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Simulation of Mass and Heat Transfer of Orange Slice during Drying Process under Vacuum Condition Using Finite Element Method

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INFO

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ABSTRACT

One of the most popular and oldest ways to preserve fruits and vegetables out of season is drying. The mass and heat transfer mechanisms during the drying of food products are complex. In this study, orange slices were dried by the natural convection with a vacuum dryer and the heat and mass transfer process of slices during drying were simulated and predicted by the finite element method using Comsol Multiphysics software. The simulation was done for temperatures of 45, 65, and 85 °C and pressure of 60 kPa. The results showed that the predicted model simulated moisture transfer (R^2 between 0.92 and 0.97) and heat transfer (R^2 between 0.97 and 0.99) with appropriate accuracy. The simulation showed that after the surface moisture drying, the moisture gradient was from the center to the surface, while the temperature gradient was from the surface to the center.

INTRODUCTION

Fruits and vegetables have a high potential for corruption and rotting, and in other words, their shelf life is short, and in the food industry, different methods such as freezing, canning, salting are used to preserve them longer (Akar and Barutçu Mazı, 2019). One of the most popular and oldest ways to preserve fruits and vegetables out of season is drying. In drying, by reducing the moisture of the tissue, water activity decreases, which subsequently limits or even stops the activity of microorganisms. But this moisture reduction is always associated with changes in the physical, chemical, and biochemical properties of the product (Wang et al., 2018). Therefore, researchers are always trying to find out the reasons for these changes and to produce a higher quality product by controlling the conditions.

It has been widely proven that the quality of the dried product depends on the processing conditions. So changes in physiochemical, chemical and biological properties depending on different parameters may occur. It is not far from expected that the drying time decreases with the increase in dryer temperature while the product is seriously damaged (Nakagawa et al., 2021). It has always been important for all researchers and artisans in this field to maintain a balance between maintaining quality and increasing drying efficiency, and many efforts have been recorded their attention(Majdi et al., 2019; Rashidi et al., 2021; Samani et al., 2018; Zhong et al., 2017). To understand better, familiarity and prediction of thermal, mechanical, physical, and chemical processes occurring in food products during various drying methods for different products have been investigated (Lee et al., 2021; Naji-Tabasi et al., 2021; Thamkaew et al., 2021). Therefore, in this research, an attempt was made to simulate and predict the mass and heat transfer process during the drying of orange slices with a vacuum dryer using the finite element method by Comsol Multiphysics software, to obtain a better understanding of the drying process.

The mass and heat transfer mechanisms during the drying of food products are complex and follow heavy mathematical equations. Among solving equations by finite element method, there is an adaptable and flexible method that is used to analyze this kind of continuum problem in which the configuration of materials and complex boundary conditions and loading conditions are different (Nosrati et al., 2020). Todays, among the various software used to solve equations using the finite element method, Comsol Multiphysics software has considerable ability to solve mathematical equations of finite elements and simulate all kinds of processes with appropriate accuracy (Oskin et al., 2021).

Emran and teammate simulated mass and heat transfer for periodic microwave convection drying with the help of Comsol Multiphysics software. They developed a 3D mathematical model for the coupled heat and mass transfer simulation of Computational Fluid Dynamics (CFD) of microwave ovens for intermittent drying of food such that the microwave absorption process followed Lambert's law. It was found that the integration of fluid flow with a macro convective periodic drying model significantly affects the drying kinetics due to the variable heat and mass transfer variables throughout the sample. This result is consistent with the experimental data. They found that regardless of CFD, the performed modeling may be effective in predicting drying kinetics such that uneven distribution of microwave

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energy leads to uneven temperature distribution in the sample (Khan et al., 2020).

In a study, using the analytical model proposed by Dincer and Dust, mass transfer parameters (moisture transfer coefficient and moisture diffusion coefficient) of shrimp samples were determined. To calculate the drying coefficients and delay factors, the experimental dimensionless moisture data were used. Then, they were included in the analytical model of thin film and cylindrical shape. The results showed that there is a sufficient fit between the experimental data and the predicted values of the correlation (Costa et al., 2018).In this research, the process of heat and moisture transfer during the drying of orange slices by a vacuum dryer was simulated and predicted for temperatures of 45, 65, and 85 °C and pressure of 60 kPa.

MATERIALS AND METHODS

Product Preparation

Fresh oranges were procured from the local market and kept in a refrigerator at 3-5℃ during the experiment. The initial moisture content of the product was estimated to be 7.75 (d.b).

Theory

In this study, orange slices were dried by the natural convection heat transfer method. So that heat is transferred from the surface to the center. Meanwhile, the moisture penetrates from the center to the surface and the moisture evaporates on the surface of the product. To simulate the process of heat and moisture transfer during the drying of orange slices, the following assumptions are considered:

• The model was simulated in a two-dimensional and symmetrical way.

• The equations were solved in a time-dependent manner.

• No cracking or wrinkling will occur in the product

• Mass transfer is only considered for humidity

• Moisture penetrates the surface of the product

• Evaporation occurs only at the surface.

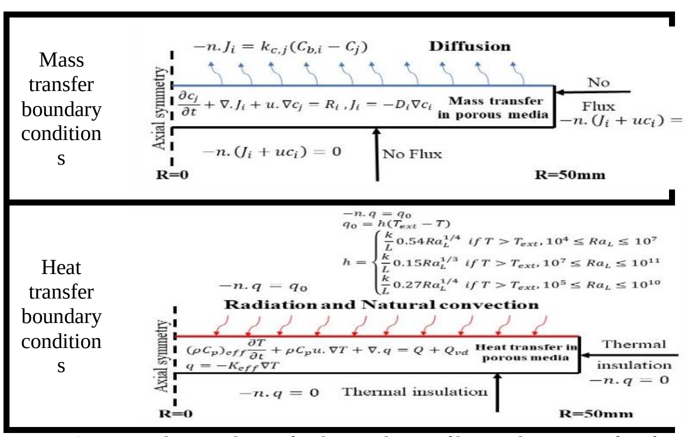

Fig 1. Boundary conditions for the simulation of heat and mass transfer of drying orange slices with a vacuum dryer

Density

After peeling the orange, the density of the orange slices was calculated from equation 1:

$$\rho = \frac{m}{V} = m/(A \times h) \tag{1}$$

Where, ρ is density (kg/m^3), m is mass (kg), v is volume (m^3), A is Area (m^2), h is height (m)

In this study, the area of the orange slice was measured by the image processing method by counting color pixels (Homayounfar et al., 2019).

Heat transfer coefficient

To obtain the thermal coefficient of displacement, the transient heat transfer method was used (Van der Held and Van Drunen, 1949).In this method, the temperature difference between the core and the wall of the material causes heat transfer from the center to the surrounding of the material. Fig. 2 shows a schematic view of the components needed to measure the thermal coefficient of displacement for a homogeneous mixture of food samples.

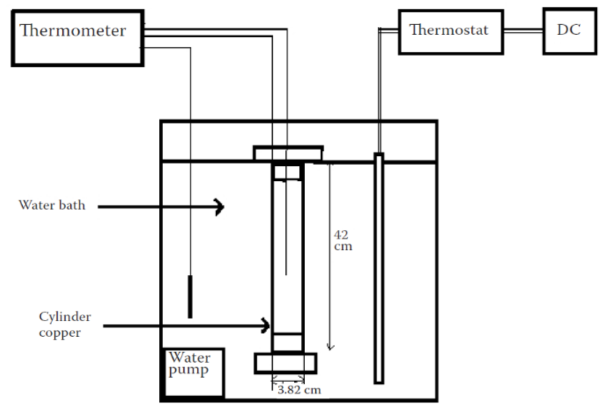

Fig 2. Schematic of the apparatus for measuring the displacement heat transfer coefficient of oranges.

Specific Heat

The coefficient of specific heat of orange was experimentally calculated and measured by mixing in a flask. In this method, a copper capsule was used which was completely sealed when closed and water did not penetrate it or moisture did not leak out of the product. A T-type thermocouple connected to a data logger was used to report the temperature.

Effective moisture penetration coefficient

The working principle of the drying solid material was considered based on the diffusion process with the physical meaning of the simultaneous effect of concentration and temperature. So that penetration occurs inside the solid, porous capillary tubes filled with air and pores. The permeation process continues until the steam enters the air through the open side of the capillary tube. Fick's second law of diffusion was used to explain the transfer of moisture from the inside of orange leaves to the surface (Equation 2):

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \tag{2}$$

Where, D_{eff} is effective moisture diffusion coefficient (m^2/s), t is drying time (s), x is axial position (m).

From Fick's second law (developed by Crank), the value of the effective moisture diffusion coefficient was obtained by plotting the experimental data of Ln (MR) versus time. So that the slope of the fitted line (K1) became equal to equation (3).

$$K_1 = \frac{\pi^2}{4L^2} D_{eff} \tag{3}$$

Mass transfer coefficient

The mass transfer coefficient was obtained by the Biot number method. The details of this method are mentioned in detail by Beigi (2016).

RESULTS AND DISCUSSION

The values of mass and heat transfer parameters of drying orange slices with a vacuum dryer at temperatures of 45, 65, and 85 °C and pressure of 60 kPa by finite element method with Comsol Multiphysics software are shown in Table 1. The value of the effective moisture diffusion coefficient and mass transfer coefficient increased with increasing temperature. The reason for this is more thermal energy to evaporate moisture from the sample. These results were similar to the results of Rajoria et al. (Rajoriya et al., 2019) and Nadi and Tzemplex (Nadi and Tzempelikos, 2018).

Table 1. Values of parameters measured to simulate the heat and mass transfer process of drying orange slices

Parameter	Unit	45˚C	65˚C	85˚C
Effective moisture penetration coefficient	m^2/s	8.452×10^{-11}	43527×10^{-10}	8.4942×10^{-10}
Mass transfer coefficient	m/s	6.72×10^{-8}	1.920×10^{-7}	10.28×10^{-7}
Radiation intensity	W/m^2	0.5	1.9	5.6
Specific heat capacity	J/kg.K		491.8	
Displacement heat transfer coefficient	W/m.K		0.6607	
Density	kg/m^3		1157	
Initial humidity	d.b		7.75	
Ambient humidity	%		0.2	

Fig. 3 shows the tissue moisture changes predicted by the finite element method versus the tissue moisture changes of the experimental tests during the drying process of orange slices. The results showed that Comsol Multiphysics software was able to simulate the changes in the moisture content of orange slices during the vacuum drying process at a pressure of 60 kPa and temperatures of 45, 65, and 85 °C with appropriate accuracy (R^2 was between 0.92 and 0.97).

Tissue moisture distribution in an orange slice was simulated by numerically solving the Fick equation during the drying process. Fig. 4 shows the simulation of moisture distribution in orange sheet layers at 45 °C and 60 kPa pressure. As the Fig. 4 shows, the moisture gradient increases gradually at the beginning of the drying rate and decreases at the end of the drying process (The second half is limited by the downward drying rate).In other words, the tissue moisture is immediately removed from the surface of the orange sheets when the drying process begins, and then the moisture spreads from the center to the surface due to the increase in the moisture gradient. At the end of the drying process, the tissue moisture gradient of all layers is almost gone.The mass transfer simulation results of this study were similar to the results of other researchers (Ghasemi and Chayjan, 2019).The intensity of the moisture concentration difference between the surface tissue and the center of the orange slice increased with the increase in air temperature, which is the most important reason for increasing the drying rate at the beginning of the drying process. It should be noted that the moisture penetration coefficient is strongly dependent on the food matrix of the material apart from the temperature. The temperature profile of the inner layers of the orange sheet for the numerical solution of the second Fick equation during vacuum drying for a temperature of 45 °C is shown in Fig. 5. Numerical simulation was able to predict the temperature changes of the orange slice surface with appropriate accuracy (Fig. 3).Based on the prediction, it was observed that the temperature of the sample reaches a stable state after a short period due to the specific biological properties of the sample (Chayjan et al., 2019).Other studies have also confirmed these results (Ghasemi and Chayjan, 2019).As it is clear from the Fig., the temperature gradient propagates from the surface to the center in the opposite direction of the humidity gradient.It is necessary to mention that the transfer of temperature from the environment to the surface of the sample was done by convection and radiation, and inside the sample, it takes place in the form of displacement.

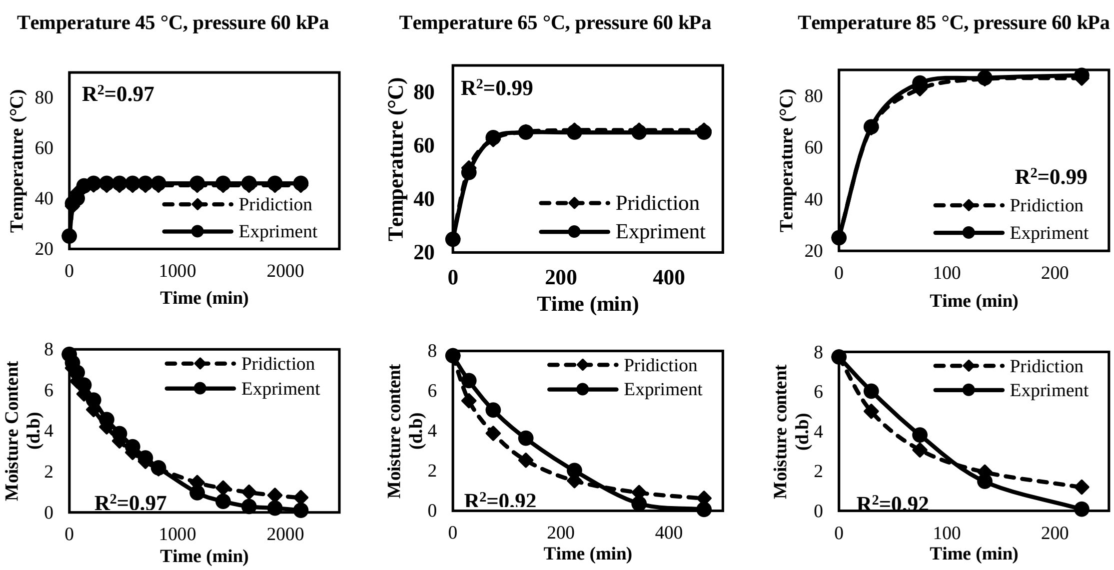

Fig 3. Kinetics of changes in temperature and humidity of orange sheet during drying with a vacuum dryer

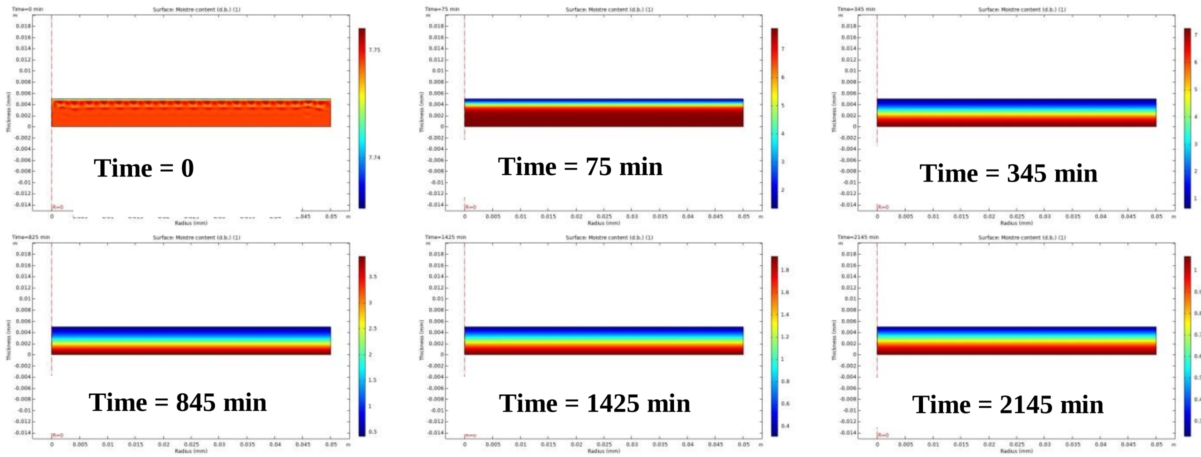

Fig 4. Profile of moisture transfer during vacuum drying of orange slices at 45°C and 60 kPa pressure

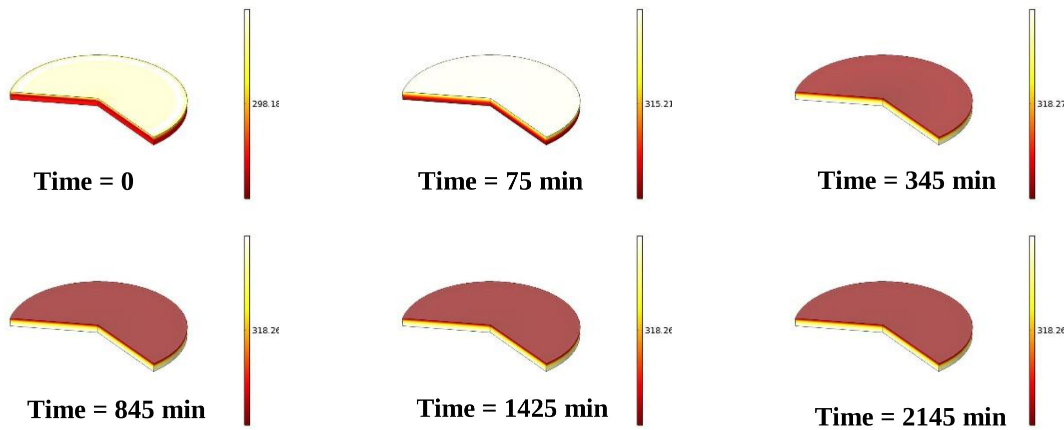

Fig 5. Heat transfer profile during vacuum drying of orange slices at 318 K temperature and 60 kPa pressure

CONCLUSIONS

The results showed that the numerical solution of mass and heat transfer of vacuum drying of orange slices by finite element method was done with the help of Comsol Multiphysics software with high accuracy and this method was able to make a good prediction of the distribution of humidity and temperature in the inner layers of the orange slice. Also, the results showed that the moisture gradient was from the center to the surface and this gradient was adjusted over time, while the temperature gradient is from the surface to the center and reaches a stable state after a short period.

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