EXPERIMENTAL AND THEORETICAL INVESTIGATION OF AGRICULTURAL MATERIAL DRYING PROCESS

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Abstract. Drying of carrots slices and different size carrot cubes layer was investigated in a laboratory dryer with a heater with thermostat. The thin carrots slices layer drying process was studied with small heated air flow by convection. Based on the experimental data, the drying time and temperature dependent drying rate was calculated and presented. Using the proposed methodology, different size (10x10x10 mm; 15x15x15 mm) carrot cube layer drying coefficients, depended on the drying time, were determined. Using the drying rate, the layer of carrot slices drying was simulated and receiving results compared with the experimental data. The obtained measurement results are in high correlation with calculations. The average difference between the calculation and measurement did not exceed 1 %. A mathematical model for thick, porous medium layers, containing small particles, drying is presented. This model contains a system of partial differential equations including the matter and environmental temperatures and mass exchange. The experimental and theoretical results showed that the carrot single cubes layer with the dimensions 10x10x10 mm dry about 10 hours, but with the size 15x15x15 mm require at least 20 hours using convective airflow with temperature 40 ºC.

Keywords: drying, drying rate, mathematical modeling, carrot.

Introduction

One of the ways for storage of agriculture material is to dry it and then store. This is the process of removing water from the product to prevent the growth of micro organisms and decay. Dried materials are more applicable to people living in a warm and dry climate. In the drying method, it does not destroy the nutrients present, it still stays the same. The drying process can give good flavor of a product in long-term storage, it is easy to transport and easy to consume.

The purpose of drying an agricultural product is to reduce its moisture content to a level that prevents its deterioration. In drying two processes take place: one is heat transfer to the product using energy from a heating source, the other is mass transfer of moisture from the inside of the product to its surface and from the surface to the surrounding air.

An important parameter is the drying temperature. On the one hand, it reduces the drying time, on the other hand a high drying temperature reduces the nutritional value of products. In order to verify the influence of the drying process on the vitamin C content in dried products, some authors studied some conventional processes using the hot air drying method. Different kinds of fruits and vegetables and different cultivars have been studied by many researchers. Apples, tomatoes, mango, peppers, potatoes, carrots, and others are examples of fruits and vegetables the drying behavior of which has been studied and their vitamin C retention has been determined. The influence of temperature on the degradation of the referred vitamin can be seen by the results obtained by Zanoni et.al. [1] for dried tomatoes. The study shows that high drying temperature significantly reduces the vitamin C content, at 110 ºC the loss was about 100 %.

Many studies were done to process carrots by air drying [2], sun drying [3] and solar drying [4]. Several researches have been done in the influence of some process parameters (temperature, sample thickness, air flow rate, etc). The effect of carrot slices on the drying kinetics was studied in [5]. The modelling of carrot cubes was made in [6]. The author studied the influence of air-flow rates and the effect of temperature on the drying curve for carrot cubes. Liu Zhenghuai [7] studied the drying process of thick carrot slices heat transfer simulation, integrated heat diffusion process, sliced carrots proposed internal heat transfer model and internal mass transfer model, the use of the third heat transfer boundary conditions were simulated and experimental comparison done.

The mathematical model for thick layer of carrot chips drying process is proposed at [8]. Using the experimental data the carrot chips drying rate expression has been obtained depending on the drying time with a constant drying temperature.

The aim of the present research was to investigate thin carrot slices drying using small heated air and determining the drying coefficient depending on the drying time and temperature. This paper presents experimental results for carrot cubes drying in thin layer to determine the integrated drying rate. The experimental and numerical results are compared. Various agricultural product drying rate expressions at constant temperature are obtained.

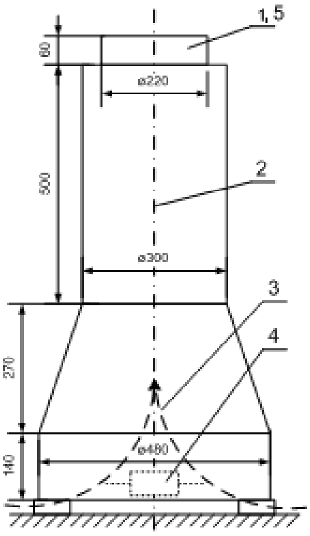
Materials and methods

The carrots were grated in slices with a thickness of 1 – 2 mm, width of 4 – 5 mm. The carrot slices were placed in a perforated container with the layer thickness of 10 – 13 mm (Fig. 1). The carrots also were cubed in 1x1x1 cm peaces and placed in a single layer of the container sieve. The carrot peaces 15x15x15 mm large single layer drying was investigated

Equipment was manufactured, which allows studying the drying process with heat convection (Fig. 2). The thermostat allows maintaining a constant temperature of the sample layer on one side. The heated air flows by convection. The inlet air temperature was 30 ºC to 45 ºC in the experiments. The container was weighted with electronic instruments to determine the quantity of water runoff, during the experiment.

Fig. 1. **Sieve with carrot slices**

a)



b)

Fig. 2. **Experimental device (a) and scheme (b):** 1 – outlet air temperature; 2 – inlet air temperature; 3 – inlet air; 4 – heater with thermostat; 5 – sieve with products

Drying of any substance is based on heat-mass transfer processes. We propose a mathematical model which contains temperature and moisture functions of the matter (carrot slices, carrot cubes etc.) and inter-matter space (air). To describe the kinetics of the drying process we assume the following:

- water evaporation in slices of carrot proceeds according to the Dalton law;
- water is liquid in carrots;
- heat transfer between the matter and drying agent (air) goes on by convection;
- the air flow takes place due to convection and its velocity is constant in the layer of the matter;
- the inner temperature gradient for a single matter slice is very small and has not been considered.

Since the slices thickness is very small, the internal diffusion in the drying process can be ignored. We obtained the following system of partial differential equations including the matter $\Theta(x, t)$, environmental $T(x, t)$ temperatures and mass exchange of matter $W(x, t)$ and inter-mater (air) $d(x, t)$ [9]:

$$\frac{\partial W}{\partial t} = K\left(W_p - W\right), \ t > 0, \quad x > 0 \tag{1}$$

$$\frac{\partial d}{\partial t} + a_1 \frac{\partial d}{\partial x} = \frac{K}{a_2}\left(W - W_p\right), \ t > 0, \quad x > 0 \tag{2}$$

$$\frac{\partial \Theta}{\partial t} = c_1\left(T - \Theta\right) + c_2\left(W_p - W\right), \ t > 0, \quad x > 0 \tag{3}$$

$$\frac{\partial T}{\partial t} + a_1 \frac{\partial T}{\partial x} = c_0\left(\Theta - T\right) \ t > 0, \quad x > 0 \tag{4}$$

where x, t – variable of space and time;

$a_1 = 3600v$; $a_2 = \dfrac{\gamma_a \varepsilon}{10\gamma_m}$; $c_0 = \dfrac{\alpha_q}{m\gamma_a c_a}$; $c_1 = \dfrac{\alpha_q}{(m-1)\gamma_m c_m}$;

$c_2 = \dfrac{K \cdot r}{100 c_g}$; $K = f\left(t, T\right)$; $\alpha_q = 12.6\dfrac{\lambda}{L^2}$;

v – air velocity, $m \cdot s^{-1}$;

γ_a, γ_m – capacity of weight (for air and matter respectively), $kg \cdot m^{-3}$;

c_a, c_m – heat of drying air and moist matter, $kJ \cdot kg^{-1}$;

r – latent heat for water evaporation, $kJ \cdot kg^{-1}$;

$\varepsilon = m / (1 - m)$ (m – porosity of matter);

W_p – equilibrium moisture content, dry basis, %;

K – drying coefficient, h^{-1};

α_q – interphase heat exchange coefficient, $kJ \cdot m^{-2} \cdot h^{-1} \cdot {}^{\circ}C^{-1}$;

λ – rate of matter heat transfer, $kJ \cdot m^{-1} \cdot h^{-1} \cdot {}^{\circ}C^{-1}$;

L – carrot slices thickness, m.

Equilibrium moisture content Wp was obtained using the S. Henderson's modified equation in Forte's interpretation:

$$W_p = \left(-\frac{1}{5869}\ln\left(1 - \frac{\varphi}{100}\right)(T + 273)^{0.775}\right)^{\frac{(T+273)^{1.363}}{5203}},$$

where φ – heated air relative humidity, %.

The initial and boundary conditions for the system (1 – 4) can be given in the following way:

$$T\big|_{t=0} = \Theta\big|_{t=0} = \Psi_1(x),\ W\big|_{t=0} = \Psi_2(x),\ d\big|_{t=0} = \Psi_3(x),\ T\Big|_{x=0} = \vartheta_1(t),\ d\Big|_{x=0} = \vartheta_2(t). \tag{5}$$

The initial conditions for the system (1)-(4) are given as follows:

$$\Psi_1(x) = \Theta_s\ ,\ \Psi_2(x) = W_s\ ,\ \Psi_3(x) = d_s\ ,$$

where Θ_s – matter and intermatter air temperature in the layer, ºC;

W_s, d_s – matter moisture and intermatter air humidity in the layer, %.

For our experiments we chose constant boundary conditions:

$$\vartheta_1(t) = T_r\ ,\ \vartheta_2(t) = d_r\ ,$$

where T_r – heated air temperature, ºC;

d_r – heated air humidity, %.

The system (1 – 4) with boundary and initial conditions (5) can be solved numerically, at known drying coefficient expression, by the difference scheme using weights [9].

Results and discussion

As shown by the experiments the drying coefficient $K=f(t, T)$ is not constant but depends on the drying temperature and drying time. Using the experimental data we determined the K dependence of the drying time at different, constant inlet air temperatures T_r .

Using the experimental results and data statistical processing we received connectedness between the drying time t, drying temperature T and moisture removal Δm from carrot slices in 10-13 mm layer in 6 hour non-stop experimental time.

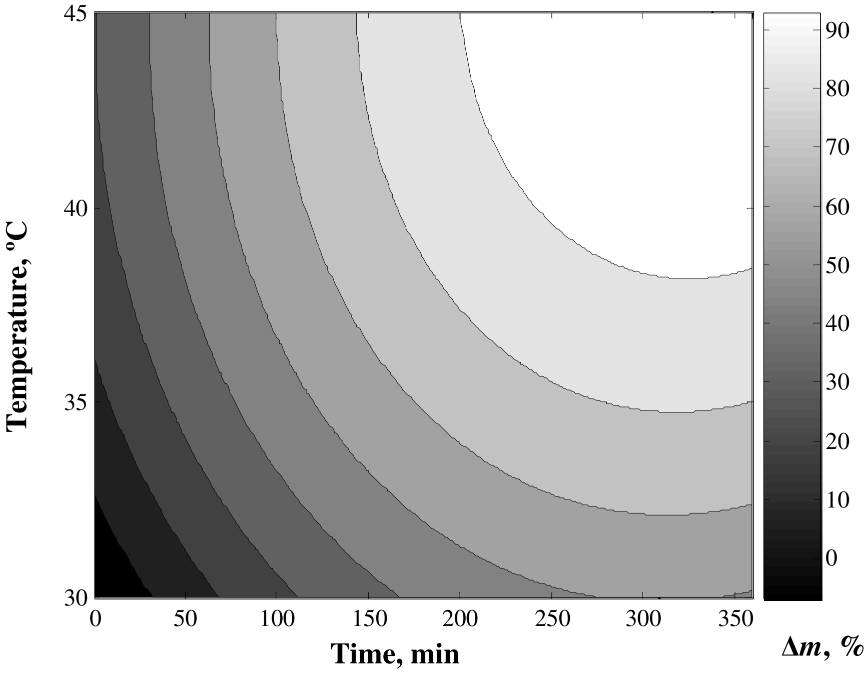


Fig.3. **Contour plot of carrot slices layer moisture removal Δm depending on drying time t and drying temperature T using heat convection**

As we do not know the real carrot slices moisture W_s and the equilibrium moisture W_p, we have taken the experimental data rationing $u(t)$:

$$u(t) = \frac{W(t) - W_p}{W_s - W_p}. \quad (6)$$

It should be noted that in the case of $W(t)$ the whole layer of the mean integral moisture is understood. Assuming that $K(t) = at + b$ and using equation (1) and condition (5) we expressed the coefficients a and b from the experimental data:

$$\frac{a}{2}t + b = -\frac{\ln(u)}{t} , \quad (7)$$

where t – drying time, min.

Using the processed data the carrot cubes (10x10x10 mm and 15x15x15 mm placed in a single layer, shown in Fig. 4) drying coefficient was obtained, depending on the drying time.

Using the experimental data and methodology (6, 7) we obtained the drying coefficients. $K(t)$ for carrot cubes single layer. $K(t)$ for single layer carrot cubes with the dimensions 10x10x10 mm drying with drying temperature 41 ºC was

$$K(t) = 402.7 \cdot 10^{-5} + 2.6 \cdot 10^{-6} \cdot t \quad (8)$$

with the coefficient of determination $\eta^2 = 0.87$.

The drying coefficient for single layer carrot cubes (dimensions 15x15x15 mm) drying with drying temperature 40 ºC was

$$K(t) = 304.4 \cdot 10^{-5} + 1 \cdot 10^{-7} \cdot t \tag{9}$$

with low coefficient of determination. The value b from (9) is close to the experimentally determined average value of the $K(t)$ which was $K_{aver} = 311.8 \cdot 10^{-5}$. This could explain the increase in the individual size of production. The role of internal diffusion of the product increased with increasing the size of the pieces. If we want to model theoretically a thicker layer with greater pieces drying process, then in the process mathematical model moisture diffusion inside of the particles should be anticipated.

a) b) c)

Fig. 4. **15x15x15 mm carrot cubes changes in the drying process with inlet air temperature 40 ºC:**
a – beginning at the process; b – after 330 min drying; c – after 2420 min drying

Using the expression (8, 9) we solved the equation (1) with the boundary condition (5) and compared the experimental and numerical results. It is shown in Fig. 5.

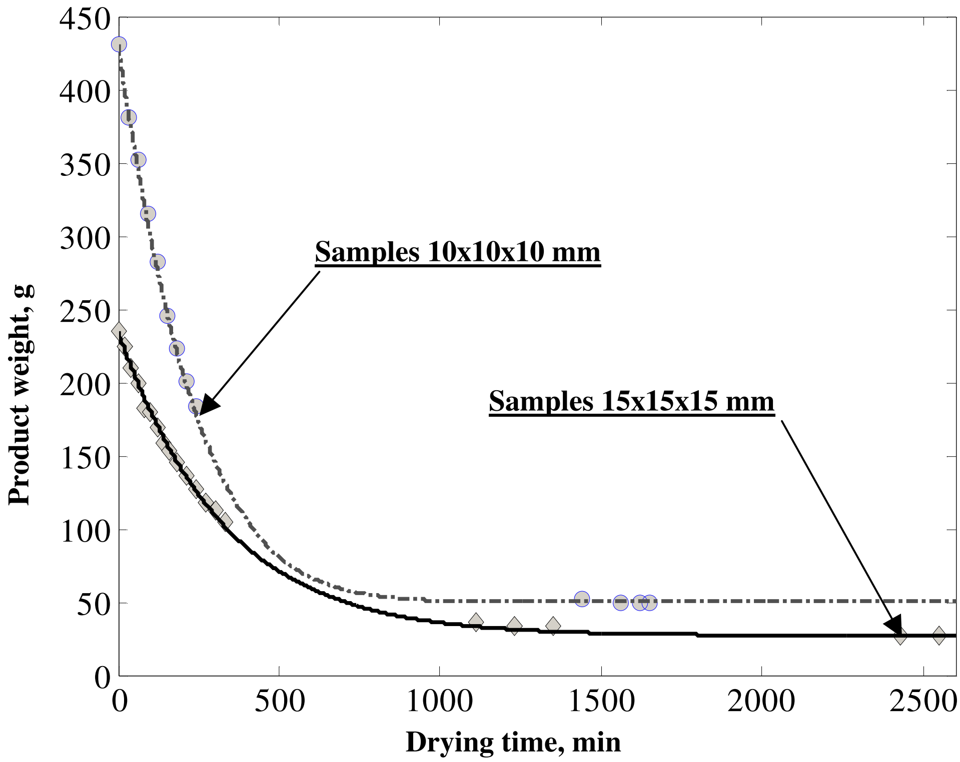


Fig. 5. **Carrot cubes layers weights change during the drying process:**
○, ◊ – experimental results; –, --- – theoretical results)

We compared the absolute value of the difference between the theoretically calculated and experimentally determined product weights at the same drying time. The average difference for carrot cubes layer weights with the carrots samples dimensions 10x10x10 mm was 2.3 g with standard deviation 2.5 g and for the samples 15x15x15 mm layer weights the average difference was 1.8 g with standard deviation 1.9 g.

Conclusions

1. Carrot cubes dimensions significantly affect the drying time. It is a layer with dimensions of 10x10x10 mm dried for about 10 hours, but with the size 15x15x15 mm it requires at least 20 hours using convective airflow with temperature 40 ºC.
2. The proposed methodology has been successfully used in various porous thin material layers to determine the drying coefficient. The offered mathematical model can be used for modeling the drying process of small particles in thick layers with the drying agent velocity v, where there is difference between the air and matter temperatures.
3. The larger particle size in the layer, the greater role is plaid by internal moisture diffusion of each particle that we must take into account.

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