialobrzewski, *Drying Technol.*, **24**, 551 (2006).
16. D. Jou, J. Casas-Vazquez, G. Lebon Extended irreversible thermodynamics (4th ed.), Springer, Berlin, (2010) pp. 36-43).
17. G. T. Santos, M. Fortes, J.H. Martins, P.M.D. Monteiro, *Drying Technol.*, **31**, 1979 (2013).
18. U. Akyol, A. Cihan, R. Shaliyev, *Inverse Problems in Science and Engineering*, **18,** 227, (2010).
19. L.P. Wang, M. Zhang, S.B. Huang., L.Q. Lu, S.M. Roknul Azam, *Drying Technol.*, **32**, 190 (2014).
20. S.W. Zhang, N.H. Kong, Y.F. Zhu, Z.J. Zhang, C.H. Xu, Mathematical Problems in Engineering, 2013.

ЕФЕКТ НА ТЕРМОФИЗИЧНИТЕ СВОЙСТВА ВЪРХУ ПРИНУДЕНИТЕ КОНВЕКЦИИ ПРИ СУШЕНЕТО НА МНОГО-СЛОЙНИ ПОРЬОЗНИ МАТЕРИАЛИ

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Постъпила на 13 април, 2014 г.

(Резюме)

Изследвано е числено конвективното сушене на порьозна среда. Съставен е математичен модел за принуденото конвективно сушене за да се оцени изменението на важността и температурата в многослоен порьозен слой. Числено е решена система от свързани частни диференциални уравнения с начални и гранични условия с помощта на софтуера MATLAB. Математичният модел е изпитан експериментално. Изследвано е сушенето на проби от картофи в динамични условия (като температура и влажност). Резултатите показват, че коефициентът на термична дифузия и значителен положителен ефект върху температурния профил, а коефициентът на молекулярна дифузия може да влияе директно на разпределението на влажността. Ефектът на Soret имс значително влияние върху топлинния поток и разпределението на температурата при големи температурни градиенти.