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INFLUENCE OF ULTRASOUND ASSIST DURING HOT AIR DRYING ON PROPERTIES OF DRIED APPLE CRISPS

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In this paper the influence of high power airborne ultrasound on drying biological material (Lobo apple) properties is considered. Apple samples were dried convectively at 75 °C and air flow of 2 m/s with and without ultrasound assist at 200 W. During experiments, sun-drenched and not sun-drenched part of fruits were considered separately to show, how the maturity of the product influences dry material properties. Dried apple crisps in a size of small bars were subjected to compression tests during which acoustic emission (AE) was used. Analysis of AE and strength test results shows that correlations between received acoustic signals and sensory attributes (crispness, brittleness) of dried apples can be found. It was noted that ultrasound improved fruit brittleness in comparison with pure convective processes, where fruit maturity determines a kind of destruction and behaviour of dried apple crisps.

Keywords: ultrasound drying, compression test, acoustic emission, apple, material properties

1. INTRODUCTION

Convective drying as easy to control technique with low investment costs is commonly used and allows to achieve good quality of dried products including sensitive materials like bio-products. However it is a very time-consuming process which influences also quite high treatment costs. Therefore there are lot of efforts to shorten such process while maintaining the adequate quality and reducing energy costs.

Sometimes one uses an opposite advanced drying technique, which are often based on different physics laws (e.g. microwave drying). Nevertheless, in many cases, not using opposite drying techniques to convective one, but a combination of such methods with convective drying gives better results of final product quality and simultaneously can lead to reduction of drying time and its costs (Chou and Chua, 2001; Chua, 2013). Such synergistic effects can be achieved only in hybrid drying (e.g. microwave-convective, convective-infrared, ultrasound-convective drying etc.).

It can be found in literature that ultrasound can be used during dewatering of bio products in different ways. Most researchers consider using ultrasound in water environment during pre-treatment or osmotic dehydration (Rodrigues et al., 2009; Shamaei et al., 2012), where the minor part of literature is focused on ultrasound wave propagation in the air or ultrasound transfer by contact (Kowalski and Pawłowski, 2015; Sabarez et al., 2012). Ultrasound can improve drying rate and positively influence material quality like nutrient preservation, reduction of colour change etc. (Fabiano et al., 2015; Gamboa-Santos et al., 2014). As most of researchers are focused on preserving chemical composition of biomaterials and their health

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properties during drying, only some of them take into account also their textural and mechanical properties as equally important for the final consumer (Zdunek et al., 2010). The TPA method using double stage compression tests is the most common one to determine material textural properties such as hardness, springiness, crispness, cohesiveness but there are also other methods. One of them is acoustic emission which is based on capturing and processing of sounds generated by the material during mechanical tests. Researchers show, that investigation of acoustic descriptors collected during experiments can be successfully used to determine bio-product structural parameters as also the sensory attribute determined during TPA tests, as there is a dependency between product character, e.g. crispness and the noises generated by them (Carsanba et al., 2018; Gregersen et al., 2015; Piazza and Giovenzana, 2015). Thus why monitoring of acoustic descriptors could be a good alternative to TPA tests which are performed only in limited range of compression determined for given investigated products.

Considering the above mentioned possibilities, this work deals with the experiences concerning hybrid ultrasonic-convective drying, where especially influence of ultrasound on mechanical and acoustical properties of dried apples is considered.

2. MATERIAL AND METHOD

Fresh apples, Lobo type (*Malus domestica 'Lobo'*),were bought in a local market and stored at 5 °C for 24 h so the whole material would achieve equal initial parameters before experiments. Next, the apples were cut axially around the nest seed into 10 mm diameter bars, separately for sun-drenched and not sun-drenched side of fruit and further the bars were cut into 16 cylinder samples 10 mm high. The average initial moisture content for fresh apples taken to the experiments was $85.65\% \pm 0.52\%$ and was evaluated with Precisa XM120 moisture analyser as also by drying samples in a chamber dryer for 24 h at 70 °C.

Drying processes were carried out in a hybrid dryer presented in Figure 1, which allowed to use different sources of energy simultaneously including hot air, microwave and airborne ultrasound. All of the process parameters including; inlet and outlet temperature and humidity, sample mass and temperature, ultrasound and microwave energy were controlled constantly during the process and collected in 5 minutes intervals on a personal computer.

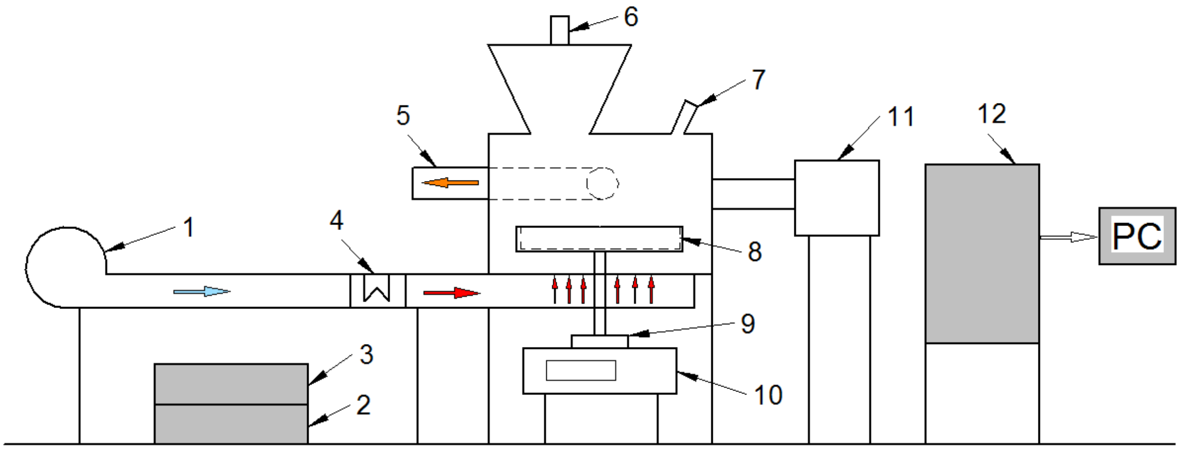

Fig. 1. Hybrid drier: 1 – fan, 2 – amplifier, 3 – ultrasound generator, 4 – air heater, 5 – air exhaust, 6 – ultrasound transducer, 7 – IR temperature probe, 8 – tray, 9 – tray rotation mechanism, 10 – balance, 11 – microwave generator, 12 – control cabinet

Experiments were done in two series for convective drying with and without ultrasound assist where apple parts with higher and lower sun dose were considered separately. Drying tests were conducted at temperature 75 °C and air flow of 2 m/s, where during ultrasound assist constant power of 200W was supplied. All processes were carried out until the moisture content in dried samples dropped below 2%. Dry samples after each process, were instantly placed in a sealed container at room temperature, where they were stored for 24 h, which allowed to achieve uniform temperature and moisture distribution in the material before making any further mechanical tests. Next the dried apple bar samples were subjected to compression tests on universal strength machine COMTECH additionally equipped with the acoustic emission (AE) set. AE broadband sensor with a frequency range of 5 kHz – 500 kHz was attached to stationary clamping head of strength machine and acoustic signals were collected during mechanical tests by AMSY-5 VALLEN system as a package of total amount of energy and signals in 300 ms time laps. Before the strength test, a few cycles imitating the compression tests without the samples were performed to eliminate the environment noises, which could affect the appropriate measurement results. The compression test was carried out with constant compression speed set on 20 mm/min.

3. RESULTS AND DISCUSSION

The experiments carried out for sunlit and not sunny part of apples did not show any difference in drying kinetics under chosen drying conditions. As the fruit maturity does not affect the drying kinetics, the kinetics for sunny and not sunny apple parts will not be considered separately. The process kinetics will be compared only in terms of the used conditions and not the maturity of the samples. A comparison of pure convective processes with those assisted with ultrasound, presented in Fig. 2, shows that acoustic energy increased the drying rate and at the same time shortened overall drying time. There could be different reasons for drying time reduction like e.g. reduction of heat and mass transfer resistance caused by vibration of the air near the sample as also the sample itself, the increase of water evaporation from the sample surface caused by water atomization by ultrasound and destroying thin liquid film on sample surface, etc. However the total reduction of drying time is not significant and in case of ultrasound assisted drying it reaches only about 8% in comparison with pure convective processes.

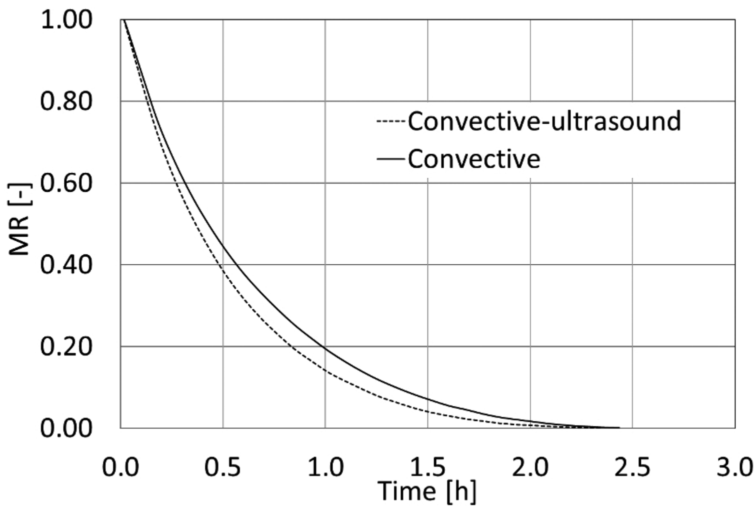

Fig. 2. Drying curves for pure convective and ultrasound assisted drying

Such small reduction of drying time in comparison with other works (Kowalski and Pawłowski, 2015) may results from high drying temperatures where air has lower density and sound attenuation is greater and also from high air velocity in direction opposite to acoustic wave.

As ultrasound has influence on kinetics of drying processes, this acoustic wave has also impact on the structure of dried material which manifest itself by mechano/acoustic changes of examined material. The change of the product structure is confirmed by the results of compression tests of dried apple crisp samples presented in Fig. 3.

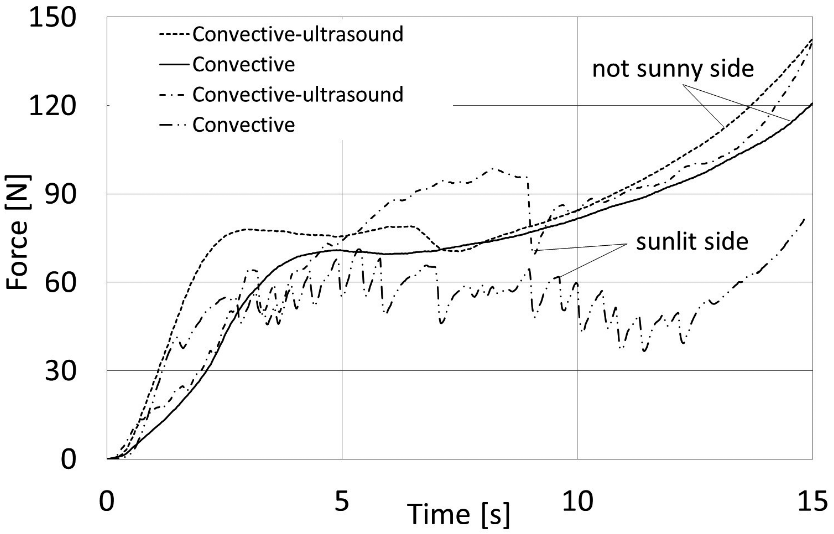

Fig. 3. Compression tests – different fracturing behaviour of apple crisps dried by convective and ultrasound-convective method

One can observe differences in kinds of sample destructive behaviour between pure convective and ultrasound aided drying methods. For both drying methods, samples taken from the sunlit side of apples showed a tendency to be brittle and crisp. Pure convective dried apples are rather crisp (Fig. 3), as there are lots of small cracks connected with step by step progressive collapsing of dried tissue under influence of increasing compression force. In comparison, ultrasound dried apples are generally more prone to single cross-sectional cracking of material skeleton than convective dried ones, which means that they will have more brittle than crispy character.

As the maturity of samples was also considered as a factor that could influence product properties, it is shown that it has significant impact on properties of dried apple crisps. The samples prepared from the not sunny side of apples are generally damaged in a typical elastic-plastic way, without any visible cracks during compression test (Fig. 3). The compression curves do not show any rapid changes in load during tests and only typical elastic properties are observed in the initial part of tests. After that the character changes into typical plastic one where compression curve is almost flat. In the final period, after about 7 seconds of the process, the observed character changed again and became elastic-plastic one for the rest of the measurement.

AE method shows that acoustic activity during compression tests is strictly connected to cracking phenomena of examined apples which is reported also by other researchers (Zdunek et al., 2010). Figure 4 presents the count rate of acoustic signals (the number of AE counts generated during a specified unit of time) and the signal energy collected during compressive strength test carried out for the samples prepared from the sunlit side of fruit. Many AE signals (on average about 4500 per time unit) during the whole test can be observed for convectively dried samples. These signals are mainly associated with collapsing of brittle apple tissue subjected to compression forces but also with friction between moving outer cell walls. Most of these signals have low energy which points to a slow gradual degradation of the dried apple structure. Nevertheless, some of the AE counts are highly energetic (tall bars in Fig. 4) which means that small cracks expand into larger ones causing higher destruction of a sample.

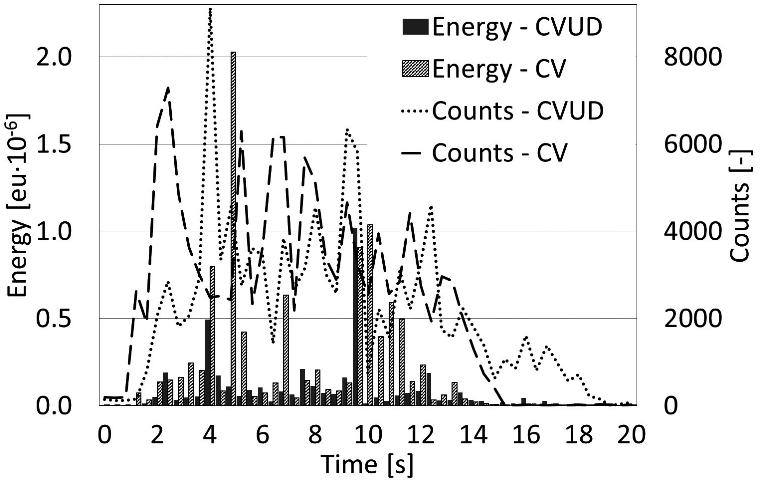

Fig. 4. Acoustic emission generated during compressive strength test for sunlit side sample

In Fig. 4 also the AE signals collected during compressive strength test for convective-ultrasound process are shown, where the number of AE signals is slightly smaller than in case of convective drying. The average AE count rate is at 3500 signals per time unit level, although there are also a few moments when their number deviates significantly (they are higher) from the average level. These AE descriptors are commonly regarded as being equivalent to stresses indicated in the samples. One can observe that at about 4th and 9th seconds of the strength test, the AE count rate is rising and then abruptly decreases to lower levels. Almost at the same time AE energy of signals starts rising, where such phenomena is typical for materials subjected to increasing external forces generating an increasing stress state. Induced stress state in the material reaches the highest value when the material strength is attained, just before the crack occurs and irrepressibly propagates which follows in releasing of internal body energy. After that the stress relaxation in the sample is observed, although instantly moving strength machine head goes to the next apple structure resistance and stresses arise again. One can observe clearly such phenomena as a sudden lowering of compressive force in Fig. 3 (ultrasound-convective processed sample) and AE descriptors in Fig. 4 between 3rd and 5th second and between 8th and 11th second of strength test. It confirms that the AE signals generated by the material are strictly connected with damage crack initiation and propagation.

In contrast, for the non-crispy samples (not sunny side of apple) one can observe very few AE descriptors collected during compressive strength test (Fig. 5). For the convective-ultrasound process, the average AE count rate reaches 1000 signals per time unit and the energy of these signals is very low. Such results from

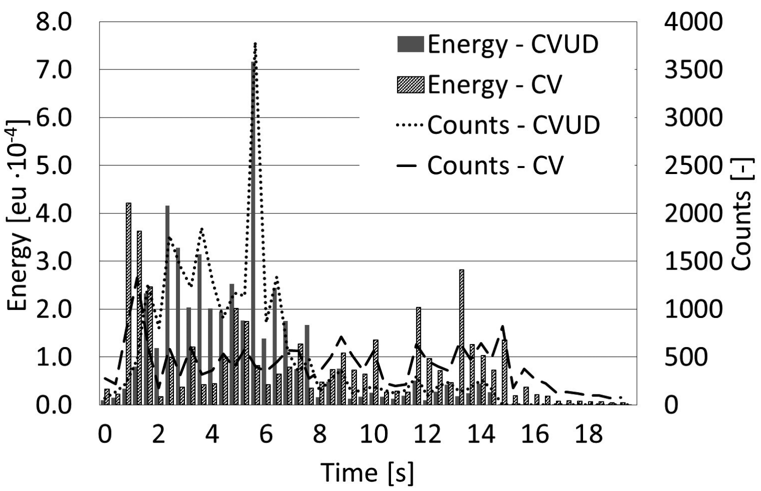

Fig. 5. Acoustic emission generated during compressive strength test for not sunny side sample

the AE confirm rather elastic than brittle character of sample tissue as lower intensity of acoustic signals can be explained by phenomena related to high attenuation of the AE signals in the elastic and plastic materials. The other reason for low number of AE signals and low energy of those signals is also lack of cracks or fractures.

Similar behaviour to samples dried with ultrasound application is observed for compressive strength test carried out for purely convective dried material. AE for such a process shows that the average number of AE count rates reaches only slightly above 500 signals per time unit. This fact connected with a very low AE energy collected during compressive test is confirmed by even more elastic and plastic behaviour of the material in comparison with the samples dried with ultrasound assist.

When analysing the AE count rate and AE energy descriptors one can find correlations between received acoustic signals and sensory attributes (crispness, brittleness) of dried apples, which is confirmed also in the literature (Carsanba et al., 2018; Zdunek et al., 2010). Brittle materials are more acoustical opposite to elastic and plastic ones. Thus why also the comparison and evaluation of mechanical and textural properties on the base of summary amount of given acoustic descriptors can be performed. Such summarizing of the results is presented in Table 1. The results clearly present and confirm that the mature part of fruit is more acoustic material as it generates in total a few times higher AE energy with only about three times higher amount of counts. This means that average energy of one signal is even six times higher for sunlit samples in comparison with not sunny ones. Nevertheless ultrasound assist diminishes the difference in the average energy of the signal between those samples and shows only about 50% higher average signal energy in case of mature material. However decrease does not affect the product behaviour. Taking into account described above changes it is necessary to evaluate the behaviour of the product based on the summary quantitative AE descriptors very carefully as their values do not always reflect the real properties of a dry product. A significantly more accurate method is the evaluation of the product texture based on the progress of AE descriptors in time.

Table 1. Acoustical properties of samples dried in different condition

Process type	Side of apple	Total AE energy	Standard deviation	Total AE counts	Standard deviation
Convective	Not sunny	5.98×10^5	1.1×10^5	2.73×10^4	0.45×10^4
Convective-ultrasound	Not sunny	4.39×10^5	0.18×10^5	2.15×10^4	0.29×10^4
Convective	Sunlit	93.2×10^5	7.1×10^5	7.31×10^4	2.4×10^4
Convective-ultrasound	Sunlit	23×10^5	0.3×10^5	7.41×10^4	1.6×10^4

Taking into account all examined apple crisps one can notice that ultrasound-convective dried apples achieve slightly higher values of compressive strength and elastic modulus than convectively dried ones. Those parameters were determined and presented in Table 2 for less mature dry apple samples with typical elastic-plastic properties during compression tests. In case of well ripe apple samples with not uniform material destruction (brittle/crispy character) and many small cracks just from the beginning of compression test, determination of Young's modulus and compressive strength was not reliable.

Table 2. Mechanical properties of dried apple crisps

	Young Modulus [MPa]	Compressive strength [kPa]
Convective dried samples	42 ± 16	764 ± 137
Ultrasound/convective dried samples	59 ± 12	917 ± 108

4. CONCLUSION

The influence of ultrasounds on drying of apple crisps was analysed. Due to ultrasound assist the overall drying process time can be reduced, although in considered cases drying time did not depend on apple maturity. The performed strength tests demonstrate the influence of acoustic wave energy on mechanical and acoustical properties of dried crisps. Ultrasound dried crisps are more brittle although less crisp than the convective dried ones. It is evident especially for well ripe apples which after drying returned more brittle/crispy fracturing than less mature ones in which only plastic damage took place. Nevertheless, in case of all samples processed with ultrasound the global tendency to improve material strength is observed where its value can be up to almost 20% higher than for samples dried convectively. Considering the overall characteristic of dried samples it can be stated that fruit maturity has significant influence on the kind of destruction and behaviour of dried apple crisps. The more mature apples are subjected to drying the more brittle/crispness properties they will have as a dry product. For the fruit of the same maturity, the drying method will not affect the changes of the dry product characteristic properties.

AE method is useful in finding crispness and brittleness or plastic behaviour of dried apples, where AE signals are strictly connected with damage crack initiation and propagation, during strength tests. Crispy products observed for mature part of apple generates over an order of magnitude higher acoustic energy than elastic-plastic ones. Together with almost three times higher number of AE signals in case of sunlit part of fruit, such measurement after initial calibration for given material type determination could be used as a non-destructive method used during evaluation and control of product quality. High power acoustic wave can generally influence material strength and Young's modulus and increase the values of those parameters in comparison with samples dried convectively. Ultrasound assist should be seriously considered as a possible method for improving the crispy properties of processed bio-products.

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