POLISH JOURNAL OF FOOD AND NUTRITION SCIENCES

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Pol. J. Food Nutr. Sci.
2007, Vol. 57, No. 4(A), pp. 131-135

# DEHYDRATION OF APPLES BY A COMBINATION OF CONVECTIVE AND VACUUM-MICROWAVE DRYING

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Key words: apples, drying, vacuum-microwaves, shrinkage, rehydration, colour

Apple cubes were dried with a convective method in a stream of air at the velocity of 4 m/s and temperature of 55°C as well as with a combined method consisting in pre-drying the apples with the convective method and finish-drying with the vacuum-microwave method (VM). The time of convective pre-drying reached: 40, 100 and 160 min, and the wattage of microwaves accounted for 240, 480 and 720 W. Drying shrinkage was measured by means of a measuring cylinder filled with linseed, whereas rehydration of the dried material was carried out in distilled water with a temperature of 21°C. Colour assessment was conducted based on results obtained with the use of a reflective colorimeter. The kinetics of apple cubes drying with the convective method was described using exponential functions. The VM finish-drying of the apples previously pre-dried with the convective method considerably shortened the total time of drying and decreased drying shrinkage. Apple cubes dried with the combined method demonstrated better rehydrating properties manifested by absorption capacity, dry mater holding capacity and rehydration ability as compared to the apples dried only with the use of the convective method. Drying resulted in the browning of apple cubes and shift of colour from green to red and a negligible shift of colour from yellow to blue. The colour of samples finished-dried with the VM method was more shifted towards red and blue when compared to the samples dried only under convective conditions.

## INTRODUCTION

Apples belong to popular fruits grown in Poland. Due to a high content of water, they require storage in strictly specified conditions or drying aimed at reducing water activity to a level assuring microbiological safety [Mathlouthi, 2001]. Dried apples may constitute an attractive snack in the form of crisps or an additive to teas or muesli. The most common method of biological materials dehydration is convective drying. Its fault is high energy consumption and low effectiveness of drying. Drying with the microwave method under conditions of reduced pressure is a novel, efficient method of food preservation [Lin *et al*., 1998]. Application of microwaves in the drying process causes heating the material from the inside. This results in a rapid increase in raw material temperature to a value depending on pressure occurring in the chamber [Drouzas & Schubert, 1996]. A low pressure in the chamber protects biological material against over-heating and, simultaneously, increases the intensity of water evaporation from the whole volume of that material. As a consequence, the rate of drying is considerably higher than in traditional methods of dehydration [Sharma, & Parasad, 2004]. An additional, crucial factor affecting drying kinetics is the wattage of microwaves [Andres *et al*., 2004; Figiel, 2006]. At a substantially reduced pressure in the chamber and – typical of microwaves – heating the material from the inside causing an increase of pressure inside cells, there occurs the so-called "puffing". That phenomenon prevents drying shrinkage and facilitates obtaining a crispy and delicate texture [Sham *et al*., 2001]. Changes in the structure of a dried product affect the course of secondary hydration, *i.e.* rehydration. During rehydration water penetrates into material interior and cellular structure is being reconstructed, which is accompanied by simultaneous washing out dry matter contained in the material to the surrounding aqueous solution. In order to make the dried product recover traits of the raw material it was made of upon dehydration, during rehydration it should absorb the same volume of water that it lost during drying, at possibly marginal loss of dry matter [Lewicki, 1998]. It is not so important in the case of mixing fruit dried material with milk, since both the hydrated dried product and the solution are consumed usually. In turn, infusion of fruit teas requires possibly fast and complete transfer of soluble dry matter contained in the dried product to an aqueous solution. The quality of a dried product is indicated by its colour [Yongsawatdigul, & Gunasekaran, 1996]. It is not only an indicator of changes proceeding in the material during drying, but also an important attribute affecting attractiveness of a food product.

The undertaken research was aimed at determining kinetics of apple cubes drying with the convective method and finish-drying with the microwave-vacuum method after pre-drying with the convective method as well as demonstrating the effect of pre-drying time and microwaves power on drying shrinkage, quality of rehydration and colour of the dried product.

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## MATERIALS AND METHODS

Cubes of 10 mm size were cut out of apples var. "Gala" and subjected to drying with two methods. The first method was convection, whereas the second was a combination of convective pre-drying and microwave finish-drying under reduced pressure. The time of convective pre-drying reached 40, 100 and 160 min. During convective drying, in a dryer designed and built at the Institute of Agricultural Engineering in Wrocław, the flow rate of air and its temperature accounted for 4 m/s and 55°C, respectively. Finish-drying with the microwave-vacuum method was carried in a VM 200 drier (Plazmatronika, Wrocław, Poland) at pressure varying in the range from 4 to 6 kPa and at microwaves wattage of 240, 480 and 720 W. Moisture content (*M*) of apples, depending on the time (*t*) with the convective method was described by means of an equation composed of two exponential components [Henderson, 1974]:

$$M = A \cdot e^{-B \cdot t} + C \cdot e^{-D \cdot t} \quad (1)$$

The process of apples finish-drying with the vacuum-microwave (VM) method was described with the use of a simple exponential function:

$$M = A \cdot e^{-B \cdot (t - t_i)} \quad (2)$$

Parameter $t_i$ in equation (2) denotes the time of pre-drying with the convective method after which the apples were re-dried with the VM method.

Drying shrinkage was evaluated by determining the relative volume of dried material ($V_s$), being a ratio of apple samples volume after drying (V) and before drying ($V_0$). The volume of apple samples was measured with the use of a measuring cylinder filled with linseed instead of toluene which is an inflammable substance detrimental to health. Due to its shape and smooth surface, linseed filled well empty spaces between apple cubes. Three replications were performed on samples including fifty cubes each.

Rehydration of dried apples was carried out in distilled water with a temperature of 21°C for 210 min. Having been taken out from water, the samples were dried with blotting paper and weighed exact to 0.001 g on a WPA60/C scale (Radwag). The quality of rehydration was presented with the use of the following parameters [Lewicki, 1998; Le Loch-Bonazzi *et al*., 1992]: water absorption capacity (WAC), dry mater holding capacity (DHC) as well as rehydration ability (RA). The WAC was computed by dividing the mass of water absorbed during rehydration by the mass of water removed in the drying process. The DHC expressed the capacity of material for retaining soluble substances and was computed by dividing dry matter content of the sample after rehydration by dry matter content of the sample before rehydration. On termination of the rehydration test, the hydrated samples were dried to enable determination of that part of dry matter which penetrated into the solution during rehydration. The RA was a product of WAC and DHC. Mean values of rehydration parameters were calculated based on twelve replications.

The colour of the dried apples was evaluated in three replications with the use of a reflective colorimeter Minolta CR–200. Results of measurements were presented as values of the following parameters: *L* (dark – light), *a* (redness – green) and *b* (yellowness – blueness).

In order to determine the significance of differences between mean values of the qualitative parameters assayed ($V_s$, WAC, DHC, RA, *L, a* and *b*), a one-way analysis of variance was carried out using the Duncan's test at a confidence level of α=0.05. The analysis of variance was carried out with ANOVA package of Statistica 7.1 software (Stat Soft Inc.).

## RESULTS AND DISCUSSION

### Kinetics of drying

The kinetics of apples drying with the convective method was depicted in Figure 1. The coefficient of determination $R^2$, determined for equation (1) describing a decrease in moisture content (*M*) of apples in the time of drying (*t*) reached a value of 0.99 at the following parameters: A=4.007, B=0.0179, C=1.929, and D=0.1198.

The process of apples finish-drying with the vacuum-microwave method (VM) was presented in Figure 2. Values of parameters A and B of the equation (2) describing apples

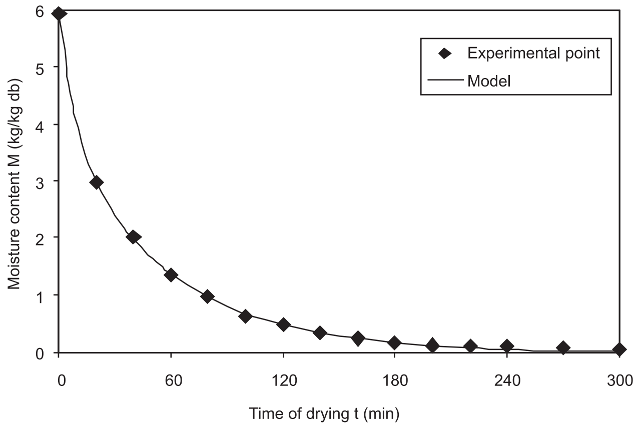


FIGURE 1. Kinetics of apple cubes drying with the convective method.

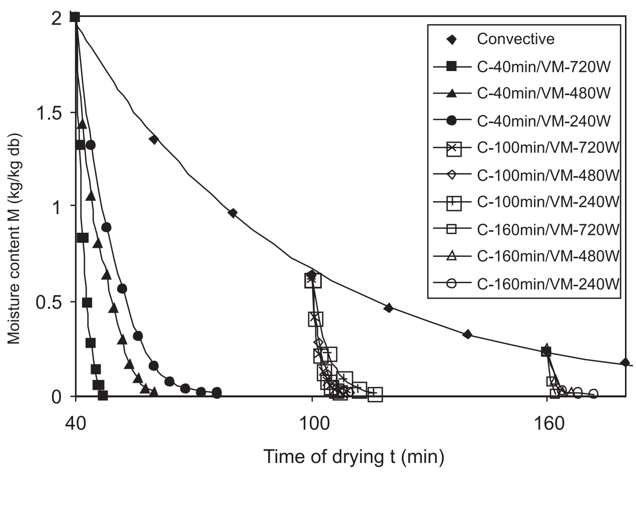


FIGURE 2. Finish-drying of apples with the vacuum-microwave (VM) method at microwave wattage of 240, 480 and 720 W previously pre-dried with the convective (C) method in time $t_i$ reaching 40, 100 and 160 min.

finish-drying with the VM method at high coefficients of determination were compiled in Table 1.

In the initial phase of drying with the convective method water loss is relatively rapid. Yet, during subsequent drying dynamics of water loss decreases and drying with that method begins to be time-consuming [Maskan, 2000]. Application of finish-drying with the VM method enabled considerable shortening of the total time of drying. The time of drying with the conventional method necessary to reach a moisture content of 0.05 kg/kg db by an apple sample reached *ca*. 300 min and was subject to a remarkable shortening (even to 50 min) at the application of VM finish-drying (at microwaves power of 720 W). The total time of drying was shorter once the VM drying was introduced earlier and the applied power of microwaves was higher. Increasing microwaves wattage from 240 to 720 W during apples drying with the VM method considerably increased the rate of drying and, consequently, shortened the time of drying from 43 to 16 min [Figiel *et al*., 2006].

### Drying shrinkage

The $V_s$ values of apple samples dried exclusively with the convective method and those pre-dried for 40, 100 and 160 min with the convective method and finish-dried with the VM method at microwaves power of 240, 480 and 720 W were collated in Table 2.

TABLE 1. Values of A and B parameters of functions describing the course of finish-drying with the VM method at various wattage of microwaves and times of pre-drying with the convective (C) method.

| Time of finish-drying/ Microwave wattage | Function parameters | | Determination coefficient $R^2$ |
|---|---|---|---|
| | A | B | |
| C-40 min/VM-720 W | 2.1 | 0.491 | 0.99 |
| C-40 min/VM-480 W | 1.997 | 0.158 | 0.99 |
| C-40 min/VM-240 W | 2.044 | 0.113 | 0.99 |
| C-100 min/VM-720 W | 0.695 | 0.552 | 0.99 |
| C-100 min/VM-480 W | 0.634 | 0.413 | 0.99 |
| C-100 min/VM-240 W | 0.616 | 0.245 | 0.99 |
| C-160 min/VM-720 W | 0.232 | 1.206 | 0.99 |
| C-160 min/VM-480 W | 0.247 | 0.547 | 0.99 |
| C-160 min/VM-240 W | 0.231 | 0.466 | 0.99 |

TABLE 2. $V_s$ values of apple sample dried exclusively with the convective method and those pre-dried for 40, 100 and 160 min with the convective method and finish-dried with the VM method using microwaves of 240, 480 and 720 W.

| Pre-drying time (min) | Microwave wattage (W) | | |
|---|---|---|---|
| | 240 | 480 | 720 |
| 40 | $0.42^{abAB}$ | $0.54^{aBC}$ | $0.58^{aC}$ |
| 100 | $0.53^{aA}$ | $0.53^{aA}$ | $0.61^{aA}$ |
| 160 | $0.5^{aA}$ | $0.53^{aAB}$ | $0.56^{aB}$ |
| Convection | $0.37^{b}$ | $0.37^{b}$ | $0.37^{b}$ |

The same lower cases in superscripts indicate a lack of significant differences (at a confidence level of $\alpha = 0.05$) between mean values of columns. The same upper cases in superscripts indicate a lack of significant differences (at a confidence level of $\alpha = 0.05$) between mean values in lines.

Drying shrinkage of apple samples dried with the combined method was substantially lower as compared with the samples dried only with the convective method. This was indicated by higher values of $V_s$ of samples finish-dried with the VM method. Smaller drying shrinkage of apples dried with the VM method, caused by the phenomenon of puffing, when compared with convective-dried apples was also observed by Sham *et al.* [2001]. The effect of microwaves on reduced drying shrinkage was also confirmed in the case of other biological materials [Durance & Wang, 2002; Lin *et al*., 1998; Maskan, 2001]. No significant effect of the time of convective drying on drying shrinkage was observed in the presented study. It turned out, however, that an increase in microwaves power during drying with the VM method caused an increase in $V_s$ and, consequently, a reduction in drying shrinkage. Statistically significant differences were noted in the case of samples pre-dried with the convective method for 40 and 160 min.

### Rehydration

Samples of apples dried with the combined method were characterised by a remarkably higher water absorption capacity (WAC) than the samples dried only with the convective method (Table 3).

Fruits and vegetables dried with the use of microwave energy usually demonstrate better rehydration properties than those dried only in air [Maskan, 2000; Khraishehn *et al*, 2004; Prabhanjan *et al.*, 1995]. It turned out that preliminary processing consisting in heating apples with the use of microwaves before convective drying also increased rehydration potential of the dried material [Funebo *et al*., 2000]. The presented study demonstrated that the method of drying and the applied parameters of the drying process did not exert such a significant effect on dry matter holding capacity (DHC) and rehydration ability (RA), (Table 3).

Though the samples pre-dried with the convective method for a shorter period of time and finish-dried at a higher wattage of microwaves were characterised by significantly higher DHC and RA as compared with the other samples dried with the combined method and those convective-dried. An increase of microwaves wattage usually caused a significant increase in values of all parameters of rehydration except for the samples that were pre-dried with the convective method for the longest period of time (160 min).

### Colour evaluation

Measurement of colour demonstrated that the process of drying, irrespective of the method applied, caused considerable darkening of apple cubes (a decrease of *L* parameter) and a shift of colour from green to red (an increase of *a* parameter) as well as negligible shift of colour from yellow to blue (a decrease of *b* parameter), (Table 4).

Both the method of drying and time of convective pre--drying in the combined method had no significant effect on the quality of dried material, however the samples dried with the VM method at the highest wattage of microwaves (720W) were generally darker than the other samples. The colour of samples finish-dried with the VM method was more shifted toward redness and blueness as compared with the samples dried exclusively with the convective method, yet the degree of

TABLE 3. Values of WAC, DHC and RA of apple samples dried exclusively with the convective method and those pre-dried for 40, 100 and 160 min with the convective method and finish-dried with the VM method using microwaves of 240, 480 and 720W.

| Pre-drying time (min) | Microwave wattage (W) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 240 | 480 | 720 | 240 | 480 | 720 | 240 | 480 | 720 |
| | WAC | | | DHC | | | RA | | |
| 40 | $0.62^{abA}$ | $0.7^{bB}$ | $0.75^{bC}$ | $0.20^{aA}$ | $0.23^{bB}$ | $0.24^{bC}$ | $0.13^{aA}$ | $0.16^{bB}$ | $0.19^{cC}$ |
| 100 | $0.66^{bcA}$ | $0.77^{cB}$ | $0.72^{bC}$ | $0.19^{aA}$ | $0.22^{bB}$ | $0.2^{aB}$ | $0.13^{aA}$ | $0.17^{bC}$ | $0.15^{bB}$ |
| 160 | $0.67^{cA}$ | $0.72^{bB}$ | $0.72^{bB}$ | $0.20^{aA}$ | $0.19^{aA}$ | $0.18^{aA}$ | $0.14^{aA}$ | $0.13^{aA}$ | $0.13^{abA}$ |
| Convection | $0.58^{a}$ | $0.58^{a}$ | $0.58^{a}$ | $0.19^{a}$ | $0.19^{a}$ | $0.19^{a}$ | $0.12^{a}$ | $0.12^{a}$ | $0.12^{a}$ |

The same lower cases in superscripts indicate a lack of significant differences (at a confidence level of α =0.05) between mean values of columns. The same upper cases in superscripts indicate a lack of significant differences (at a confidence level of α =0.05) between mean values in lines.

TABLE 4. Values of *L, a* and *b* of fresh apple samples, samples dried exclusively with the convective method and those pre-dried for 40, 100 and 160 min with the convective method and finish-dried with the VM method using microwaves of 240, 480 and 720W.

| Pre-drying time (min) | Microwave wattage (W) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 240 | 480 | 720 | 240 | 480 | 720 | 240 | 480 | 720 |
| | *L* | | | *a* | | | *b* | | |
| 40 | $45.2^{bA}$ | $43.8^{bA}$ | $35.4^{bB}$ | $4.73^{bA}$ | $4.39^{dAB}$ | $4.93^{bB}$ | $22.2^{abA}$ | $21^{abA}$ | $16.7^{cB}$ |
| 100 | $46.3^{bAB}$ | $44.3^{bA}$ | $49.1^{cB}$ | $3.99^{cA}$ | $2.6^{cB}$ | $2.83^{cB}$ | $20.7^{bA}$ | $20^{bcA}$ | $20.7^{bA}$ |
| 160 | $43.3^{bA}$ | $43.9^{bA}$ | $29.7^{dB}$ | $1.9^{dA}$ | $1.03^{bB}$ | $5.92^{dC}$ | $18.5^{cA}$ | $18.7^{cdA}$ | $15.6^{cB}$ |
| Convection | $42.6^{b}$ | $42.6^{b}$ | $42.6^{e}$ | $0.81^{e}$ | $0.81^{b}$ | $0.81^{e}$ | $17.5^{c}$ | $17.5^{d}$ | $17.5^{c}$ |
| Fresh | $84^{a}$ | $84^{a}$ | $84^{a}$ | $-4.96^{a}$ | $-4.96^{a}$ | $-4.96^{a}$ | $22.7^{a}$ | $22.7^{a}$ | $22.7^{a}$ |

The same lower cases in superscripts indicate a lack of significant differences (at a confidence level of α =0.05) between mean values of columns. The same upper cases in superscripts indicate a lack of significant differences (at a confidence level of α =0.05) between mean values in lines.

shift was increasing along with shortening time of pre-drying with the convective method. The wattage of microwaves in finish-drying of the samples with the VM method had not such a tangible effect on the values of *a* and *b* parameters. Surprisingly, low values of *L* and *b* parameters as well a high value of *a* parameter for the sample pre-dried with the convective method for 160 min and finish-dried with microwaves of 720 W may point to changes resulting from too high temperature evoked by the action of microwaves at the end of finish-drying when water content of the material was low [Drouzas & Schubert, 1996].

## CONCLUSIONS

1. Kinetics of apple cubes drying with the convective method may be described by means of an equation consisting of two exponential components, whereas kinetics of finish-drying with the VM method – with the use of simple exponential function.

2. Finish-drying of the apples with the VM method preliminary dried with the convective method considerably shortens the total time of drying and reduces drying shrinkage. The time of drying is shortening along with earlier introduction of VM drying, and with a higher wattage of microwaves applied. In turn, drying shrinkage decreases along with increasing power of microwaves.

3. Apple cubes dried with the combined method demonstrate substantially higher water absorption capacity than those dried exclusively with the convective method. At an increased power of microwaves, short-term convective pre-drying and finish-drying with the VM method improves dry matter holding capacity and rehydration ability of dried apples.

4. The process of drying results in the darkening of apple cubes and in the shift of colour from green to red as well as a negligible shift of colour from yellow to blue. The colour of samples finish-dried with the VM method was more shifted towards redness and blueness as compared to the samples dried only by means of convection, yet the degree of colour shift was increasing along with shortening the time of pre-drying with the convective method.

## ACKNOWLEDGEMENTS

The study was financed by the Ministry of Science and Higher Education under grant No. N312 031 32/2036 in the years 2007-2009.

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## SUSZENIE JABŁEK PRZEZ POŁĄCZENIE METODY KONWEKCYJNEJ I MIKROFALOWEJ W OBNIŻONYM CIŚNIENIU

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Kostki jabłek wysuszono metodą konwekcyjną w strumieniu powietrza o prędkości 4m/s i temperaturze 55°C oraz metodą łączoną polegającą na podsuszeniu jabłek metodą konwekcyjną i dosuszeniu metodą mikrofalowo-próżniową (VM). Czas podsuszania konwekcyjnego wynosił: 40, 100 i 160 minut, a moc mikrofal 240, 480 i 720 W. Do pomiaru skurczu suszarniczego użyto cylindra pomiarowego wypełnionego siemieniem lnianym, a rehydrację wysuszonego materiału przeprowadzono w wodzie destylowanej o temperaturze 21°C. Ocenę barwy przeprowadzono na podstawie wyników uzyskanych przy użyciu kolorymetru odbiciowego. Kinetykę suszenia kostek jabłek metodą konwekcyjną opisano przy użyciu funkcji wykładniczych. Dosuszenie jabłek metodą VM wstępnie podsuszonych metodą konwekcyjną znacznie skróciło całkowity czas suszenia i zmniejszyło skurcz suszarniczy. Kostki jabłka wysuszone metodą łączoną wykazywały lepsze właściwości rehydracyjne wyrażone zdolnością absorpcji, zdolnością utrzymania suchej masy i zdolnością rehydracji niż wysuszone wyłącznie metodą konwekcyjną. Suszenie spowodowało pociemnienie kostek jabłek oraz przesunięcie barwy od zielonej do czerwonej i nieznaczne przesunięcie barwy od żółtej do niebieskiej. Kolor próbek dosuszonych metodą VM był bardziej przesunięty ku czerwieni i niebieskości w porównaniu z próbkami wysuszonymi jedynie w konwekcji.