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EXPERIMENTAL AND NUMERICAL INVESTIGATON OF STRAWBERRY DRYING

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Abstract: Strawberry drying was investigated experimentally and numerically in this study. In the experiments, samples of strawberry slices with 1 cm thicknesses were used to investigate the effect of the drying air velocity. 5-hour experiments were conducted for three different velocities (0.5, 1 and 2m/s) at 70°C air temperature. It was observed that increasing the drying air velocity from 0.5 up to 2 m/s decreased the drying duration by 17% on average. Moreover, the data obtained from the experimental study were compared to the numerical results. The results were found compatible with each other. Finally, the effect of air temperature and product thickness on drying was examined numerically.

Keywords: Heat and mass transfer, Drying, Fick and Fourier equations, Validation

Çilek Kurutulmasının Deneysel ve Nümerik Olarak İncelenmesi

Öz: Bu çalışmada çilek kurutulması deneysel ve nümerik olarak incelenmiştir. Deneylerde kurutma hava hızının etkisini incelemek için 1 cm dilim kalınlığındaki çilek örnekleri kullanılmıştır. 70°C hava sıcaklığında üç farklı hız için (0,5-1 ve 2m/s) 5 saatlik deneyler gerçekleştirilmiştir. Kurutma hava hızının 2 m/s ye çıkarılmasının kurutma süresini ortalama %17 azalttığı görülmüştür. Ayrıca deneysel çalışmadan elde edilen veriler nümerik sonuç ile karşılaştırılmıştır. Elde edilen sonuçların birbiri ile uyumlu olduğu görülmüştür. Son olarak hava sıcaklığının ve ürün kalınlığının kurutma üzerine etkisi nümerik olarak incelenmiştir.

Anahtar Kelimeler: Isı ve kütle transferi, Kurutma, Fick ve Fourier denklemleri, Doğrulama

1. INTRODUCTION

Drying vegetables and fruit has a great importance today. Drying sector, which has a significant role in the agricultural industries, constitutes a big commercial share in the country's economy. Juice in fruit and vegetables causes chemical degradation and bacterium formation in time. Therefore, drying procedure is applied so that agricultural products can be preserved for a long time in a healthy way. While warm air flow is sent onto the substance in the drier and heat is transmitted to the substance through convection in drying, evaporated juice is cast out of the medium. This procedure continues until equilibrium moisture is formed in the product depending on the relative humidity and temperature of the air (Darıcı ve Şen, 2012).

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Drying problems are expressed as simultaneous heat and mass transfer equations. These problems depend on the thermophysical characteristics of the products. Because the thermophysical characteristics influence the drying process, drying characteristics must be known well. Parameters that affect the drying rate can be stated as the velocity, temperature, relative humidity of the drying air and product thickness. In the literature, there are studies on drying, which examine the effects of different parameters. Zhu and Shen (2014) experimentally investigated the effect of drying air temperature, velocity and product thickness on the drying process in their study. Silva (2014) examined pear drying experimentally and numerically in his study. He compared the model that he developed and the experimental results. Kumar et al. (2012) developed the mathematical model of simultaneous heat and mass transfer during fruit drying through forced convection in their study. Darıcı and Şen (2012) experimentally examined kiwi drying. Lemus-Modaca et al. (2013) examined drying a solid foodstuff both numerically and experimentally by using different drying air temperatures from 40°C up to 80°C. Karim and Hawlader (2005) developed a mathematical model that solved heat and mass transfer equations while drying the tropical fruit through forced convection in their study. Hussain and Dinçer (2003) numerically modeled the heat and moisture transfer simultaneously while drying a moist, 2-dimensional rectangular-sliced product through forced convection in their study. Maskan (2001) examined kiwifruit drying in his study.

Experimental strawberry drying was performed and the simultaneous heat and mass transfer equations were solved numerically by means of the Comsol software. Drying was experimentally performed at different velocitys and results were obtained. Then, a comparison was made to confirm the experimental and numerical results. Finally, the effect of the temperature and thickness on drying behavior was investigated numerically.

2. THEORETICAL ANALYSIS

In order to state the moisture content within the product on the basis of wetness and dryness,

$$\%\mathrm{W}_{\mathrm{JB}} = \left(\frac{W_J}{W_J + W_S} \right) \times 100 \tag{1}$$

$$\%\mathrm{W}_{\mathrm{SB}} = \left(\frac{W_J}{W_S} \right) \times 100 \tag{2}$$

are used. Here, the weight of the juice in the product is expressed as W_J and the weight of the dry product as W_S. Also, in order to state the moisture rate of the product (MR),

$$\mathrm{MR} = \left(\frac{N_t}{N_0} \right) \tag{3}$$

N_t represents the moisture rate of the product at the ‘t’ moment and N_0 reflects the initial moisture rate of the product.

3. NUMERICAL ANALYSIS

A 3-dimensional model was developed to define the simultaneous heat and mass transfer during strawberry drying through forced convection. Air flow is turbulent so that in analysis Standard k- ε Turbulance model were used. In this model “k” represents the turbulent kinetic energy and “ε” represents the dissipation rate. Standard k- ε Turbulance model has two equations which are:

$$\frac{\partial(\rho k)}{\partial t}+div(\rho kU)=div\left[\frac{\mu_t}{\sigma_k}gradk\right]+2\mu_t S_{ij}.S_{ij}-\rho\varepsilon \tag{4}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+div(\rho\varepsilon U)=div\left[\frac{\mu_t}{\sigma_\varepsilon}grad\,\varepsilon\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t S_{ij}.S_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

During the drying process, Fourier's law was used for the heat transfer in the mathematical model and Fick's law was used for the mass diffusion. While the heat is transferred from the air to the substance, the juice in the substance is transferred onto the surface through diffusion and evaporated into the air. Physical problem includes constant temperature and constant moisture content at the beginning. The 3-dimensional solid model was formed to be at Cartesian coordinates (3 cm×3 cm×1 cm). Heat and mass transfer occurs from the other surfaces surrounded by the warm air except for the lower surface. Geometry of the physical model is seen in Figure 1. This model was not considered as a cubic geometry because strawberry surface isn't symmetrical. Because of that reason cubic geometry consideration is adapted on geometric model.

The following considerations were adopted for the development of this drying model:

a) The velocity, temperature and relative humidity of the air are fixed during the drying process.
b) No deformation occurs within the product.
c) The product was modeled 3-dimensionally.
d) There is no heat generation in the product.
e) The thermophysical characteristics (specific heat, conductivity coefficient etc.) of the product are fixed.
f) It was thought for the drying procedure through forced convection that heat transfer firstly happened from the air to the surface through convection and then the heat was transferred (Fourier's Law) from the surface to the product center through conduction.
g) It was accepted that the mass transfer occurred from the inside of the product to the surface through moisture diffusion (Fick's Law) and evaporated from the surface into the outside air.

Relying on the assumptions above, the equations of the temperature and moisture transfer in the substance, continuity, momentum and energy are written as follows:

$$\rho c_p\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{6}$$

$$\frac{\partial M}{\partial t}=\frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial M}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial M}{\partial z}\right) \tag{7}$$

$$\frac{\partial(\rho \mathrm{u})}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{8}$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{9}$$

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{10}$$

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{11}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{12}$$

T and M are the temperature (K) and moisture (%) contents of the substance in the equations above. Density ρ (kg/m^3), specific heat c_p (kj/kgK), thermal conductivity k (W/mK) and diffusion coefficient D (m^2/s) are thermophysical characteristics of the substance. Diffusion is spreading the molecules from one media to another media. The basic principle of diffusion is transfering the molecules from high concentration media to low concentration media. In this study the diffusion coefficient of strawberry is determined as 2.57×10^{-9} m^2/s (Çengel, 2011).

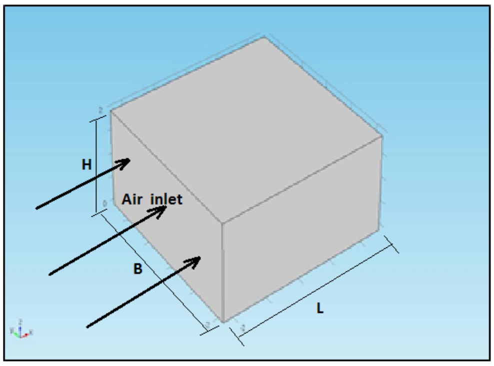

Figure 1:
The dimensions of the model

3.1. Boundary Conditions

T_0 (50-70-90°C) and M_0 (%83) are the temperature and moisture contents that the substance had at the beginning. The air channel input rate is 0.5 m/s. The boundary conditions related to warm air- contacting 5 surfaces (considering no heat and mass transfer from the base) of the moist substance, which have L (3cm) length, H (0.5-1-2cm) height and B (3cm) width, are given for x, y and z directions as follows:

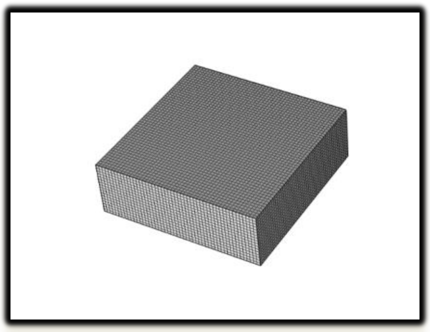

Figure 2:
Grid structure of the solid model

Table 1. Boundary conditions

$T\left(x,y,z,0\right)=T_0$	$M\left(x,y,z,0\right)=M_0$
x = 0; 0 ≤ y ≤ B and 0 ≤ z ≤ H	
$-k\dfrac{\partial T\left(0,y,z,t\right)}{\partial x}=h_T(T_\infty-T)$	$-D\dfrac{\partial M\left(0,y,z,t\right)}{\partial x}=h_t(M-M_b)$
x = L; 0 ≤ y ≤ B and 0 ≤ z ≤ H	
$-k\dfrac{\partial T\left(L,y,z,t\right)}{\partial x}=h_T(T_\infty-T)$	$-D\dfrac{\partial M\left(L,y,z,t\right)}{\partial x}=h_t(M-M_b)$
y = 0; 0 ≤ x ≤ L and 0 ≤ z ≤ H	
$-k\dfrac{\partial T\left(x,0,z,t\right)}{\partial y}=h_T(T_\infty-T)$	$-D\dfrac{\partial M\left(x,0,z,t\right)}{\partial y}=h_t(M-M_b)$
y = B; 0 ≤ x ≤ L and 0 ≤ z ≤ H	
$-k\dfrac{\partial T\left(x,B,z,t\right)}{\partial y}=h_T(T_\infty-T)$	$-k\dfrac{\partial T\left(x,B,z,t\right)}{\partial y}=h_T(T_\infty-T)$
z = H; 0 ≤ x ≤ L and 0 ≤ y ≤ B	
$-k\dfrac{\partial T\left(x,y,H,t\right)}{\partial z}=h_T(T_\infty-T)$	$-k\dfrac{\partial T\left(x,y,H,t\right)}{\partial z}=h_T(T_\infty-T)$

4. MATERIAL AND METHOD

Strawberries bought from a market in Bursa were used in the experiments. Drying procedures were conducted with the drying device in the Heating Techniques Laboratory of Uludag University. Real appearance and solid model of the experiment set are presented in Figure 3 and Figure 4. The parts of the machine are shown as below (Fig. 4.)

1- Fan (Air inlet)
2- Automatic control unit (velocity, temperature, moisture and weight)
3, 4 - Temperature, moisture and velocity sensors
5- Sensitive bascule

The experiment device consists of inlet air fan, canal connection, temperature, humidity and velocity sensors, precision scales, outlet air canal and automatic control unit. Inlet air velocity and temperature can be adjusted to the intended values in the experiment. Experiments were conducted at 0.5-1 and 2m/s drying air velocities keeping the 70°C air temperature and 10% humidity rate fixed. The changes in the product weight, air velocity, air temperature and air humidity rate, which were obtained in the experiment device, were noted with measuring elements and recorded for every second. Measurement precisions for drying air temperature, velocity and moisture content were respectively measured as ±0.5°C, ±0.89m/s, ± 0.9.

Figure 3:
Experimental setup

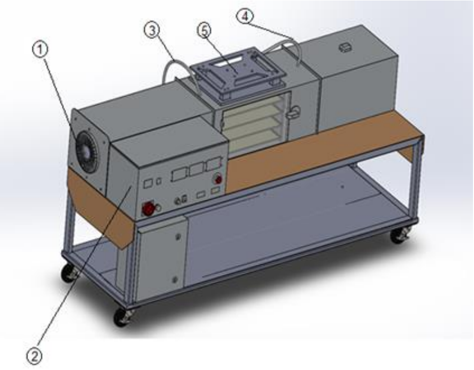

Figure 4:
Figure of the experimental setup

The samples bought were kept in the fridge at 4°C for 24 hours. Afterwards, they were left in the laboratory environment for 3 hours until their temperature increased up to the room temperature. Strawberries were sliced as 1 cm with the specially-produced cutter and put on the tray. Strawberry appearances before and after drying are given in Figure 5.

Figure 5:
The strawberry appearance before and after drying

4.1. Process of the Experiments

The air at 70°C and with 10% moisture content was sent onto the product at 0.5-1 and 2 m/s for the investigation of the effect of the drying air velocity on drying. First of all, the empty tray was weighed and recorded; strawberries were sliced as 3 mm and put on the tray. Then, the experiment device was run until reaching the steady state. When the desired conditions were achieved, the tray with strawberry slices was placed into the device. The change in the product weight was recorded during the experiment with the automation system for every second. The experiments were repeated 3 times and their average was found.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were performed to examine the effect of the drying air velocity. The results of the experiments are given in Figure 6 and Figure 7 graphically.

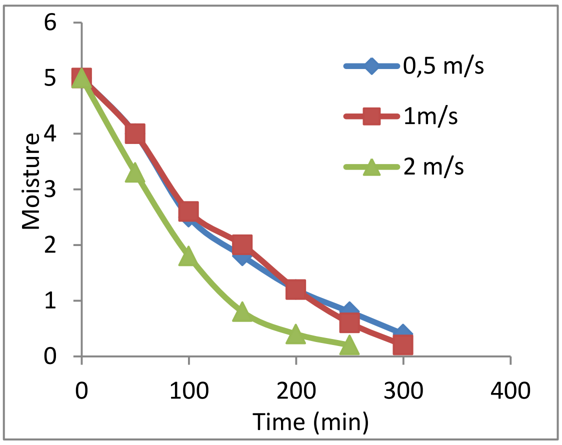

Figure 6:
Moisture content over time (%)

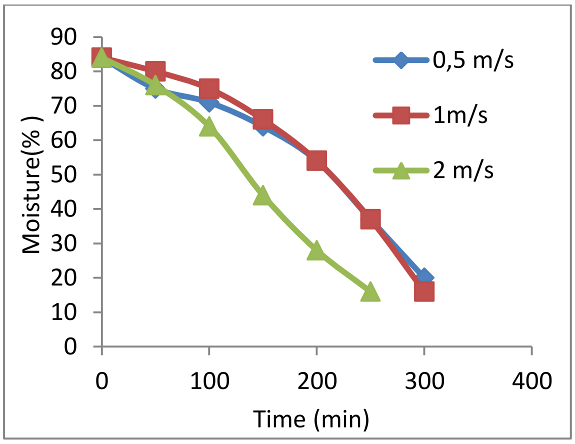

Figure 7:
Moisture content over time (g juice/g dry)

It is seen in Figure 7 that drying duration is 300 minutes at 1 m/s drying velocity, 250 minutes at 2 m/s and more than 300 minutes at 0.5 m/s. On the basis of dryness in moisture content changes, moisture contents were measured as 1 g juice/g ds for 0.5 m/s, 0.6 g juice/g ds for 1m/s and 0.2 g juice/g ds for 2m/s after 250 minutes. It can be said according to these results that increasing the drying rate shortens the drying duration. It can be seen in Figure 6 and Figure 7, the values of the velocities of 0.5 m/s and 1 m/s are close each other. The reason of that the strawberries are placed the upper tray. It is seen that obstacle which is in front of the tray reduce the impact of the velocity.

Error analysis is made using moisture content for wet product.

$$MR = \frac{M_t - M_e}{M_b - M_e} \tag{13}$$

In this formula MR is dimensionless moisture content, M_t is time-varying moisture content, M_e is balance moisture content for the end of the drying process, M_b is moisture content for the beginning of the drying process. Firstly using the Equation 13. MR which is dimensionless moisture content is calculated. After that, analysis were made by using linear regression model. For testing accuracy of the data, coefficient of determination (R^2) and standard deviation (RMSE) expressions are used. Standard deviation can be written as follows;

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right)^2}{N}} \tag{14}$$

In this formula MR_{exp} is dimensionless moisture content observing in experiment and MR_{pre} is predicted dimensionless moisture content, N is the number of observations in the experiment, z is the number of constants.

Table 2. Coefficient of determination and standard deviation values for different inlet velocities

Coefficient Inlet Velocity	R^2	RMSE
0.5 m/s	0.9447	0.0911
1 m/s	0.9117	0.1090
2 m/s	0.9826	0.0526

Calculated R^2 and RMSE values are given in Table 2. When the coefficient of determination (R^2) is closer to "1", it is said that linear regression equation is well estimator. When the standard deviation value is smaller than "1", it is said that range of the experimental data is favorable. It can be seen in Figure 8 and Figure 9, comparison the predicted values and obtained experimental values for different velocities. According to these results it can said that degree of accuracy of the error analysis for three different velocities is sensible.

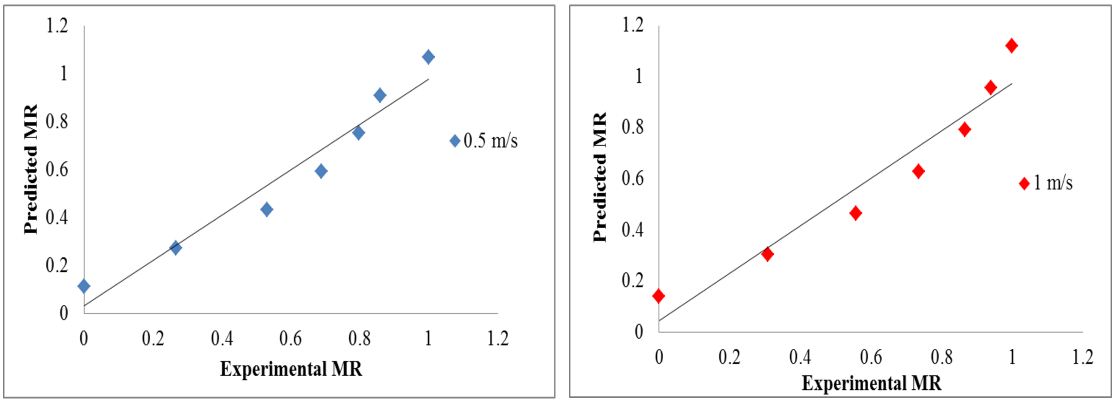

Figure 8:

Predicted values and obtained experimental values for 0.5 m/s and 1 m/s

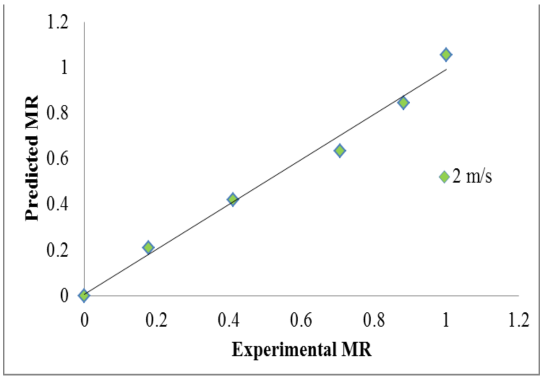

Figure 9:

Predicted values and obtained experimental values for 2 m/s

6. NUMERICAL RESULTS

Strawberry was modeled on Comsol finite elements software and simultaneous heat and mass transfer equations were solved time-dependently and numerically. Experimental and numerical moisture content results of 0.5 m/s were compared for the confirmation of the numerical and experimental study (Fig. 12). Besides, numerical analysis was conducted for different drying air temperatures (50, 70, 90 °C) and different product thicknesses (0.5, 1cm, 2cm) and the effect of temperature and thickness on drying behavior was investigated (Comsol Multiphysics 4.3a).

It is seen that the thermophysical properties of strawberry is similar with grape. Therefore in analaysis the thermophysical properties of grape is determined for the thermophysical properties of strawberry. The thermophysical properties of strawberry and air are given in Table 3 and Table 4 respectively.

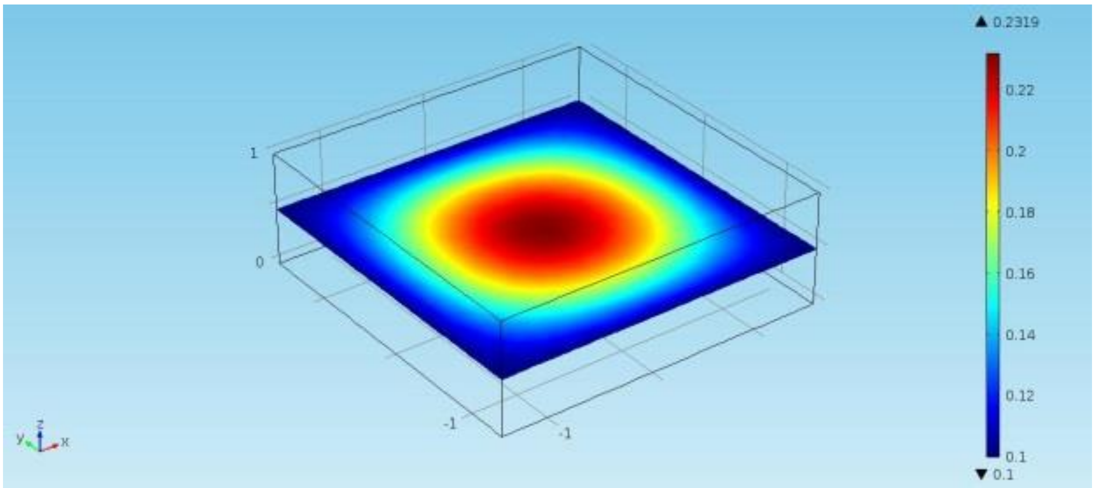

Figure 10:
Moisture distribution of the strawberry model

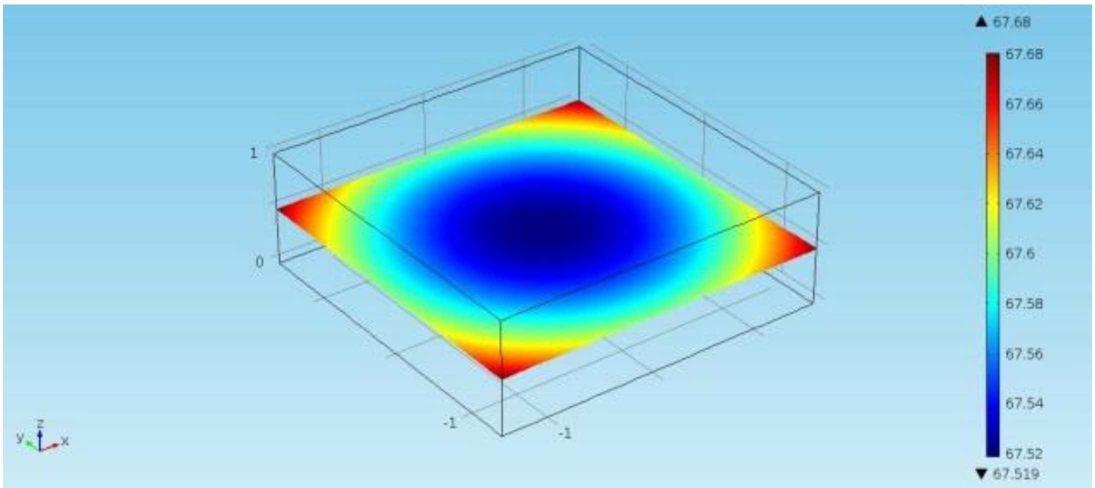

Figure 11:
Temperature distribution of the strawberry the model

Table 3. The thermophysical properties of strawberry 25°C (Çengel, 2011)

Parameter (Unit)	**Value**
Density (kg/m^3)	1000
Moisture Content (%)	83
Thermal Conductivity (W/mK)	0.567
Evaporation Heat (J/kg)	0.25×10^7
Specific Heat (J/kgK)	3910

Table 4. The thermophysical properties of air for different temperature (Çengel, 2011)

Parameter (Unit) / **Inlet Temperature**	Density (kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)
50°C	1.092	0.02735	1007
70°C	1.028	0.02881	1007
90°C	0.9718	0.03024	1008

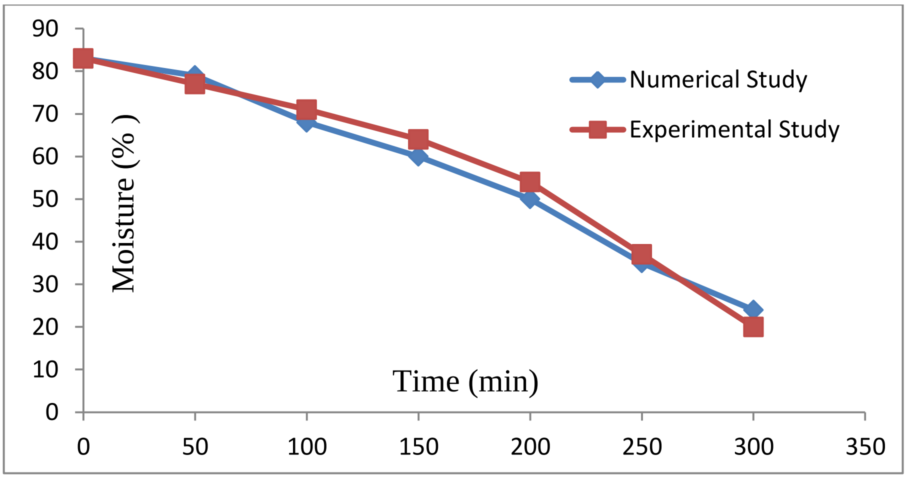

Figure 12:
Experimental and numerical change in the moisture content (air velocity=0.5 m/s)

It was seen that the change in the experimental and numerical results for the 300-minute drying duration at 0.5 m/s drying air velocity were compatible with each other.

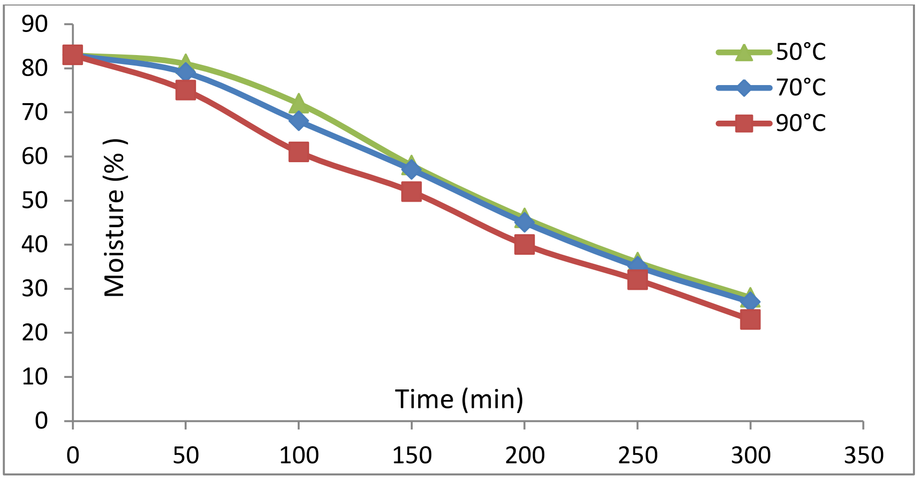

Figure 13:
Numerical results of strawberry drying at different temperatures

In Figure 13, the results of the numerical study conducted for different drying air temperatures at 0.5 m/s drying air velocity are seen. Increasing the drying air temperature enhanced the drying rate and shortened the drying duration. Drying result curves for 50°C and 70°C were found quite close to each other. When the velocity is low, heat and mass transfer coefficients are low so that increasing the temperature does not impact the drying time too much. The humidity rates of the drying airs at 50°C, 70°C and 90°C after 300 minutes were discovered as 28%, 27% and 23%, respectively. Accordingly, the following interpretation can be made: the more the air temperature increased, the more the drying rate increased.

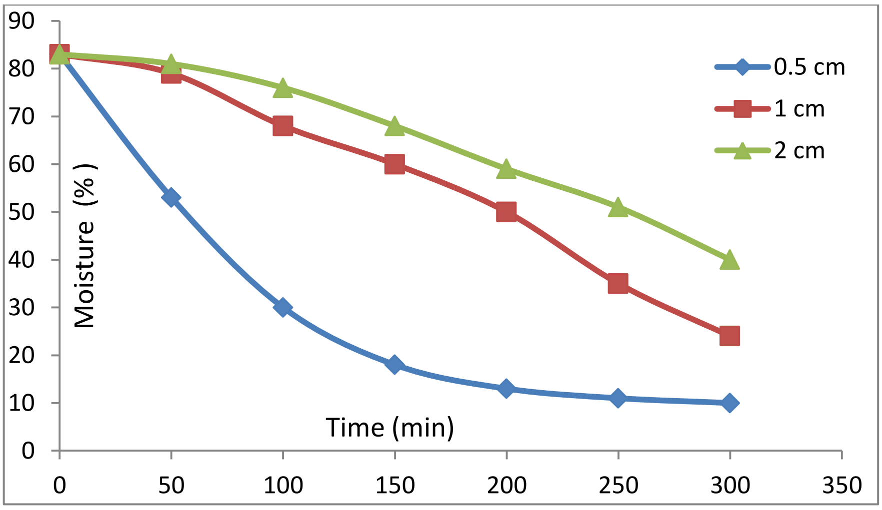

Figure 14:
Numerical results of the moisture content for different strawberry thicknesses

In Figure 14, the results of the numerical study that investigates the effect of the thickness on the drying duration by using products at different thicknesses at 0.5 m/s drying air velocity are seen. It was observed when the effect of the thickness on drying was examined that the strawberries with 1 cm and 2 cm thicknesses respectively dried till 22% and 10% moisture values whereas the moisture rate of the strawberry with 2 cm thickness decreased approximately down to 40% after 300 minutes. Twofold decrease in the thickness provided an approximately twofold decrease in the moisture rate. Consequently, drying rate decreases as the product thickness increases.

7. CONCLUSIONS

- Strawberry drying procedure was examined both experimentally and numerically in this study. Experiments were performed at 3 different velocities (0.5-1 and 2m/s) for 300 minutes to investigate the effect of primarily the air velocity, which is among the parameters that influence the drying. It was noticed as per these results that 300 minutes have to pass at 1 m/s air velocity and 250 minutes at 2 m/s air velocity so that the moisture content of the strawberry, the beginning moisture content of which was 83% on the basis of wetness, could decrease down to 16%.
- It was seen that drying results at 0.5 and 1 m/s were close to each other. It was seen with these results that the increase in the air velocity shortened the drying duration.
- Then, results of the experiment performed at 0.5 m/s air velocity and results obtained numerically were compared and the results were found to be compatible with each other.
- After the results of the numeric analysis were confirmed with experimental data, the effect of the temperature on drying was investigated by keeping all the other attributes fixed and changing the drying air temperature (50-70-90°C). It was observed that drying duration shortened and drying rate increased when the drying air temperature increased.
- Again, the effect on drying was numerically investigated by keeping all the other attributes fixed and changing the product thickness (0.5cm-1cm-2cm). It was seen that drying duration shortened when the product thickness decreased.

The following interpretation can be made according to these results: drying air temperature can be increased or product thickness can be decreased in order to shorten the drying duration. Optimum drying conditions must be discovered for energy and economic saving. Otherwise, financial losses are experienced from the product which cannot be dried under the desired circumstances. It is important for the system’s economy to assess the experimental study results together with mathematical modeling.

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