Please cite as: Inż. Ap. Chem. 2016, 55, 5, 203-204

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Non-stationary convective drying assisted with microwaves and ultrasound

Introduction

Convective drying is commonly used in the food industry, but it is also characterized by low drying performance and high operating costs. Combination of various drying techniques like convection, microwaves, ultrasound, etc. as well as its periodical application can contribute to higher drying performance, lower energy consumption and better product quality. Non-stationary drying called as *intermittent drying* is based on changes in drying conditions, e.g., temperature [*Chua et al., 2003; Kowalski et al., 2013*]. Microwave drying reduces total drying time and food product oxidation, but high power ultrasound causes various phenomena such as heating of the material, micro-vibrations and air turbulences near the material [*Kowalski and Pawłowski, 2015*]. Many experimental investigations have shown that integration of different drying techniques results in higher quality, shorter drying time and energy savings. However, there is little information in literature on hybrid drying carried out in intermittent mode. Therefore, the aim of the study was to analyze the effect of convective-intermittent drying with microwaves and ultrasound on drying kinetics, energy and quality aspect of dried biological material.

Material and methods

Apricots (*Prunus armeniaca* L.) var. '*Orangered'* were used in the drying tests. The fruits are very attractive, yellow-orange, medium juicy and aromatic. Before drying the apricots were washed, drained, deprived of kernels and cut into 8 quarters. The samples of approx. 80 g and moisture content of 0.86 kg/kg w.b., were placed on the pan, skin-side down, and dried to a final moisture content of 0.02 kg/kg w.b. Four drying programs were carried out, including convective drying as a reference (Tab. 1). The basis for all hybrid programs was continuous CV or CVUS drying with MW ON/OFF cycles applied at the beginning of each drying test. Experiments were carried out in duplicate, and the results were averaged for data interpretation.

Tab. 1. Drying tests

No.	Drying program	Description
1	CV	Convective drying
2	$CVUSMW_{5\text{-}30}$	Convective-ultrasound drying with intermittent application of microwaves (5 min ON and 30 min OFF)
3	$CVUSMW_{5\text{-}30(IV)}$	Convective-ultrasound drying with intermittent application of microwaves (5 min ON and 30 min OFF/IV cycles)
4	$CVMW_{5\text{-}30(IV)}US$	Convective drying with intermittent application of microwaves (5 min ON and 30 min OFF/IV cycles) followed by convective-ultrasound final drying

The drying tests were carried out in an innovative laboratory hybrid dryer equipped with magnetron and airborne ultrasound generator. The apparatus allows drying with the use of convection, microwave radiation and ultrasound separately or simultaneously. The process parameters were as follows: air temperature T_a = 60°C, air velocity v_a = 0.4 m/s, microwave power (MW) of 100 W and ultrasound power (US) of 200 W. The initial moisture content was calculated on the basis of fresh material dried for 24 h at 60°C in the chamber dryer, model SN75 (*Memmert,* Germany). The moisture content *X* kg/kg w.b. was determined according to equation:

$$X = \frac{m_t - m_d}{m_0} \quad (1)$$

where:
m_t – sample mass determined at time *t*, [kg]
m_d – mass of the dry sample, [kg]
m_0 – initial mass of the sample, [kg]

The total energy consumption *EC* is defined as the sum of electric energy in kWh consumed in drying process by the hybrid dryer and control equipment. The specific energy consumption *SEC* in kWh/kg is the ratio of the *EC* to the amount of water removed by drying m_w kg:

$$SEC = \frac{EC}{m_w} \quad (2)$$

The quality of apricots was assessed by the total color change, water activity and ability to rehydration. The total color change ΔE between fresh and dry apricot was measured using a colorimeter, model CR-400 (*Konica Minolta*, Japan), and indicated by CIE *L*a*b** color space:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3)$$

where:
L^* – lightness, [-]
a^* – color parameter from red to green, [-]
b^* – color parameter from yellow to blue, [-]

Water activity a_w was measured before and after drying experiments with the *LabMaster-aw Standard* (*Novasina AG*, Switzerland). The dry product ability to rehydration (water absorption) was tested in a 500 mL beaker containing 150 mL of distilled water by boiling one sample for 5 min. *RR* was calculated according to equation:

$$RR = \frac{m_R}{m_{BR}} \quad (4)$$

where:
m_R – mass of the rehydrated sample, [kg]
m_{BR} – mass of the sample before rehydration, [kg]

Results and discussion

The non-stationary convective drying was assessed in terms of drying kinetics, on the basis of drying and temperature curves. At first, the CV process was carried out, and then the hybrid-intermittent tests assisted with MW and US were performed (Fig. 1). The CV drying was found to be the longest process as the apricots achieved the final moisture content after about 920 min. The results of hybrid-intermittent drying, showed a significant reduction in drying time, namely between 60-80%, in comparison to the CV drying.

Each pulse of MW "pumped" moisture to the material surface, in turn the ultrasound heated slightly the material surface and enhanced the moisture removal from biological tissue. The shortest drying time (by about 80%) was observed for the $CVUSMW_{5\text{-}30}$, i.e.,

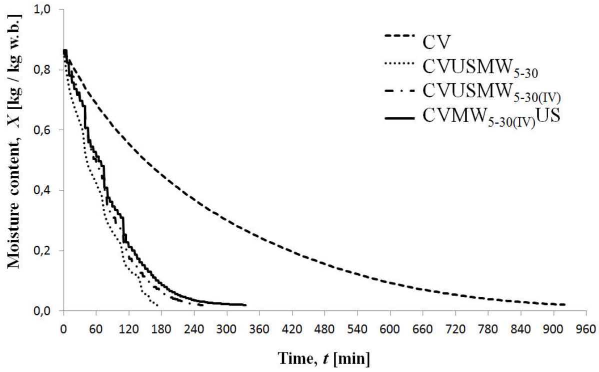

Fig. 1. Drying curves

175 min, on average. When the combination of CV, US and 4 cycles of MW radiation were used (CVUSMW$_{5\text{-}30(IV)}$), the overall drying time reduced to 255 min, which means a 72% decrease, as compared to CV drying. Furthermore, it was found that intermittent drying with US-assisted final drying (CVMW$_{5\text{-}30(IV)}$US) lengthened the drying time as compared with the previous non-stationary processes. In this case, the total drying time was 334 min, on average. Fig. 2 shows the variation of material temperature during drying.

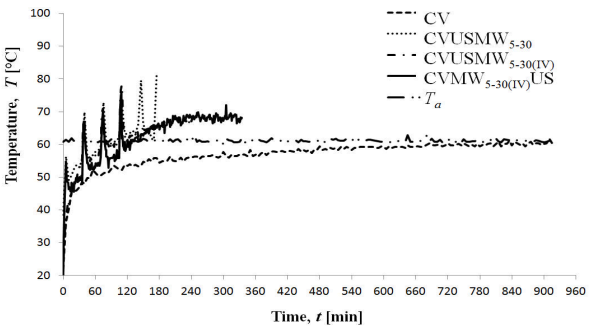

Fig. 2. Temperature curves

During CV drying, the material temperature was lower than air temperature for a long time. A comparison of CV with hybrid-intermittent processes has shown that periodical MW as well as US application have a strong impact on the temperature profile. Intermittent drying causes a temporary material temperature increase (max. to 80°C) and decrease. Such temperature variations depend on the heat source used in drying program as well as its duration.

Tab. 2 presents the total energy and the specific energy consumed in different drying processes.

Table 2. Total energy *EC* and specific energy consumption *SEC*

No	Drying program	*EC* kWh	*SEC* kWh/kg
1	CV	9.03 ± 0.18	137.17 ± 2.74
2	CVUSMW$_{5\text{-}30}$	3.02 ± 0.06	46.55 ± 0.93
3	CVUSMW$_{5\text{-}30(IV)}$	5.05 ± 0.10	74.76 ± 1.49
4	CVMW$_{5\text{-}30(IV)}$US	5.62 ± 0.11	83.17 ± 1.66

The highest *EC* and *SEC* were obtained for the CV drying. The total energy and specific energy consumption were definitively lower for all the hybrid-intermittent processes, i.e., in the range of 38-66%, as compared to CV drying. The lowest values of these parameters were noted for the CVUSMW$_{5\text{-}30}$. It was found that energy consumption is proportional to the total drying time.

Fig. 3 presents the results of the total color change ΔE between fresh and dry apricots. The highest total color change, i.e., 22.71 ± 0.96, was observed after CV drying. In this case, discoloration of apricots was due to long processing with a hot air that resulted in degradation of natural dyes. The samples dried with US and MW application were characterized by lower ΔE, but the best dry product from the color viewpoint was obtained after convective-ultrasound drying with intermittent MW (CVUSMW$_{5\text{-}30(IV)}$), i.e., 8.84 ± 0.44.

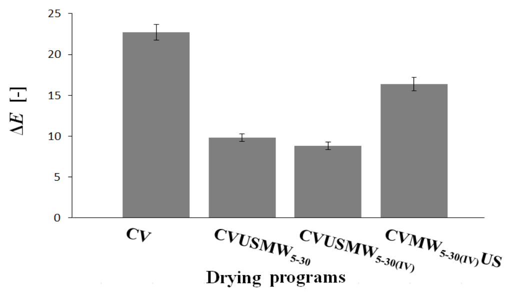

Fig. 3. Total color change (ΔE)

The next, very important quality factor was water activity a_w (Fig. 4), as one of the measurements to verify the dried product stability, e.g., development of microflora.

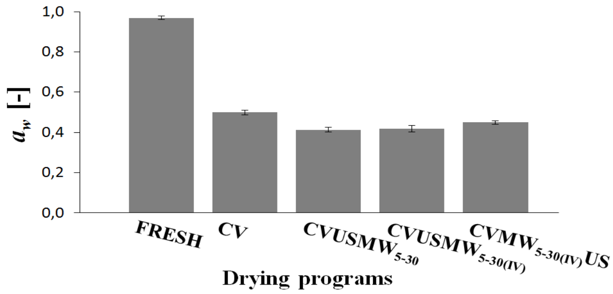

Fig. 4. Water activity (a_w)

The results showed a significant decrease in a_w, as compared to fresh apricot, the value of which was 0.969 ± 0.009. After each drying process the value of a_w was less than 0.6, thus the microbial growth was inhibited and biologically stable products were obtained. However, for all the samples dried by hybrid-intermittent programs water activity was lower than for the CV drying.

The last parameter was rehydration ratio *RR* (Fig. 5). Rehydration, as a reverse process to dehydration, shows the degree of structure damage after drying.

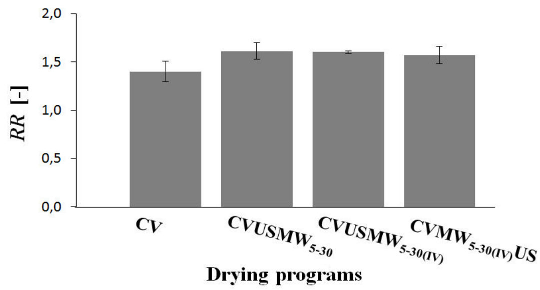

Fig. 5. Rehydration ratio (*RR*)

The lowest ability to rehydration was observed for the CV. Its *RR* value of 1.40 ± 0.11 shows a destructive influence of this drying method, e.g., material shrinkage and pores closure. Because the apricots dried in hybrid-intermittent processes reached a higher *RR*, as compared to the CV, these products were characterized by a better preserved structure. Moreover, no major differences were found between different intermittent drying tests.

Conclusions

The results of hybrid-intermittent drying of apricots showed that application of microwaves and ultrasound in convective drying improves drying kinetics and is beneficial from the final product quality point of view, as it provides smaller change of color, safe level of water activity and better rehydration. Such benefits appear to be of interest to dryer manufactures and food producers.

LITERATURE

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ACKNOWLEDGMENTS

This study was conducted as a part of research project No. 2014/15/D/ST8/02777 sponsored by the National Science Center in Poland.