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KINETIC STUDY OF CARROTS DRYING

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ABSTRACT. The present study presents the drying of carrot slices as thin-layer of 4 mm thickness in a laboratory dryer with the drying air temperature in the range of 40–60 ^{0}C. The effect of drying air temperature on the drying kinetics, the drying rates, the effective diffusion coefficients and the activation energy were determined. The effective diffusivity was found to be between $2.6 \cdot 10^{-10}$ and $5.2 \cdot 10^{-10}$ m^2/s. The Newton, Page, modified Page and Henderson & Pabis models available in the literature were fitted to the experimental data using nonlinear regression analysis. The models were compared using the coefficient of determination (R^2). Henderson & Pabis model has shown a better fit to the experimental drying data as compared to other two models.

Keywords: *carrot, thin-layer drying, drying modeling, effective moisture diffusivity*.

INTRODUCTION

The drying operation is frequently used for agricultural products preservation. It is also used for the substantial reduction in weight and volume, minimizes packaging, storage and transportation costs [1].

The basic objective in drying agricultural products is the removal of water or moisture from the surface and from the interior of material up to certain level by evaporation. Thus, the operation involves simultaneous transfer of heat to evaporate the liquid and mass transfer (moisture transfer) as liquid or vapour within the solid and vapour from the surface, usually into a hot carrier gas. The transfer of liquid inside the solid may occur by several mechanisms, such as diffusion in homogeneous solids, capillary flow in granular and porous solids, flow by shrinkage and pressure gradients, and flow caused by a sequence of vaporisation and condensation [2].

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The evolution of drying can be characterised by the drying curve and drying rate curve. The form of drying rate curve varies with the structure and type of material. There are two typical drying curves: constant-rate drying and falling-rate drying. Drying of fruits and vegetables occurs generally in falling-rate period, the moisture transfer during drying being controlled by internal diffusion [3].

The Fick's second law of unsteady state diffusion (equation 1) was used to calculate the effective moisture diffusivity, considering constant moisture diffusivity, infinite slab geometry, and a uniform initial moisture distribution as equation 2 [4]:

$$\frac{\mathbf{dM}}{\mathbf{dt}} = \nabla(\mathbf{D_{eff}}\nabla\mathbf{M}) \tag{1}$$

$$\mathbf{M_R} = \frac{\mathbf{M}-\mathbf{M_e}}{\mathbf{M_0}-\mathbf{M_e}} = \mathbf{A}\mathbf{e}^{-\frac{\pi^2\mathbf{D_{eff}}}{4\mathbf{L}^2}\mathbf{t}} \tag{2}$$

where: M is the moisture in kg water/kg dry material at time t, M_R – the moisture ratio, D_{eff} – the effective moisture diffusivity in m^2/s; L – the thickness of the material layer (carrot slab), M_e – the equilibrium moisture content in kg water/kg dry material, and M_0 – the initial moisture content in kg water/kg dry material.

In the simplified form, as equilibrium moisture (M_e) content has negligible effect, the moisture ration becomes:

$$\mathbf{M_R} = \frac{\mathbf{M}}{\mathbf{M_0}} = \mathbf{A}\mathbf{e}^{-\frac{\pi^2\mathbf{D_{eff}}}{4\mathbf{L}^2}\mathbf{t}} \tag{3}$$

The linear form of equation 3, obtained by plotting ln(M_R) as a function of time offers the possibility to reach the effective diffusivity from experimental data.

The drying rate during experiments was calculated using the following equation:

$$\mathbf{D_R} = \frac{\Delta\mathbf{M}}{\mathbf{A}\cdot\Delta\mathbf{t}} \tag{4}$$

The correlation between the variation of the moisture content and time is a particular dependence for each material and drying conditions, which can not be generalized, but can be experimentally determined.

The present study was undertaken to investigate the thin-layer drying characteristics of carrot slices in a convective dryer and to fit the experimental data to some mathematical models available in the literature.

Carrot was chosen as row material in our research because it is one of the most common vegetables used natural or dried for human nutrition due to the high vitamin and fibre content.

RESULTS AND DISCUSSION

The initial moisture content of carrot slices was found to be 8.10 ± 0.05 (kg water/kg dry matter). The final moisture content of the carrot slices varied with the experimental conditions from 0.25 ± 0.05 to 0.35 ± 0.03 (kg water/kg dry matter).

The variations in the moisture content as a function of drying time at various drying air temperatures and a constant velocity of 0.6 m/s are shown (Figure 1). It can be seen that the moisture content decreases continually with the drying time. The carrot slices of 4 mm will reach the final moisture content within 870-450 min when the air temperature varied from 40^{0}C to 60^{0}C.

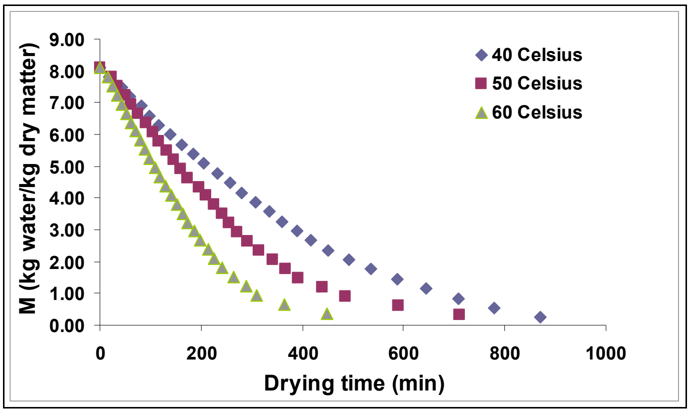

Figure 1. Effect of drying air temperature on moisture content for carrot slices.

Figure 2 show the drying rates, obtained by equation 4, as a function of moisture content at various drying air temperatures.

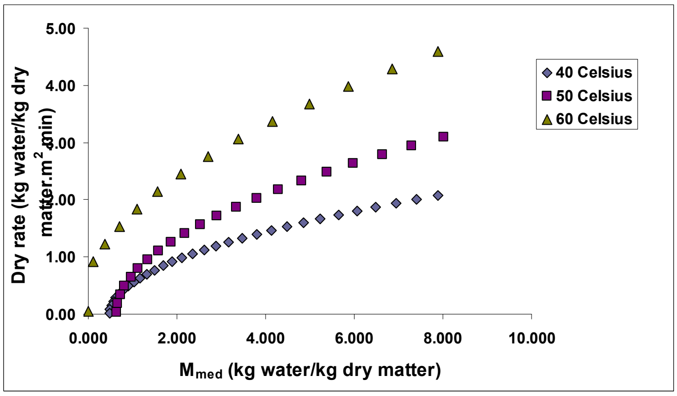

Figure 2. Effect of air temperature on drying rate.

The drying of carrot slices occur in the falling rate period, a continuously decreasing of the drying rate with decreasing moisture content can be seen. In the same time, the increase of drying rates is observed with the increase of drying air temperatures. This means, at high temperatures the transfer of heat and mass is higher and the water loss is more excessive. Similar effects of air temperature are obtained in the drying of apple slices [5].

In order to determine the effective diffusivity the moisture content was converted into the moisture ratio expression M_R. The drying curves for thin layer drying of carrots are shown in Figure 3.

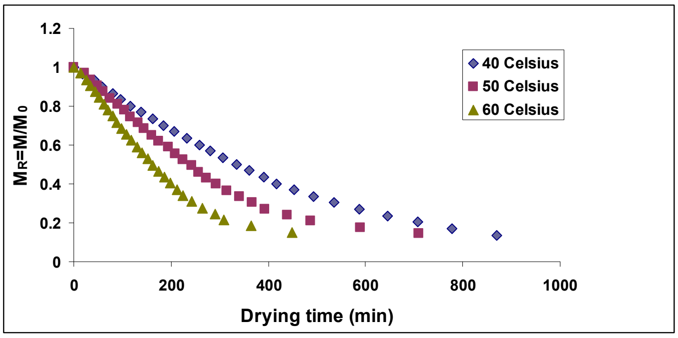

Figure 3. Variation of moisture ratio with the air temperature.

The transport of water during dehydration of carrot is described by applying the Fick's diffusion model. The effective diffusivity can be calculated from the slope of the plot ln(M_R) versus drying time (Fig. 4).

$$\text{slope} = \frac{\pi^2 D_{eff}}{4L^2} \quad (5)$$

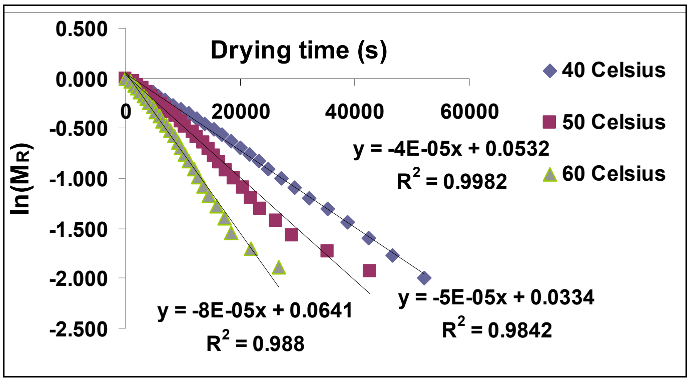

Figure 4. Determination of effective diffusivity coefficient (D_{eff}).

The values of effective diffusivity coefficient obtained by experimental data are shown in Table 1. The values are comparable with those obtained in literature [6]. The effective diffusion coefficient varied with the air temperature from $2.6 \cdot 10^{-10}$ at 40^0C to $5.2 \cdot 10^{-10}$ m^2/s at 60^0C, increasing as temperature increase, which is accordance to the literature mentioned for drying processes of agricultural products. The differences could be due to the differences of drying conditions and drying equipments.

Table 1. Variation of diffusivity coefficient with temperature.

Temperature (^{0}C)	D_{eff} (m^2/s)$\cdot 10^{10}$	1/T
40	2.60	0.0032
50	3.245	0.0031
60	5.20	0.0030

Effect of temperature on effective diffusivity is generally expressed using an Arrhenius-type equation [1, 7]:

$$\mathbf{D_{eff}} = \mathbf{D}_0 \exp\left(-\frac{\mathbf{E_a}}{\mathbf{T} \cdot \mathbf{R}}\right) \quad (6)$$

where: E_a is the activation energy of the moisture diffusion (kJ/mol), D_0 – the diffusivity value for a infinite moisture content, R- the universal gas constant (kJ/mol·K, and T - the absolute drying air temperature (K).

A plot of $\ln(D_{eff})$ versus 1/T from equation (6) gives a straight line with the slope of E_a/R (Fig. 5).

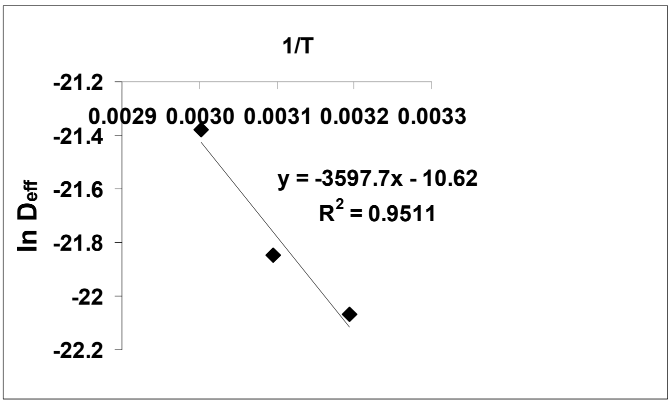

Figure 5. Arrhenius-type representation for activation energy determination.

The obtained value of activation energy of the moisture diffusion was 29.91 kJ/mol and the Arrhenius factor D_0 was $2.44 \cdot 10^{-5}$ m^2/s, which are comparable with the values found in literature [8].

The semi-theoretical models of Newton [3, 9], Page [3, 10] and Henderson & Pabis [3, 10], widely used in thin-layer drying, are considered in the present study to describe the drying behavior of carrots:

$$\mathbf{M_R} = \exp(-\mathbf{kt}) \qquad \text{Newton} \qquad (7)$$

$$\mathbf{M_R} = \exp(-\mathbf{kt^n}) \qquad \text{Page} \qquad (8)$$

$$\mathbf{M_R} = \mathbf{a}\exp(-\mathbf{kt}) \qquad \text{Henderson \& Pabis} \qquad (9)$$

where k is the drying constants, t – the drying time, a and n - the specific drying coefficients.

From each model the drying constant k and the specific drying coefficients determined considering the experimental data are shown in Table 2. As it was expected, the drying coefficient k has increased with the temperature of the drying air. In the same time the models coefficients are affected by the change of air temperature.

Table 2. Drying constant k of model coefficients.

Temperature and relative humidity of drying air	Newton model	Page model	Henderson & Pabis model
40 (^{0}C) RH % = 17.5	k = 0.1332 (h^{-1}) R^2 = 0.995	k = 0.108 (h^{-1}) n = 1.1156 R^2 = 0.999	k = 0.140 (h^{-1}) a = 1.056 R^2 = 0.998
50 (^{0}C) RH % = 11.3	k = 0.180 (h^{-1}) R^2 = 0.983	k = 0.18 (h^{-1}) n = 1.188 R^2 = 0.984	k = 0.184 (h^{-1}) a = 1.034 R^2 = 0.984
60 (^{0}C) RH % = 8.7	k = 0.270 (h^{-1}) R^2 = 0.983	k = 0.252 (h^{-1}) n = 1.245 R^2 = 0.983	k = 0.288 (h^{-1}) a = 1.063 R^2 = 0.988

The models were compared considering the coefficient of determination (R^2) [3, 10]. The Henderson & Pabis model was selected as the best mathematical model for describing the drying kinetics of the carrot slices in our case.

CONCLUSIONS

The experimental results have shown that the carrot slices of 4 mm thick layer were dried between 870 and 450 min when the air temperature was varied from 40^0C to 60^0C.

The moisture content and the drying rate were affected by the air temperature.

The effective diffusion coefficient varied with the air temperature from $2.6 \cdot 10^{-10}$ at 40^0C to $5.2 \cdot 10^{-10}$ m^2/s at 60^0C.

The obtained value of activation energy using Arrhenius type equation was 29.91 kJ/mol and the Arrhenius factor D_0 was $2.44 \cdot 10^{-5}$ m^2/s.

The Henderson & Pabis model was selected as the best mathematical model for describing the drying kinetics of the carrot slices.

EXPERIMENTAL SECTION

Carrots were purchased from the local vegetable market, hand peeled and washed in tap water. The carrots were then cut into slabs with a thickness of 4 mm and putted into the dryer. The initial moisture content of carrot slices of 89 % w. b. (wet basis) was determined drying the sample into a drying stove 70 ^{0}C for 20 h.

The air was supplied by a centrifugal blower, heated to the required temperature with an electrical wire placed inside the heating chamber and connected with a variable transformer which can change the tension. The temperature and the relative humidity in drying chamber were measured with an HD2001.3 - Relative Humidity – Temperature Transmitter. The sample tray with the carrot slices were put into the dryer on the pan of the balance. The loss of each gram from the moisture was recorded as a function of time in order to determine the drying behavior.

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