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SHRINKAGE OF APPLES DURING INFRARED DRYING

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Changes in the volume of cylindrical (40 mm in diameter, 2.5, 5 and 10 mm in thickness) samples of apple variety Lobo were determined after drying with infrared radiation whose intensity corresponded to power consumption by radiators equal to 200, 550, 900 and 1250 W. These measurements provided the basis for determining a correlation between shrinkage, infrared radiation and the thickness of the dried material. It turned out that the coefficient of shrinkage is directly proportional to the thickness of the dried material. In the case of apple samples 2.5 mm thick, the coefficient of shrinkage was inversely proportional to the intensity of infrared radiation. There was no significant correlation between this coefficient and the intensity of infrared radiation in 5 mm and 10 mm samples.

Key words: drying, shrinkage, apples, infrared radiation, mathematical model

NOMENCLATURE

δ – error (-); ρ_t – mass density of toluene (kg/m^3); d – sample diameter (m) g – sample thickness (m); m_0 – initial sample mass (kg); m(t) – instantaneous sample mass (kg); m_t – toluene mass (kg); P – power consumption by radiators (W); S – relative shrinkage (-); u_0 – initial moisture content ($kg_{water}/kg_{dry\ matter}$); u(t) – instantaneous moisture content ($kg_{water}/kg_{dry\ matter}$); V_0 – initial sample volume (m^3); V_k – sample volume after drying (m^3); V(t) – instantaneous sample volume (m^3).

INTRODUCTION

The initial moisture content of apples is very high, reaching even 85% [Ginzburg 1969; Lisowa *et al.*, 1997]. This kind of material is characterized by shrinkage during drying [Murakowski, 1994; Fortes & Okos, 1980; Kompany *et al.*, 1993; Markowski, 1994; Markowski & Białobrzewski, 1998; Mulet, 1994; Białobrzewski, 1999; Górnicki, 2000]. This phenomenon results from thickening of the material structure caused by internal forces. Shrinkage centers, located on the outer surface of the material or inside it, may be distinguished during the process. In the first case, flat surface changes into concave, in the other shrinkage cavities are formed inside the material. Free shrinkage may be observed when drying conditions are steady, and ideal shrinkage – when changes in the material volume are equal to the volume of evaporated moisture [Kneule, 1970]. An analysis of the professional literature on the topic allows assuming a linear dependence between changes in the volume of the material dried and its moisture content [Pabis, 1994; Zosgas *et al.*, 1994; Lozano, 1983; Murakowski, 1994; Lewicki *et al.*, 1994; Kamiński *et al.*, 1994].

The aim of the studies was to determine the correlation between shrinkage of apple samples (var. Lobo) during infrared drying, the intensity of infrared radiation and the thickness of the dried material.

MATERIAL AND METHODS

Changes in the volume of cylindrical (40 mm in diameter, 2.5, 5 and 10 mm in thickness) samples of apple var. Lobo were determined after drying with infrared radiation whose intensity corresponded to power consumption by radiators equal to 200, 550, 900, and 1250 W. These values were adopted due to the limitations of the equipment used in the investigations. The intensity of infrared radiation was determined indirectly, measuring the power consumption by radiators. The apple samples were radiated on both sides. The experiment was performed in five replications for each set of parameters. Infrared drying was carried out on an original test stand (Figure 1).

The stand design enables continuous recording of changes in the moisture content of the sample dried. The sample was radiated on both sides by two sets of infrared lamps (radiators). Each set consisted of four 150 W lamps. The distance between the lamps and the sample was 40 cm, to ensure infrared radiation uniformity over the whole drying surface. Air ventilation with ambient parameters was applied in order to improve the conditions of heat transfer and mass exchange. The air velocity measured at the central point of the drying chamber was 0.2 m/s.

The initial and final moisture contents of the experimental samples are given in Table 1. The values are means for five replications. Table 1 presents also the time needed for achieving the final moisture content. It was assumed that the final moisture content had been achieved by the

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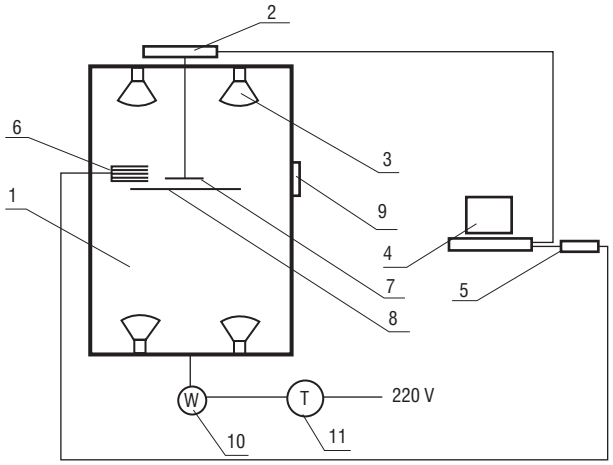

FIGURE. 1 Test stand. 1 – radiator chamber, 2 – electronic balance, 3 – infrared lamp (radiator), 4 – computer, 5 – amplifier, 6 – thermo-couples, 7 – movable pan, 8 – immovable pan, 9 – fan, 10 – wattmeter, 11 – autotransformer.

TABLE 1. Mean values of the process parameters.

Sample thickness g [mm]	Power consumption by radiators N [W]	Moisture content [kg/kg] initial $U_{śr\,0}$	Moisture content [kg/kg] final $U_{śr\,k}$	Process duration $t_{śr}$ [min]	Final relative volume V_k/V_0 [–]
2.5	200	5.94(1)±0.36(2)	0.27±0.03	548±16	0.54±0.02
	550	6.89±0.43	0.21±0.01	380±5	0.55±0.03
	900	6.27±0.27	0.20±0.01	265±13	0.58±0.03
	1250	6.46±0.45	0.19±0.02	222±17	0.65±0.05
5.0	200	7.20±0.29	0.30±0.01	962±10	0.30±0.01
	550	7.91±0.30	0.31±0.02	462±17	0.30±0.02
	900	7.28±0.58	0.30±0.02	338±12	0.30±0.03
	1250	7.31±0.60	0.20±0.01	258±2	0.34±0.01
10.0	200	6.22±0.62	0.36±0.02	1852±6	0.24±0.02
	550	7.14±0.59	0.29±0.01	877±16	0.24±0.01
	900	6.19±0.24	0.24±0.01	623±19	0.24±0.01
	1250	6.61±0.24	0.20±0.02	437±21	0.24±0.01

(1) – mean values, (2) – standard deviation

experimental material when the same value was recorded during three successive sample mass measurements, conducted every 5 min. The initial volume of samples (V_0) was determined as the volume of a cylinder with height g and diameter d. The volume of samples after drying was determined on the basis of the mass of toluene displaced by them. Knowing the specific density of toluene (ρ_t = 870 kg/m^3 according to PPH "POCh" S.A. Gliwice), we could determine the volume of each sample after drying from the dependence (1):

$$V_t=m_t/\rho_t \quad (1)$$

with the maximum measuring error δV_k:

$$\delta V_k=(\delta m_t/m_t+1/\rho_t)\cdot V_k=0.3 \text{ cm}^3 \quad (2)$$

where: m_t is the mass of toluene displaced by the smallest sample, 2.5 mm thick, subjected to infrared radiation whose intensity corresponded to power consumption by radiators equal to 1250 W; V_k is the highest, for these parameters, volume of the dried material. The mass was determined using an electronic balance Medicat 1600, exact to ± 0.01 g. The coefficient of shrinkage was determined as the difference between the initial volume and the volume after drying, in relation to the initial volume from the dependence (3):

$$S=(V_0-V_k)/V_0 \quad (3)$$

The initial volume (V_0) was determined with the measuring error δV_0 (4):

$$\delta V_0=[(\delta g/g)+2\cdot(\delta V_0/V_0)]\cdot V_0=0.07 \text{ cm}^3 \quad (4)$$

The coefficient of shrinkage was determined with the measuring error δS (5):

$$\delta S=[(\delta V_k/V_k)+(\delta V_0/V_0)]\cdot S=0.01 \quad (5)$$

The values in dependence (5) are mean values for the set of parameters given above (sample thickness – infrared radiation intensity).

The instantaneous moisture content u(t) and the initial moisture content u_0 were determined from the dependence (6):

$$u(t)=[m(t)-m_s]/m_s \quad (6)$$

The maximum error is made for the maximum value m(t), *i.e.* in the boundary case for $m(t)=m_0$ (7):

$$\delta u(t)=[(\delta m_0/m_0)+(\delta m_s/m_s)]\cdot u_0=0.01 \text{ kg/kg} \quad (7)$$

When the equilibrium moisture content had been achieved, the samples were subjected to further drying in a laboratory drier (24 h, 104°C), in order to determine their dry mass content.

Table 1 presents the values of relative final volume V_k/V_0 which are means for five measurements. They were calculated on the basis of the initial and final volume of the experimental material. Arithmetic means and standard deviations were determined using the package Statistica 6.0 (Stat Soft).

RESULTS AND DISCUSSION

The fact that the final moisture contents are comparable for all variants of the process parameters (Table 1) indicates that there is a non-linear dependence between the coefficient of shrinkage S and the thickness of samples (Figure 2). The value of this coefficient rises with an increase in the sample thickness. This is confirmed by the values of mean final relative volume, included in Table 1. They indicate that this volume decreases with an increase in sample thickness. An increase in the sample thickness from 2.5 mm to 5 mm causes an inversely proportional change in relative volume, from 0.61 to 0.31. The situation changes with a further increase in the sample thickness. Changes in the volume are becoming much smaller and in the case of the sample thickness equal to 10 mm relative volume decreases to 0.24 only. A change in this tendency is probably caused by the

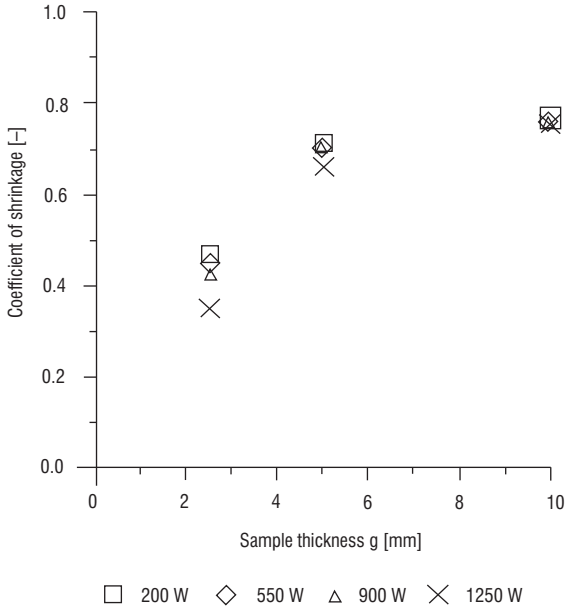

FIGURE 2. Correlation between the coefficient of shrinkage and sample thickness.

fact that short-wave infrared radiation penetrates into the material to a depth of 3 mm [Ginzburg, 1969; Lisowa *et al.*, 1997; Wesołowski, 2001]. Therefore, a 10 mm thick sample is not radiated all over its section. Heating of the material inner layers takes place as a result of heat diffusion, not radiation. The mean relative volume of the dried material (V_k/V_0) is 0.61±0.09, 0.31±0.04 and 0.24±0.01 for samples 2.5, 5.0 and 10 mm thick, respectively (Table 1). The standard deviations of mean values for 5 mm and 10 mm samples are very low (lower than 0.05), which shows that for the above thickness of the material changes in its volume after drying (shrinkage) are independent of infrared radiation intensity. This is also confirmed by Figure 2. It was found that for samples 2.5 mm thick and electric power of 1250 W shrinkage depends on the intensity of infrared radiation. This dependence is inversely proportional (Figure 3).

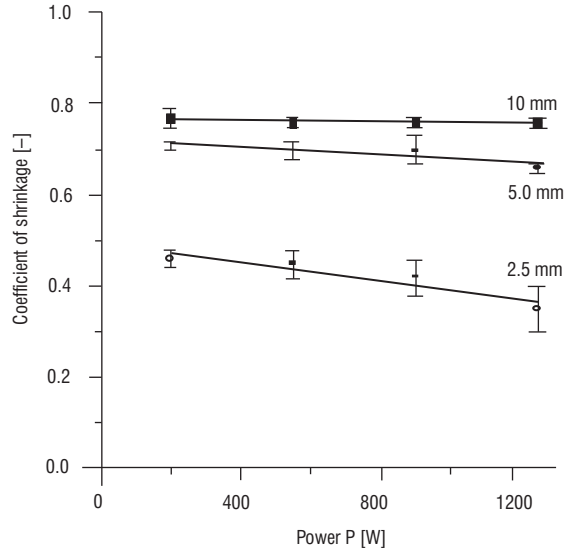

FIGURE 3. Correlation between the coefficient of shrinkage and power consumption by radiators.

TABLE 2. Simple regression equations.

Sample thickness [mm]	Regression equation $Y=V_k/V_0$, $X=u/u_o$	Coefficient of correlation	Significance level
2.5	$Y=0.4946-1.0286\cdot10^{-4}\cdot X$	0.936	0.04
5.0	$Y=0.7236-4.2857\cdot10^{-5}\cdot X$	0.873	0.10
10.0	$Y=0.7687-8.5714\cdot10^{-6}\cdot X$	0.775	0.19

The figure shows straight lines approximating the dependence of V_k/V_0 on the power consumption by radiators for particular values of the sample thickness. The lines were determined by linear regression, using the package Statistica 6.0 (Stat Soft). They remain within the margins of errors.

Equations of straight lines and coefficients of correlation are given in Table 2. The data included therein show that the correlation between the coefficient of shrinkage and the intensity of infrared radiation may be considered significant only in the case of 2.5 mm samples, and that it is inversely proportional.

CONCLUSIONS

1. The value of the coefficient of shrinkage rises with an increase in the thickness of samples of apple var. Lobo subjected to infrared drying.
2. In the case of apple samples 5 mm and 10 mm thick, shrinkage is independent of the intensity of infrared radiation, whereas in 2.5 mm samples its value is inversely proportional to this intensity.

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SKURCZ SUSZARNICZY JABŁEK SUSZONYCH PROMIENIAMI PODCZERWONYMI

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Celem przeprowadzonych badań było określenie zależności skurczu suszarniczego plastrów jabłek odmiany Lobo suszonych promieniami podczerwonymi od natężenia promieniowania podczerwonego i grubości materiału.

Do pomiarów próbek w kształcie plastrów o grubości 40 mm i średnicach 2.5 mm, 5 mm i 10 mm pobranych z jabłek odmiany Lobo. Plastry nie były poddane żadnej obróbce wstępnej i nie były pozbawione skórki. Tak przygotowane próbki były naświetlane obustronnie 8 lampami promiennikowymi o mocy 150 W każda (rys. 1). Natężenie promieniowania podczerwonego odpowiadało poborowi przez promienniki mocy 200W, 550W, 900W i 1250W. Dodatkowo w celu polepszenia warunków wymiany ciepła i masy zastosowano równoległy do złoża przepływ powietrza i prędkości 0,2 m/s. Objętość początkowa V_0 próbek wyznaczano z zależności geometrycznych. Objętość końcową V_k zaś wyznaczano pośrednio, określając masę wypartego przez próbkę toluenu (tab. 1).

Stwierdzono istnienie nieliniowej zależności współczynnika skurczu suszarniczego S od grubości próbki. W rozpatrywanym zakresie w miarę wzrostu grubości próbki wartość tego współczynnika rośnie (rys. 2). Współczynnik skurczu zdefiniowano jako różnicę objętości początkowej i objętości po suszeniu odniesionej do objętości początkowej:

$$S=(V_0-V_k)/V_0$$

W miarę wzrostu grubości próbki stwierdzono zanik zależności współczynnika skurczu od mocy pobieranej przez promienniki (rys. 3). Dla próbki o grubości 2,5 mm zależność ta jest odwrotnie proporcjonalna. Natomiast dla próbek o grubości 5,0 mm i 10,0 mm zależność ta jest pomijalnie mała. Odchylenie standardowe przyjmuje wartości poniżej 0,05 (tab. 1).