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3-D simulation of simultaneous heat and mass transfer of apple

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Drying is a complex process associated with the coupled mechanism of heat and mass transfer which plays an important role in almost all industrial sectors. For this reason, the intensive research on drying is carried on specially based on optimisation of energy and process control. The aim of this study is to present a numerical method for drying processes widely used in food industries to provide enhanced product quality and economically advantages at definite production conditions. The governing equations of drying process in a 3-D rectangular object (e.g. apple slices) are solved numerically to predict the temperature and moisture distributions inside the object. Then, statistical tests of agreement between results are performed by determining the coefficient of regression (R^2), chi-square test (χ^2) and standard error of estimate (SEE) values, and it is found that predicted results agree well with the results in literature. Finally, a parametric study is conducted to emphasize the role of parameters on food drying as an important contributor to energy consumption.

Keywords: Heat and mass transfer, drying, numerical modelling

INTRODUCTION

The drying of solids is an operation of widespread importance in the food and pharmaceutical industries, production of textiles, chemical process, and also in the manufacture of paper and plastics. The investigations on the effective drying of foods is becoming increasingly important in the rapidly growing food industry, because the energy and food resources are limited. This is because the practical and easily adaptable drying models should be developed to augment the simultaneous heat and mass transfer consistent with the lowest capital and running costs in the sustainable products policies. Among these, numerical modelling is an essential part of food industry activities which is committed to maximising the process efficiency.

Drying of a food product is one of the oldest preservation methods to reduce microbial deterioration significantly. Nowadays, drying is regarded not only as a preservation process, but also as a method for increasing added value of foods. Therefore, drying process results in a product that is more convenient for final users. According to Avci and Can [1], the designers of industrial dryers, also, have a need for quite basic heat transfer data to achieve optimum results for drying operations. So, to achieve the desired results for dry foods with defined physical structure, the process should provide the optimum simultaneous heat and mass transfer within the food product.

Numerous papers reported on different aspects and problems of drying for relevant sectors in industry. For example, different authors reported on new numerical and/or experimental models, and, many researchers presented drying characteristics of various solid objects [2-9].

Vega et al. [10] presented a study on maximum surface temperatures of products, which controlled automatically to avoid exceeding the allowable temperature values for convective drying process of fruits and vegetables. Bezerra et al. [11] determined the moisture diffusivity and the moisture transfer coefficient of passion fruit peel during convective drying process. Ateeque et al. [12] developed a 3D numerical model for convective drying of rectangular food material and solved the simultaneous heat and mass transfer equations by a MATLAB code. Lemus-Mondaca et al. [13] investigated the drying characteristics of papaya slices in range of air temperature from 40°C to 80°C both experimentally and numerically.

Understanding the mechanisms during the drying process of solid objects is essential for dryer design, quality control and energy savings. Thus, in literature, numerical investigations are presented for simulating heat and moisture transfer by Hussain and Dincer [14], Kaya et al. [15] and Kim et al. [16]. Similarly, Etemoglu et al. [17, 18] and Harchegani et al. [19] developed mathematical models for drying of thin layers, and validated their results with experimental data.

Aghbashlo et al. [20] stated that drying of wet materials is a complex, dynamic, unsteady, highly nonlinear, strongly interactive, successively interconnected, and multivariable thermal process

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whose underlying mechanisms are not yet perfectly understood. Therefore, the drying process still needs to be investigated by different perspectives. So, the objective of this study is to simulate the drying process in a 3-D rectangular object, to examine the influence of parameters which affect the heat and mass transfer rates such as temperature, velocity, moisture content, time, effective diffusion coefficient, and to validate the predicted results inside the object with available data in the literature.

MATERIAL AND METHOD

Mathematic modelling

Dried apples are often consumed in daily life because of nutritional values such as vitamin, fibre and low calorie. Thus, the most suitable drying conditions of apples should be determined for quality, hygiene and economical requirements in convective dryers which commonly used in industry. Drying process is a simultaneous heat and mass transfer operation in which the energy and evaporation of a liquid from a solid can be easily characterised and described in terms of the four empirical graphs shown in Fig.1 [1, 18]. A 3-D model is developed to evaluate the simultaneous heat and mass transfer for convective air drying of apple.

Briefly, the liquid inside the apple is transferred to the surface by diffusion and evaporates into the air by transferring heat from air to the food product by convection. Therefore, Fourier's law of heat transfer and Fick's law of mass diffusion are used for the drying process for the energy and water mass balance [14, 21]. The assumptions considered in the numerical model are as follows:

During the drying process, the air velocity, temperature and relative humidity are kept constant [14, 22].

a) During the drying process, the air velocity, temperature and relative humidity are kept constant [14, 22]

b) Gravity effects are negligible [23].

c) The thermophysical properties of the product are kept constant during drying [14, 22-25].

d) Food sample is homogenous [22-24].

e) The heat and mass transfer analogy is applicable [14, 26, 27].

f) There is no heat generation inside product [12, 14, 15, 23].

g) The shrinkage in the product is neglected (12-16, 23, 24, 26].

h) Radiation effects are negligible [13, 15].

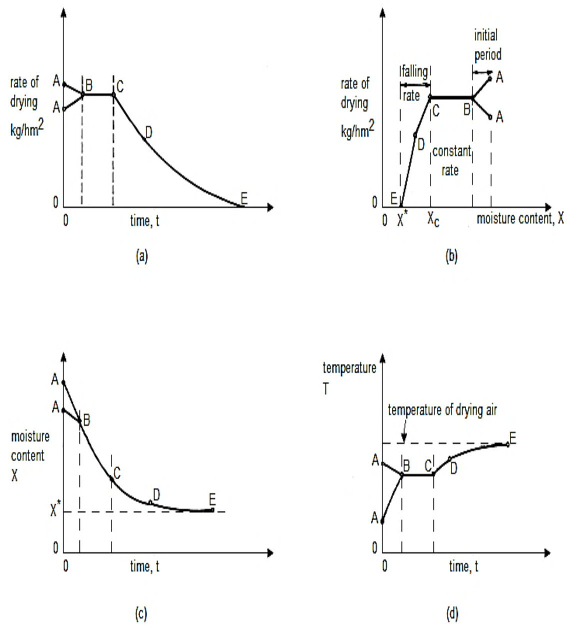


Fig.1. Characteristic drying graphs

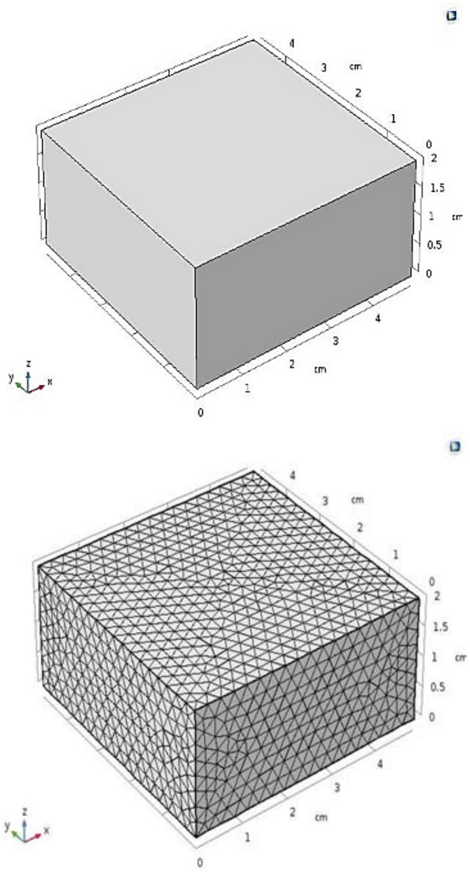


Fig.2. Model and mesh structure of the model

Table 1. Boundary conditions

	Heat Balance	Mass Balance
x = 0; 0 ≤ y ≤ B and 0 ≤ z ≤ H	$-k\frac{\partial T(0,y,z,t)}{\partial x} = h_T(T - T_\infty)$	$-D_{AB}\frac{\partial M(0,y,z,t)}{\partial x} = h_M(M - M_\infty)$
x = L; 0 ≤ y ≤ B and 0 ≤ z ≤ H	$-k\frac{\partial T(L,y,z,t)}{\partial x} = h_T(T - T_\infty)$	$-D_{AB}\frac{\partial M(L,y,z,t)}{\partial x} = h_M(M - M_\infty)$
y = 0; 0 ≤ x ≤ L and 0 ≤ z ≤ H	$-k\frac{\partial T(x,0,z,t)}{\partial y} = h_T(T - T_\infty)$	$-D_{AB}\frac{\partial M(x,0,z,t)}{\partial y} = h_M(M - M_\infty)$
y = B; 0 ≤ x ≤ L and 0 ≤ z ≤ H	$-k\frac{\partial T(x,B,z,t)}{\partial y} = h_T(T - T_\infty)$	$-D_{AB}\frac{\partial M(x,B,z,t)}{\partial y} = h_M(M - M_\infty)$
z = H; 0 ≤ x ≤ L and 0 ≤ y ≤ B	$-k\frac{\partial T(x,y,H,t)}{\partial z} = h_T(T - T_\infty)$	$-D_{AB}\frac{\partial M(x,y,H,t)}{\partial z} = h_M(M - M_\infty)$

These assumptions are widely used because they provide acceptable accuracy and a more practical solution in engineering applications. The dimensions of the material are determined as 4.9 cm×4.8 cm×2 cm. The geometry of the physical model and mesh structure are shown in Fig.2.

Boundary conditions used in the analysis are shown in Tab.1.

Governing equations

The heat and mass transfer equations for moisture diffusion and temperature within food product can be expressed as:

$$\frac{\rho c_p}{k}\left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) \quad (1)$$

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial M}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial M}{\partial z}\right) \quad (2)$$

Initial conditions

The boundary conditions for the numerical solution are given as follows:

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

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

T_0 and M_0 are the initial temperature and the moisture content of the material, respectively.

Five surfaces of the moist material which has length L, height H and width B are in contact with the hot air; i.e. there is no heat or mass transfer from the base (see Fig.2). The boundary conditions in the x, y and z directions are given in Tab.1.

Heat and mass transfer coefficients (h_T, h_M) can be calculated by well-known semi-empirical correlation equations using the average Nusselt and Sherwood numbers for laminar flow over flat plates [21].

$$\mathrm{Nu} = \frac{h_T L_k}{k} = 0.664\ \mathrm{Re}^{0.5} Pr^{0.33} \quad (5)$$

$$\mathrm{Sh} = \frac{h_M L_k}{D_{AB}} = 0.664\ \mathrm{Re}^{0.5} Sc^{0.33} \quad (6)$$

Solution methodology

Non-linear simultaneous heat and mass transfer equations are solved numerically by COMSOL Multiphysics using appropriate initial and boundary conditions and assumptions to obtain the temperature and moisture distributions in the apple during drying. The main steps of the solution process are as follows:

- Heat and mass transfer coefficients calculation
- Defining geometry
- Creating mesh structure
- Realizing the physical conditions (initial, boundary conditions etc.)
- Integrating and solving the governing equations [28].

The independence of the solution with respect to the mesh structure in the model geometry was carried out for moisture content and the maximum difference was found 1%. Mesh structure which consists of 12465 tetrahedral, 1468 triangular and 124 edge elements was used for all analysis (Fig.2). The time-dependent problem was solved by an implicit time stepping method. The non-linear coupled heat and mass transfer equations were solved using Newton's method with relative tolerance 0.01 and absolute tolerance 0.001.

Moisture ratio

Apple samples were dried by a convective dryer, so, the dimensionless moisture ratio, MR, is obtained as follows;

$$\mathrm{MR} = \frac{M_t - M_e}{M_b - M_e} \quad (7)$$

where MR is the moisture ratio, M_t is the moisture content at time t (kg water/kg dry solid), M_e is the equilibrium moisture content (kg water/kg dry solid), and M_b is the initial moisture content (kg water/kg dry solid). Since the value of M_e is very small compared to the values of M_t and M_b, moisture ratio was calculated as;

$$\mathrm{MR} = \frac{M_t}{M_b} \quad (8)$$

Statistical parameters

The non-linear regression analysis was applied for the drying models which are given in Tab.2 by SigmaPlot. The coefficient of regression (R^2), standard error of estimated (SEE) and chi-square test (χ^2) were used to evaluate the accuracies of the data.

Table 2. Considered drying models

Model No	Model Name	Equation	Reference
1	Lewis	$MR=\exp(-kt)$	[2]
2	Henderson and Pabis	$MR=a\exp(-kt)$	[3]
3	Two Term Exponential	$MR=a\exp(-k_0t)+b\exp(-k_1t)$	[4]
4	Wang and Singh	$MR=1+at+bt^2$	[5]
5	Midilli et al.	$MR=a\exp(-kt^n)+bt$	[7]

$$\mathrm{SEE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{analysis} - MR_{prediction}\right)^2}{N-z}} \quad (9)$$

$$x^2 = \frac{\sum_{i=1}^{N}\left(MR_{analysis} - MR_{prediction}\right)^2}{N-z} \quad (10)$$

where $MR_{analysis}$ and $MR_{prediction}$ are estimated dimensionless moisture ratio by numerical analysis and the SigmaPlot program, N is the number of data points, z is the number of parameters in model.

RESULTS AND DISCUSSION

Model verification

The results of the present study is compared with numerical results by Younsi et al [23] and experimental results by Chiang and Petersen [29] under the same drying conditions. Thermophysical properties of material and the drying conditions are given in Tab.3.

The predicted centre temperature and moisture distributions inside the sample object are compared with experimental and numerical data available in the literature and are shown in Fig.3. As seen from Fig.3, considerably high agreement is found between predicted and numerical/experimental results.

Table 3. Thermophysical properties and initial conditions of the sample

Parameter (Unit)	Value
Density (kg/m^3)	856
Air temperature (°C)	81
Moisture content of material (%)	87
Moisture content of air (%)	12
Thermal conductivity (W/mK)	0.577
Heat of molar evaporation (J/kg)	0.25×10^7
Specific heat (J/kgK)	4201.4
Moisture capacity (kg/kg)	0.01
Moisture conductivity (kg/ms)	2.2×10^{-8}
Heat transfer coefficient (W/m^{2}K)	25
Mass transfer coefficient (kg/m^{2}s)	0.0001
Water molecular weight (gr/mol)	18

Thin layer drying models commonly used in the literature were also used to verify the drying curves obtained as a function of predicted data (see Tab.2). The statistical results from these models such as regression coefficient (R^2), chi-square (χ^2) and standard error of estimated (SEE) are given in Tab.4.

From the statistical analysis, it is revealed that the Midilli model yielded the highest R^2 and the lowest χ^2 and SEE values. Hence, the Midilli model gave better predictions than the other considered models.

Table 4. Statistical results of the drying models

Model/Coefficient	a	b	k	k_0	k_1	n	R^2	SEE	x^2
Lewis			6.81×10^{-5}				0.95	0.0751	0.0056
Henderson and Pabis	1.07		7.76×10^{-5}				0.97	0.0622	0.0039
Two Term	3.9×10^{-3}	1.07		1.03×10^{-12}	7.82×10^{-5}		0.97	0.0803	0.0064
Wang and Singh	-6.97×10^{-5}	1.24×10^{-9}					0.98	0.0593	0.0035
Midilli et al.	1.03	3.49×10^{-6}	1.50×10^{-6}			1.43	0.99	0.0480	0.0023

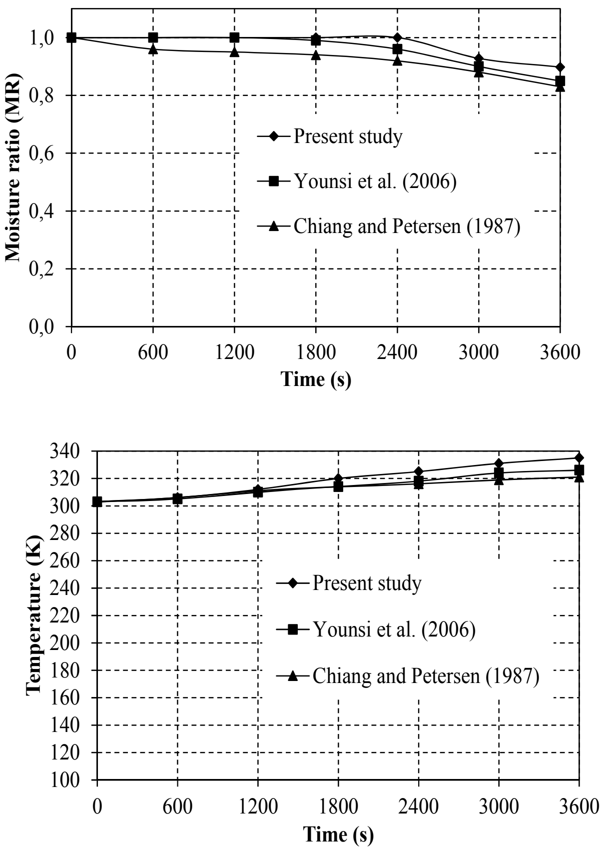


Fig.3. Comparison of the model prediction with the given results in literature

Numerical results

Fig.4 shows that the present numerical model can be used to predict the effects of many parameters on the operation conditions of dryers. The temperature and moisture distribution inside the food products are important knowledge for the producers because of the determination of quality and storage conditions. The moisture variation of the y-axis and z-axis inside the material, and the central temperature change of the y- and z-axes inside the material are shown in Fig.4a, 4b, 4c and Fig.5a, 5b and 5c respectively. The central moisture contents (on wet basis) are calculated for 3 different drying time (1800 s, 3600 s and 7200 s) as 87%, 86% and 80%, respectively. The central moisture content of the product decreases slowly with time.

During initial stage of drying, surface moisture is removed and in later stage, internal moisture movement governs the moisture removal rate. When surface moisture is removed, internal moisture movement starts. This is a slow process due to resistance in flow of moisture from inside to surface. Similarly, the central temperatures of the product after 1800, 3600 and 7200 seconds are 62°C, 75°C and 80°C, respectively. Drying processes lead to changes of foods at microstructural level, consequently it affects their macroscopic characteristics. Loss of water and segregation of components occurring during drying result in rigidity of cell walls. Damage and disruption of the cellular walls may happen, and even collapse of the cellular tissue may occur.

Frequently, during drying processes, the product surface dries much faster than its core, a phenomenon that originates internal stresses that results in very cracked and porous product interior. These changes are associated with volume reduction and colour change of the product.

So, the temperature and moisture values should be known for practical purposes. Tab.5 shows the temperature and the moisture ratios for 1000, 2000 and 4000 seconds for different depths from the surface of the product. The variations of the product temperature and the moisture ratio are presented as a function of drying time in Fig.6.

Table 5. Temperature distribution and moisture ratio of the material through the z-axis

Time (s)	1000	2000	4000
z-axis distance (cm)	Temperature (°C)		
0	46	63	76
0.5	46.8	63.55	76.65
1	49	64.55	76.92
1.5	52.2	66.5	77.35
2	57	69	78
	Moisture ratio (MR)		
0	1	1	1
0.5	1	1	1
1	1	1	0.78
1.5	1	0.56	0.33
2	0.03	0.02	0.02

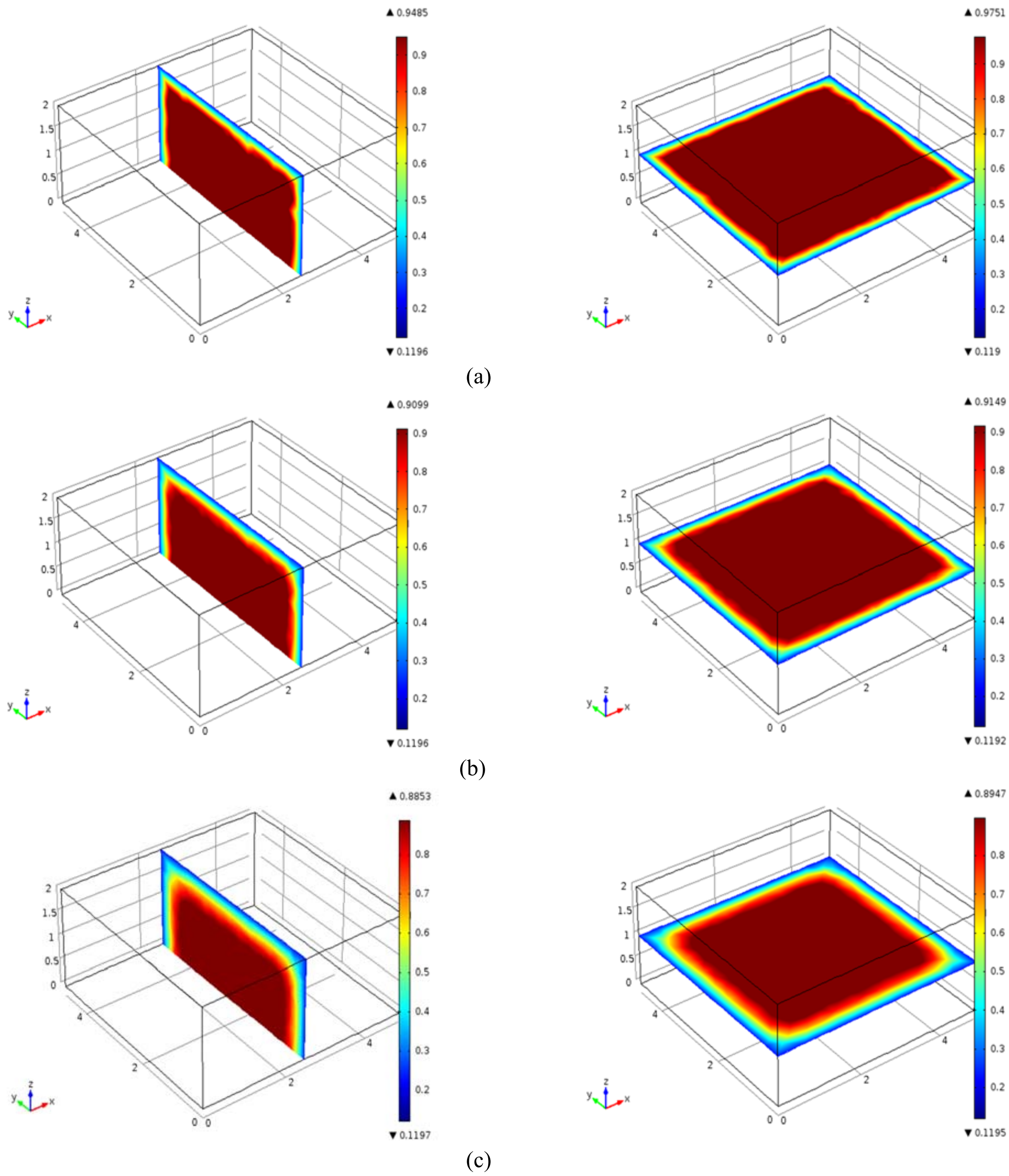
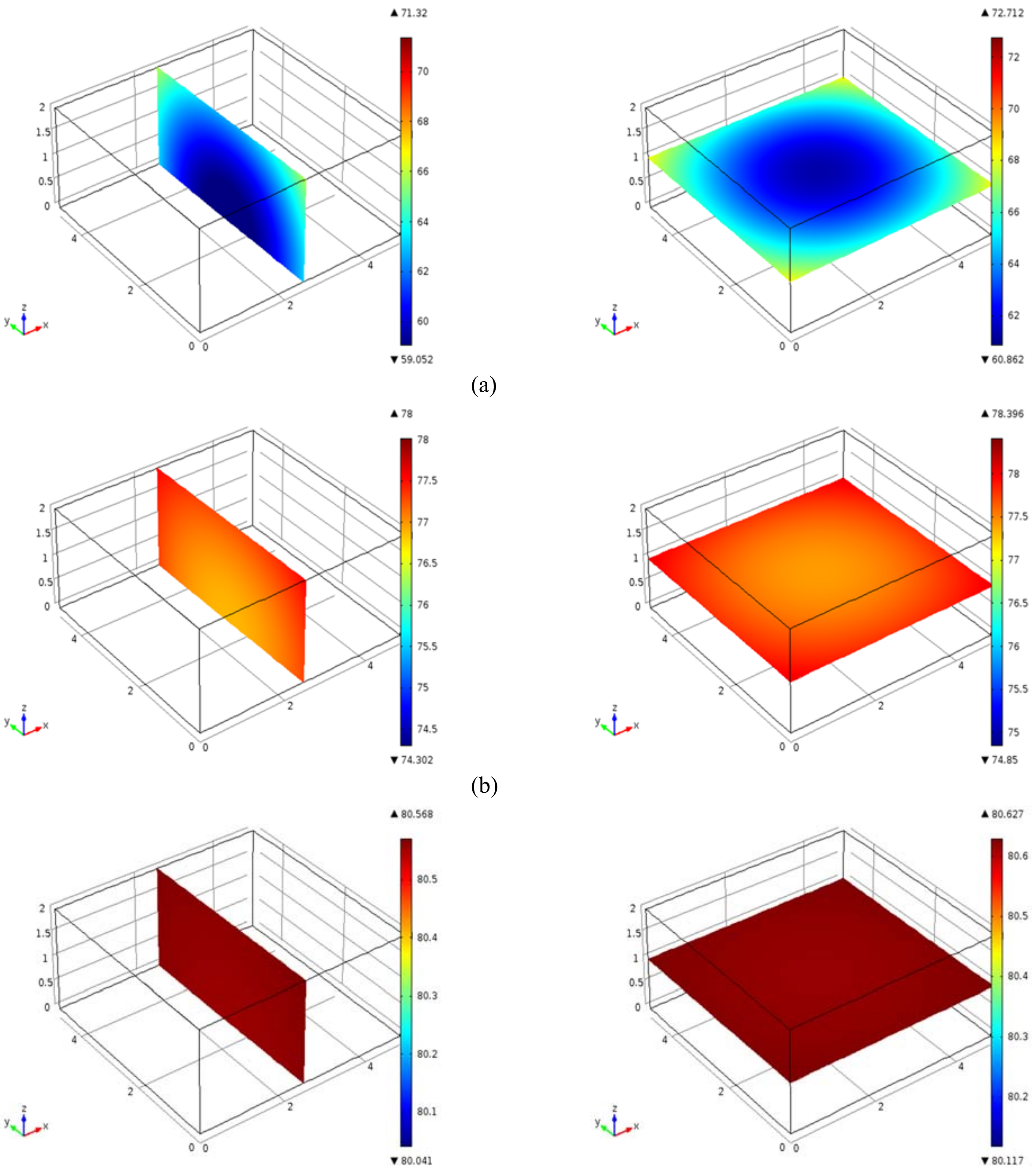


Fig.4. Moisture distribution inside the material (a-1800 s, b-3600 s, c-7200 s)

As can be seen from Fig.6, the central temperature of the product reached quickly 80°C after approximately 8000 seconds and, the total drying process consists of a short constant rate period and then first and second falling rate periods.

If the temperature of the drying air is not too high, the constant rate period can be observed in the drying of fruits containing high amount of moisture. In the constant rate drying period, the product surface is continuously wet and covered with a moisture layer. As the liquid evaporates from the surface, liquid transfer takes place through diffusion from the product inside to the surface. The constant rate period continues until the first critical point that the liquid layer on the surface is reduced. After which the first falling rate period (between2400 and 16000 seconds) starts.



(c)

Fig.5. Temperature distribution inside the material (a-1800 s, b-3600 s, c-7200 s)

The amount of liquid transferred by diffusion to the surface during this period is less than the amount of liquid evaporated from the surface. The liquid film layer on the surface continues to decrease until the surface is completely dry at second critical point (0.27 MR). The moisture content continues to decrease after this point.This period is called the second falling rate period. Different parameters, which affect the drying process such as temperature and velocity of air, initial moisture contents of product, were investigated by numerical model.

And the predicted results are also compared with the Midilli model giving the best results (see Fig.7). It can be seen from the Figs.7-8, drying is speeded up either by increasing the average heat and mass transfer coefficients, or by increasing drying air velocity and temperature. When the drying air temperature is high, the temperature rise of the product is great. The product dries more rapidly due to the large difference between its temperature and that of the drying air.

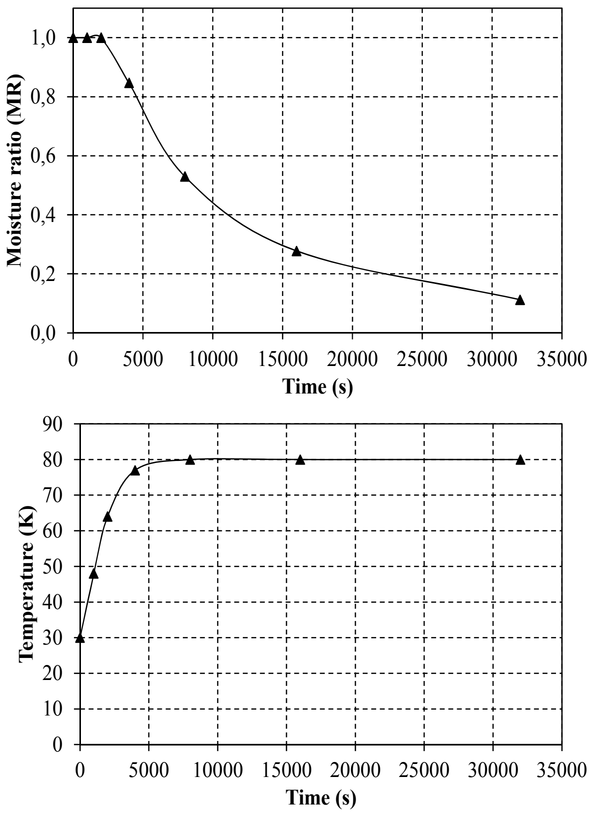


Fig.6. Temperature and moisture ratio values during drying

The changes in the moisture ratios and central temperatures of the product with different initial moisture contents (on wet basis) are also given in Fig.7. When the initial moisture content is high, the temperature rise is relatively slow and drying takes long time, because the higher moisture content needs much more heat for evaporation from the product.

CONCLUSIONS

In this study, the drying process of a three-dimensional model was numerically investigated. The numerical model considers simultaneous heat and mass transfer through the moist porous material. Five surfaces of the food product were assumed to be in contact with hot air. For validation, the present numerical model was compared with two different numerical and experimental studies in the literature. The predicted numerical results of the model agree well with the results in literature. Numerical modelling offers us the advantage of observing the conditions in advance. So, the developed numerical model is a powerful tool for evaluation of the drying behaviour of food products and dryer performance for given thermo-economic constraints.

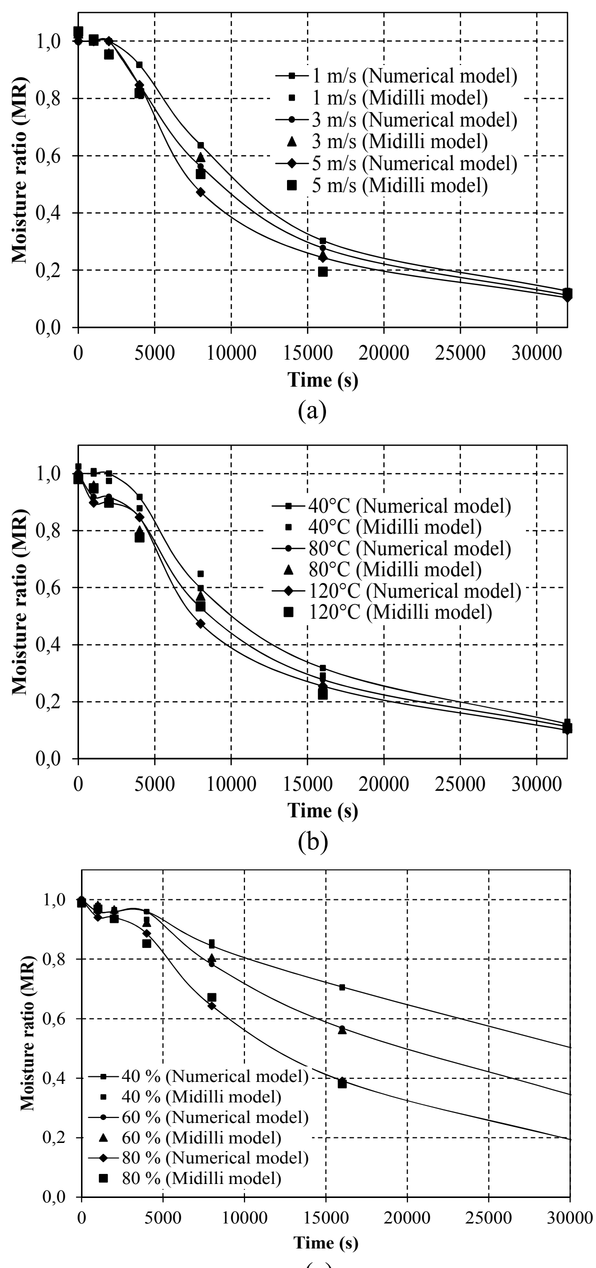


Fig.7. Moisture variation of different drying conditions (a-80°C, 40% ; b- 3 m/s, 40%; c- 80°C, 3 m/s)

Moisture ratio data were also applied into 5 different thin-layer drying models, and statistical analysis was performed. According to the statistical indicators, Midilli model well describe the thin layer drying kinetics of the apple at investigated conditions. Finally, a parametric analysis is presented to demonstrate that the numerical model

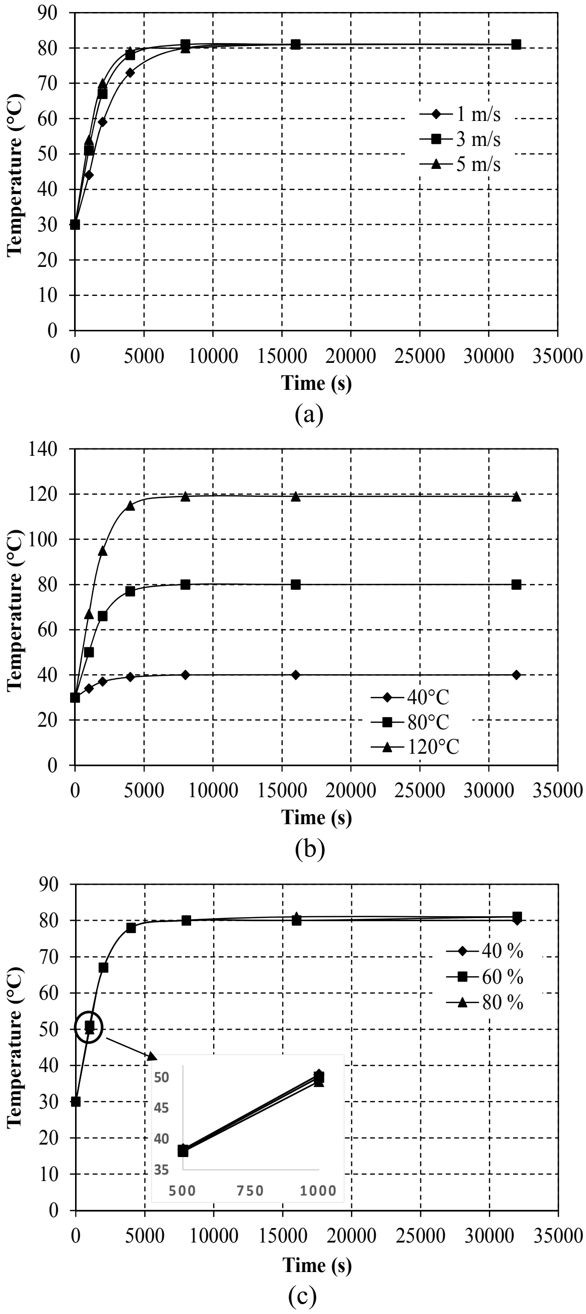


Fig.8. Temperature variation of different drying conditions (a-80°C, 40% ; b- 3 m/s, 40%; c- 80°C, 3 m/s)

can be used for modelling, optimization, estimation, monitoring and control of drying processes.

For this purpose, different parameters, which affect the drying process such as temperature, initial moisture contents, velocity, dimension, depth and time, were investigated.

Numerical modelling provides sufficient information to ensure that food products are dried under optimum conditions without deformation, deterioration or loss of vitamins. And, the results of the numerical study also contribute to better understanding of the drying process for industrial and academic users.

NOMENCLATURE

B - width, m;
c_p - specific heat, J/kgK;
D_{AB} - diffusion coefficient, m^2/s;
H - height, m;
h_T - heat transfer coefficient, W/m^2K;
h_M - mass transfer coefficient, m/s;
k - thermal conductivity, W/mK;
L - length, m;
L_k - characteristic length, m;
M - moisture content, kg water/kg dry solid;
MR - moisture ratio, %;
Nu - Nusselt number,-;
Pr - Prandtl number,-;
Re - Reynolds number,-;
Sc - Schmidt number,-;
Sh - Sherwood number,-;
T - temperature, K;
t - time, s;
u - air velocity, m/s.

Greek symbols

α - thermal diffusivity, m^2/s;
υ - viscosity, m^2/s;
ρ - density, kg/m^3.

Subscripts

e - equilibrium
b,0 - initial condition

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