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Fruit Drying Process Investigation in Infrared Film Dryer

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Abstract. The work analyzes three different product (apple slices, banana slices and grape halves) drying process in the infrared film dryer. Such drying takes place at low temperatures (to 40 °C), allowing to keep the maximum value of fresh products. The drying process is analyzed in detail in the first 8 hours. The quantity of water runoff, drying product temperature changes and flowing air humidity changes during drying were analyzed. It demonstrates the impact of the product placement on the drying progress. Using the experimental data, average diffusion coefficients are obtained for each product group. The results showed that diffusion coefficients were changing during the drying process. Using mathematical modelling and experimental data, the concentration-dependent diffusion coefficient for apple slices was obtained. The study finds that apple and banana drying using the infrared film is comparatively successful, but the drying process of the half of grape berry is slower. This can be explained by the impact of grape peel on the water diffusion.

Key words: infrared film, fruits, drying coefficient, model, moisture.

INTRODUCTION

The drying process is the most common process of processing agricultural products, in which heat is transferred from the heated air to the product by convection, and later the evaporated water is also transported to the air by convection. In convective drying, resistances to the heat and mass transfer are in the boundary layer and their magnitude is dependent on the air velocity. On the other hand, resistances to heat and mass transfer in the material during drying are high and strongly affect the kinetics of water evaporation. Convective drying usually requires a great amount of time and causes many undesirable changes in the material (Nowak & Lewicki, 2004).

Infrared drying (IR) is based on the fact that the infrared radiation of certain wavelengths is actively absorbed by water contained in the product, but is not absorbed by tissue of a dried product. That is, unlike all other types of drying, energy is applied directly to the water of the product, and this is achieved by high efficiency and economy. When infrared waves are radiated to the material to be dried, the internal temperature of the particle is increased. The moisture concentration (content) gradient is the driving force for the moisture to transfer towards the sample surface, where it is removed by the surrounding air (Sharma et al., 2005; Abbasi & Mowla, 2008). The depth of penetration depends on the property of the material and wavelength of radiation. When a material is exposed to radiation, it is intensely heated and the temperature gradient in the material reduces within a short period of time. Under this principle, it is not necessary to raise the temperature significantly for product drying, and the evaporation process can be rapidly conducted at a temperature of 40–60 °C, which gives almost complete preserve of vitamins, biologically active substances, natural color, flavor and aroma of the dried products.

When using other methods it is necessary to warm the product up to 100–105 °C, otherwise the drying process will last for 20–30 hours.

Infrared radiation is harmless to the environment and humans, because the main source of infrared rays is the sun, which our ancestors used for drying products for many centuries. Drying of products based on this technology can save the contents of vitamins and other biologically active substances in the dry product at a level of 80–90% from the baseline. The results of infrared drying compared to conventional drying allowed to conclude that this process provides a more uniformly heated product, resulting in better quality characteristics (Hebbar & Rastagi, 2001).

The product quality is also better, particularly in drying of heat sensitive materials (Ginzburg, 1969). IR drying has been the subject of investigations by recent researchers. Paakkonen et al. (1999) have shown that IR drying improves the quality of herbs, Pan et al. (2005), Sharma et al. (2005) studied the quality characteristics and advantages of onion infrared drying with different drying temperatures and inlet air velocities, Prabhanjan et al. (1995) investigated thin layer carrot microwave assisted convective drying, Funebo & Ohlsson (1998) investigated microwave assisted mushroom dehydration and showed a possibility to reduce the drying time. Zbicinski et al. (1992), investigating convective air drying and IR drying, have suggested that the use of an intermittent irradiation drying mode coupled with convective air drying is the best for heat sensitive materials.

The advantages of infrared radiation cover high heat transfer coefficients, short time of drying and easy control of material temperature (Nowak & Lewinski, 2004). In view of these advantages it is likely that IR drying in combination with convection or vacuum will become increasingly popular (Mujumdar, 1995). Jaturonglumlert & Kiatsiriroat (2010) showed that higher mass transfer is obtained with combined convective and far-infrared drying.

Nowadays, many food properties exist, which can help evaluate the quality of dried products, such as the color, texture, flavor, and nutritional content, ability to absorb water, mechanical properties, microstructure and others.

Such material properties as the color, ability to uptake water, and mechanical resistance to breakage are not dependent on the way how the heat is supplied to the material undergoing drying (Kocabiyik & Tezer, 2009). There are two most important parameters: the drying rate and material drying temperature. High drying rate damages tissue and the material becomes fragile (Kocabiyik & Tezer, 2009). During IR drying, the drying rate decreases with the moisture content decreasing and with the infrared power decreasing (Ong & Law, 2011). Drying temperature causes some browning because of chemical changes (Kocabiyik & Tezer, 2009).

For short soaking (15–20 minutes) after infrared drying, the product restores all its natural physical, chemical properties and can be used fresh or subjected to any type of cooking. Infrared ray dried products at low ambient humidity can be stored without special packaging. Even in such conditions of storage the products will lose 10–15% of vitamins.

Recently numerous researches in the infrared drying use for individual products have been carried out. Nowak & Lewicki (2004), Slegun & Popa (2009) studied apple slice drying, Renata C. dos Reis et al. (2012) investigated the temperature effects on basil leaves in the IR drying process. Chua and Chou (2005) investigated potato and carrot IR drying.

The present paper has two specific objectives. Firstly, to examine the IR film drying possibilities with small heating up to 40 °C. Most of the researchers use IR drying temperature from 60 to 90 °C. Secondly, to investigate and compare three different products: apple slices, banana slices and grape halves.

MATERIALS AND METHODS

The experiment was carried out at the Grain Drying and Storage Scientific Laboratory at the Latvia University of Agriculture.

Equipment and materials

The infrared (IR) dryer (Fig. 1) consisted of a drying chamber (80 x 50 x 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 maximum heating of this film is not more than 40–45 °C. The IR film power is 140 W m^{-2}.

Figure 1. IR dryer in practice.

Figure 2. Samples at the beginning of the drying experiment.

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 peephole is located on the bottom of the opposite side wall, Fig. 3.

The apples and bananas were cut into 1 cm thick slices and the grapes were cut in halves, Fig. 2. The samples were placed on a round drying tray (diameter 20 cm) which consisted of a fine mesh aluminum screen with a plastic frame. These sample plates were put on the drying chamber trays. The trays were placed 10 cm from the IR film on the top and bottom, the distance between the trays was 10 cm, Fig. 3.

The moisture content in the material was identified by gravimetric measurement in time intervals. The samples were weighed on the digital laboratory balance

KERN-440-35N with maximum load weight 400 g and with resolution 0.01 g. The total drying time was adapted to the need for determination of the final moisture content.

The average inlet air temperature during the experiment was 18.8 °C with standard division 0.6 °C. The dry matter is determined by laboratory equipment Memmert, drying the product at 102 °C to constant weight of the product.

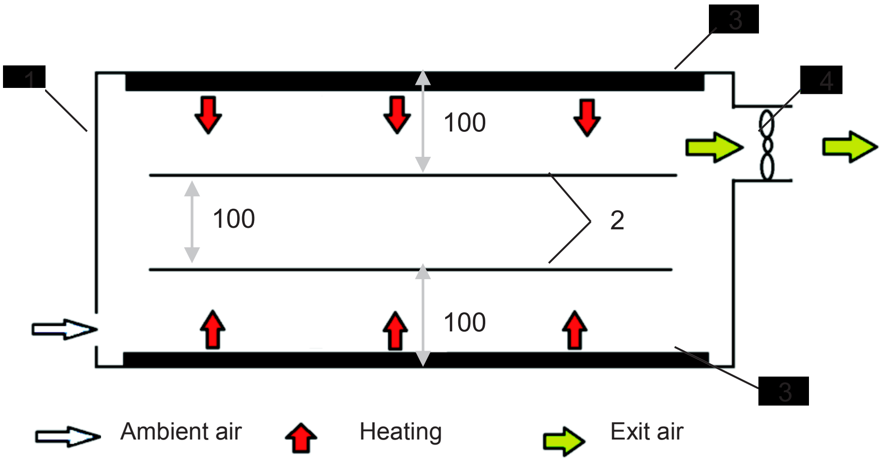

Figure 3. Schematic view of IR dryer: 1 – Body of dryer; 2 – Trays; 3 – IR drying film; 4 – Fan.

Mathematical model

In order to determine the effective moisture diffusion, we use the mass maintenance law usually presented in the following form:

$$\frac{\partial \tilde{c}}{\partial t} = div(D\, grad\, \tilde{c}) \qquad (1)$$

D – coefficient of diffusion; $\tilde{c}(x,y,z,t)$ – concentration of moisture in sample; x,y,z – space coordinates; t – time.

Since the surface of apple and banana slices on the top and bottomis greater than on the sides, the overal diffusion of vapours on the top and the bottom is greater than on the side, and we can choose 1-dimentional model with D_x (diffusion in a plane sheet $\tilde{c}(x,y,z,t) \approx c(x,t)$).

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D_x \frac{\partial c}{\partial x}\right] \qquad (2)$$

We have a case, where diffusion occurs through all surfaces of the samples, and we assume that the diffusion coefficient D_x is constant. At the moment $t = 0$, concentration of moisture in the samples is constant, c_s. The water vapour concentration on the surfaces is constant, $c(x,t)$ =0. The diffusion process in our case can be considered as a symmetrical situation, and we get a mathematical problem:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} \qquad -l < x < l\,, \quad t > 0 \qquad (3)$$

$$c\big|_{t=0} = c_s \qquad (4)$$

$$c\big|_{x=-l} = c\big|_{x=l} = 0\,, \qquad (5)$$

where *2l* – sample thickness in x direction.

The problem (3) – (5) with $D_x = const$ solution is (Crank, 1956):

$$c(x,t) = \frac{4c_s}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cdot e^{-\frac{D_x (2n+1)^2 \pi^2 \cdot t}{4l^2}} \cdot \cos \frac{(2n+1)\pi \cdot x}{2l} \qquad (6)$$

If M_t denotes the amount of diffusing moisture which has come out from the material at time t, and M_∞ the corresponding quantity after infinite time, then (Crank, 1956):

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \cdot e^{-\frac{D_x (2n+1)^2 \pi^2 \cdot t}{4l^2}} \qquad (7)$$

At first we must estimate D_x. Looking at the series (7), we see that itconvergesvery fastand that is whywe chooseonly the firstmember of theseries and expression (7) becomes

$$\frac{8}{\pi^2} \cdot e^{-\frac{D_x \cdot \pi^2 \cdot t}{4l^2}} = 1 - \frac{M_t}{M_\infty} \qquad (8)$$

The right-hand side of the equation (8) is known (experimental data at time $t = t_i$), and the coefficient of diffusion can be expressed:

$$D_x = -\frac{4l^2 \ln\left(\frac{\pi^2 (M_\infty - M_t)}{8 \cdot M_\infty}\right)}{\pi^2 \cdot t} \qquad (9)$$

We can calculate D_x^i for each experimental measurement at time t_i from (9) and find $D_x = const$ as

$$D_x = \tfrac{1}{k} \sum_{i=1}^{k} D_x^i\,,$$

where k – number of measurements.

If D_x depends on the drying time $D_x = D_x(t)$, we can use the methodology, see (Aboltins, 2013) and find the expression of $D_x(t)$. For solving (2),(4),(5) $D_x(t)$, we can use difference schemes (Samarskii, 1988).

RESULTS AND DISCUSSION

The moisture removal dynamics shows that the grape half drying rate is less than the drying rate of the apple and banana slices, Fig. 4.

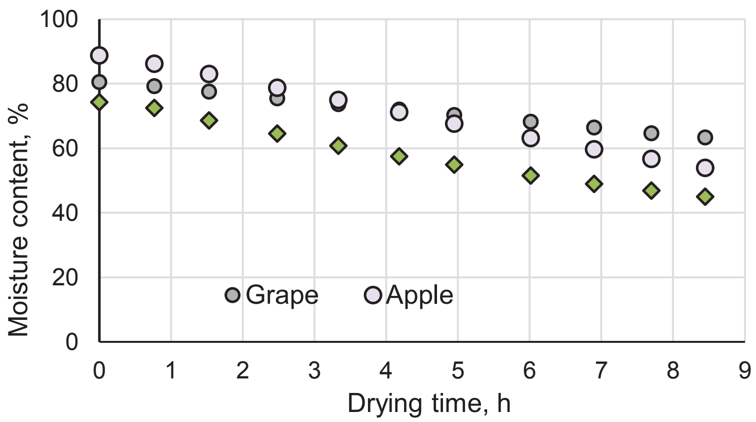

Figure 4. Moisture changes of fruit samples by forced convection in IR film dryer.

This can be explained by the fact that the grape peel has significant impact on decreasing the drying speed. Grape mostly dries from the cut part.

Temperature and humidity fluctuations are observed at the beginning of the drying process.

For banana samples, fluctuations are shown in Fig. 5.

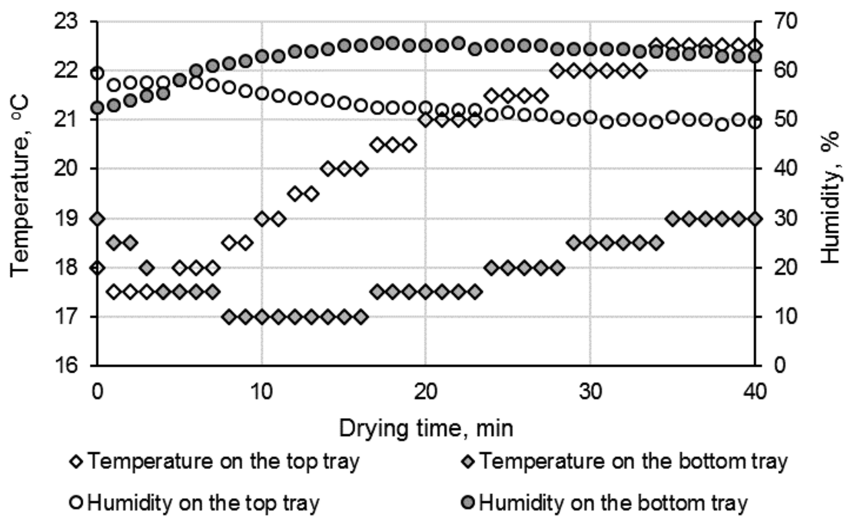

Figure 5. Banana sample temperature and humidity changes on top and bottom trays at the first 40 min of drying.

These fluctuations can be explained by moisture removal from the sample surface. It is happening faster on the upper tray because there IR rays directly affect the samples. IR rays interfere with the tray base on which the samples are placed on the bottom. Air humidity on the top tray is lower due to the faster output by the help of the fan, and the sample temperature is higher. These differences decrease during drying.

Similar situation is observed in all samples. After the first 15 minutes the wet is removed from the boundary layer and the temperature begins to rise steadily. This indicates that there is moisture diffusion of the sample inside.

Using the experimental data and (9) average diffusion coefficients for the viewed fruit samples were calculated (Table 1).

Table 1. Average diffusion coefficients of samples

Fruit samples	Average diffusion coefficient, $m^2\ s^{-1}$	Standard deviation, $m^2\ s^{-1}$
Apple slices	2.04E-10	1.17E-10
Banana slices	2.10E-10	9.11E-11
Grape halves	1.56E-10	1.05E-10

The results show that the diffusion coefficients of the apple and banana slices are practically the same, but for the grape halves they are remarkably lower (Table 1).This can be explained by the consistency of the samples and grape peel effect on the drying process. The processed results of the high standard deviation value indicate that the diffusion coefficient is variable depending on the drying time or the moisture content of the sample. Using the proposed methodology (Aboltins, 2013), we can calculate the changing drying coefficient $K(t)$ depending on the drying time t at constant drying conditions.

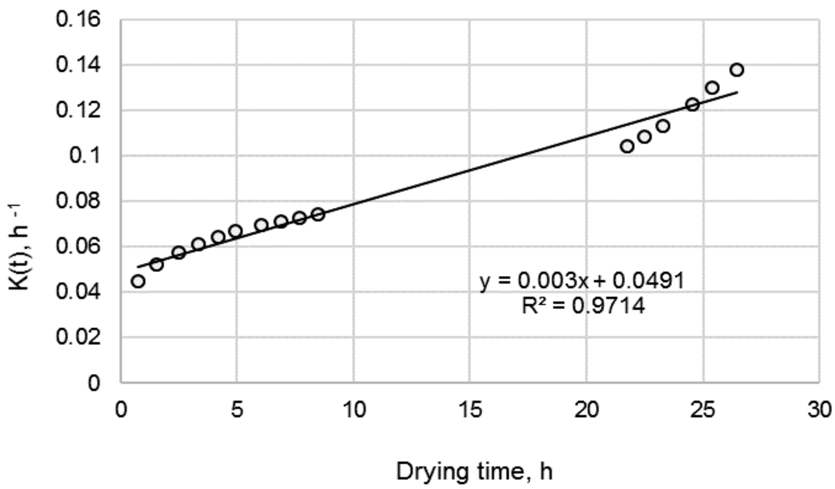

Figure 6. Drying coefficient determination of apple slice drying in IR film dryer.

The drying coefficient of apple slices was $K(t) = 0.003 \cdot t + 0.0491$ with the determination coefficient R^2=0.97 (Fig. 6), where t – drying time, h.

We can calculate D_x^i for each experimental measurement at time t_i from (9) and find $D_x^i = D_x(t_i)$. Eatch time moment t_i corresponds to the product concentration c_i, and we can get $D_x^i = D_x(c_i)$. Using data processing, it is possible to obtain the changing diffusion coefficient D(c) (Fig. 7).

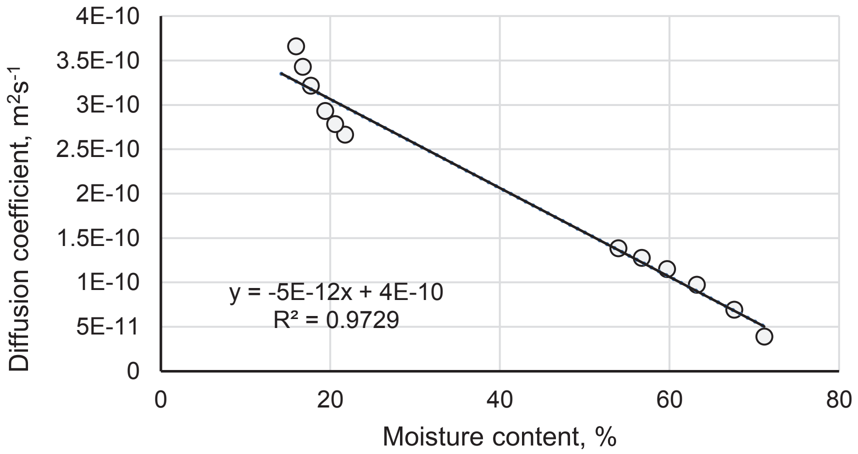

Figure 7. Diffusion coefficient determination of apple slice drying in IR film dryer.

Using the experimental results of apple slice drying in the IR film dryer, we determined the expression of the diffusion coefficient depending on the moisture concentration c:

$$D(c) = -5 \cdot 10^{-12} \cdot c + 4 \cdot 10^{-10}$$

It is possible to use difference schemes (Samarskii, 1988) for solving the problem (2), (4), (5) with the changing diffusion coefficient $D(c)$.

CONCLUSIONS

The study finds that apple and banana slice drying using the IR film is comparatively successful, but the drying process of the half of grape berry is slower. The average diffusion coefficient of the grape halves is 25% lower than for the apple and banana slices. This can be explained by the impact of grape peel on the water diffusion.

The experimental data processing showed that the diffusion coefficients are changing during the drying process. The proposed methodology allows calculating the diffusion coefficient depending on the concentration.

In order to ensure suitable moisture for drying products with economic benefits, optimization of the drying time is necessary and should be respected.

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