Shrinkage effect on diffusion coefficient during carrot drying

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Abstract. Many studies have been previously carried out on the carrot drying and the undergoing processes. The developed mathematical models provide an opportunity to gain an understanding of this complex process and its dynamics. But they are simplified and based on a number of assumptions, including calculation of diffusion coefficient values. In one of the previous studies, the authors of this study determined that the diffusion coefficient is linearly dependent on the moisture concentration with the assumption that the sample's geometric shape does not change. The aim of this study is to determine the dependence of the diffusion coefficient on the moisture concentration taking into account the change in sample thickness during the drying experiment. The experiments were carried out with carrot slices of three different thicknesses: 5 mm, 10 mm and 15 mm thickness on the film infrared dryer at temperature 40 °C. During the experiments, measurements of the weight and thickness of the slices were performed. Using the experimental data the average thickness and diffusion coefficient of slices was calculated depending on the moisture concentration. Obtained results show that thickness depends linearly on the moisture concentration. Using experimental data and obtained average values of samples thickness, the values of diffusion coefficient was calculated. The results indicate that diffusion coefficient value depend linearly on moisture concentration. Their values are close and tend to zero when the concentration decreases if the thickness changes are taken into account during the experiment.

Key words: carrot, diffusion coefficient, drying, thickness.

INTRODUCTION

Vegetables are very important for human nutrition. For example, carrot contains high amount of vitamin, fibre and other valuable nutrients. The importance of carrot is reflected by its global production. Accordingly to the data available on the World Carrot Museum website (2018) and MapsOfWorld (2018) the leading producers of carrot are China, Russia, United States of America, Uzbekistan and Poland. As argue the statistical office of EU Eurostat (2018) in 2016 the total production of vegetables in the EU was 63.9 million tonnes and the vegetable sector was a key sector in EU agriculture, weighting 13.7% of EU agricultural output. The most important producers were Spain (24.1%) and Italy (17.4%). But a year earlier in 2015 the leading supplier of carrots was Israel (56.8%) in EU (Cicco, 2016). Tomatoes, carrots and onions were the most

important vegetables in 2016. There were produced 5.6 million tonnes of carrots, including Latvia with its contribution 14.8 thousand tonnes.

Vegetables contain large quantities of water in proportion to their weight that has important effect on the storage period length (Bastin & Henken, 1997; Rashidi et al., 2010). Drying is one of most popular food preservation methods that causes moisture evaporation in the product. Drying provides safety of product longer time in better quality for consumers and additional economic opportunity for producers.

Many studies have been previously carried out on the food drying (Togrul, 2006; Srikiatden & Roberts, 2008; Aboltins & Upitis, 2011; Aboltins, 2013; Guinē & Barocca, 2013; Aboltins et al., 2017) and the undergoing processes with the main goal to foster optimum utilization of financial, physical and human resources. Without knowledge of drying mechanisms there is no way to predict methods for the improving product quality (Margaris & Ghiaus, 2007). There are various aspects that must be considered when drying small fruits and vegetables, whether for the food or nutraceutical and functional food industries. A system which minimizes exposure to oxidations, light and heat may help conserve quality of product (Ahmed et al., 2013).

Several studies have been carried out using various types of drying. For example, Monghanaki et al. (2013) have compared the advantages of microwave drying with convectional drying methods. While Ahmed with colleagues (2013) has focused upon conventional and new drying technologies and pre-treatment methods based upon drying efficiency, quality preservation, and cost effectiveness. But Daymaz & Kucuk (2017) have investigated drying characteristics of peas in a cabinet dryer at three different temperatures 55, 65 and 75 °C and constant air velocity of 2 m s^{-1}. They have calculated the values of effective diffusivity of the pre-treated and control samples.

Research results focused on drying kinetics investigation have shown that drying rate has strong relationship with drying temperature and drying air velocity (Ndukwu, 2009; Putr & Ajiwiguna, 2017). Drying rate increased with drying temperature and air velocity, but decrease with drying time at the same drying temperature. In addition Putr & Ajiwiguna (2017) have concluded that evaporation process needs more energy when moisture content in the object is low.

The developed mathematical models provide an opportunity to gain an understanding of complex drying process and its dynamics. Most popular are the models of thin layer drying. These models allow many physical variables consider as constants (Aboltins, 2013; Onwude et al., 2016). But they are simplified and based on a number of assumptions, including calculation of diffusion coefficient values. Several studies were focused on the influence of shrinkage investigation on drying kinetics. For example, Dissa et al. (2008) have experimentally established and simulated drying kinetics and bulk shrinkage of the Amelie mangoes.

Researchers group with Botelho (2011) have verified the effective diffusion coefficients at temperatures ranged from 50 °C to 100 °C for carrot slices, but Lamharrar et al. (2017) for Urtica dioica leaves at three temperatures 40, 50, 60 °C. But Aboltins et al. (2017) have shown that the diffusion coefficient is linearly dependent on the moisture concentration with the assumption that the sample's geometric shape does not change. Study results show that the diffusion coefficient increases when the moisture concentration decreases. It was concluded that for approximate calculation of the diffusion coefficient value a simplified formula (Hassini et al., 2004) can be used. But

for highest precision, a series formula with a larger number of terms (at least 15 terms) should be used at small experiment times (Aboltins et al., 2017).

The aim of this study is to determine the dependence of the diffusion coefficient on the moisture concentration taking into account the change in sample thickness during the drying experiment.

MATERIALS AND METHODS

Vegetables materials

The research object of current study is fresh carrots (*Daucus Carota Sativus*) that were purchased from a local market in Jelgava, Latvia. Before the experiment carrots were washed under running water, wiped, prepared with a diameter 25 mm and cut into slices (Fig. 1, a) with three different thicknesses: 5 mm, 10 mm and 15 mm thickness. Carrots were not peeled and blanched. Each sample contains carrot slices that were uniformly placed in a single layer on individual tray with a network base.

Experimental procedure and equipment

In order to obtain experimental data carrot samples were dried in the film infrared dryer (IR) approximately 24 hours at temperature 40 °C (Fig. 1).

The dryer consist of a drying chamber ($80 \times 50 \times 30$ cm) with a heat source IR film (South Korea EXCEL) with total area 0.8 m^2 mounted on the top and bottom of the chamber. The drying temperature of dryer is not more than 40–45 °C with IR film power 140 W m^{-2}.

The experiments were performed with the fan with a total maximum capacity of 100 m^3 h^{-1} and power 15 W, which is placed on the top of the side wall of the equipment, the air intake holes located on the bottom of the opposite side wall (Fig. 1).
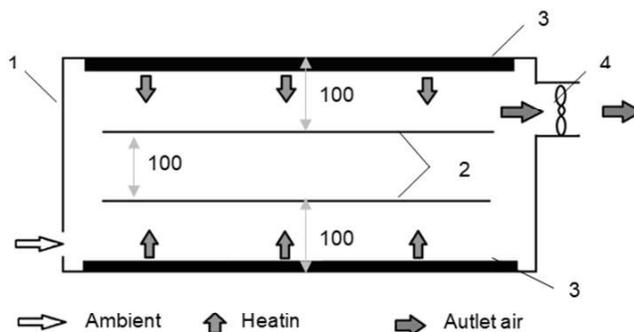

Figure 1. Schematic view of IR dryer: 1 – Body of dryer; 2 – Dryer shelves; 3 – IR drying film; 4 – Fan.

In each experiment, 4 material trays were used for each thickness (Fig. 2), which were placed in the dryer both shelves.

The drying chamber Memmert was used for the determination of dry matter. After experiment carrot samples were dried at temperature 105 °C during the remainder of the experiment until they did not change the weight during the hour in order to obtain dry

matter. During drying process free ventilation was performed. Each tray was weighed before inserting it in dryer.
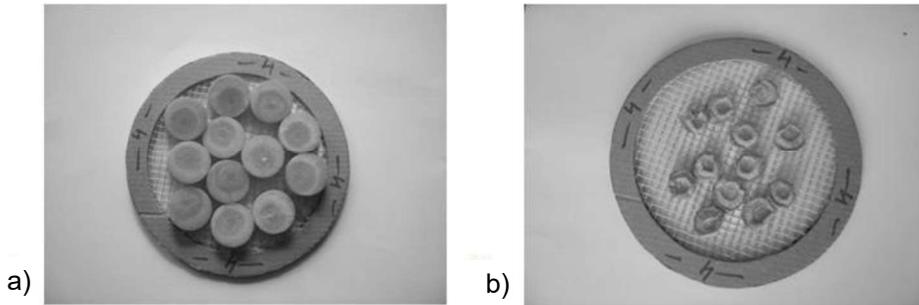

a)   b)

Figure 2. Tray of carrot slices with 15 mm thickness: a) before drying; b) after drying.

During the experiments, measurements of the weight, diameter and thickness of the slices were regularly performed at specified time intervals. Further additional measurements were carried out at the end of the experiment. Values were recorded to determine the mass and geometric shape changes on drying time.

A laboratory balance Kern EW 1500-2M was used for weighing, with measurement accuracy ± 0.01 g. The diameter and thickness were measured using Digital Caliper 1103, with measurement accuracy ± 0.01 mm.

Using the experimental data the average thickness of sample slices and diffusion coefficient were calculated depending on the moisture concentration.

Mathematical modelling

The moisture concentration in % was calculated using the expression (1):

$$C(\%) = \frac{M_i - M_\infty}{M_0} \cdot 100\% \tag{1}$$

where M_i – weight of sample at time moment t_i, g; M_∞ – equilibrium weight of sample, g; M_0 – weight of sample before drying, g.

Drying coefficient value $K(t_i)$ at each time moment t_i was calculated using the formula (2) described by Aboltins & Upitis, 2011:

$$K(t_i) = - \frac{ln\left(\frac{M_i - M_\infty}{M_0 - M_\infty}\right)}{t_i} \tag{2}$$

where t_i – drying time, h.

Diffusion coefficient with constant conditions can be expressed from equation (3) mentioned in Rubina et al. (2016):

$$\frac{M(t)}{M_\infty} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{-D\frac{(2n+1)^2 \pi^2 t}{L^2}} \tag{3}$$

where L – thickness of carrot slices, mm.

Taking the first member of sum (3) (next will be more that 10 time less) and making simplifications of the obtained expression based on assumption can receive the formula (4). It can be used to calculate diffusion coefficient value $D(t_i)$ at certain moment in time t_i in hours:

$$D(t_i) = \frac{K(t_i)L^2}{\pi^2} \qquad (4)$$

where $K(t_i)$ – drying coefficient at time moment t_i, h^{-1}; L – thickness of carrot slices, mm.

The area ration λ was calculated for drying dynamics determination:

$$\lambda = \frac{S_1}{S_2} = \frac{2\pi R^2}{2\pi RH} = \frac{R}{H} \qquad (5)$$

where S_1 – sum of top and bottom area of sample, mm^2; S_2 – area of side surface of sample, mm^2; R – half of carrot slices diameter, mm; H – thickness of carrot slices, mm.

Using the experimental data and performing regression analysis the average thickness of sample slices and diffusion coefficient dependence on the moisture concentration were determined, as well as moisture concentration $C(t,\lambda)$ dependence on the drying time and area ratio.

Linear and exponential regression equations and coefficient of determination (R^2) were determined using Microsoft Excel. In order to perform nonlinear multivariable regression analysis and represent analysis results mathematical packages MathCad and Matlab were used.

RESULTS AND DISCUSSION

Three series of measurements concerning the drying of carrot slices were taken: one with 5 mm thick sliced carrots, second with 10 mm thick and third with 15 mm thick sliced carrots with an average diameter of 25 mm ± 0.5 mm.

The evolution of weight for 15 mm thick slices during the drying process is given in Fig. 3. The scattered points show the values of weight of four trays.
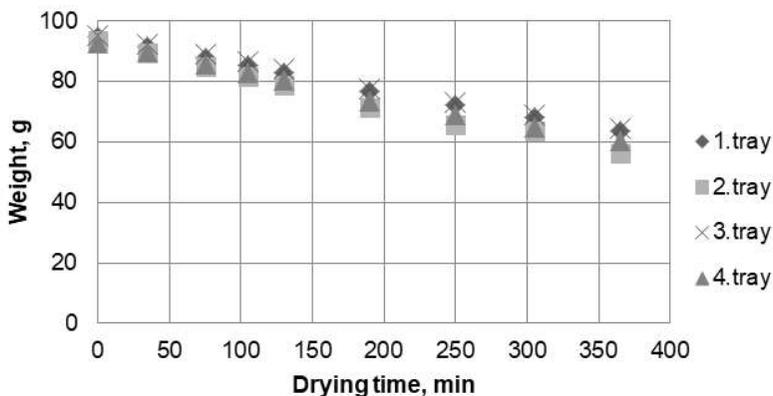

Figure 3. Experimental data of 15 mm thick slices.

Obtained results show that average initial moisture concentration was 94.3% for 5 mm thick carrot slices, 88.3% for 10 mm thick carrot slices and 93.0% for 15 mm thick carrot slices. During the drying experiment after first 4 hours average moisture concentration decreases down to 45.4% ± 9.3, 55.5% ± 5.2 and 67.5% ± 4.6 *(P = 95%)* accordingly. But after a drying period of 20 hours it reached 4.9% ± 0.6, 7.0% ± 2.5 and 28.9% ± 1.9 in slices with the above mentioned thicknesses appropriately.

The evolution of average moisture concentration with confidential interval (*P* = 95%) during the drying process, expressed in (%) is presented in Fig. 4. The red, blue and green scattered points are values of calculated average moisture concentration and the continuous line is the exponential regression.
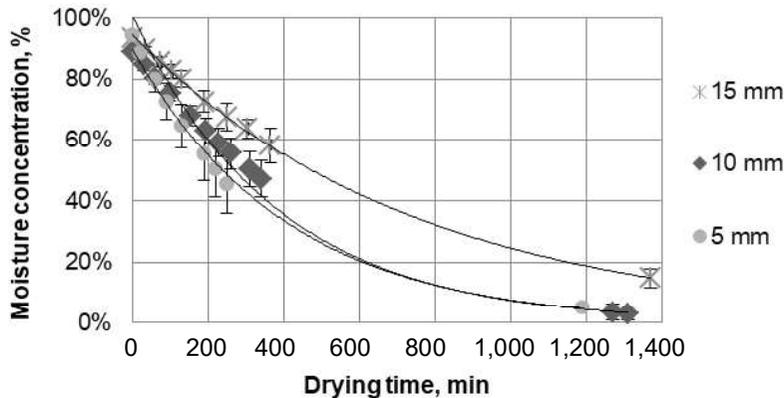

Figure 4. Average moisture concentration dependence on the drying time.

Using experimental data and Excel built in facilities was obtained exponential expression between average moisture concentration *c* and drying time t expressed in minutes for 5 mm (6), 10 mm (7) and 15 mm (8) thick carrot samples:

$$C = 0.8995e^{-0.002t} \qquad (6)$$

with determination coefficient R^2 = 0.998;

$$C = 1.0086e^{-0.003t} \qquad (7)$$

with determination coefficient R^2 = 0.995;

$$C = 0.9462e^{-0.001t} \qquad (8)$$

with determination coefficient R^2 = 0.999.

To achieve the goal set for study during the drying experiments the measurements of slices thickness *L* were recorded. As shown in Fig. 5, the average thickness, expressed in millimetres, depends strongly linearly on the moisture concentration with determination coefficient R^2 = 0.976 for 5 mm thick slices, R^2 = 0.960 for 10 mm and R^2 = 0.999 for 15 mm thick slices. For example, in case of 5 mm thick slices it means that 99.9% of average thickness changes directly depend on moisture concentration changes using linear regression.

Using obtained functional relationship, it became possible to take into account thickness changes in calculation of diffusion coefficient. Evolution of the measured diffusion coefficient including shrinkage changes in fibber direction (thickness) during the drying process, expressed in square millimetres per hour is presented in Fig. 6. The scattered points are values of measured diffusion coefficient and the continuous line is the linear regression of the type:

$$D = k_0 C + k_1 \tag{9}$$

where D – drying coefficient in $mm^2 h^{-1}$; C – moisture concentration in %; k_0, k_1 – regression coefficients.

The results indicate that diffusion coefficient value depends linearly on moisture concentration. In Fig. 5 is shown comparison of diffusion coefficient values obtained from formula (3). Blue scattered points indicate values of diffusion coefficient in case of slices with constant thickness, but red points are values of coefficient which were calculated taking into account thickness changes during drying.
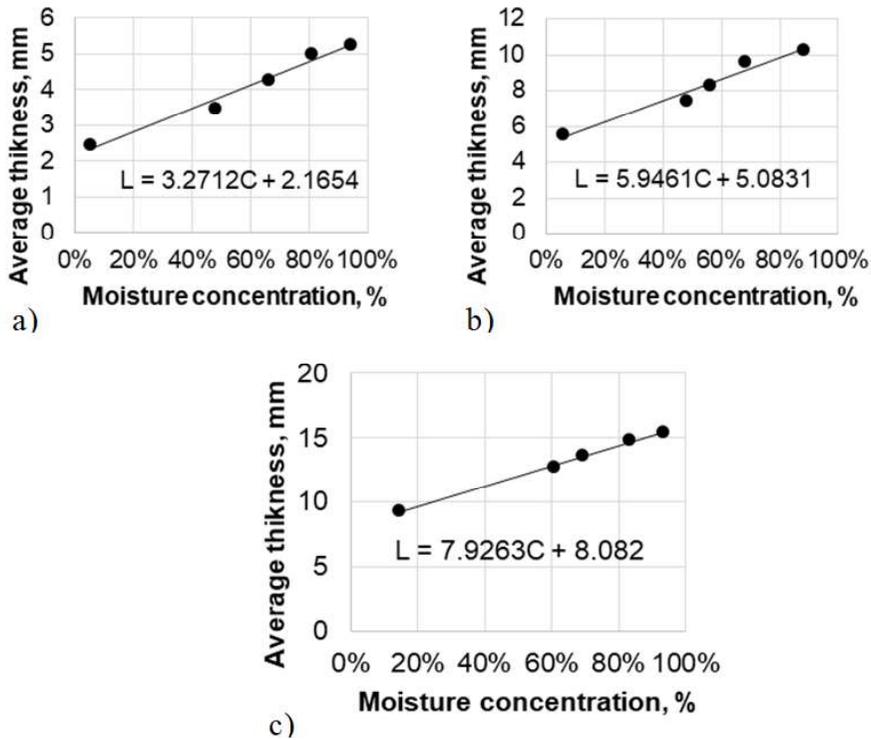

a)

b)

c)

Figure 5. Average thickness dependence on the moisture concentration of slices with: a) 5 mm thickness, b) 10 mm thickness, c) 15 mm thickness.

As shown in Fig. 6 ignoring the thickness change results in values of diffusion coefficient increasing during the drying experiment if the moisture concentration decreases. Totally opposite result is obtained when the thickness variation is taken into account. The results show that diffusion coefficient values tend to zero when the

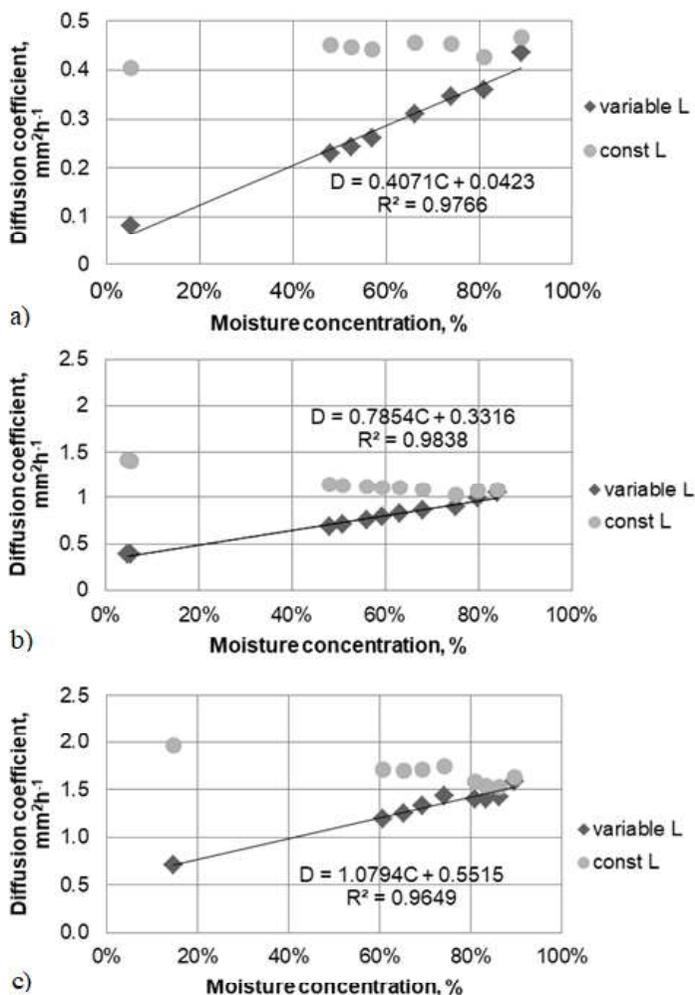concentration decreases if the material thickness changes are taken into account during the experiment.

a)

b)

c)

Figure 6. Diffusion coefficient dependence on the moisture concentration of slices taking and not taking into account the change in thickness during drying with: a) 5 mm thickness, b) 10 mm thickness, c) 15 mm thickness.

Taking into account thickness changes it is became possible to describe more precisely diffusion process and its dependence on moisture concentration. Moreover during drying not only shrinkage changes in fibre direction takes place, but also changes in side direction. It means that surface area influences diffusion process. In order to take into consideration the effect of surface area on the moisture concentration changes during drying the area ratio λ coefficient was introduced. Area ratio describes ratio between sum of basic surface area and area of side surface (4).

Using experimental data and mathematical packages MathCad and Matlab capabilities was obtained nonlinear multivariable expression between moisture concentration $C(t, \lambda)$, drying time t *(hours)* and carrot samples area ratio λ (10) at drying temp erature 40 °C:

$$C(t, \lambda) = 106.3 - 3.43t + 0.014t^2 - 27.7\lambda + 7.41\lambda^2 - 0.5t\lambda \qquad (10)$$

with determination coefficient $R^2 = 0.93$.

Graphically, this relationship is presented in Fig. 6. It can be seen that at given situation, removal of moisture occurs most rapid if the thickness of the samples is close to the diameter of the sample. It is interesting because the minimum surface of the cylinder at a certain volume is in a situation where its height is equal to the diameter
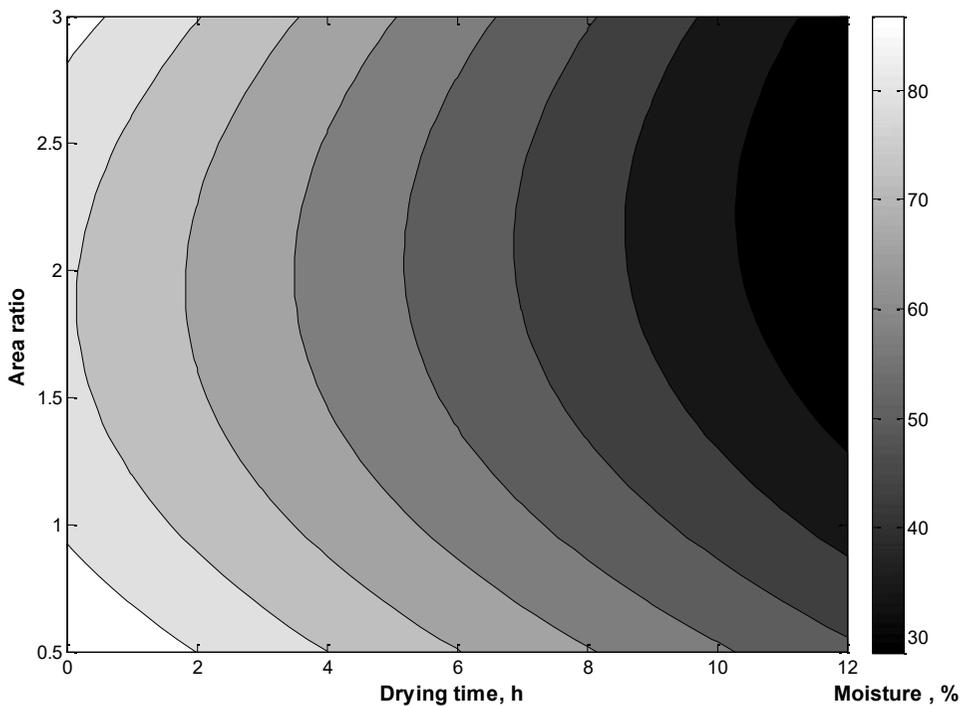

Figure 6. Moisture concentration dependence on the drying time and area ratio.

CONCLUSIONS

Study have shown that, in theoretical description, modelling of the drying process must take into account the dimensional changes in the product itself during the drying process. As the product (carrot cylinder) thickness increases, the effect of its moisture on the thickness changes in the drying process increases: from 3.2 to 5 mm thick to 7.9 to 15 mm thick. Using the obtained results it is possible to determine more precisely the variability of the product's diffusion coefficient, which depends on the moisture content of the product. Since weighing results in a common change in moisture, then the precise study of the diffusion problem requires the effect of the surface of the product on the

drying process, especially if the diffusion in the direction of the fibres (top and bottom) is not the same in the perpendicular direction (side of cylinder).

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