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Infrared drying of apple slices

Summary

The aim of this work was to study the infrared (IR) drying of apple slices. In present article are investigated the effects of blanching, of air velocity and of different air temperatures on the drying time and on the rehydration ratio as a quality property. In the article a simultaneous heat and mass transfer model is presented that calculates the rate of moisture vaporization with the approximation about 13.8% in average. The food materials slices were dried by near infrared (NIR) heating by the natural convection and also by the forced convection with air velocities 0.25 and 0.5 m·s⁻¹ and at different air temperatures 23 and 28°C. NIR drying presents good results for dehydration of thick materials that is needed for better preservation of food quality. The qualities of dried slices were compared by a rehydration ratio because of its relation to the dependence of degree and of rehydration duration on the initial properties of raw materials, on the accuracy of the drying process, and on the storage conditions. The test of the effect of blanching confirms that the drying time of blanched apple slices is much shorter than for unblanched raw materials slices. Decrease of air velocity reduces the drying time. The lower air temperature makes the duration of drying longer. The rehydration ratio was found higher for blanched dried samples.

Key words: *drying, infrared, vaporization, blanching, rehydration*

Suszenie plastrów jabłka promieniami podczerwonymi

Streszczenie

Celem pracy było przeprowadzenie badań dotyczących suszenia plastrów jabłka promieniami podczerwieni (IR). W artykule przedstawione zostały badania dotyczące wpływu blanszowania, prędkości przepływu powietrza i różnych temperatur powietrza na czas suszenia i stopień dehydratacji. W artykule zaprezentowano model jednoczesnego ogrzewania i przenikania masy, który wskazuje szybkość parowania wilgoci ze średnią aproksymacją 13,8%. Plastry jabłka suszono przy użyciu promieni podczerwonych (NIR) przy naturalnej konwekcji, a także przy konwekcji wymuszonej, z prędkością przepływu powietrza rzędu 0,25 i 0,5 m·s⁻¹ i w dwóch różnych temperaturach – 23 i 28°C. Suszenie metodą NIR wykazuje korzystne rezultaty odnośnie odwadniania materiałów o większej grubości, gdzie wymagane jest zachowanie wyższej jakości żywności. Jakość suszonych plastrów jabłka została oceniona na podstawie porównania współczynnika rehydratacji, zależnego od jego stopnia i czasu trwania rehydratacji, do początkowych właściwości surowego materiału, a także na podstawie oceny dokładności procesu suszenia i warunków przechowywania. Badania dotyczące określenia wpływu procesu blanszowania potwierdzają, że czas suszenia blanszowanych plastrów jabłka jest znacznie krótszy w porównaniu do czasu suszenia nieblanszowanych plastrów jabłka. Obniżenie prędkości przepływu powietrza zmniejsza czas procesu suszenia. Niższa temperatura powietrza wydłuża proces suszenia. Stwierdzono, że współczynnik rehydratacji był wyższy w przypadku suszenia uprzednio blanszowanych prób.

Słowa kluczowe: *suszenie, promieniowanie podczerwone, parowanie, blanszowanie, rehydratacja*

Nomenclature:

A – absorptivity,
$C_{m,v}$ – coefficient of relative emittence,
C_0 – emittence of black body, $C_0 = 5.67\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$,
D – diameter of sample, $D = 0.025$ m,
$F_{m,v}$ – view factor (sometimes called a configuration factor), $F_{m,v} = 1$,
H – thickness of the sample, $H = 0.007$ m,
K – rehydration ratio ,
m_d – weight of dried apple slice, [g],
m_i – weight of rehydrated apple slice, [g],
n_w – rate of moisture vaporization by calculation, [$\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$],
$n_{w\ ex}$ – rate of moisture vaporization by calculation experimental data, [$\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$],
Q_A – absorbed heat flow, [W],
Q_{cond} – conducted heat flow, [W],
Q_{conv} – heat flow by convection, [W],
Q_{evap} – evaporated heat flow, [W],
Q_E – emitted heat flow, [W],
q – density of radiation of emitter, $q = 5000\ \mathrm{W \cdot m^{-2}}$,
r_w – heat of vaporization, $r_w = 2383\ \mathrm{kJ \cdot kg^{-1}}$,
S_{hor} – area of horizontal surface, [$\mathrm{m^2}$],
S_{vert} – area of vertical surface, [$\mathrm{m^2}$],
$S_\perp$ – area of sample surface perpendicular to radiation direction, $S_\perp = 0.491 \cdot 10^{-3}\ \mathrm{m^2}$,
S – area of sample surface, $S = 1.53 \cdot 10^{-3}\ \mathrm{m^2}$,
T_a – air temperature, [K],
T_m – material temperature, [K],
T_{m1} – temperature of upper surface of sample, [K],
T_{m2} – temperature of bottom surface of sample, [K],
V – air velocity, [$\mathrm{m \cdot s^{-1}}$],
Δ – deviation of n_w from $n_{w\ ex}$, [%],
$\Delta\tau$ – duration of drying section, [min],
α^C – convective heat transfer coefficient, [$\mathrm{W \cdot m^{-2}\,K^{-1}}$],
α^E – radiative heat transfer coefficient, [$\mathrm{W \cdot m^{-2}\,K^{-1}}$],
ε – emissivity,
λ' – thermal conductivity of the air, $\lambda' = 0.027\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$,
λ'' – thermal conductivity of the sample, $\lambda'' = 0.42\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$,
ξ – temperature coefficient of radiation, [$\mathrm{K^3}$],
τ – time, [min].

Introduction

Drying is probably the oldest method of food preservation and it is one of the most common processes used to improve food stability, since it decreases the water activity of the product, reduces microbiological activity and minimizes physical and chemical changes during storage (Mayor, Sereno 2004). Apart from conservation of nutrients, vitamins and minerals, this method allows serious minimization of costs of transportation and storage.

Infrared drying is an effective method of dehydration. IR radiation energy is transferred from the heating element to the product surface without heating the surrounding air. The radiation impinges on the exposed material and penetrates it and then is converted to sensible heat (Ginzburg 1969). During the drying the absorptivity of the dried material decreases and its reflectivity and transmisivity increases, because of water content decreases in it. The absorptivity, the skin depth and the transmisivity are dependent on the density and on the wavelength of IR heating and on the properties of irradiated materials.

Advantages of infrared radiation cover high heat transfer coefficients, short time of drying and easy control of material temperature (Nowak, Lewicki 2004). In view of this advantages it is likely that IR drying in combination with convection or vacuum will become increasingly popular (Ratti, Mujumdar 1995).

Drying kinetics depends on the density and on the wavelength of radiation, on the distance between infrared energy emitters and the heat–irradiated surface, and on the air velocity. Generally, the drying rate increases with material temperature increasing and relative humidity of the drying medium decreasing. However, the drying temperature should not be too high, because it could cause thermal degradation of heat–labile phytochemicals (Rieger, Šesták 1993). Decrease of sizes of dried materials also reduces the duration of drying.

Usually, raw fruits and vegetables are blanched before drying. Blanching is a short–term heat treatment of raw materials that main goal is: inactivation of enzymes and improving the microbiological purity of products (Kiseljova 2007).

In the past drying was performed with less emphasis on quality of dried products but at present the quality attributes become much more important. Quality includes safety of dried–food and its sensory properties (Rahman 2005). Nowadays many food properties exist, which can help to evaluate the quality of dried products, such as color, texture, flavor, nutritional content, ability of water absorption, mechanical properties, microstructure and others.

Such material properties as 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 most important two variables: the rate of drying and material final temperature. High drying rate damages tissue and the material becomes fragile (Kocabiyik, Tezer 2009). During the IR drying, the drying rate decreases with the moisture content decreasing and with the infrared power decreasing (Ong, Law 2011). Material temperature, especially at the final stages of the drying, causes some browning because of chemical changes (Kocabiyik, Tezer 2009).

At present there is a need for developing low–cost, simple and accurate measurement techniques for industrial use for evaluation of product quality, and for control of drying process efficiency (Rahman 2005). As such circumstances a rehydration ratio could be measured in relation to the dependence of degree and of rehydration duration on the properties of raw materials, on the accuracy of the drying process, and on the storage conditions (Kiseljova 2007).

The aim of this work was to study the effects of blanching, of air velocity and air temperature on drying time and on rehydration property infrared dried apple slices. Also it was planned to investigate the rate of moisture vaporization.

Materials and methods: experimental drying device

The infrared–convective experimental drying device was designed especially for the study of IR drying of food materials wherein radiant flux density and air velocity could be varied within the experimental range. A schematic view of the experimental drying device is shown in figure 1. It comprises of two main components: an IR glass lamp (Philips) with power 175 W, emitting radiation with peak wavelength 1 µm, and a rotating disk covered with aluminum foil whereon there are vertically fixed the small wooden needles for fixing the dried samples on them. The rotating disk was placed on the engine with final speed 80 revolutions per minute. The drive is stationed on the scale measuring a samples weigh during drying.

The radiant flux density could be varied by regulating a distance from infrared glass lamp to the dried slices. The wavelength peak was regulated by a transformer.

The needed air velocity is possible to set by changing slices location radius on the rotating disk. In such a way, the rotated samples were blasted by dried air. The air velocity could be varied especially in range from 0 to 0.5 $m \cdot s^{-1}$. During experiments was used also the moisture analyzer Sartorius MA35 for determination of the initial moisture contents of dried materials. The temperature was measured by infrared thermometer Fluke 568 that accuracy is ±0.1°C. The accuracy of the scale was ±0.001 g.

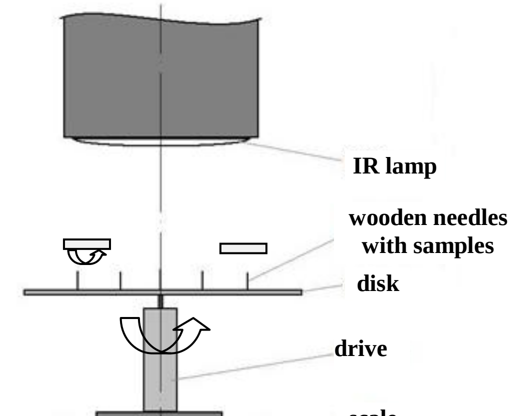

Fig. 1. Schematic view of the experimental drying device

Rys. 1. Schemat urządzenia służącego do przeprowadzania doświadczania związanego z procesem suszenia

Experimental procedures

In the present study were used apples Gala. The initial moisture contents of the blanched and unblanched apple slices were accordingly 87 and 85 (% of mass) respectively.

Apples were washed and cut into slices of thickness 7 mm with a diameter of 25 mm. Some of apple samples were labeled with one or two different color cottons along needles. A part of slices were not pretreated before drying, others were blanched in boiled water at temperature 97 – 98°C during 20 – 30 seconds to avoid enzymatic browning and after that superfluous water was removed from samples surfaces by a filter paper. The duration of blanching of different food materials depends on the degree of enzyme inactivation (peroxidase, polyphenoloxidase, catalase). The weight of each sample was determined before drying, or before and after blanching according the goal of the experiment. After these procedures slices were fixed on the wooden needles of rotating disk for drying. The radius of samples location was chosen according to the needed air velocity.

Drying was done with or without preliminary blanching at the density of radiation approximately 5000 $W \cdot m^{-2}$, wavelength peak 1 μm, and at the distance between the emitter and dried product 100 mm. The air velocities were 0; 0.25 and 0.5 $m \cdot s^{-1}$. The air temperatures were 23 and 28°C for every air velocities.

Rehydration experiments for the dehydrated apple slices were executed by immersing of dried samples into distilled water. It comprised of two stages. The blanched and unblanched samples were dried at air velocity 0.5 $m \cdot s^{-1}$ and then were rehydrated in distilled water at 80°C for 2 hours and 15 minutes. Partially rehydrated apple samples were gently get out in each 15 minutes during the test and were weighed after removing of superfluous moisture from the surfaces by filter paper. The rehydration ratio was estimated from the ratio of weight of rehydrated sample m_i to weight of dried sample m_d (1) (Kiseljova 2007; Sharma et al. 2005).

$$K = \frac{m_i}{m_d} \tag{1}$$

In the second rehydration test the apple samples were left in the same water for 24 hours at room temperature. By this way the maximum of water uptake ability for each sample was determined.

Each experiment has done 2 – 3 times or more if was needed.

Mathematical modeling of drying process and the rate of moisture vaporization

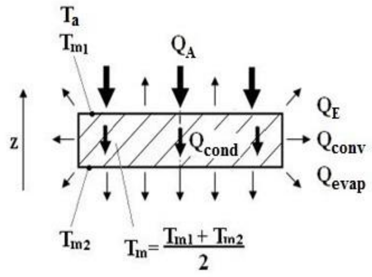

Fig. 2. Distribution of the absorbed heat flow

Rys. 2. Rozkład absorbowanego przepływu ciepła

During the infrared–convective drying of the apple slices simultaneously occur:

· a heat absorption by the dried material by the transformation of IR radiation into sensible heat;

· a heat transfer from the slices to the surrounding environment;

· a mass transfer from the slices to the surrounding air.

The developed mathematical model of the IR–convective drying process, which is presented schematically in figure 2, is based on the following assumptions:

1. The slice of dried material is considered as the partially transparent particle in which the heat conduction is one–dimensional;
2. The volumetric absorption of IR radiation within the slice is neglected because of unification of the absorption micro–areas in one total area $S_{\perp}$ that is perpendicular to radiation direction;
3. The air between the product and IR emitters is completely transparent to radiation because of the poor content of water vapor that absorbs IR radiation;
4. The radiation (heat) that is emitted by the dried product is absolutely absorbed by surrounding environment;
5. The mass transfer is one–dimensional (from dried slices to air) and is governed by diffusion. Moisture evaporation takes place at the whole external surface of the material and is dependent on the moisture content of sample, on the absorption of IR heat and on the convection properties between the product and surrounding environment;
6. The distributions of moisture content and temperature within slice are uniform;
7. The velocity of drying air is constant and its distribution is uniform;
8. The dried samples are shrinking particles;
9. Heat transfer between the dried particles (and possible contact diffusion) is negligible.

All these assumptions were met. The drying velocity during these tests, was not constant in all places of dried samples but for simplicity of our calculations we used the mean velocity. The difference between samples velocities on internal and external radiuses is not too high. For example about 70% of all sample surfaces had the velocity differences in the range ±0.05 $m \cdot s^{-1}$. But the samples rotated during the drying. Therefore all parts had the same drying conditions.

Experimental data for this model are: sample diameter D, thickness of sample H, surrounding air temperature T_a, sample upper surface temperature T_{m1}, sample bottom surface temperature T_{m2}, weight of dried sample m_d, and time τ. All data are changeable during the experiment but to simplify the calculation T_a is constant.

The energy balance equation of the process of infrared–convective drying, which is written according to the energy conservation law by schematic view of the absorbed heat flow distribution on figure 2, has the following form (2),

$$Q_A = Q_E + Q_{conv} + Q_{cond} + Q_{evap} \tag{2}$$

or in more detailed form (3),

$$A\,q_{ray}S_{\perp} = \alpha^{E}F_{m,v}(T_m - T_a)S + (\alpha^{c\prime}S_{hor} + \alpha^{c\prime\prime}S_{vert})(T_m - T_v) + \\ + \frac{\lambda^{\prime\prime}}{H}(T_{m1} - T_{m2})S_{\perp} + n_w r_w S\,, \qquad (3)$$

where a view factor (sometimes called a configuration factor) $F_{m,v}$ = 1, because we determine the heat flow by radiation provided that the sample is completely surrounded by the environment with a temperature equal to the ambient air temperature.

The radiative heat transfer coefficient α^E could be calculated by the equation (4) (Hemzal 2007).

$$\alpha^{E} = C_{m,v}\,\xi = \varepsilon C_0 \frac{\left(\frac{T_m}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4}{(T_m - T_a)} \qquad (4)$$

The convective heat transfer coefficient α^C could be determined for both horizontal and vertical surfaces separately by means of the appropriate criterial correlations for Nusselt criterion (Rieger, Šesták 1993; Lin et al. 2009; Hemzal 2007).

According to the equations 2 and 3, the rate of moisture vaporization n_w [kg·m^{-2}·s^{-1}] is equal to (5).

$$n_w = \frac{Q_{evap}}{r_w S} = \frac{Q_A - Q_E - Q_{conv} - Q_{cond}}{r_w S} \qquad (5)$$

Based on the drying experiments of apple slices the average rate of moisture vaporization was determined by the equation (6).

$$n_{w\,ex} = \frac{m_{d1} - m_{d2}}{60\,\Delta\tau\,S} \qquad (6)$$

The deviation of the calculated average rate of moisture vaporization from the experimentally determined average rate of moisture vaporization could be defined according to the equation (7).

$$\Delta = \frac{n_w - n_{w\,ex}}{n_w} \cdot 100\ \% \qquad (7)$$

Results and discussion: effect of blanching

NIR drying of blanched and unblanched apple slices was done at the density of radiation approximately 5000 W·m^{-2}, at wavelength peak of 1 μm, at air temperature 23°C and air velocity 0.5 m·s^{-1}. The distance between emitter and dried products was 100 mm. The drying curves are shown in figure 3. The drying curves are typical ones for similar fruits and vegetables. The moisture content decreased exponentially with elapsed duration of drying.

The moisture content of slices a little increased during blanching procedure because of taking water but the drying duration of blanched samples was shorter by 74 minutes in case of 10% final moisture content. That is caused by changes in the structure, in the chemical composition and in the colloidal properties. It could be considered that drying of the blanched apple slices is more effective and more practical.

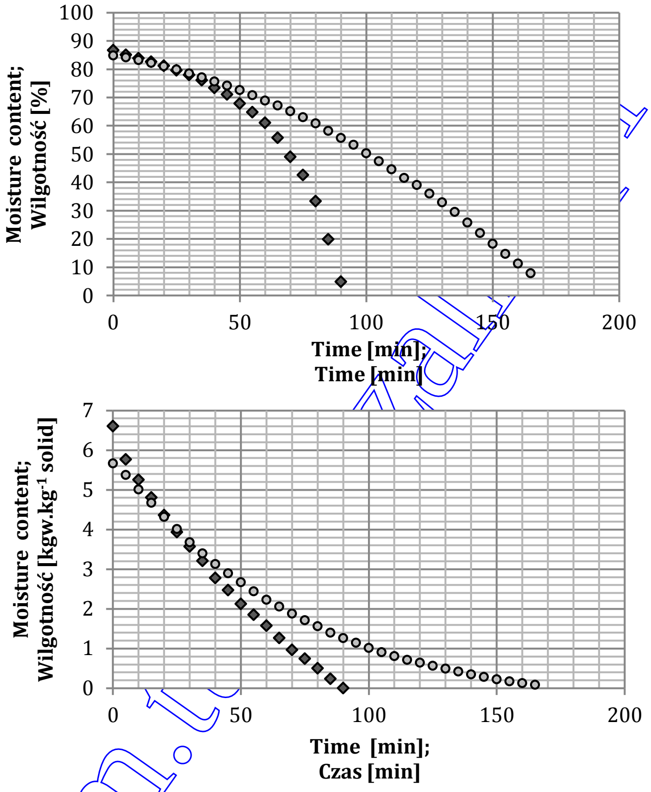

Fig. 3. Drying curves of blanched ◆ *and unblanched* ● *apple slices (q_{ray} = 5000 W·m^{-2}, λ = 1 μm, l = 100 mm, v = 0.5 m·s^{-1})*

Rys. 3. Krzywe suszenia blanszowanych ◆ *i nieblanszowanych* ● *plastrów jabłka (q_{ray} = 5000 W·m^{-2}, λ = 1 μm, l = 100 mm, v = 0,5 m·s^{-1})*

Effects of air velocity and of air temperature

The data of loss of the moisture content with elapsed duration of drying were analyzed to study the effect of different air velocities and different air temperatures for apple slices. There were executed under either the natural or the forced convection with air velocity 0.25 m·s^{-1}. The air temperatures were about 23 and 28°C during experiments.

The air velocity influences the drying duration of apple slices as shown in figure 4. The decrease of drying air velocity reduces the drying duration in case of infrared drying (also see Nowak, Lewicki 2004). That means that at the natural convection (v = 0 m·s^{-1}), because of lower cooling effect on the dried material surface, the time needed for drying is shorter then in case of forced convection. The difference was about 13 min in case of 20% final moisture content.

In a similar way the lower air temperature causes the higher heat transfer from dried sample but also causes the lower mass transfer from apple slices to surrounding environment, and that makes the duration of drying longer. At air temperatures 23 and 28°C the difference was 15 minutes for approximately 17% final moisture content (Fig. 5). The higher heat transfer is caused by higher difference between material and surrounding air in case of 23°C then in case of 28°C. This is also confirmed by equation 3. The lower mass transfer should be caused by influence of cooling effect on the surface of dried material.

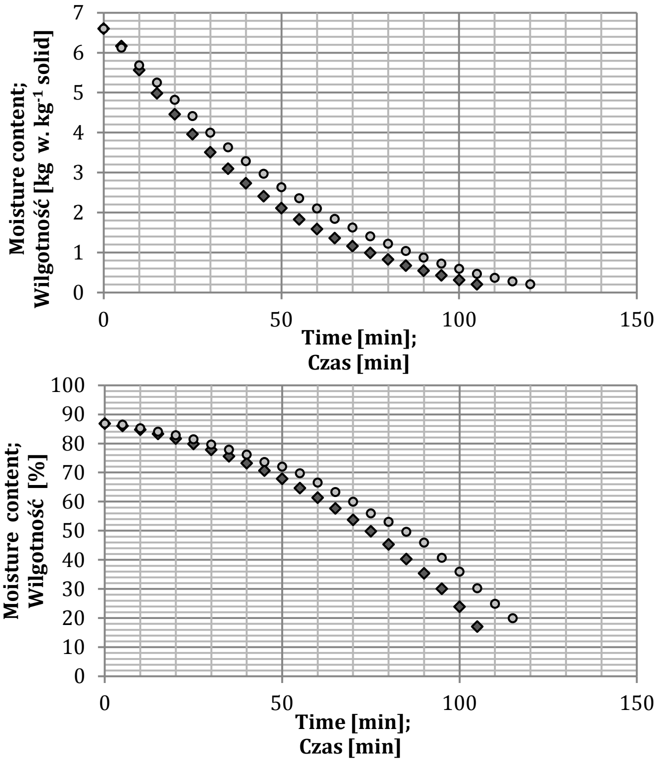

Fig. 4. Drying curves of blanched apple slices at different air velocities: ◆ 0 m·s^{-1}; ● 0.25 m·s^{-1} (q_{ray} = 5000 W·m^{-2}, λ = 1 μm, l = 100·mm, T_a = 301 K)

Rys. 4. Krzywe suszenia blanszowanych plastrów jabłka w zależności od prędkości przepływu powietrza: ◆ 0 m·s^{-1}; ● 0,25 m·s^{-1} (q_{ray} = 5000 W·m^{-2}, λ = 1 μm, l = 100·mm, T_a = 301 K)

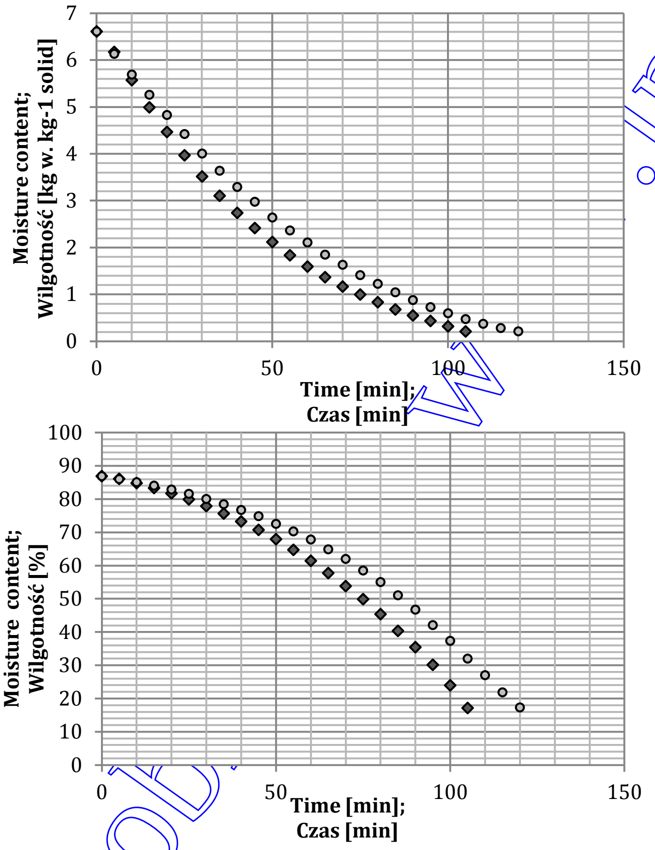

Fig. 5. Drying curves of blanched apple slices at different air temperatures:

◆28°C; ● 23°C (q_{ray} = 5000 W·m^{-2}, λ = 1 μm, l = 100 mm, v = 0 m·s^{-1})

Rys. 5. Krzywe suszenia blanszowanych plastrów jabłka w zależności od różnych temperatur powietrza: ◆28°C; ● 23°C (q_{ray} = 5000 W·m^{-2}, λ = 1 μm, l = 100 mm, v = 0 m·s^{-1})

Rehydration ratio

The rehydration ratio was considered for the dried apple slices as one of the important quality attribute. The rehydration ratio values of dried samples were estimated as it was described in earlier section (see equation 1). Relationship between the rehydration ratio and the rehydration duration of blanched and unblanched dried slices is presented on figure 6.

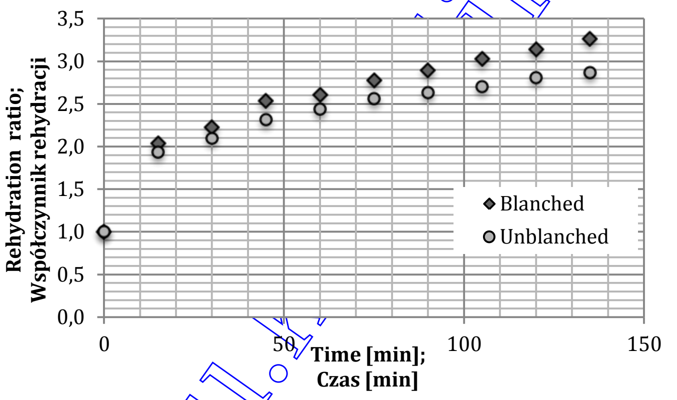

Fig. 6. Relationship between the rehydration ratio and the duration of rehydration of blanched and unblanched dried apple slices (for the range 0 – 135 minutes)

Rys. 6. Zależność pomiędzy współczynnikiem rehydratacji, a czasem trwania rehydratacji blanszowanych i nieblanszowanych suszonych plastrów jabłka (dla zakresu 0 – 135 minut)

The maximum of water uptake ability (after 24 hours rehydration) was for blanched dried samples 3.96 and for unblanched dried slices 3.46 on the average.

The degree of restoration during rehydration is dependent on different drying conditions and on the final moisture content. At the beginning the rehydration rate was much faster for the samples that had lower final moisture content as is shown on figure 7.

The rehydration degree of unblanched dried samples was lower than for blanched apple slices.

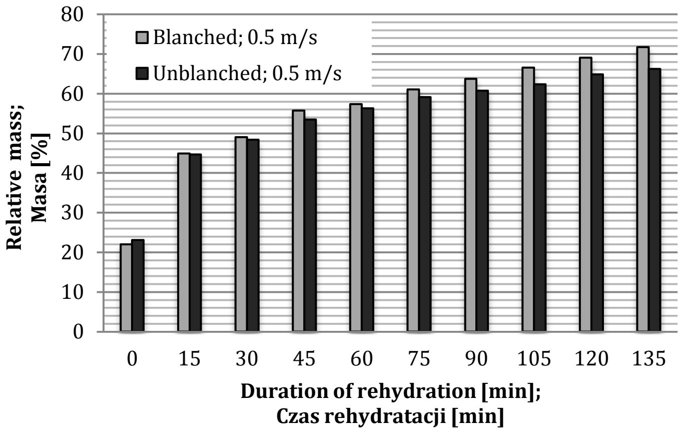

Fig. 7. Influence of the different drying conditions and the final moisture content on the ability of restoration of apple slices

Rys. 7. Wpływ różnych warunków suszenia i końcowej wilgotności na zdolność przywrócenia plastrów jabłka

Rate of moisture vaporization

The rates of moisture vaporization by calculation and by experimental data (Fig. 8.) were determined according to the equations 5 and 6.

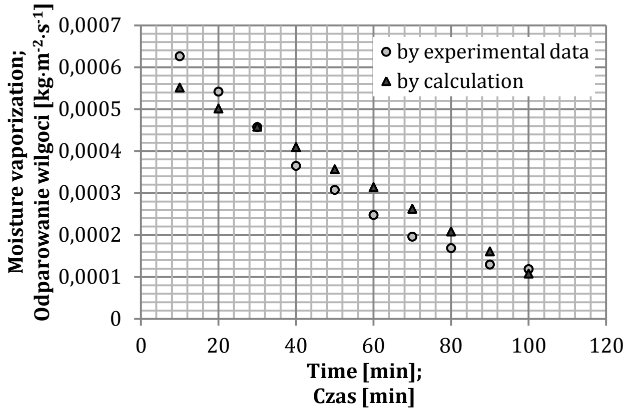

Fig. 8. The rate of moisture vaporization by calculation and by experimental data

Rys. 8. Szybkość parowania wilgoci uzyskana na podstawie danych teoretycznych i danych doświadczalnych

Experimental data are particularly given in nomenclature and part of them is presented in table 1 and on figure 9 and 10.

Table 1. Some experimental data and the deviations of moisture vaporization

Tabela 1. Dane doświadczalne i odchylenia parowania wilgoci

	$T_m=(T_{m1}+T_{m2})/2$ (K)	**$\Delta T_m=T_m-T_a$**	$\Delta = \frac{n_{w\,ex}-n_w}{n_{w\,ex}} \cdot 100\ \%$
0	301	0	–
10	312.6	11.6	11.93
20	318	17	7.42
30	321.25	20.25	0.18
40	324.23	23.23	10.94
50	328.1	27.1	13.77
60	331.8	30.8	21.11
70	336	35	25.37
80	340.1	39.1	19.02
90	344.5	43.5	19.05
100	350.3	49.3	8.93

The average rate of moisture vaporization $n_{w\,ex}$ (kg·m^{-2}·s^{-1}) was defined for every 10 minutes sections from 6 to 105 minutes of IR drying experiment, that data are shown by figure 9.

The changes of sample diameter D and thickness H was determined experimentally too.

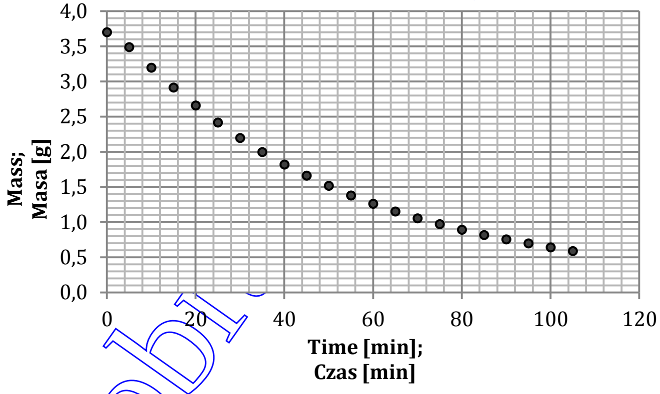

Fig. 9. Drying curve of an apple sample with the initial weight 3.7 g and the final moisture content 17.1%

Rys. 9. Krzywa suszenia próbki jabłka z początkową masą 3,7 g i końcową wilgotnością rzędu 17,1%

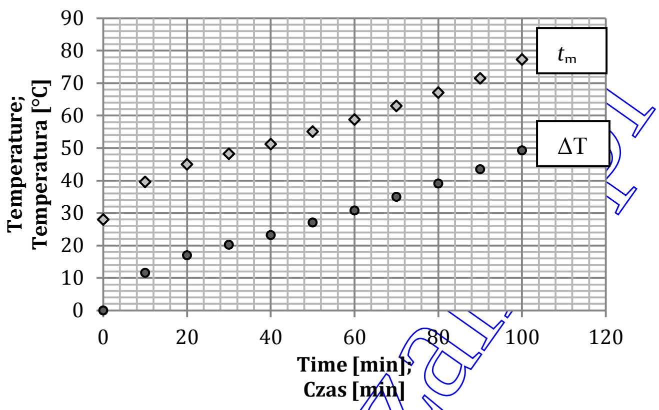

Fig. 10. Average material temperatures and temperature differences between air and material

Rys. 10. Średnie temperatury materiału i różnice temperatur pomiędzy powietrzem i materiałem

The deviations of the calculated average rate of moisture vaporization from the experimentally determined average rate of moisture vaporization were established according to the equation 7 and are presented in table 1.

The deviation of the calculated average rate of moisture vaporization from the experimentally determined average rate according to equation 7 is shown in table 1. Certain deviation of the calculated data (defined by equation 5) from the experimental ones (defined by equation 6) could be explained by the complexity of determining the exact values of the radiation density of the IR lamp (due to uneven distribution of the radiation on the irradiated surface), of the absorptivity and of the samples sizes (because they are constantly changeable). Therefore in all cases it is better to calculate the rate of moisture vaporization in successively small sections of drying.

Conclusions

The infrared–convective drying of apple slices is quite effective. The test of the effect of blanching confirms that the drying time of blanched apple slices is much shorter than for unblanched raw materials slices. Decrease of air velocity reduces the drying time. The lower air temperature makes the duration of drying longer.

The rehydration ratio was found higher for blanched dried samples. The maximum of water uptake ability was 3.96 for blanched apple samples and it was equal to 3.46 for unblanched dried slices on the average. The lower final moisture content influenced the faster restoration at the beginning of rehydration process.

Results of calculation of the rate of moisture vaporization seem to be in a reasonable agreement with experimental data.

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