NAUKI INŻYNIERSKIE I TECHNOLOGIE ENGINEERING SCIENCES AND TECHNOLOGIES
3(30) • 2018

ISSN 2080-5985
e-ISSN 2449-9773

Dariusz Piotrowski
Warsaw Universiy of Life Sciences, SGGW-WULS in Warsaw
e-mail: dariusz.piotrowski1@wp.pl
ORCID: 0000-0002-1466-8322

Marcin Ignaczak
Warsaw Universiy of Life Sciences, SGGW-WULS in Warsaw
University of Social Sciences and Humanities, SWPS in Warsaw
e-mail: marcin.ignaczak@mail.com
ORCID: 0000-0002-6567-2006

INFLUENCE OF PRESSURE IN VACUUM DRYING CHAMBER ON SHRINKAGE OF DEFROSTED DRIED STRAWBERRIES

WPŁYW CIŚNIENIA W KOMORZE SUSZARKI PRÓŻNIOWEJ NA SKURCZ ROZMROŻONYCH WYSUSZONYCH TRUSKAWEK

DOI: 10.15611/nit.2018.3.04
JEL Classification: L66, O33

Summary: The material were raw or defrosted strawberries of Senga Sengana variety with the diameter of 26-30 mm. Fruits were dried for 16 hours at the temperature of 60°C under constant or variable conditions considering level of pressure. Pressure during the drying process was on a fixed level of: 5, 10 and 15 kPa or a change of pressure was introduced among extreme values. Shrinkage of strawberries was examined with the use of two methods: the volumetric method and measurement of linear dimensions in horizontal and vertical space. Shrinkage obtained under the fixed pressure level was greater for higher values in the drying chamber. Horizontal linear shrinkage of dried fruit was always lower than vertical linear shrinkage. For dried strawberries volumetric shrinkage obtained for defrosted fruits after vacuum drying under variable pressures did not reveal clear differences between respective values of shrinkage. The lowest level of pressure (5 kPa), applied in any phase of vacuum drying under variable pressure, caused a shrinkage decrease in comparison to drying shrinkage after processes under other fixed pressure.

Keywords: shrinkage, vacuum drying, constant and variable conditions, pressure, moisture content, dried strawberries.

Streszczenie: Materiałem do badań były rozmrożone truskawki odmiany Senga Sengana o średnicach z zakresu 26-30 mm. Owoce były suszone przez 16 godzin w temperaturze 60°C i ciśnieniu niższym niż ciśnienie atmosferyczne. Wartości ciśnienia podczas procesu suszenia były na ustalonym poziomie: 5, 10 i 15 kPa lub zastosowano zmianę ciśnienia pomiędzy przedstawionymi wartościami ekstremalnymi. Skurcz suszarniczy truskawek został zbadany z wykorzystaniem dwóch metod: objętościowej i pomiarów liniowych wymiarów w poziomie i w pionie. W warunkach ustalonego ciśnienia uzyskany poziom skurczu był większy dla wyższych ciśnień w komorze suszarniczej. Poziomy liniowy skurcz suszonych owoców był zawsze mniejszy niż skurcz pionowy liniowy. Dla rozmrożonych truskawek skurcz objętościowy po suszeniu próżniowym w warunkach zmiennych ciśnień nie ukazał wyraźnych różnic dla zastosowanych modyfikacji. Najniższy poziom ciśnienia (5 kPa) zastosowany na jakimkolwiek etapie suszenia przy zmiennym ciśnieniu powodował zmniejszenie skurczu w porównaniu ze skurczem uzyskanym po procesach realizowanych przy pozostałych stałych poziomach ciśnienia.

Słowa kluczowe: skurcz, suszenie próżniowe, stałe i zmienne warunki, ciśnienie, zawartość wilgoci, suszone truskawki.

1. Introduction

Drying of fruits as a process of removing water from materials with cell structure is accompanied by changes of several physical properties including shrinkage. The properties of wet and dried material or the drying method and parameters are usually considered in scientific research with respect to shrinkage, deformation level or structural damage used for product quality evaluation [Panyawong, Devahastin 2007; Bhat, Stamminger 2015; Qiu et al. 2015; Kowalska et al. 2018; Li et al. 2019].

It is possible to decrease shrinkage of drying fruit by selecting the right pre-treatment method e.g. based on changes in surface tension or structure rigidity [Sham et al. 2001; Prothon et al. 2003; de Bruijn et al. 2016: Gamboa-Santos, Campañone 2019]. Despite complex shrinkage phenomena in heterogeneous materials during drying, including the vacuum drying method, the application of linear equation for shrinkage with the function of moisture content ratio gave satisfying results in numerous research [Prothon et al. 2003; Wu et al. 2007; Witrowa-Rajchert, Rząca 2009; Thanh Khuong et al. 2018]. Determination of degree and pattern of shrinkage and deformation shape factor of carrot cubes undergoing different drying methods under reduced pressure resulted with presence of more and less uniform periods during drying [Panyawong, Devahastin 2007; Agudelo-Laverde et al. 2014]. The level of shrinkage due to plant tissue water loss was determined not only by the drying method but also to certain extend by species and cultivars [Nawirska et al. 2009; Balzarini et al. 2018; Li et al. 2019].

Favourably maintained structure in case of certain types of vacuum dried fruits can be explained due to the existence of expansion effect obtained under low pressures, which preserve a greater number of pores and prevent structure deterioration [Sitkiewicz et al. 2014]. The featured effect is augmented when in the conditions of low pressure heat is in the form of the microwaves [Szarycz et al. 2006; Figiel, Michalska 2017] or superheated steam [Panyawong, Devahastin 2007].

The purpose of this research was to examine the influence of fixed and variable pressures during vacuum drying on the final moisture content and shrinkage of defrosted strawberries.

2. Materials and methods

For the purpose of this work investigated were both defrosted i.e. frozen and thawed or raw (from a cold store) strawberries of Senga Sengana variety with the diameter of 26-30 mm. Fresh strawberries were stored at 4 to 8°C and in the test day sorted by size, stalked, washed and drained on surface. However, most of the previously prepared fruits were frozen and stored until the test day in a freezer at a temperature of approx. –18°C. For each test twenty eight frozen strawberries were defrosted in a microwave (5 min.) and natural convection at room temperature (20-24°C). The drying chamber of vacuum dryer [Piotrowski 2009] was heated up to the setting temperature of 60°C measured near the wall of the dryer.

Cone-shaped fruits, base-laid on 2 trays with sieves, were dried for 16 hours at the temperature of 60°C in a lower pressure than the atmospheric one. Only one level of stable pressure (15 kPa) was tasted for vacuum drying for fresh strawberries (reference dried fruits). The rest of vacuum drying experiments under constant or variable pressure level, built in control algorithm in vacuum dryer [Piotrowski 2009] were carried out on defrosted strawberries. Pressure during the process was on constant, fixed level (results coded with symbol "–"): 5, 10 and 15 kPa or a change of pressure was introduced. Variable pressure was investigated even as:

1) step increase or decrease at the begging of 6th hour of the process (results coded with symbol "↑" or "↓"),

2) linear increase or decrease from the beginning of the process during 16 hours among extreme values of pressure: 5 and 15 kPa; the rate of pressure changes: 0.01042 kPa/min. (results coded with symbol "/" or "\" respectively).

Drying experiments for defrosted strawberries with a constant, fixed level of pressure were carried out in triplicate and the rest of them in duplicate.

The water content (X) for dried strawberry fruits was determined using the drying method under atmospheric pressure at the temperature of approx. 60°C for 24 hours (in laboratory cabinet dryer SUP-4M, Wamed, Poland). Dried strawberries were cut into small parts and crumbled in a mortar for mass measurements analytical balance WPA 120/C (Radwag, Poland) with precision ± 0,0001 g. The final moisture content (M_f [%]) was calculated in three repetitions.

Shrinkage level was examined by two methods in 20-25°C after 36-48 hours from the end of the main drying process. The first method was based on linear measurement of strawberries diameter and height. For raw, still frozen or dried strawberries 2 vertical and 3 or 4 horizontal measurements were made by the digital calliper (± 0.01 mm).

$$LS(h)(\%) \text{ or } LS(v)(\%) = \left(1 - \frac{d_{Lf}}{d_{Li}}\right) \times 100, \tag{1}$$

where: *LS(h)* – horizontal linear shrinkage, *LS(v)* – vertical linear shrinkage (%), d_{Li} – initial linear dimension, d_{Lf} – final linear dimension (mm).

The second method was based on Archimedes' principle. Water was used for raw or still frozen strawberries and toluene (C_7H_8) for dried fruits. For 5 strawberries the volume was measured before and after the drying process to establish a size change for volumetric shrinkage (S_V) calculation.

$$S_V(\%) = \left(1 - \frac{V_f}{V_i}\right) \times 100, \qquad (2)$$

where: S_V – volumetric shrinkage (%), V_i, V_f – initial or final volume (cm^3).

Proposed ways of evaluation of shrinkage are often presented in literature [Nawirska et al. 2009; Sitkiewicz et al. 2014; Qiu et al. 2015].

One-way analysis of variance (ANOVA) was used to examine the effects of fixed or variable pressure on the average moisture content or shrinkage calculated from experiments repetitions. Depending on the results of the homogeneity of variance for each dependent variable either an F-test or Welch test was chosen. Bonferroni or Tamhane multiple comparison tests (means with equal or unequal variances) were applied to determine the significant differences between group means. A significance level $\alpha = 0.05$ was chosen in all cases. For statistic calculations a statistical program IBM SPSS Statistics for Windows (IBM Corp.) within the statistical software package PS IMAGO (Predictive Solutions) was used [Krejtz et al. 2012].

3. Results

As a result of vacuum drying of defrosted strawberries at a temperature of 60°C for 16 hours in constant or fixed and variable pressure, dried fruits reached the moisture content (M_f) from 3.22 to 9.93% (wet basis) (Table 1), corresponding to water content from 0.0333 kg water/kg dry mater to 0.1103 kg water/kg dry mater. Drying processes fixed the levels of pressure: 5, 10 and 15 kPa and produced dried strawberries with

Table 1. Final moisture content (M_f) for vacuum dried defrosted (D) strawberries under fixed and variable pressure (values represents means ± standard deviation *SD*)

Code of drying	M_f (%)	SD M_f (%)	Code of drying	M_f (%)	SD M_f (%)
D5-5kPa	3.222^a	±0.632	D15↓5kPa	4.316^a	±0.221
D10-10kPa	4.822^b	±0.624	D5↑15kPa	5.520^{ab}	±1.715
D15-15kPa	9.926^c	±1.363	D15/5kPa	9.327^c	±1.855
R15-15kPa	18.230*	±0.479*	D5/15kPa	7.304^b	±0.858

a, b, c – averages in the same column appointed with diverse letters differ significantly ($p < 0.05$).

* – final moisture content for raw material (R) (reference dried fruits) was calculated based on experimental drying kinetics and data available in another set of experiments [Piotrowski 2009]; this highest value is not included in statistical analysis.

Source: own data.

significantly different moisture content (probability $p < 0.05$), based on Tamhane test applied even for unequal variances. Among the dried fruits received in variable conditions the highest amount of moisture was left when the pressure was linearly lowered from 15 to 5 kPa during 16 hours. Dried defrosted strawberries after the process with linearly increased pressure from 5 to 15 kPa during 16 hours maintained lower, significantly different, moisture content. This confirms the conclusion about lower water content for a porous material by Kozanoglu et al. [2005] who applied pressure step change from 20 to 60 kPa during vacuum fluidized bed drying.

Figure 1 shows shrinkage for defrosted or fresh strawberries which were dried under fixed levels of pressure. The sub-zero values of shrinkage in the horizontal plane for the pressure of 5 kPa were obtained due to increased fruit volume. In this case the authors could not present a coherent explanation for the horizontal linear shrinkage for fruits obtained in vacuum dryer where resistance heaters emitted heat energy. However, the second method of evaluation of shrinkage entirely showed that vacuum dried fruits D5-5kPa reduced their volume (Table 3). Fruits for all other experiments shrank and positive values of shrinkage were obtained. The range of shrinkage change in the horizontal plane (LS(h)) was definitely lower than appropriate values of linear vertical shrinkage (LS(v)). It was probably caused by the sieve structure on the basis level to which the fruits adhered and stronger gravitation affect.

Table 2. The statistical comparison of the effect of fixed and variables pressures on vacuum drying shrinkage based on Welch robust tests of equality of means

Group of drying experiments with:	Kind of shrinkage	Welch statistic	Degrees of freedom		Significance
			df1	df2	
fixed pressures	LS(h)	10.93	3	2.897	**0.043**
variable pressures	LS(h)	6.024	3	2.165	0.133
fixed pressures	LS(v)	2.473	3	4.263	0.194
variable pressures	LS(v)	0.266	3	1.706	0.848
fixed pressures	S_V	274.34	3	2.105	**0.003**
variable pressures	S_V	1.028	3	2.110	0.522

Source: own data.

Table 3. The statistical comparison of the effect of fixed pressure on volumetric shrinkage during vacuum drying based on Bonferroni test ($a = 0.05$)

Code of vacuum drying	Volumetric shrinkage S_V (%)	Standard deviation of volumetric shrinkage $SD\ S_V$ (%)
D5-5kPa	24.84^{a}	±3.770
D10-10kPa	53.10^{bcd}	±0.023
D15-15kPa	55.32^{bcd}	±0.087
R15-15kPa	63.18^{bcd}	±4.870

a, b, c, d – averages with the same letter do not differ significantly ($p > 0.05$).

Source: own data.

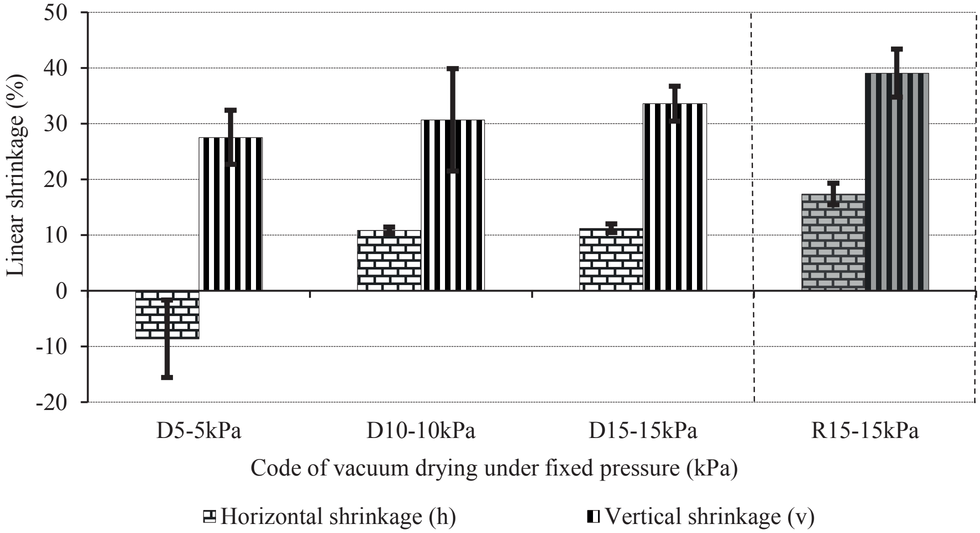

Fig. 1. Horizontal (LS(h)) and vertical (LS(v)) shrinkage for defrosted (D) or raw (R) strawberries vacuum dried under fixed pressure

Source: own data.

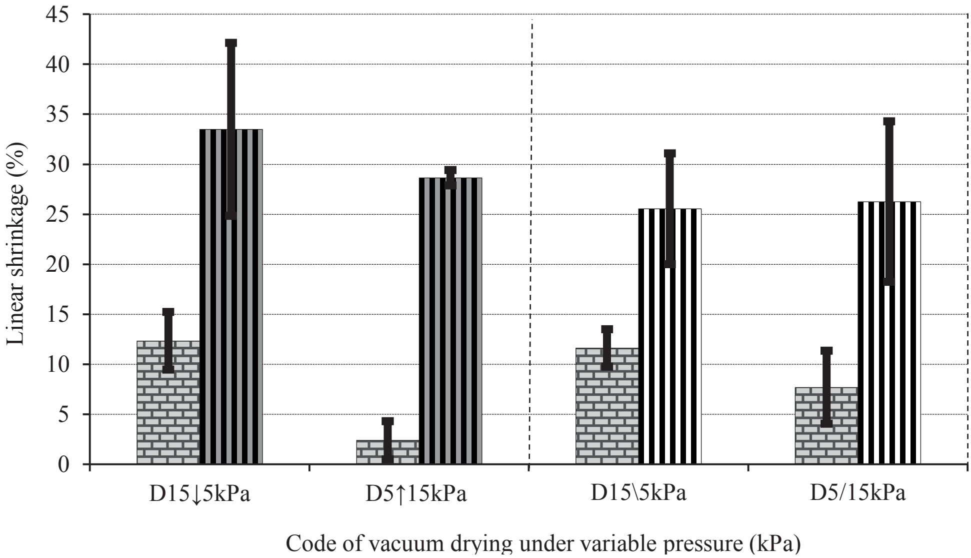

Fig. 2. Horizontal (LS(h)) and vertical (LS(v)) shrinkage of defrosted (D) strawberries vacuum dried under variable pressures

Source: own data.

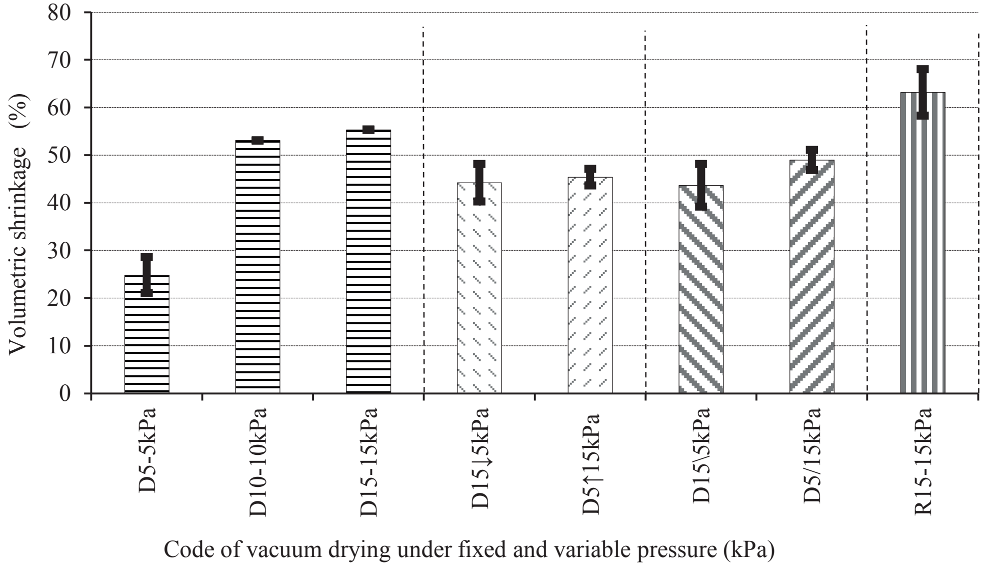

Fig. 3. Volumetric shrinkage (S_V) for defrosted (D) or raw (R) strawberries vacuum dried under fixed and variables pressures

Source: own data.

It was also noticed that in both perpendicular directions there is a relationship between pressure level in the drying chamber and shrinkage. The lower pressure was applied during the drying process, the smaller the shrinkage. However, in case of defrosted strawberries and considered constant pressures of 10 and 15 kPa, the differences were definitely smaller (around 1% in horizontal plane ΔLS(h) and around 3% in the vertical one ΔLS(v)), absolute percentages) comparing to the lowest applied pressure in drying processes, i.e. 5 kPa. It was observed that linear shrinkages for raw strawberries were greater than for defrosted ones (ΔLS(h) − 6.1% and ΔLS(v) − 4.8%, absolute percentages), but this tendency was statistically insignificant (Table 3).

During the analysis of changes in linear shrinkages (LS(h)) and LS(v)) for the respective experiments under variable pressure it was affirmed that the lower pressure in the first part of the process promoted retaining the initial size of the fruit, particularly in the horizontal orientation. When 5 kPa pressure was applied in the first part of the process, with step pressure changes, 10% lower shrinkage was achieved in the horizontal plane and around 5% in the vertical plane. In analogical process, with the linear change, 4% difference was observed in horizontal shrinkage and only about 1% increase in the linear plane. Averages for measurements (LS(h)) and LS(v) for dried fruits under variable pressure did not differ significantly (Table 2). A comparison of linear and step changes of pressure and their influence on fruit shrinkage did not show any unambiguous relationship and it demonstrated inconsistent tendencies in case of individual fruit and separate measurements.

Within the scope of analyzing dried fruit shrinkage, research was also carried out with the use of volumetric technique (Figure 3). Similarly to linear dimension analysis, the fruit dried under more reduced pressures had lower volumetric shrinkage (S_v) levels. The fruit dried in the lowest pressure (5 kPa) had two times smaller shrinkage as compared to remaining products dried in fixed pressure conditions of 10 or 15 kPa.

The strongest tendency to the highest volumetric shrinkage was obtained for raw strawberries as the reference material then for defrosted ones. In the second method of shrinkage evaluation under pressure 15 kPa the difference of drying shrinkage among raw and defrosted fruits was on the level $\Delta S_v - 4.3\%$ (absolute percentages) (Figure 3). Tendency was statistically insignificant because calculated value of Welch test was on the level of $0.327 > 0.05$. However, for dried fruits under pressure of 15 kPa smaller shrinkages in both considered methods were always obtained for defrosted strawberries and then for raw ones (reference material). Moreover, raw strawberries decreased moisture content more gradually during vacuum drying and after 16 hours of processing obtained about two times higher final moisture content than defrosted dried strawberries (Table 1).

The analysis of volumetric shrinkage of defrosted strawberries after vacuum drying under variable pressures did not show any explicit differences between the individual experiments. However, it is worth mentioning that the lower pressure (5 kPa), applied in any phase of drying, caused a shrinkage decrease in comparison to the drying process under the fixed pressure of 15 or 10 kPa regardless of the way of its modification.

Based on Welch robust tests of equality of means only for average linear horizontal shrinkage LS(h) and average volumetric shrinkage S_V obtained under fixed pressure levels can be rejected on the significance level 0.05 (Table 2). Moreover, Bonferroni test, applied in situations where the variances were equal for volumetric shrinkage obtained under fixed pressures, showed that the lowest average shrinkage of strawberries dried under pressure 5 kPa created a significantly different group in relation to other averages (Table 3).

4. Discussion

The analysis of shrinkage for vacuum dried defrosted strawberries showed that the average shrinkage, measured by means of the volumetric method, in this set of drying experiments under vacuum, was approx. 45%. Definitely, the lowest shrinkage was achieved in strawberries dried under a fixed pressure of 5 kPa, which on average was more than 2 times smaller than in the case of shrinkage obtained under higher pressure levels (10-15 kPa). The obtained level of volumetric shrinkage can be evaluated as small, especially in relation to shrinkage obtained in result of convective drying [Gołoś et al. 2014; Sitkiewicz et al. 2014]. Sitkiewicz et al. [2014] identified that volumetric drying shrinkage for processing temperature of 50°C for convective drying can be 1.79 or 1.89 higher than for vacuum drying carried out under absolute pressure of 4 or 16 kPa, respectively. The use of combined drying for strawberries causes smaller shrinkage in comparison with dried fruits obtained by convective method and the tendency was better pronounced for pressure level of 4 kPa. For example, the use of convective-vacuum drying with half of the initial moisture content removed at the convective drying stage caused lowering of volumetric shrinkage to the value of 18.9% for pressure 4 kPa and 36.2% for pressure 16 kPa in the vacuum chamber [Sitkiewicz et al. 2014].

Nevertheless, four drying methods under atmospheric and reduced pressure (in the range from 4 to 6 kPa) on pumpkin slices indicated that shrinkage was not disapproving for air drying in comparison to vacuum drying [Nawirska et al. 2009]. Only minimal shrinkage of 12 pumpkin cultivars was observed for freeze-dried slices under the pressure of 65Pa.

Oikonomopoulou and Krokida [2012], who studied freeze-dried potatoes, mushrooms and strawberries under pressure ranging from 6 to 150Pa, underlined that considered materials shrinkage was not significant. Shrinkage after freeze drying is really small and within the applied range of pressure can be a thousand times or a bit less lower than during vacuum drying. These authors suggested that a consequent practical higher temperature during freeze drying or other under low pressure has an influence on the decrease of complex viscosity which leads to the greater shrinkage of considered materials. In contrast, high viscosity of concentrated amorphous liquid around ice may prevent shrinkage. Based on structure objectives it seems to be appropriate to use frozen raw materials for a range of drying methods regardless the level of pressure [Piotrowski et al. 2004; Oikonomopoulou, Krokida 2012].

The carried out calculation related to vertical (LS(v) and horizontal (LS(h)) linear shrinkage confirmed results determined by the volumetric method. For experiments with the fixed pressure during the process obtained, shrinkage level was greater for higher pressures in the drying chamber. The discussed relationship was relevant to both shrinkage planes for defrosted dried fruits. It is worth noticing that soft tissue of defrosted strawberries had more chances to extend their dimensions than raw from a cold fruit store just after the reduction of pressure in the drying chamber. Additionally, in case of drying carried out under the fixed pressure of 5 kPa, there was an unexpected increase of dimensions in the horizontal plane (LS(h)), which cannot be explained by this form of energy. In previously published results of radial shrinkage of strawberries in a vacuum dryer equipped with resistance heaters under pressure of 4 kPa [Gołoś et al. 2014] for 3 considered temperatures obtained values of shrinkage in the very narrow range were from 20.2% to 20.7%, which was classified in the same homogenous group. Recently, Alaei et al. [2018] presented results of application near infrared (NIR) and medium infrared (MIR) radiation for vacuum drying quince slices under fixed temperature in the range from 50 to 70°C. The results from this infrared-vacuum dryer were available for absolute pressures of

20, 40 and 60 kPa and the minimum shrinkage of 40.4% and 50% of substantial firmer tissue of quince rather than soft fruits was obtained for NIR and MIR conditions, respectively.

As a rule, horizontal linear shrinkage was lower than vertical linear shrinkage for vacuum dried strawberries, regardless of the level of pressure in the range of 5 to 15 kPa. This observation has confirmed strawberry shrinkage for air or vacuum drying in different range of temperature [Piotrowski et al. 2011; Gołoś et al. 2014]. The source of these phenomena is not only associated with drying method but also with the preparation or pre-treatment of fruits before drying [Sham et al. 2001; Bhat, Stamminger 2015; Kowalska et al. 2018]. Based on observations of softened strawberries during defrosting stage, lowering their vertical dimension was more probable than decreasing their diameters. The increase of temperature by 20°C was more favourable for shrinkage lowering of defrosted strawberries vacuum dried under pressure of 16 kPa than 4 kPa [Piotrowski et al. 2011]. During vacuum drying under pressure of 16 kPa the level of temperature caused more diversity in the drying rate. In the present research final moisture and horizontal shrinkage increased with the increase pressure level (5, 10, 15 kPa). Less favourable conditions for removing moisture (M_f for vacuum drying under fixed pressure were classified to a different homogenous group) resulted with differences in the same direction for all considered drying shrinkages. Measurements of various dimensions and shrinkage of more compact particles showed another tendency. Thickness of air dried fermented cocoa beans was found to shrink more than its length and width [Hii et al. 2009]. For the evaluation of drying shrinkage Chauhan and Srivastava [2009] used only the longest dimension of peas for the optimisation of vacuum-assisted microwave drying. Linear shrinkage in dried under pressure of 6.67, 30 and 53.33 kPa hard material (for example beans) primarily depended on moisture contents and drying rates during the initial stages of drying processes. Higher linear shrinkage ratios were obtained when higher microwave power level and higher vacuum were applied [Chauhan, Srivastava 2009].

For pressure changes from 5 to 15 kPa, a tendency was observed that slightly lower shrinkage values appeared than for corresponding types of pressure changes (step decrease at the begging of 6th hour or linear decrease during 16 hours). As a result of the drying process in variable conditions, which included the pressure of 5 kPa, a decrease in shrinkage was observed compared with fruit dried under the fixed pressure of 10 kPa (D10-10kPa). Generally, mentioned in the literature on vacuum drying outcomes suggested also that application of lower pressure levels during the process resulted in slightly smaller shrinkage of dried vegetables [Devahastin et al. 2004; Wu et al. 2007]. Nevertheless, lowering the pressure level from 10 to 2.5 kPa for soft tissue of eggplant caused greater influence on shrinkage than a change of fixed temperature in the range of 30 to 50°C under the pressure of 2.5 kPa [Wu et al. 2007].

For production of dried fruits or (potato/fruit/vegetable) chips application of microwave energy was proposed within several drying methods. At the same time superheated steam brought a result which was alternative to shrinkage − puffing effect during vacuum step of drying [Panyawong, Devahastin 2007; Nawirska et al. 2009; Figiel, Michalska 2017; Kowalska et al. 2018]. Low shrinkage of the obtained product resulted from the applied pressure as well as the structure of the soft fruit tissue, which was able to expand when energy for drying in appropriate form [Devahastin et al. 2004; Szarycz et al. 2006; Panyawong, Devahastin 2007; Nawirska et al. 2009; Li et al. 2019] under low pressure was delivered.

5. Conclusions

1. The level of pressure, lower than the atmospheric one, applied in the drying chamber during vacuum drying, had significant influence on the final moisture content in dried strawberries.
2. Under the usage of the same pressure in the vacuum drying chamber, smaller shrinkage in both considered methods was always obtained for defrosted strawberries than for raw ones (reference material).
3. The level of shrinkage depends on the vacuum drying pressure. The reduction of fixed pressure levels from 15 kPa to 5 kPa causes shrinkage decreases and it is particularly noteworthy after decreasing the fixed pressure level from 10 kPa to 5 kPa.
4. Horizontal linear shrinkage was always lower than vertical linear shrinkage for vacuum dried strawberries, regardless of the level of applied pressure in the range of 5 to 15 kPa.
5. Vacuum drying of defrosted strawberries with introduced pressure changes which decreased from 15 kPa to 5 kPa at a certain stage, produced dried fruits with lower shrinkage in comparison to the product received after the process under a fixed pressure of 10 kPa.

References

Agudelo-Laverde L.M., Schebor C., Buera M.D., 2014, *Evaluation of structural shrinkage on freeze--dried fruits by image analysis: Effect of relative humidity and heat treatment*, Food and Bioprocess Technology, 7(9), pp. 2618-2626, DOI: 10.1007/s11947-013-1242-1.

Alaei B., Dibagar N., Chayjan R.A., Kaveh M., Taghinezhad E., 2018, *The effect of short and medium infrared radiation on some drying and quality characteristics of quince slices under vacuum condition*, Quality Assurance and Safety of Crops & Foods, 10(4), pp. 371-381, DOI: 10.3920/qas2017.1252.

Balzarini M.F., Reinheimer M.A., Ciappini M.C., Scenna N.J., 2018, *Comparative study of hot air and vacuum drying on the drying kinetics and physicochemical properties of chicory roots*, Journal of Food Science and Technology-Mysore, 55(10), pp. 4067-4078, DOI: 10.1007/s13197-018-3333-5.

Bhat R., Stamminger R., 2015, *Preserving strawberry quality by employing novel food preservation and processing techniques – Recent up-dates and future scope – An overview,* Journal of Food Process Engineering, 38(6), pp. 536-554, DOI: 10.1111/jfpe.12184.

Chauhan A.K.S., Srivastava A.K., 2009, *Optimizing drying conditions for vacuum-assisted microwave drying of green peas (Pisum sativum L.)*, Drying Technology, 27(6), pp. 761-769, DOI: 10.1080/07373930902828120.

de Bruijn J., Rivas F., Rodriguez Y., Loyola C., Flores A., Melin P., Borquez R., 2016, *Effect of vacuum microwave drying on the quality and storage stability of strawberries*, Journal of Food Processing and Preservation, 40(5), pp. 1104-1115, DOI: 10.1111/jfpp.12691.

Devahastin S., Suvarnakuta P., Soponronnarit S., Mujumdar A.S., 2004, *A comparative study of low--pressure superheated steam and vacuum drying of a heat-sensitive material*, Drying Technology, 22(8), pp. 1845-1867, DOI: 10.1081/DRT-200032818.

Figiel A., Michalska A., 2017, *Overall quality of fruits and vegetables products affected by the drying processes with the assistance of vacuum-microwaves*, International Journal of Molecular Sciences, 18(1), pp. 1-18, DOI: 10.3390/ijms18010071.

Gamboa-Santos J., Campañone L.A., 2019, *Application of osmotic dehydration and microwave drying to strawberries coated with edible films,* Drying Technology, 37(8), pp. 1002-1012, DOI: 10.1080/07373937.2018.1481426.

Gołoś A., Piotrowski D., Grzegory P., Wojnowski M., 2014, *Wpływ temperatury na strukturę i barwę truskawek suszonych wybranymi metodami*, Nauki Inżynierskie i Technologie, 4(15), pp. 31-42.

Hii Ch.L., Law Ch.L., Cloke M., 2009, *Shrinkage of bean dimensions during hot air drying of cocoa,* [in:] Proceedings of the 12th Polish Drying Symposium, Technical University of Lodz, Lodz, CD-ROM, pp. 383-390.

Kowalska J., Kowalska H., Marzec A., Brzeziński T., Samborska K., Lenart A., 2018, *Dried strawberries as a high nutritional value fruit snack,* Food Science and Biotechnology, 27(3), pp. 799-807, DOI: 10.1007/s10068-018-0304-6.

Kozanoglu B.U., Welti Chanes J., Gonzalez Pena A., Berlin Tolentino D.M., Mancebo M., Martinez F., 2005, *Stepwise change of operating pressure in vacuum fluidized bed drying: An experimental study*, The Canadian Journal of Chemical Engineering, 83, pp. 316-322, DOI: 10.1002/cjce.5450830218.

Krejtz K., Krejtz I., Albiński R., 2012, *Jednoczynnikowa analiza wariancji w planie międzygrupowym*, [in:] S. Bedyńska, M. Cypryańska (eds), *Statystyczny drogowskaz. 2*, Academical Publishing House Sedno, Higher School of Social Psychology, Warszawa, pp. 29-60.

Li K., Zhang M., Mujumdar A.S., Chitrakar B., 2019, *Recent developments in physical field-based drying techniques for fruits and vegetables*, Drying Technology, 37, pp. 1-20, DOI: 10.1080/07373937.2018.1546733.

Nawirska A., Figiel A., Kucharska A.Z., Sokol-Letowska A., Biesiada A., 2009, *Drying kinetics and quality parameters of pumpkin slices dehydrated using different methods,* Journal of Food Engineering, 94(1), pp. 14-20, DOI: 10.1016/j.jfoodeng.2009.02.025.

Oikonomopoulou V.P., Krokida M.K., 2012, *Structural properties of dried potatoes, mushrooms, and strawberries as a function of freeze-drying pressure,* Drying Technology, 30, pp. 351-361, DOI: 10.1080/07373937.2011.639475.

Panyawong S., Devahastin S., 2007, *Determination of deformation of a food product undergoing different drying methods and conditions via evolution of a shape factor*, Journal of Food Engineering, 78, pp. 151-161, DOI: 10.1016/j.jfoodeng.2005.09.012.

Piotrowski D., 2009, *Wpływ ciśnienia i temperatury na przebieg suszenia próżniowego truskawek i ich wybrane właściwości*, Treatises and Monographs, Warsaw University of Life Sciences Press, Warszawa, pp. 1-172.

Piotrowski D., Janowicz M., Sitkiewicz I., Ciurzyńska A., Lenart A., 2011, *Wpływ temperatury i ciśnienia w komorze suszarki próżniowej na proces suszenia oraz na skurcz truskawek*, Zeszyty Problemowe Postępów Nauk Rolniczych, z. 558, pp. 197-206.

Piotrowski D., Lenart A., Wardzyński A., 2004, *Influence of osmotic dehydration on microwave-convective drying of frozen strawberries*, Journal of Food Engineering, 65(4), 519-525, DOI: 10.1016/j.jfoodeng.2004.02.015.

Prothon F., Ahrne L., Sjoholm I., 2003, *Mechanisms and prevention of plant tissue collapse during dehydration: A critical review*, Critical Reviews in Food Science and Nutrition, 43(4), pp. 447-479, DOI: 10.1080/10408690390826581.

Qiu J., Khalloufi S., Martynenko A., Van Dalen G., Schutyser M., Almeida-Rivera C., 2015, *Porosity, bulk density, and volume reduction during drying: Review of measurement methods and coefficient determinations*, Drying Technology, 33(14), pp. 1681-99, DOI: 10.1080/07373937.2015.1036289.

Rahman S.A., Mujumdar A., 2008, *Combined radiant and conductive vacuum drying in a vibrated bed,* International Journal of Food Engineering, 4, art. 12, pp. 1-18, DOI: 10.2202/1556-3758.1314.

Sham P.W.Y., Scaman C.H., Durance T.D., 2001, *Texture of vacuum microwave dehydrated apple chips as affected by calcium pretreatment, vacuum level, and apple variety*. Journal of Food Science, 66(9), 1341-1347, DOI: 10.1111/j.1365-2621.2001.tb15212.x.

Sitkiewicz I., Janowicz M., Piotrowski D., Szlendak L., Krasowicz E., 2014, *Selected physical properties and structure of strawberries convective and vacuum dried*, [in:] J. Andrieu, R. Peczalski, S. Vessot-Crastes (eds), A.S. Mujumdar (series ed.), Proceedings of the 19th International Drying Symposium (IDS 2014), Lyon France, EDP Sciences, Les Ulis 2014, CD-ROM, Paper / file: ids2014140073.pdf, pp. 1-7.

Szarycz M., Jałoszyński K., Pełka A., Ostrowska M., Świerk B., 2006, *Wpływ parametrów mikrofalowo-próżniowego suszenia truskawek na przebieg procesu i skurcz suszarniczy*, Inżynieria Rolnicza, 10(4(79)), pp. 229-237.

Thanh Khuong N., Mondor M., Ratti C., 2018, *Shrinkage of cellular food during air drying*, Journal of Food Engineering, 230, pp. 8-17, DOI: 10.1016/j.jfoodeng.2018.02.017.

Witrowa-Rajchert D., Rząca M., 2009, *Effect of drying method on the microstructure and physical properties of dried apples*, Drying Technology, 27(7-8), pp. 903-909, DOI: 10.1080/07373930903017376.

Wu L., Orikasa T., Ogawa Y., Tagawa A., 2007, *Vacuum drying characteristics of eggplants*, Journal of Food Engineering, 83(3), pp. 422-429, DOI: 10.1016/j.jfoodeng.2007.03.030.