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Large Eddy Simulation of Drying of a Potato Slice in Turbulent Flow

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Abstract **-** In this paper, the drying of the potato parallelepiped slice by a turbulent air stream is analysed in a conjugate model with the Large Eddy Simulation (LES) technique. The heat and mass transport equations are solved inside of the potato and continuity, movement, energy and species transport equations are solved to the external flow. Transport equations are discretized in the space and time using the McCormack scheme and a refined mesh at boundary of solid is utilized. The diffusion coefficient is calculated through Arrhenius equation for potato and the numerical model is developed in a Fortran code. Two cases are analysed: air stream at 333K and air stream at 353 K. Numerical simulations agree with the behaviour of the flow around immersed body and diffusion mechanism inside of food match with Chandramohan results. Predictions show the diffusion coefficient inside of potato slice is strongly related to the air temperature. The moisture loss in the potato slice is better in a semi-elliptic temperature distribution because changes of temperature imply variations in density of moisture, where mass transfer is promoted.

Keywords**:** Drying Of Potato, Mass Transport, Heat Transport, Diffusion Coefficient, LES.

1. Introduction

Drying is one of the most cost-effective ways of preserving foods of all varieties which involves removal of water by the application of heat. A variety of food sub-types are preserved using drying, these include: marine products, meat products as well as all fruits and vegetables. Food products can have moisture content as high as 90% or more (e.g. watermelon has moisture content as high as 93%), which needs to be reduced to an acceptable value in order to avoid microbial growth [1]. To achieve the desired results for dehydrated foods, with a defined physical structure, the process must provide the optimum heat and mass transfer within the product. The design of these processes requires a careful analysis of the heat and mass transfer occurring within the product structure [2]. Mass transport in solids can performed on two types according to the physical structure: 1) solid structure is considered homogeneous and liquid diffusion is assumed; 2) the material is a solid porous, which is considered as a capillary movement. In general, the transport may be considered as molecular diffusion, caused by a concentration gradient, and an overall (effective) diffusion is usually estimated. The diffusion of the various compounds in the solid depends on the temperature, and the Arrhenius equation can be applied according to [3].

In numerical simulations, the drying phenomena are analysed via conjugate and non-conjugate cases. In conjugate case, the transport equations are solved simultaneously in food and air drying. In this type of analysis, the mathematical conditions are introduced to apply continuity of heat and mass transfer between food and air flow. In addition, works as [4, 5 and 6] have studied drying process in laminar flow around the food. On the other hand, non-conjugated case the transport equations for external flow are solved in order to obtain convective heat and mass coefficients on the surface of the material. Also, in [7-9] regime laminar flow in the chamber is considered as a flow around bluff body, which under normal circumstances usually create a massive wake region downstream and this type of flow commonly is turbulent. Numerical simulations of the drying process, available in the open literature model turbulent flows with the RANS technique and turbulence models used are the k-ε or k-ω [10, 11 and 12] 1D, 2D and 3D analyses respectively.

Therefore, the aim of this paper is to study and simulate the drying process of a potato parallelepiped slice using a conjugate model with a 3D computer model finite difference which technic LES is employed to model turbulent flow around solid. The Arrhenius equation fitted to potato is used to calculate the diffusion coefficient in species transport equation inside food material.

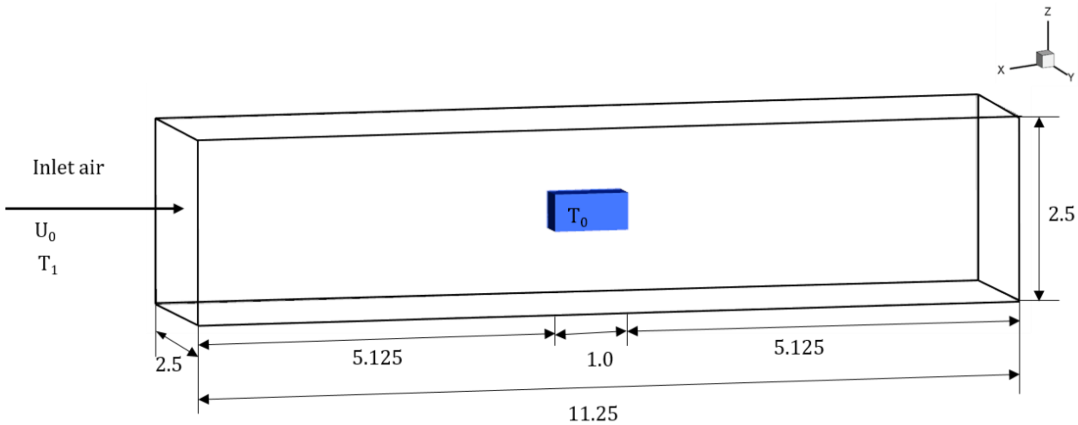


Fig. 1: Configuration drying chamber.

2. Methodology

In this work, a three dimensional model is solved using LES technique which, assumes specific turbulence scales are directly affected by boundary conditions while small scales hold characteristics universal and isotropic. In modelling approach LES, the important large scales are fully resolved whilst the small sub-grid scales are modelled [13].

During drying through diffusion, resistance mass transfer of water vapour from the surface is generally very low; in consequence solid diffusion control drying speed [14].

2.1. Problem Formulation

The numerical model considers a rectangular parallelepiped of potato fixed at the centre of a drying chamber whose dimensions are 0.45×0.1×0.1 m. The potato is dehydrated with the air flowing around it, the flow is described in a Cartesian coordinate system (x, y, z) in which the x-axis is aligned with the inlet flow direction, the z-axis is parallel to the parallelepiped axis and y-axis is perpendicular to both x and z. Otherwise an air flow with Reynolds number of 3000 [15] goes around the solid. The inlet velocity U_0 corresponds to 0.6m/s and the food temperature T_0 is assumed 300 K while the inlet air flow was 330 K in the first case and 353 K in the second case. Binary diffusion coefficient D_{AB} is assumed 0.26×10^{-4} [m^2/s] [16]. The dimensions of computational domain are normalized using the length of food (0.04 m) and are shown in Fig.1.

2.2. Governing Equations

Mass, momentum, energy and species transport equations, which are shown below in compact form (1-6), are accurately normalized according to the inlet velocity of hot air U_0, large of solid, which correspond to 0.04 m, temperature of potato T_0 and binary mass diffusion coefficient of water vapour in air D_{AB} to obtain them in non-dimensional form. The geometric domain is discretized by means of a grid structured.

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_i}\rho u_i=0 \tag{1}$$

$$\frac{\partial\rho u_1}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i u_1)+\frac{\partial}{\partial x_i}(p\delta_{i1})-\frac{\partial}{\partial x_i}(\mu S_{i1})=0 \tag{2}$$

$$\frac{\partial\rho u_2}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i u_2)+\frac{\partial}{\partial x_i}(p\delta_{i2})-\frac{\partial}{\partial x_i}(\mu S_{i2})=0 \tag{3}$$

$$\frac{\partial\rho u_3}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i u_3)+\frac{\partial}{\partial x_i}(p\delta_{i3})-\frac{\partial}{\partial x_i}(\mu S_{i3})=0 \tag{4}$$

$$\frac{\partial \rho e}{\partial t}+\frac{\partial}{\partial x_i}\left((\rho e+p)u_i\right)+\frac{\partial}{\partial x_i}\left(\mu S_{ij}u_i\right)-\frac{\partial}{\partial x_i}\left(\kappa\frac{\partial T}{\partial x_i}\right)=0 \tag{5}$$

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x_i}(u_i C)-\frac{\partial}{\partial x_i}\left(D\frac{\partial C}{\partial x_i}\right)=0 \tag{6}$$

In the above equations u_1, u_2, and u_3 are the velocities (m/s) in the *x*, *y* and *z* directions, x_i and u_i represents the spatial directions and the velocity components (i=1,2,3), respectively, ρ is the density (kg/m^3), *e* represents the internal energie, *T* is the temperature (K), μ is the dynamic viscosity (Pa·s), *p* is the pressure (Pa), *C* is the mass concentration (kg/m^3), κ is the thermal diffusivity (m^2/s), *D* is the mass diffusion coefficient (m^2/s) and *t* is the time (s). The term S_{ij} denotes the deviatoric part of the strain tensor, defined as

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}(\nabla\cdot u)\delta_{ij}\right) \tag{7}$$

where ∇ is the nabla operator and δ_{ij} represents the Kronecker delta.

2.3. Initial and Boundary Conditions

Initial conditions for external flow:

When the process begins at time zero dimensionless variable values are: $T(x,y,z,0)=T_1=1.1$; $C(x,y,z,0)=0$; $D(x,y,z,0)=D_{AB}=1.0$; $U(x,y,z,0)=U_0=1.0$; $V(x,y,z,0)=0$; $W(x,y,z,0)=0$. In the second simulation carried out T_1 value corresponds to 1.176.

Boundary conditions:

No-slip conditions are assumed at the surfaces of potato and the value of diffusion coefficient water-air is assumed constant $D_{AB}=0.26\times10^{-4}\ m^2/s$ [16].

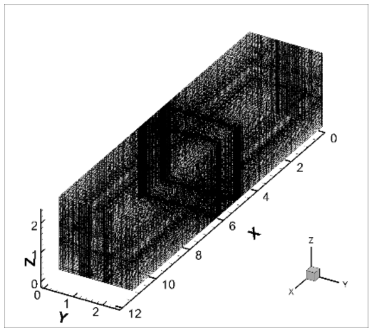
Initial conditions for internal flow:

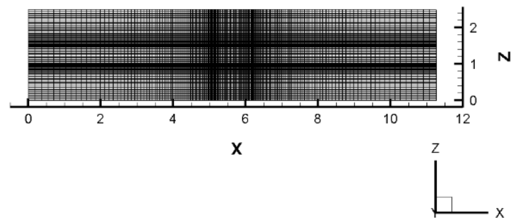
$T(x,y,z,0)=1.0$; $C(x,y,z,0)=0.5$; $D(x,y,z,0)=0$; $U(x,y,z,0)=0$; $V(x,y,z,0)=0$; $W(x,y,z,0)=0$. Due to velocity inside of solid is considered zero only Eqs. (5) and (6) are solved. Moreover, the transport of moisture within solid or semi-solid foods can be expressed by the effective diffusion *(D)*, which is an overall transport property, accounting for all transport mechanisms in the liquid and gas phases [2] hence, to calculate the diffusion coefficient, the model Arrhenius is adopted in a similar way to [4, 6, 9, 17-19] where the diffusion is function of temperature only. In case of potato the diffusion coefficient D_p is calculated by:

$$D_p=1.82\times10^{-8}\exp\left(\frac{-1119}{T}\right)\quad [m^2/s] \tag{8}$$

2.4. Numerical Solution

The governing equations are solved using the McCormack scheme, which is essentially a predictor-corrector scheme of second order in time and fourth order in the space, in a Fortran code. The transport and physical properties are continuously updated at each time step of computing, which in this case is 0.0001s and a grid resolution of 189×90×90 nodes, which corresponds to directions *x*, *y* and *z*, respectively, is used. Fig. 2a) shows the dimensions of computational domain 11.25, 2.5 and 2.5 in the directions *x*, *y* and *z*, respectively. In Fig. 2b) it is observed the mesh is refined with a hyperbolic tangent function around the body. This mesh refinement around solid was made to obtain accurate at interface food-air where convection of heat and mass is performed and strain variation of velocity and temperature are expected.





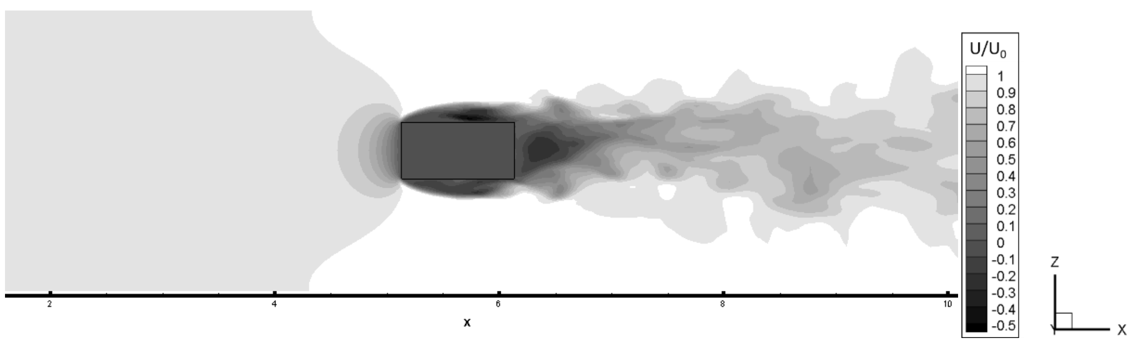
a) b)

Fig. 2: a) Computational domain in three axes; b) Computational domain in the middle of the plane XZ.

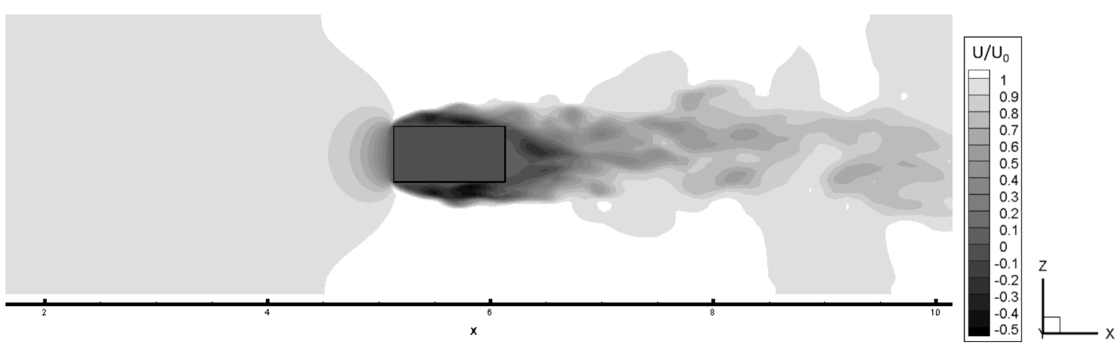
3. Results

Two CFD simulations are carried out for inlet temperatures of 1.1 and 1.176 non-dimensional values and at Reynolds number of 3000 where turbulent flow was developed. Heat and mass transfer transport equations are solved simultaneously in the external flow and inside of the potato and 25s of drying time is analysed.

Figures 3a) and 3b) shows velocity contours in the direction U around the solid to inlet temperatures of 1.1 and 1.176, respectively in the XZ plane and in the middle of Y axis. In both figures the darkest contours corresponds to negative velocity values which is evidence of recirculating zones that are formed on the sides and behind of the rectangular shape of the potato. Also, the separation points are formed at leading edges and trailing edge of the solid, this fact agrees with external flow over cylinder square theory. In Fig. 3a) and 3b) flow behind of food exhibits an irregular motion which is a characteristic of turbulent flow.



a)



b)

Fig. 3: Velocity contours obtained in two different simulations; a) at 333K b) at 353K.

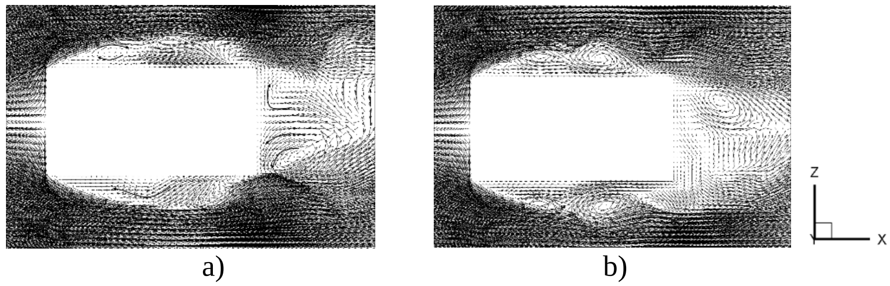


Fig. 4: Vectors of flow formed around solid in plane XZ at the middle of the Y axis; a) at 1.1 and b) at 1.176 non dimension temperature.

According to the flow pattern over the bluff body, eddies are formed around the object. Figs. 4a) and 4b) shows the vectors of flow in contact with the solid. It can observe the flow is divided upstream and downstream forming recirculating zones which are characteristics of a turbulent flow. On the other hand, the existence of these recirculation zones contributes the heat transfer by convection between air and food.

At the beginning of the drying process, the potato is completely moist while air is dry. Figs. 5a) and 5c) show contours of concentration of food and hot air after 25 s of drying time. At the edges of the potato it observes white contours which indicate a loss of moisture which is transported to the air, this fact can be noticed by a grey shade around of the potato. Figs. 5b) and 5d) shows the diffusion contours of a potato slice located in the middle of the Y axis which behave similar to the heat transport due to the dependence of this coefficient on temperature. Also, comparing above mentioned figures it can be observed that the diffusion coefficient values are the highest in zones where there is a notable change in concentration. Therefore, temperature is an important parameter to promote concentration changes.

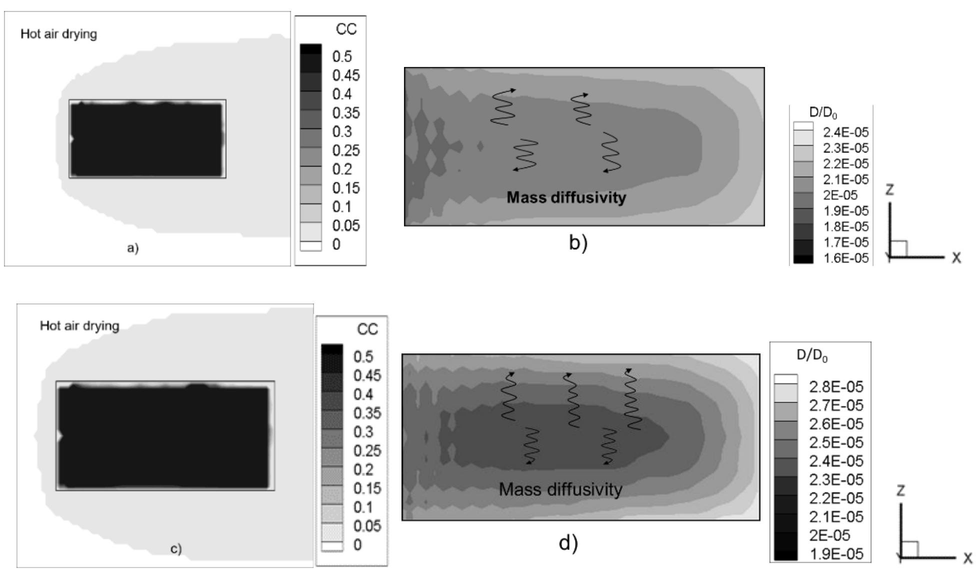


Fig. 5: a) and c): change of concentration of moist food and air, when drying process is simulated at 1.1 and 1.176 non-dimensional temperature, respectively; b) and d): mass diffusivity coefficient contours inside of food, when drying process is simulated at 1.1 and 1.176 non-dimensional temperature, respectively.

According to diffusion theory in solids, the diffusion is strongly related to temperature through Arrhenius equation, this can be observed in the contours of the diffusion coefficient and temperature where at higher temperatures, the diffusion coefficient increases. On the other hand, observing the data of moisture diffusion coefficient inside of a potato, which was calculated in the present simulation, range between 1.6×10^{-5} and 2.4×10^{-5} non-dimensional values, which correspond to 4.16 $\times10^{-10}$ - 6.24×10^{-10} m^2/s, these results agree with the compiled data by [20] which ranges between 8.00×10^{-12} and 1.25×10^{-08} m^2/s. Also, diffusion coefficient values agree with results presents in the study done by Chandramohan [15] which shows figures of contours of this parameter in the range of 6.31949×10^{-10} to 6.31943×10^{-10} m^2/s at temperature of 333K and

7.64481×10^{-10} to 7.64478×10^{-10} m^2/s at 353 K. Therefore, the numeric code utilized is capable to represent a diffusion mechanism inside of the potato.

In drying process, the heat transfer mechanism is carried out by convection from air drying of food surface, later this heat is transported by conduction from surface of food to the inside of this one. The above it can observe in the figures 6a) and 6c), which show the temperature contours of the potato slice and air flow taken in the plane XZ in the middle of Y axis at inlet non-dimensional temperatures of 1.1 and 1.176, respectively. In Fig. 6c), the convective heat transfer is higher than the case show in figure 6a) as can be appreciated in changes of colour in the contours around the potato. On the other hand, Figs. 6b) and 6d) show temperature contours that increased from the outside. In the Fig. 6b) contours values range in the order of 0.01 while in Fig. 6d) contours of temperature in the slice range in the order of 0.02. Above non dimension values are equivalent to 3 K and 6 K, respectively. This fact is relevant because a high difference of temperature is an important factor in heat transfer. Also, it is observed that the shape of contours is different in each case since in Fig. 6b) contours tends to take an elliptical form, however, at the centre it is observed a form just begins to develop, while in Fig. 6d) it is observed that all the contours have a semi-elliptic shape. Last case indicates a heat transfer more uniform in the potato slice and comparing the differences of temperature, it is possible infers that at the process at an inlet dimensionless temperature of 1.1 the heat transfer is slow, which demands a higher drying time. Therefore, changes of temperature imply variations in density of moisture inside of food which, are accompanied by a change of concentration and as a consequence, a loss of moisture according to Fick's law.

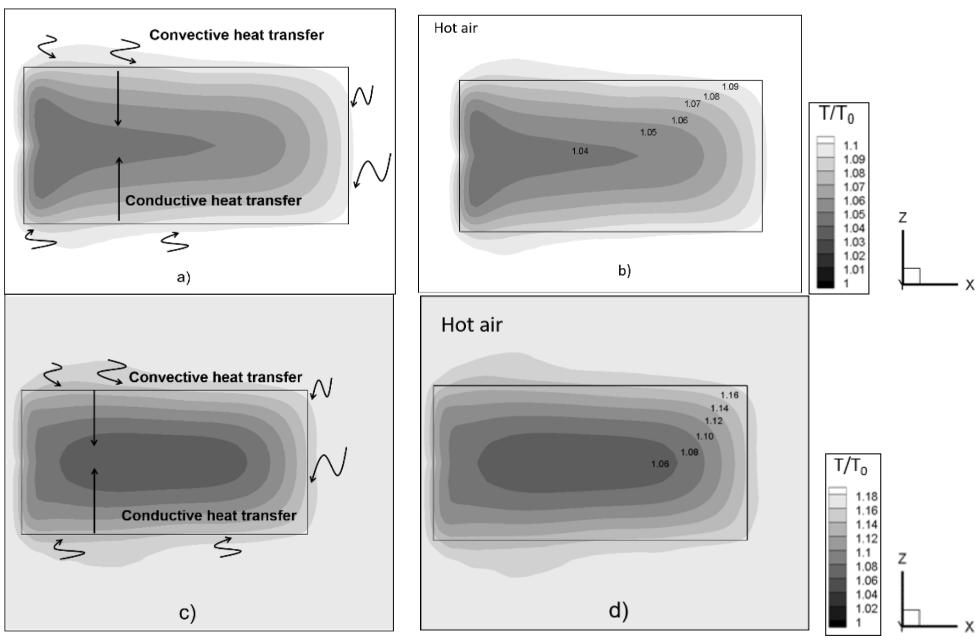


Fig. 6: Temperature contours a) at 1.1 non-dimensional initial temperature and b) temperature contours values in the potato slice; c) at 1.176 non-dimensional initial temperature and d) temperature contours values in the potato slice.

4. Conclusion

Numerical model is capable to represent the diffusion mechanism inside of potato due to diffusion coefficient values obtained agree with Chandramohan [15]. Furthermore, velocity contours show simulation agrees with the behaviour of the flow around immersed body, it was allowing identify mean zones where convection mechanism occurs. In two cases analysed, the differences of temperature between contours resulted 3 K (first case at inlet temperature 333K) and 6 K (second case at inlet temperature 353 K), also, in the second case, the temperature contours showed a semi-elliptic shape, which indicate a better heat transfer. Therefore, the moisture loss in the potato slice is better in a semi-elliptic temperature distribution because temperature changes imply variations in density of moisture, as well as, the mass transfer is promoted by density variations since moisture concentration can be defined as a function of density.

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References

[1] S. V. Jangam, C. L. Law, A. S. Mujumdar, *Drying of foods, vegetables and fruits*, vol. 1, pp. 3, 2010.

[2] W. A. M. McMinn and T. R. A. Magee, “Principles, Methods and applications of the convective drying of foodstuffs,” *IChemE*, vol. 77, Part C, 1999.

[3] R. P. Singh and D. R. Heldman, *Introduction to Food Engineering*. Ed. Elsevier, pp. 679.

[4] C. Lamnatou, E. Papanicolaou, V. Belessiotis, N. Kyriakis, “Numerical study of the interaction among a pair of blunt plates subject to convective drying – a conjugate approach,” *Int. J. Therm. Sci*. vol. 49, pp. 2467-2482, 2010.

[5] F. A. Khan, A. G. Straatman, “A conjugate fluid-porous approach to convective heat and mass transfer with application to produce drying,” *Journal of Food Engineering*, vol. 179, pp. 55-67, 2016.

[6] S. Curcio, M. Aversa, S. Chakraborty, V. Calabrò, G. Iorio, “Formulation of a 3D conjugated multiphase transport model to predict drying process behavior of irregular-shaped vegetables,” *Journal of Food Engineering*, vol. 176, pp. 36-55, 2016.

[7] A. Kaya, O. Aydın, “Numerical modeling of forced convection drying of cylindrical moist objects,” *Numer. Heat Transfer*, Part-A 51, pp. 843-854, 2007.

[8] A. Kaya, O. Aydın, I. Dincer, “Heat and mass transfer modeling of recirculating flows during air drying of moist objects for various dryer configurations,” *Numer. Heat transfer*, Part-A 53, pp. 18-34, 2008.

[9] A. Kaya, O. Aydın, I. Dincer, “Experimental and numerical investigation of heat and mass transfer during drying of Hayward kiwi fruits (Actinidia Deliciosa Planch),” *Journal of Food Engineering*, vol. 88, pp. 323-330, 2010.

[10] D. A. Tzempelikos, D. Mitrakos, A. P. Vouros, A. V. Bardakas, A. E. Filios, D. P. Margaris, “Numerical modeling of heat and mass transfer during convective drying of cylindrical quince slices,” *Journal of Food Engineering*, vol. 156, pp. 10–21, 2015.

[11] T. Defraeye, A. Radu, “Convective drying of fruit: A deeper look at the air-material interface by conjugate modelling,” *International Journal of Heat and Mass Transfer*, vol. 108, pp. 1610–1622, 2017.

[12] A.Md, Udayraj, M. R., Chandramohan, V. P. Talukdar P., “Numerical modeling of convective drying of food with spatially dependent transfer coefficient in a turbulent flow field,” *International Journal of Thermal Sciences*, vol. 78, pp. 145-157, 2014.

[13] C. D. Argyropoulos, N. C. Markatos, “Recent advances on the numerical modelling of turbulent flows,” *Applied Mathematical Modelling*, pp. 693–732, 2015.

[14] C. J. Geankopolis, *Transport process and unitary operations*, ed. Continental. 1998, pp. 613-619.

[15] V. P. Chandramohan, “Experimental analysis and simultaneous heat and moisture transfer coupled CFD model for convective drying of moist object,” *International Journal for Computational Methods in Engineering Science and Mechanics*, vol. 17, pp. 59-71, 2016.

[16] F. P. Incropera, and D. V. DeWitt, *Fundamental of Heat and Mass Transfer*. Ed. NJ: Wiley, pp. 2007.

[17] A. Zhu and X. Shen, “The model and mass transfer characteristics of convection drying peach slices,” *International Journal of Heat and Mass transfer*, vol. 72, pp. 345-351, 2014.

[18] R. A. Lemus-Mondaca, C. E. Zambra, A. Vega-Gálvez, N. O. Moraga, “Coupled 3D heat and mass transfer model for numerical analysis of drying process in papaya slices,” *Journal of Food Engineering*, vol. 116, pp. 109-117, 2013.

[19] A. Kaya, O. Aydın, I. Dincer, “Numerical modeling of heat and mass transfer during forced convection drying of rectangular moist objects,” *International Journal of Heat and Mass Transfer*, vol. 49, pp. 3094-3103, 2006.

[20] Z. B. Maroulis, G. D. Saravacos, N. M. Panagiotou and M. K. Krokida, “Moisture diffusivity data compilation for foodstuffs: effect of material moisture content and temperature,” *International Journal of Food Properties*, vol. 4, pp. 225-237, 2001.