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ORIGINAL CONTRIBUTION

Numerical Solution and it's Analysis during Solar Drying of Green Peas

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Abstract A mathematical model is developed for solar drying of green peas (Botanical name: Pisum Sativum). The problem is solved assuming the shape of the green peas is spherical. The governing transient mass transfer equation is discretized into finite difference scheme. The time marching is performed by implicit scheme. The governing equations and boundary conditions are non-dimensionalized to get generic results. The product in the chamber is in contact with air which is heated by solar energy, so the boundary conditions of third kind (convective boundary conditions) are considered. By space and time discretization a set of algebraic equations are generated and these algebraic equations are solved by tridiagonal matrix algorithm. A computer code is developed in MATLAB in order to compute the transient moisture content distribution inside the product. Center point, boundary and mean moisture of green peas are estimated at different temperatures and drying time. Present numerical result is compared with experimental result from literature and it was found that there is a good agreement of results. The drying time is predicted for how quickly the mean moisture of green peas is reached to 50, 40, 30, 20 and 10% of its initial moisture corresponding to different temperatures.

Keywords Solar drying ·
Finite difference method (FDM) · Implicit scheme ·
Tridiagonal matrix algorithm · MATLAB

Notations

D	Coefficient of diffusion, m^2/s
M	Moisture content of the product, kg/kg of db
M_{air}	Moisture content of the air, kg/kg of db
M_o	Initial moisture content, kg/kg of db
r	Space coordinate, m
R	Radius of the product, m
t	Time coordinate, s
h_m	Mass transfer coefficient, m/s
T	Temperature, °C

Superscript

*	Non dimensional parameter

Introduction

In many countries, the use of solar thermal systems to dry vegetables, fruits, and other crops has been implemented and proven to be practical and environment friendly. Solar drying can process the vegetables and fruits in clean and hygienic conditions as compared to other classical open drying methods. Drying a moist material and decreasing the moisture content means reduction of bound water from inside the solid material and elimination of unbound water from the surface into atmosphere. The process of breaking water bonds, releasing, and transferring heat conduction requires energy. The required drying energy is obtained by convective (warm air), radiative (infrared rays) and excitation (microwave) energies. All the above methods are consuming more conventional energy, therefore these

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processes are very expensive. Solar drying technology offers an alternative as it is a non-conventional source of energy. In solar drying, the air is taken from atmosphere and heated by solar energy. The aim of the hot air is to transfer heat to the material being dried and to transfer moisture into the air.

Many experimental and numerical studies were performed in the past on solar drying of agricultural products. Different mathematical models under different boundary conditions were used in order to investigate the moisture content present inside vegetables. Wang and Brennan [1] have developed a mathematical model for simultaneous heat and moisture transfer during drying of slab shaped solid (potato slice). Variable physical and thermal properties are considered in this model. They have considered Crank Nicolson method to solve the transient simultaneous heat and moisture transfer equations. The experimental and numerical results were compared and good agreement was noticed. Hussain and Dincer [2] have carried out a numerical study by developing a model of simultaneous heat and moisture transfer for a cylindrical object during drying. An explicit finite difference method (FDM) was used to solve the governing equations. Non-dimensional temperature and moisture distribution were estimated for a cylindrical shaped apple and broccoli stems. Oztop and Akpinar [3] have developed a numerical model for simultaneous heat and moisture transfer for two dimensional rectangular object using finite volume method. Here the analysis is performed for apple and potato slices. Experimental analysis is carried out in a cyclone type dryer. Chandramohan and Talukdar [4] carried out an experimental work on potato to study the drying kinetics under variable external conditions. The drying parameters of potato such as density, shrinkage, porosity and volume of water were estimated at different drying conditions. An experimental setup for convective drying of agricultural product was also explained with its different accessories and measuring instruments.

Simal, et al. [5] developed drying models for green peas. They developed two models; the first one is based on fixed boundary conditions and solution is obtained by separation of variables, whereas the second one is based on moving boundary conditions in which shrinkage is considered and solution is obtained by FDM. Experiments were conducted at different air temperatures (40, 60 and 80°C) and two equations of Arrhenius type for diffusivity as a function of air temperature were developed. Finally the two models were compared and found that the second model was more precise than the first model. Bennamoun and Belhamri [6] carried out an experimental work to study the drying kinetics under variable external conditions on seedless grapes. Based on experimental data diffusion coefficient is obtained as a function of temperature and velocity of air.

A review work was made by Fudholi, et al. [7] and Chauhan, et al. [8] on solar drying systems. Fudholi, et al. [7] described the design and performance levels of different types of commercial scale solar drying systems with air-based solar collectors. The performance parameters of different solar drying systems also were estimated and explained in detailed manner. Chauhan, et al. [8] reviewed the details of softwares and programmic tools such as ANSYS and FLUENT, MATLAB and FORTRAN were used for predicting the drying parameters.

From the literature survey, it is concluded that there are a large number of drying problems solved experimentally [1, 3–5, 8–11], numerically [1–3, 5, 6, 12–15] and analytically [5, 9–11, 16] with different drying methods. Among the numerical works, a few works were solved through explicit scheme [2] and semi implicit scheme [1, 5, 13, 17] which are conditionally stable and the time interval should be small in order to obtain the required accuracy. The coordinates considered for the analysis are cartesian [1, 3, 4, 10–12, 14–16] and cylindrical [2, 9, 14, 17, 18]. Very few works were found on spherical coordinates [4, 6]. Their results also were limited with only numerical solution. Constant temperature and moisture boundary conditions were used by few works [5, 9, 10, 19] to solve the governing equations. During the solar drying the product was exposed to hot air. Therefore, the convective boundary condition should be used as it is realistic than Dirichlet (constant temperature and moisture) boundary condition.

Hence, the present work concentrates on developing a numerical model for solar drying of green peas. It is assumed that the green peas have 100% sphericity, therefore the spherical coordinate is selected. The transient governing equation for spherical coordinates is discretized into FDM with fully implicit scheme which is unconditionally stable. Convective boundary condition is used to solve the transient mass transfer governing equation. The governing equation is non-dimensionalized to get the generic results. Drying time needed to dry the green peas up to its comfortable preservation condition is estimated at different air temperature. Mean moisture, center point and boundary moisture content are estimated at different drying time and drying temperatures.

Hence the main objectives of the present work are

- To develop a mathematical model of transient mass transfer during solar drying of green peas by finite difference method.
- To perform transient mass transfer simulation by implicit scheme with different drying air temperatures.
- To inhibit the convective boundary conditions as it is more realistic to drying problems

- To perform the grid and time sensitivity tests in order to obtain the optimum number of grid and time steps for better accuracy.
- To evaluate the mean, center point and boundary moisture content corresponding to time.
- To estimate the distribution of moisture inside the product along the radius.
- To find the comfortable preserved drying time at different levels of initial moisture content.

Mathematical Model

For mathematical analysis it is required to consider Fick's law of diffusion.

The following assumptions are to be considered

- One dimensional problem in spherical coordinate system.
- The material is assumed to be homogeneous and isotropic.
- Drying chamber air temperature is constant.
- Thermo-physical properties remain constant throughout the process.
- The internal heat generation inside the product is negligible.
- The shrinkage effects in the product are negligible.

After considering the above mentioned assumptions the governing equation is as follows:

Moisture transfer equation:

$$\frac{\partial \mathrm{M}(\mathrm{r},\mathrm{t})}{\partial \mathrm{t}} = \frac{\mathrm{D}}{\mathrm{r}^2}\frac{\partial}{\partial \mathrm{r}}\left(\mathrm{r}^2\frac{\partial \mathrm{M}(\mathrm{r},\mathrm{t})}{\partial \mathrm{r}}\right) \quad (1)$$

where, M is moisture content of the product in kg/kg of db, D is coefficient of diffusion in m^2/s, r space coordinate in m and t time coordinate in s.

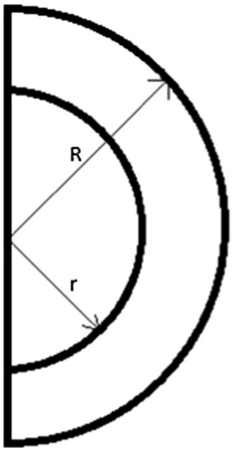

Fig. 1 Symmetric section of the sphere

Figure 1 shows the symmetric sectional view of a spherical object. Here, R indicates the corresponding radius of the product and r mention the distance of small strip from the center.

Initial condition:

$$\text{At} \quad \mathrm{t} = 0; \quad \mathrm{M} = \mathrm{M}_0 \quad (2)$$

where, M_0 is initial moisture content of the product in kg/kg of db.

Boundary conditions:

$$\text{At} \quad \mathrm{r} = 0; \quad \frac{\partial \mathrm{M}(0,\mathrm{t})}{\partial \mathrm{r}} = 0 \quad (3)$$

$$\text{At} \quad \mathrm{r} = \mathrm{R}; \quad -\mathrm{D}\frac{\partial \mathrm{M}(\mathrm{R},\mathrm{t})}{\partial \mathrm{r}} = \mathrm{h}_\mathrm{m}(\mathrm{M} - \mathrm{M}_\mathrm{air}) \quad (4)$$

where, h_m is mass transfer coefficient in m/s.

Now it is considered that the non-dimensional parameters as follows

$$\mathrm{M}^* = \frac{\mathrm{M} - \mathrm{M}_\mathrm{air}}{\mathrm{M}_0 - \mathrm{M}_\mathrm{air}} \quad (5)$$

$$\mathrm{r}^* = \frac{\mathrm{r}}{\mathrm{R}} \quad (6)$$

$$\mathrm{t}^* = \frac{\mathrm{Dt}}{\mathrm{R}^2} \quad (7)$$

After substituting the above non dimensional parameters in Eq. (1) the altered non-dimensional equation is as follows,

$$\frac{\partial \mathrm{M}^*(\mathrm{r}^*,\mathrm{t}^*)}{\partial \mathrm{t}^*} = \frac{\partial}{\partial \mathrm{r}^*}\left(\frac{\partial \mathrm{M}^*(\mathrm{r}^*,\mathrm{t}^*)}{\partial \mathrm{r}^*}\right) + \frac{2}{\mathrm{r}^*}\frac{\partial \mathrm{M}^*(\mathrm{r}^*,\mathrm{t}^*)}{\partial \mathrm{r}^*} \quad (8)$$

Therefore, the initial and boundary conditions in non dimentional terms are changed as follows,

Initial condition:

$$\text{At} \quad \mathrm{t} = 0; \quad \mathrm{t}^* = 0 \quad (9)$$

Boundary conditions:

$$\text{At} \quad \mathrm{r}^* = 0; \quad \frac{\partial \mathrm{M}^*(0,\mathrm{t}^*)}{\partial \mathrm{r}^*} = 0 \quad (10)$$

$$\text{At} \quad \mathrm{r}^* = 1; \quad \frac{\partial \mathrm{M}^*(1,\mathrm{t}^*)}{\partial \mathrm{r}^*} = -\frac{\mathrm{h}_\mathrm{m}\mathrm{M}^*}{\mathrm{D}} \quad (11)$$

Methodology

The Eqs. (1) and (8) are the governing equations in dimensional and non-dimensional parameters, respectively. Also the convective boundary conditions are considered as the mass transfer at the boundary which occurs due to convection.

The product is symmetric about its central axis, therefore half spherical object is considered for this analysis.

The necessary assumptions are imposed on the governing equations in order to simplify the problem. In this analysis the discretization is carried out in FDM and transient governing equations are discretized through fully implicit scheme because it has the following advantages, (a) stability can be maintained over much larger values of time step dt, (b) fewer time steps to make calculations over a given interval of time and (c) lesser computer time.

The domain of solution is divided into equal spaced structural grid of size dr and each nodal point is taken as i in the below equations. The governing equations are discretized and converted into partial differential equation into finite difference equation at every node which leads to set of finite difference equations. The problem is unsteady which requires an iterative process in time which is given by n in the below equations and the solution is possible by adopting a MATLAB computer program.

Where $i = 1,2,3,4,\ldots m$; m represent the total number of nodes along the radial direction.

$n = 1,2,3,4,\ldots j$

Where, j represent the total number of time steps.

Moisture transfer equation after discretization in dimensional parameters:

$$M(i,n) = C1 \times M(i-1,n+1) + C2 \times M(i,n+1) + C3 \times M(i+1,n+1) \tag{12}$$

where

$$F = \left(\frac{D \times dt}{(dr)^2}\right) \tag{13}$$

$$C1 = F\left(\frac{dr}{r} - 1\right) \tag{14}$$

$$C2 = 1 + 2 \times F \tag{15}$$

$$C3 = -F\left(\frac{dr}{r} + 1\right) \tag{16}$$

Moisture transfer equation after discretization in non-dimensional parameters:

$$M^*(i,n) = C4 \times M^*(i-1,n+1) + C5 \times M^*(i,n) + C6 \times M^*(i+1,n+1) \tag{17}$$

Where

$$C4 = \left(\frac{dr^*}{r^*} - \frac{dt^*}{(dr^*)^2}\right) \tag{18}$$

$$C5 = \left(1 + 2\frac{dt^*}{(dr^*)^2}\right) \tag{19}$$

$$C6 = -\left(\frac{dr^*}{r^*} + \frac{dt^*}{(dr^*)^2}\right) \tag{20}$$

The non-dimensional equations were derived from dimensional form and both forms were discretized and solved through Tridiagonal Matrix Algorithm (TDMA). A MATLAB computer code is developed to solve the finite difference equations. Transient moisture distribution inside the object is estimated.

Results and Discussion

The properties considered in this numerical analysis are mentioned in Table 1. The diffusion coefficient is assumed as a function of air temperature [6].

The grid independent and time independent test were performed in order to obtain the optimum number of grid and time steps. Figure 2 shows the grid independent test. It is conducted by varying grid step dr, where it is dependent on number of nodes, so here number of nodes are varied as n = 10, 25, 50, 100, 150 and 200. The moisture content plot is drawn at t = 1 h. The error percentage between the nodes 10 and 25 is 2.85%, 25 and 50 is 0.64%, 50 and 100 is 0.27%, 100 and 150 is 0.09%, 150 and 200 is 0.04%. Therefore, the number of nodes selected for this analysis is 150.

Similarly the time independent test (Fig. 3) is performed with different time steps, dt = 100, 50, 30, 10 and 5 with the drying time of 1 h and the number of nodes are 150. There is not much variation noticed with time step 10 and 5 s. Hence, the remaining simulations are run with the time step of 10 s.

The present numerical results are compared with the experimental results [20] and it is shown in Fig. 4. The air drying temperature considered here is 60°C. Moisture content at every node is estimated and from that the average moisture content of green peas is estimated and it is considered as mean moisture content. During the initial drying region (the region up to 10,000 s or 2.78 h) this numerical result slightly deviated from experimental results and in the remaining stage the answers are convincing.

The diffusion coefficient is taken as a function of temperature [6] and it is given by

$$D = \left(-0.00067T^2 + 0.29300T - 7.30833\right) \times 10^{-10} \tag{21}$$

Table 1 Properties considered in this work

Properties	
Initial moisture content (M_o)	3 kg/kg of db [6]
Diameter of green peas	1 cm
Moisture content of the air (M_{air})	0.196 kg/kg of db [4]
Mass transfer coefficient (h_m)	10^{-6} m/s [19]

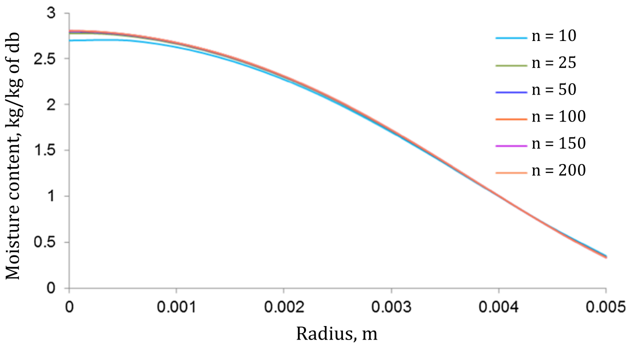

Fig. 2 Grid independent test

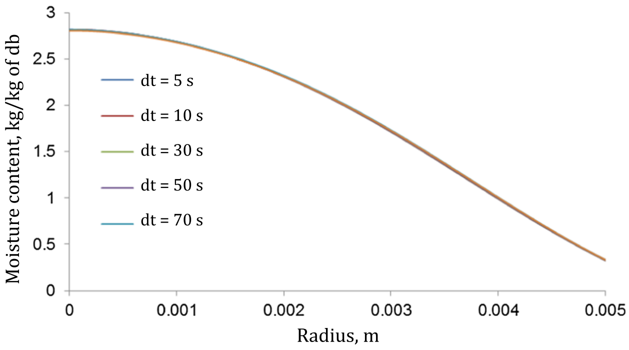

Fig. 3 Time independent test

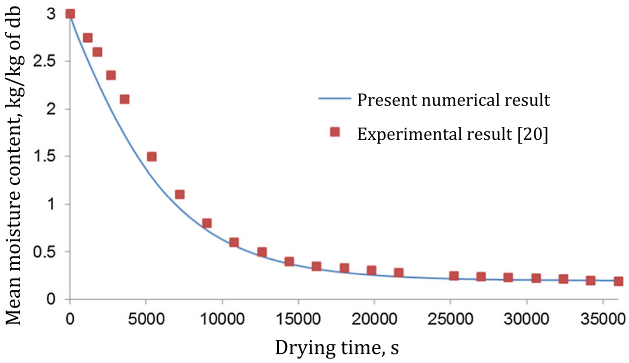

Fig. 4 Comparison of present work with experimental result [20] at air drying temperature 60°C

The variation of non-dimensional mean moisture content and drying time with different temperatures are shown in Fig. 5. The non-dimensional parameters are estimated using Eqs. (5–7). The total drying time considered for this analysis is 12 h (t* = 1.358). The moisture content of green peas is reduced while the drying time is increased. In the first 4 h (14,400 s, t* = 0.628) the drying rate is fast compared to the remaining drying time for all the drying temperatures. The surface moisture content is removed during this region and interior moisture is transfered towards the surface and from the surface again it is removed to air. Almost all the bound moisture is removed and unbound moisture is started to migrate during this initial drying region. This stage comes in falling rate period. The mean moisture content is approximately constant after this drying region (drying time >4 h or t* = 0.628) and it is considered as second drying stage. This implies that during this second drying region the drying rate is less as the unbound moisture is removed. This region takes more energy to eliminate the unbound moisture, because breaking and transferring of unbound moisture need more drying time. When the drying time is increased from 45 to 75°C, the drying rate is increased. The higher drying rate is noticed at 60, 70 and 75°C. The diffusion coefficient is function of temperature, as mentioned in Eq. (21) and therefore the moisture is diffused quickly, while the drying temperature increases.

The distribution of the moisture content along the radius of the product at different time periods and at different drying air temperatures 45, 50, 60, 70 and 75°C is shown in the Fig. 6a–e. These Fig. 6a–e are shown with dimesnionalised values as it gives more understanding about the real picture of initial moisture content of green peas and how the moisture content decreases with different drying times. In these Fig. 6a–e, r = 0 is centre and r = 0.005 m is boundary of green peas. The center point moisture conetnt of green peas is more in all cases compared to boundary moisture content for all drying time and temperature conditions. It also shows that the moisture content gradually decreases towards the boundary from center at constant drying time. The boundary of the product is easily

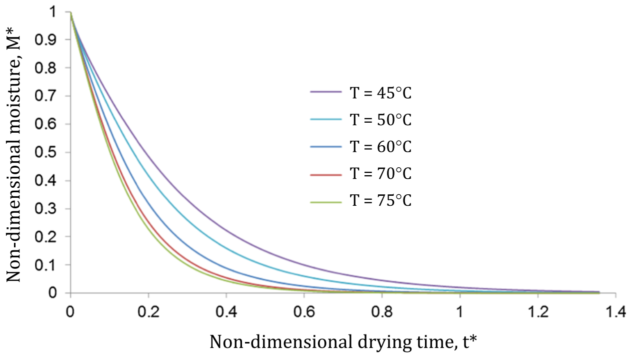

Fig. 5 The variation of non-dimensional mean moisture and drying time with different temperatures

exposed to hot air, therefore, lower moisture conent is noticed near the boundary and when the radius decreases towards its center the mositure gradient increases. The Fig. 6a–e also show that when the drying is progressing product is always losing its moisture content at each nodes/ locations.

Table 2 gives the quantitaive numerics of moisture content at the center of the green peas at different drying time and drying temperatures. It is noticed that from all drying times the moisture of the product is decreased when drying temperature is increased from 45 to 75°C. The minimum center point moisture content is noticed as 0.204 kg/kg of db at t = 7 h and at maximum drying temperature (75°C) considered in this study. This is 6.8% of green peas' initial moisture content.

The boundary moisture content at different drying time and drying temperatures are shown in Table 3. Moisture content at boundary is reduced while the drying temperature increases. Within 1 h the boundary moisture content of green peas is reduced to 0.531 kg/kg of db from 3 kg/kg of db. Once the boundary of the object is dried, then only the interior moisture is transferred towards the boundary because of the moisture gradient persist.

Mean moisture content is estimated at different drying time and drying temperatures and it is shown in Table 4. As the literature [21] mentioned, it is enough to dry the

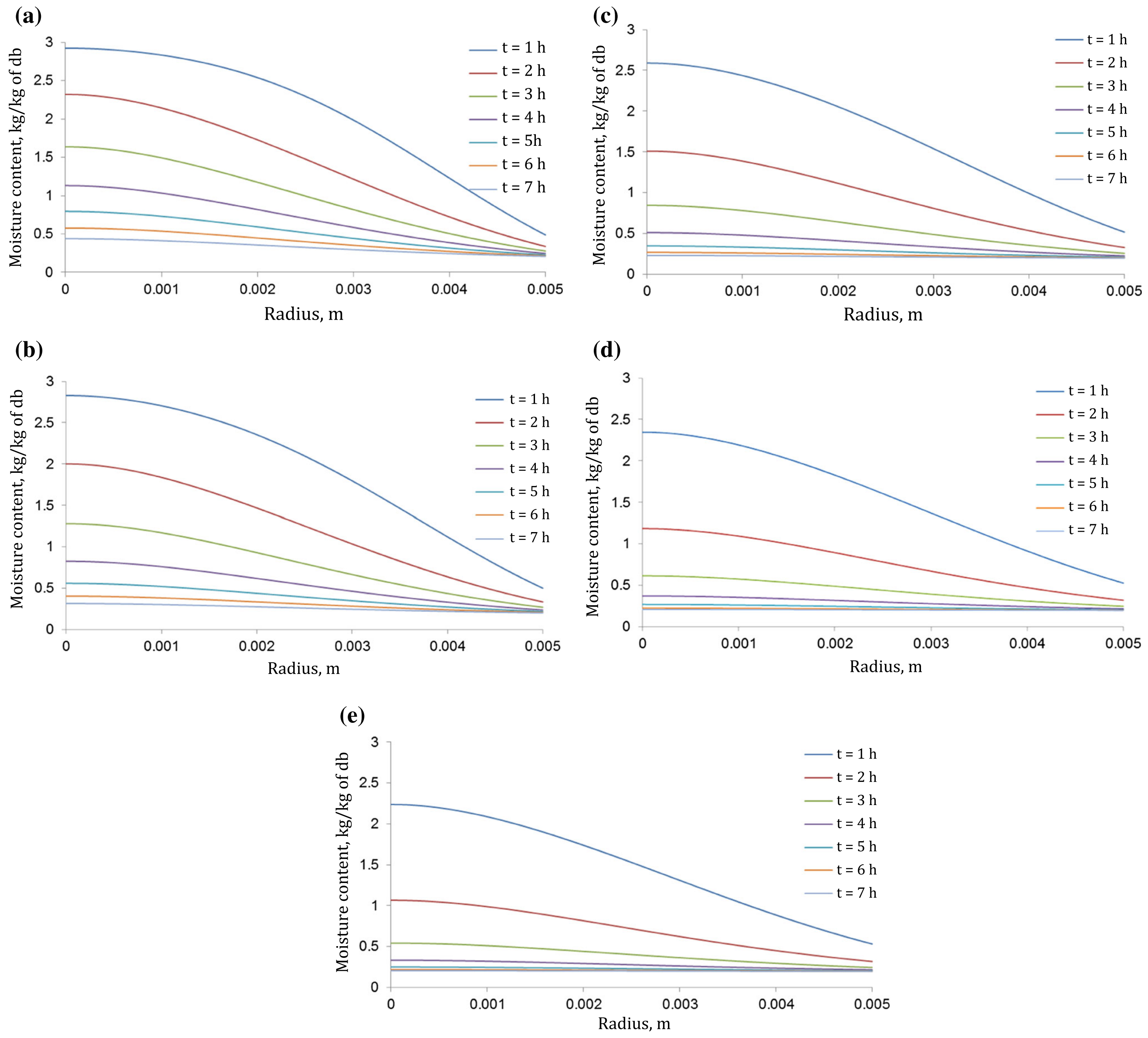

Fig. 6 Moisture distribution inside green peas at drying temperatures **a** 45, **b** 50, **c** 60, **d** 70 and **e** 75°C

Table 2 Moisture content at center of green peas at different drying time and drying air temperatures

Drying air temperature, °C	Moisture content at center point, kg/kg of db						
	t = 1 h	t = 2 h	t = 3 h	t = 4 h	t = 5 h	t = 6 h	t = 7 h
45	2.93	2.32	1.64	1.13	0.794	0.58	0.44
50	2.83	2	1.282	0.83	0.56	0.406	0.317
60	2.59	1.51	0.846	0.512	0.35	0.27	0.232
70	2.347	1.184	0.615	0.372	0.27	0.227	0.21
75	2.236	1.065	0.541	0.332	0.249	0.217	0.204

Table 3 Moisture content at boundary of green peas at different drying time and drying air temperatures

Drying air temperature, °C	Moisture content at boundary of green peas, kg/kg of db						
	t = 1 h	t = 2 h	t = 3 h	t = 4 h	t = 5 h	t = 6 h	t = 7 h
45	0.531	0.34	0.28	0.246	0.23	0.216	0.21
50	0.528	0.336	0.272	0.24	0.22	0.21	0.204
60	0.518	0.33	0.26	0.226	0.21	0.203	0.2
70	0.508	0.327	0.25	0.22	0.205	0.201	0.1976
75	0.49	0.317	0.243	0.215	0.203	0.2	0.1971

food product up to 5 to 10% of the product's initial moisture content for preserving it up to 5–6 months. It is evident from Table 4 that this drying temperatures and drying time is enough to dry the food products in solar drier. Therefore, it is enough to dry the green peas up to 6, 5, 4 and 3.5 h (approximately) at drying temperatures 50, 60, 70 and 75°C, respectively to reach the 10% of green peas's initial moisture content (0.3 kg/kg of db).

The Fig. 7a–e give a deep perception as to how quickly the mean moisture of green peas is reached 50, 40, 30, 20 and 10% of its initial moisture corresponding to different temperatures. Inorder to reach 50% of moisture at air temperature 45, 50, 60, 70 and 75°C, the drying times needed are 6750, 5650 4430, 3780 and 3550 s (1.875, 1.57, 1.23, 1.05, 0.986 h), respectively (Fig. 7a). Similarly, to maintain 40% of initial moisture, the drying times needed for various air temperatures 45, 50, 60, 70 and 75°C are 8920, 7420, 5790, 4910 and 4600 s (2.48, 2.06, 1.61, 1.364 and 1.28 h), respectively (Fig. 7b).

Figure 7c shows that in order to reach 30% of initial moisture content of green peasat different drying temperatures 45, 50, 60, 70 and 75°C, the product should be dried up to 11,790, 9780, 7590, 6410 and 6000 s (3.275, 2.72, 2.11, 1.78 and 1.67 h), respectively. For maintaining 20% of moisture content, the product needs to be dried up to 16,240, 13,430, 10,360, 8720 and 8170 s (4.5, 3.73, 2.88, 2.42 and 2.27 h) at different air drying temperature 40, 50, 60, 70 and 75°C respectively (Fig. 7d). Similarly, to maintain 10%, the product should be dried up to 26,320, 21,700, 16,660, 14,350 and 13,420 s (7.31, 6.03, 4.63, 3.986 and 3.73 h), respectively at different drying temperatures considered in this study (Fig. 7e). Based on this analysis, one can fix their drying conditions to achieve the required moisture content.

Table 4 Mean moisture content of green peas at different drying time and drying air temperatures

Drying air temperature, °C	Mean moisture content of green peas, kg/kg of db							
	t = 0.5 h	t = 1 h	t = 2 h	t = 3 h	t = 4 h	t = 5 h	t = 6 h	t = 7 h
45	2.46	2.067	1.432	0.993	0.705	0.52	0.402	0.327
50	2.4	1.936	1.235	0.8	0.544	0.397	0.312	0.262
60	2.3	1.722	0.957	0.566	0.376	0.283	0.238	0.216
70	2.197	1.554	0.78	0.441	0.3	0.24	0.214	0.203
75	2.16	1.485	0.714	0.401	0.277	0.228	0.208	0.2

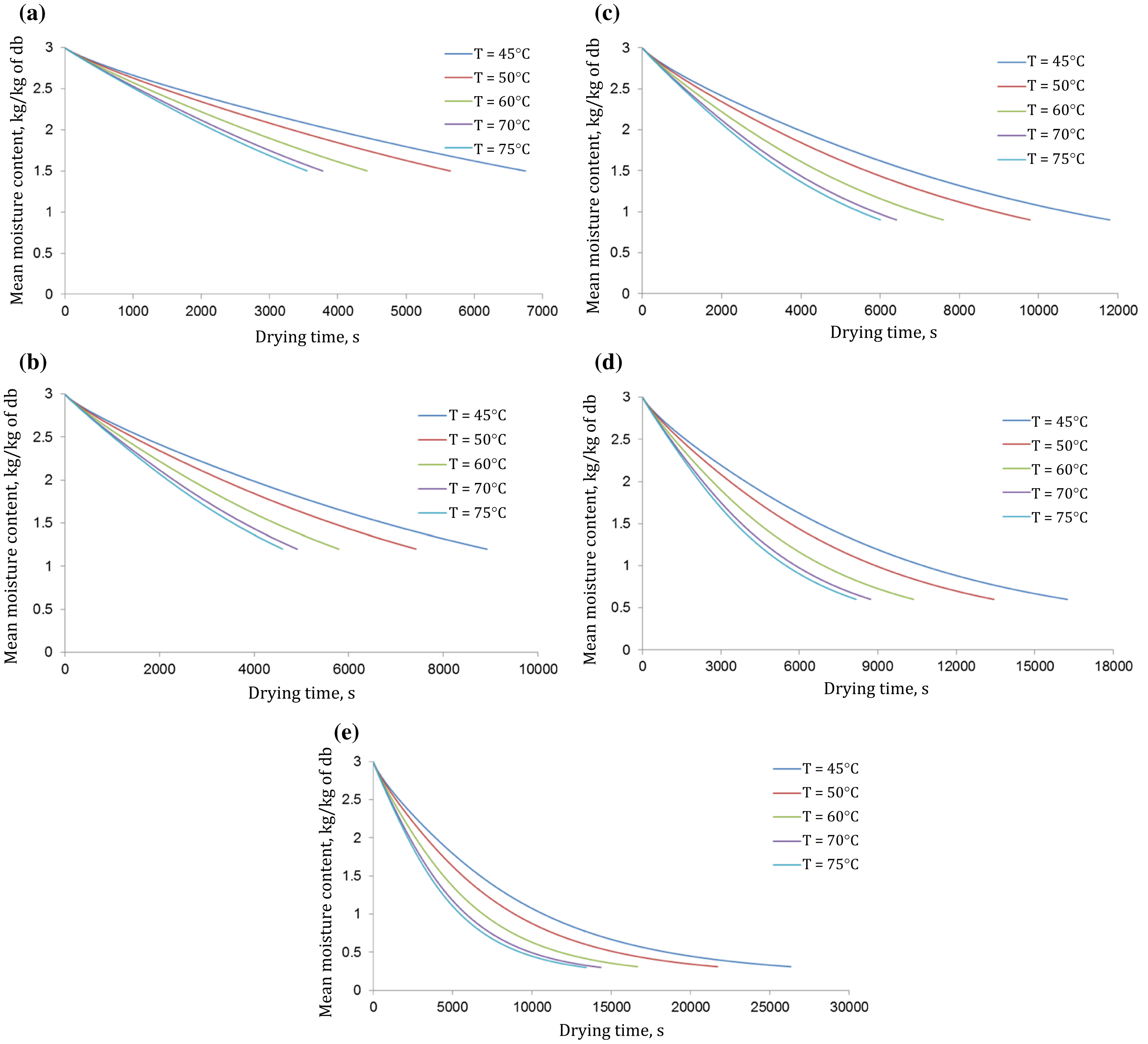

Fig. 7 Time required to reach **a** 50, **b** 40, **c** 30, **d** 20 and **e** 10% of initial moisture of green peas at different temperatures

Conclusion

A numerical model was developed to predict the transient moisture distribution inside the spherical object during solar drying. The sample object considered here was green peas. Finite difference with fully implicit scheme was used to descretize the transient mass transfer governing equation. Convective boundary condition was used to solve the problem. Time and grid independent studies were carried out to confirm the time step and space interval. The results were non-dimensionalized to get generic way. The results were compared with experimental results and good agreement was noticed. Moisture distribution at different drying time and drying temperature were estimated.

It was observed that initially the moisture content decreases with respect to time and the decrement is very steep which implies more amount of moisture is transferred during the initial stage and after certain time it reached constant approximately. As expected, the drying time was reduced while the drying temperature increased from 45 to 70°C. The center point moisture was maximum and boundary moisture was minimum under all drying temperatures and drying time considered in this work and at both points the moisture continuously decreased when drying progressed. To achieve 10% of green peas's initial moisture content (0.3 kg/kg of db), the product should be dried up to 7.31, 6.03, 4.63, 3.986 and 3.73 h at drying temperatures 45, 50, 60, 70 and 75°C respectively.

References

1. N. Wang, J.G. Brennan, A mathematical model of simultaneous heat and moisture transfer during drying of potato. J. Food Eng. **24**, 47–60 (1995)
2. M.M. Hussain, I. Dincer, Two-dimensional heat and moisture transfer analysis of a cylindrical moist object subjected to drying. Int. J. Heat Mass Transf. **46**, 4033–4039 (2003)
3. H.F. Oztop, E.K. Akpinar, Numerical and experimental analysis of moisture transfer for convective drying of some products. Int. Commun. Heat Mass Transf. **35**, 169–177 (2008)
4. V.P. Chandramohan, P. Talukdar, Experimental studies for convective drying of potato. Heat Transf. Eng. **35**(14–15), 1288–1297 (2014)
5. S. Simal, A. Mulet, J. Tarrazo, C. Rossello, Drying models for green peas. Food Chem. **55**(2), 121–128 (1996)
6. L. Bennamoun, A. Belhamri, Numerical simulation of drying under variable external conditions. Application to solar drying of seedless grapes. J. Food Eng. **76**, 179–187 (2006)
7. A. Fudholi, K. Sopian, B. Bakhtyar, M. Gabbasa, M.Y. Othman, M.H. Ruslan., Review of solar drying systems with air based solar collectors in Malaysia. Renew. Sustain. Energy Rev. **51**, 1191–1204 (2015)
8. P.S. Chauhan, A. Kumar, P. Tekasakul, Applications of software in solar drying systems: a review. Renew. Sustain. Energy Rev. **51**, 1326–1337 (2015)
9. E.K. Akpinar, Evaluation of convective heat transfer coefficient of various crops in cyclone type dryer. Energy Convers. Manag. **46**, 2439–2454 (2005)
10. D. Velic, M. Planinic, S. Tomas, M. Bili, Influence of airflow velocity on kinetics of convection apple drying. J. Food Eng. **64**, 97–102 (2004)
11. W.J.N. Fernando, A.L. Ahmad, S.R.A. Shukor, Y.H. Lok, A model for constant temperature drying rates of case hardened slices of papaya and garlic. J. Food Eng. **88**, 229–238 (2008)
12. V.P. Chandramohan, Numerical prediction and analysis of a surface transfer coefficients on moist object during heat and mass transfer application. Heat Transf. Eng. **37**(1), 53–63 (2014)
13. S. Simal, C. Rossello, Heat and mass transfer model for potato drying. Chem. Eng. Sci. **49**(22), 3739–3744 (1994)
14. A. Kaya, O. Aydın, Numerical modeling of forced convection drying of cylindrical moist objects. Numerical Heat Transf. A. **51**, 843–854 (2007)
15. A. Kaya, O. Aydın, I. Dincer, Numerical modeling of heat and mass transfer during forced convection drying of rectangular moist objects. Int. J. Heat Mass Transf. **49**, 3094–3103 (2006)
16. J.A. Hernandez, G. Pavon, M.A. Garcia, Analytical solution of mass transfer equation considering shrinkage for modeling food-drying kinetics. J. Food Eng. **45**, 1–10 (2000)
17. S. Simal, C. Rossello, A. Berna, A. Mulet, Drying of shrinking cylinder-shaped bodies. J. Food Eng. **37**, 423–435 (1998)
18. B. Honarvar, D. Mowla, Theoretical and experimental drying of a cylindrical sample by applying hot air and infrared radiation in an inert medium fluidized bed. Braz. J. Chem. Eng. **29**(2), 231–242 (2012)
19. M. Markowski, Air drying of vegetables: evaluation of mass transfer coefficient. J. Food Eng. **34**, 55–62 (1997)
20. S.K. Dutta, V.K. Nema, R.K. Bhardwaj, Drying behavior of spherical grains. Int. J. Heat Mass Transf. **31**(4), 855–861 (1988)
21. A.S. Mujumdar, *Handbook of Industrial Drying*, 3rd edn. (Published by CRC Press, Taylor and Francis group, Boca Raton, 2006)