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ULTRASOUND-ASSISTED OSMOTIC DEHYDRATION AND CONVECTIVE DRYING OF APPLES: PROCESS KINETICS AND QUALITY ISSUES

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The aim of the present theme issue was to study the influence of ultrasound enhancement on the kinetics of osmotic dehydration and the effect of convective drying from the point of view of drying time and quality of dried products. Apple fruit was used as the experimental material. The kinetics of osmotic dehydration with (UAOD) and without (OD) ultrasound enhancement were examined for 40% fructose and sorbitol solutions. The effective dehydration time of osmotic process was determined. Preliminary dehydrated samples with OD and UAOD were next dried convectively with (CVUS) and without (CV) ultrasound assistance. The influence of OD and UAOD on the kinetics of CV and CVUS drying was analysed. The parameters of water activity and colour change were measured for the assessment of product quality after drying process.

Keywords: osmotic dehydration, ultrasound, drying, kinetics, product quality

1. INTRODUCTION

Among different techniques used to preserve biological foods, the treatment with hypertonic solutions is the oldest and but still commonly used method in food processing. This kind of treatment induces changes in bio-product composition and reduces the amount of moisture, being favourable to product degradation, enzyme reactions and microorganism growth (Cárcel et al., 2007). Properly conducted osmotic pretreatment allows to minimise negative effects of drying such as loss of flavours, colour degradation, shrinkage or deformations etc. (Kowalski and Mierzwa, 2013).

The crucial factor which hampers mass transfer during OD is fruit epidermis. Due to its low permeability the barrier to the osmotic solution, both water and substances dissolving in vacuolar sap increases (Kucner et al., 2013). Because of the slowness in solid–liquid mass transfer, several methods have been considered to accelerate the kinetics of this process (Cárcel, et al., 2007; Rastogi et al., 2002), among others the application of pulsed vacuum (Escriche et al., 2000), centrifugal forces (Azuara et al., 1996), electrical fields (Ade-Omowaye et al., 2003; Rastogi et al., 1999) or high intensity ultrasound (Cárcel, et al., 2007; Kowalski and Szadzińska, 2014; Mulet et al., 2003; Siucińska and Konopacka, 2014).

The use of ultrasound to improve mass transfer in fruit dehydration can be direct or indirect. Especially fruits require pretreatment with osmotic solution for water removal. When ultrasound is directly applied to a hypertonic solution with immersed samples, and there is no such a barrier as a probe system, strong cavitation near the tip of the probe may generate free radicals being detrimental to foods. The ultrasonic

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probe can deliver about 100 times much higher of US intensity than an ultrasonic bath (Kek et al., 2013; Santos et al., 2009). For indirect sonication of food placed in the ultrasonic water bath, the ultrasound is transferred through water and affects the food immersed in the bath. The ultrasound applied to the bath with food first passes through the walls of the container, therefore its intensity inside the bath is lower than that of the ultrasound source (Feng and Yang, 2010; Kek et al., 2013; Santos et al., 2009).

Studies on osmotic dehydration and ultrasound assisted osmotic dehydration have shown that different fruits respond differently to the application of this pretreatment method (Rodrigues et al., 2009). Studies with melons showed that ultrasound caused elongation of cells, which resulted in an easier path for water diffusion (Fernandes et al., 2008a; Rodrigues and Fernandes, 2007). The effect of ultrasound on papaya showed that microscopic channels were produced because of adhesion loss between cells, however, the short length of the microscopic channels did not improve much the effective diffusivity of water in papayas (Fernandes et al., 2008b). In pineapple, the ultrasonic pretreatment induced the formation of long microscopic channels, while application of ultrasound-assisted osmotic dehydration provoked the breakdown of cells (Fernandes et al., 2009; Rodrigues, et al., 2009).

The presence of intercellular spaces in fruits such as apples is characteristic for the parenchymatical tissue (Simal et al., 1998). According to Fito (1994) the pore volume represents ca. 20% of the total apple volume. These pores are assumed to be occupied by gas, which can be removed by the application of low pressure as in vacuum osmotic dehydration (Shi and Fito, 1994). A reduction in pressure causes pore expansion and thus the gas occluded in the pores escapes. When pressure is restored, pores can be occupied by the osmotic solution, thus increasing the mass transfer. This phenomenon has been named the hydrodynamic mechanism of mass transfer (Fito and Pastor, 1994). When ultrasound is applied to an osmotic system, similar effects could be obtained. This would explain the increase in mass diffusion when sonication is used (Simal, et al., 1998).

The aim of the present study was to analyse the influence of ultrasound enhancement on the kinetics of osmotic dehydration and on the effect of convective drying such as drying time and dried product quality. Kinetics of osmotic dehydration with ultrasound enhancement (UAOD) and without ultrasound enhancement (OD) were examined to find out the effective time of dehydration. Influence of OD and UAOD pretreatments on the kinetics of convective (CV) and convective-ultrasound (CVUS) drying was analysed and the quality of obtained products was assessed.

2. MATERIAL AND METHOD

2.1. Material

Apples (*Malus Domestica* var. Rubin) from a local market were used as the experimental material. The raw material was stored at the temperature of 277 K, at least for 24 h, to stabilise its humidity and temperature. Before processing, each apple fruit was washed, peeled and sliced with a ceramic knife to prevent reactions between metal and biological material. Next, 8 cylindrical samples of diameter 0.035 m and 0.005 m high (total mass of ~0.033 kg) were cut from prepared slices, with a polypropylene form. The samples prepared in this way were dehydrated with osmotic solutions and dried convectively.

2.2. Osmotic dehydration

Osmotic dehydration was performed with aqueous solutions of analytically pure fructose or d-sorbitol in one concentration (Cp = 40% w/w). The solutions were prepared in a room temperature (294 K) by mixing (for 10 min) the predetermined amount of osmotic agent with distilled water. The ratio of solution to sample mass was at least 4:1 to avoid the dilution effect. A given volume (200 mL) of the solution was poured into a transparent container (600 mL), which was next placed in a water bath for 15 min to stabilise the temperature. The apple samples were weighted using the laboratory balance model AJH-2200CE (10^{-5} kg precision) produced by Vibra/Shinko Denshi (Japan) and then immersed in an osmotic solution. In the first part of research the kinetics of simple osmotic dehydration (OD) and ultrasound-aided osmotic dehydration (UAOD) were determined. For this purpose the samples were dewatered in an osmotic solution for 120 min and their mass was measured periodically every 10 min for the first 60 min of dehydration and every 15 min for the next 60 min of dehydration. In order to measure mass reduction the samples were taken out from the container and drained gently with absorbent paper. Each dehydration process was carried out in an ultrasonic bath model IS-14S produced by INTERSONIC (Poland) in stabilised temperature of bath $T_{OD} = 308$ K. In the case of UAOD the ultrasounds of frequency $f = 25$ kHz and intensity of $I_{US} > 1$ W/cm^2 were used.

The kinetics and effectiveness of osmotic dehydration were assessed on the basis of the solid gain (SG) and water loss (WL) determined in compliance with the following formulas:

$$SG = \frac{s_t - s_i}{s_i} \tag{1}$$

$$WL = \frac{(m_i - m_t) + (s_t - s_i)}{s_i} \tag{2}$$

Initial mass of dry matter (s_i) was determined comparatively with a moisture analyser model XM120 (precision 0.01 %), produced by Precisa (Switzerland) and after 24-hrs of drying at T_a = 343 K in a convective dryer, model SML42/250/M, produced by Zalmed (Poland). For samples processed with the osmotic solution (OD/UAOD) dry matter mass (s_t) was determined only after 24-hrs of drying at T_a = 343 K in the convective dryer.

Results showed which of the osmotic agents used in the studies (fructose or d-sorbitol) was more efficient. The most effective period of dehydration was also determined. Thus, in the second part of research apple samples were dehydrated only for 30 min in a 40% fructose solution, in both OD and UAOD dehydration processes.

2.3. Drying process

Next, samples pretreated with OD and UAOD were subjected to convective drying both with (CVUS) and without (CV) ultrasound enhancement. Each drying experiment was performed in triplicate, in a special laboratory hybrid dryer, constructed by PROMIS-TECH (Poland) and equipped with an ultrasound generation system AUS produced by PUSONICS (Spain) (Kowalski and Mierzwa, 2015). The following settings of drying parameters were chosen:

- air temperature T_a = 323 K
- airflow velocity v_a = 2 m/s
- ultrasound power P_{US} = 200 W (if used)

During drying all process parameters such as air temperature, air velocity, RH, ultrasound power, mass and temperature of samples etc., were measured constantly (on-line) and recorded by data acquisition software. These data were next processed (e.g. by averaging) and used to determine and analyse the drying kinetics. On the basis of the measured mass alteration, moisture content (*MC*) and moisture ratio (*MR*) were calculated in accordance with following formulas:

$$MC(t) = \frac{m_m(t)}{s} = \frac{m(t) - s}{s} \tag{3}$$

$$MR(t) = \frac{MC(t) - MC_{eq}}{MC_0 - MC_{eq}} \tag{4}$$

For control processes, convective drying of samples not processed with OD/UAOD, s in Equation (3) denotes the initial mass of dry matter (s_i). If samples were processed with OD/UAOD, then it refers to s_t determined after 24-hrs of drying at T_a = 343 K in a convective dryer.

2.4. Quality assessment

The quality of the dried products was assessed on the basis of water activity and colour change measurements. Water activity of fresh and dried samples was measured with a Testo 650 meter at a room temperature (~296 K). The colour of the samples' surface was measured before and after drying with a Konica Minolta CR400 colorimeter (Japan) and expressed in CIE*Lab* colour space (precision 0.01). On the basis of obtained results, the differences in sample colour (before and after drying) were assigned as a relative colour change parameter:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{5}$$

3. RESULTS

Figure 1 shows water loss (WL), solid gain (SG) and moisture content (MC) of samples dehydrated with fructose (FRU) and d-sorbitol (SOR) solutions for osmotically dehydrated (OD) and ultrasonically aided osmotically dehydrated (UAOD) apple samples.

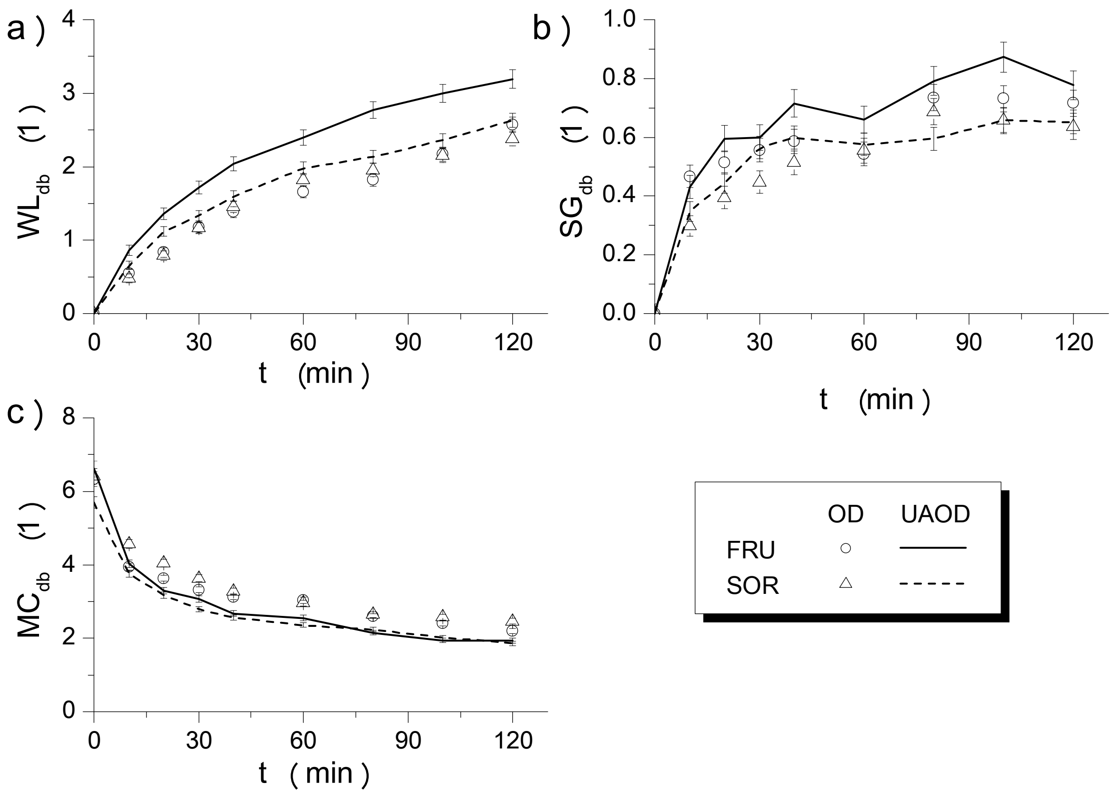

Fig. 1. Kinetics of osmotic dehydration: a) water loss; b) solid gain; c) moisture content

One can notice from Fig. 1 that the application of ultrasound influenced the kinetics of osmotic dehydration. In the case of UAOD processes WL achieved noticeably higher values in comparison to OD but the beneficial effect of ultrasound was revealed to a different degree for both analysed osmotic agents. For FRU the advantage of ultrasound enhancement was significantly higher compared to SOR.

The results of SG obtained during osmotic pretreatment are not so unequivocal. Although the highest values were also observed for UAOD in FRU solution, d-sorbitol SG achieved similar or even smaller values in comparison to OD process. Such a phenomenon may result from numerous factors such as agent chemical composition and constitution, osmotic pressure, solution viscosity etc.

The analysis of MC curves obtained during the first part of research (Fig. 1c) allows to state that the most effective period of dehydration took place in the first 30 minutes of the process, regardless of the type of osmotic agent (FRU/SOR) and the variant of process (OD/UAOD). In all considered cases MC fell rapidly during the first 10-20 minutes, and next tended slowly to reach the equilibrium value. This is the reason that the interval of 30 minutes of dehydration (t_{OD}) was chosen in further investigation.

Samples initially dehydrated in the fructose solution were next dried convectively with (CVUS) and without (CV) ultrasound enhancement. Moisture ratio (MR) and temperature (T) curves determine in individual tests are presented in Fig. 2.

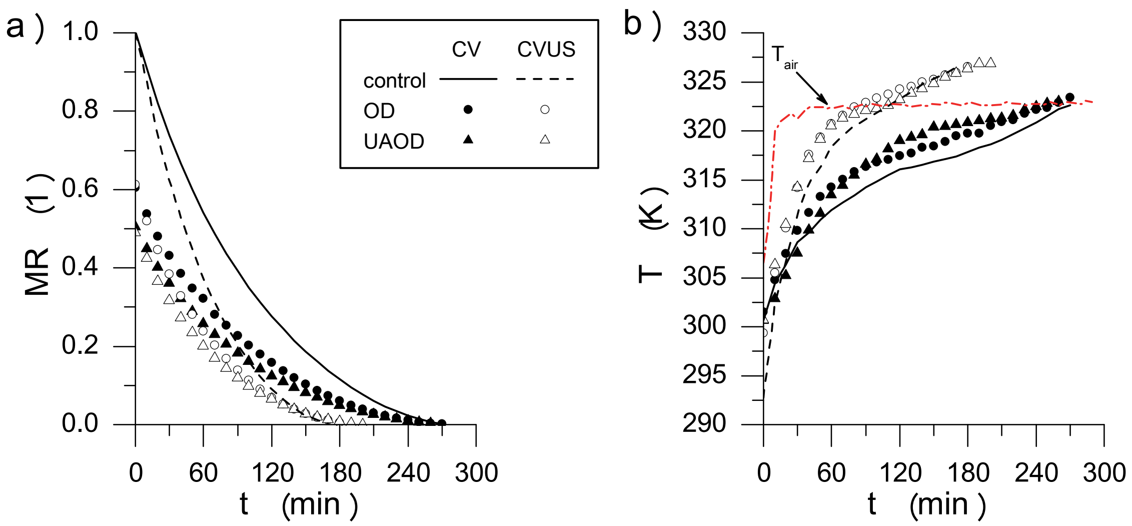

Fig. 2. Moisture ratio (a) and temperature curves (b) obtained during drying

The main aim of ultrasound application during convective drying was to enhance this long lasting and highly energy consuming unit operation. Moreover, it was expected that ultrasound would overcome the problem of precipitation present on the sample surface after osmotic pretreatment (OD). The adsorbed hypertonic sugar hinders the mass and heat transport during drying (Kowalski and Mierzwa, 2013). The ultrasound affects positively the drying kinetics for fresh (not pretreated OD or UAOD) samples. Fig. 2 shows that application of US reduced significantly the drying time from 270 min by CV to 170 min by CVUS, despite identical process parameters, including T_a and v_a. This tremendously positive effect may result from special vibration mechanism and phenomena accompanying CVUS drying. The main reason for drying acceleration may be the vibration effect which reduces the disturbance on the boundary layer coming from the resistance factor. The continuous alternation of air pressure just above the material's surface triggers turbulence and leads to intensification of heat and mass transfer. Another explanation of this phenomenon can be “sponge effect” which “squeezes out” the moisture from porous material (Cárcel, et al., 2007; Mulet et al., 2003; Simal, et al., 1998).

Unfortunately, contrary to the expectation, the application of ultrasound did not influence the kinetics of convectively dried samples initially dehydrated with OD or UAOD. Although, vast majority of moisture was removed from the material during OD or UAOD pretreatments, the drying processes were not shortened and proceeded in a similar way as without initial pretreatment. This negative outcome was probably caused by sugar which penetrated the material during osmotic processes. Contrary to the expectations, US applied during both osmotic dehydration and convective drying did not weaken the sugar precipitate present on material's surface.

Analysis of the temperature curves present in Fig. 2b allows to notice another phenomenon of CVUS drying processes. The temperature of samples dried with US assistance was higher than the temperature of drying air. This "heating effect" results from dissipation of ultrasound energy transferred with US waves to the samples, and it can be a promising result of US enhancement. As was found in the authors' previous work (Kowalski and Mierzwa, 2015), if the material achieves temperature higher than the surrounding medium (air), "synergistic effect" may occur together with thermal ("heating effect") and mechanical ("vibration effect") ones, causing significant acceleration of the drying operation.

In food processing, and especially in processing of agricultural products, quality is a crucial factor determining safety and suitability of food for people. In our study, product quality was assessed on the basis of colour and water activity measurements. The graphs in Fig. 3 illustrate changes in sample colour and water activity.

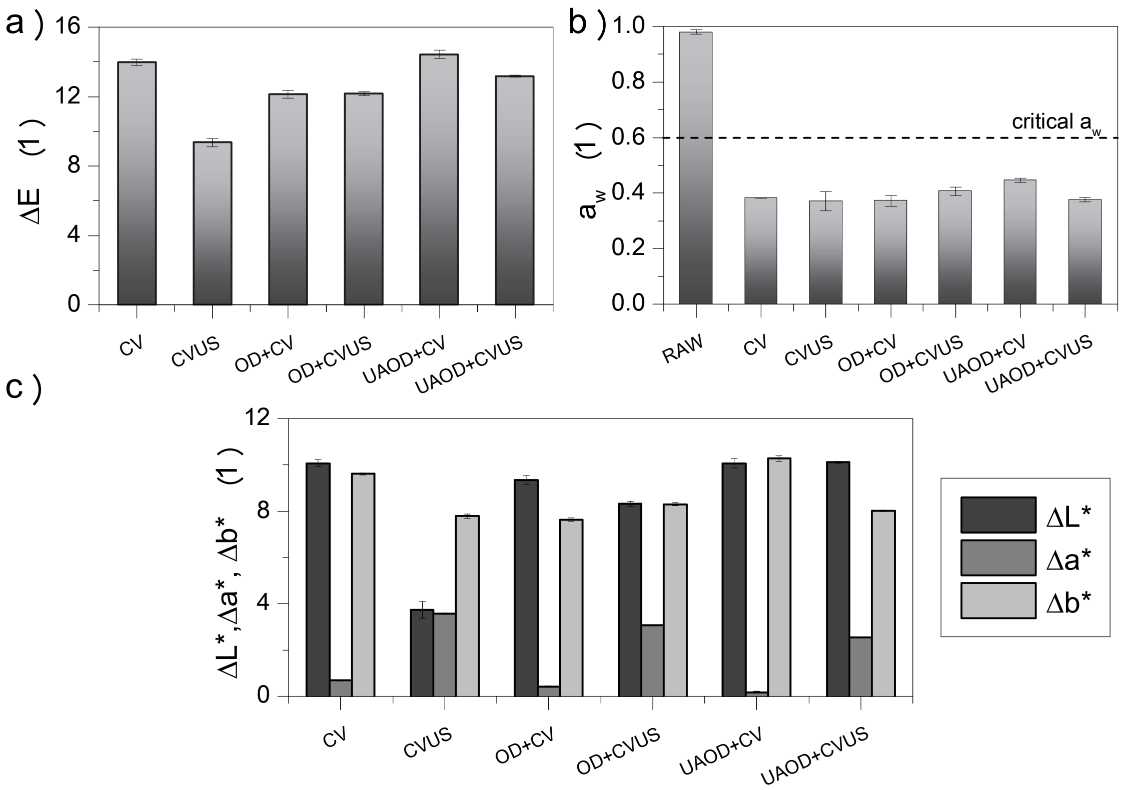

Fig. 3. Quality parameters of obtained products: a) overall colour change; b) water activity; c) differences of tristimulus values (e.g. $\Delta L^*=L_{dry}-L_{fresh}$)

A relative colour change for a particular process is presented in Fig. 3a. A small ΔE value informs that the colour of a processed product is similar to the fresh one. It is generally accepted that if ΔE is smaller than 4, the average observer is not able to notice a difference between the colours of fresh and processed products. Results in Fig 3a are significantly higher, so noticeable changes in colour occurred after each processed variant. The highest values were obtained for samples dehydrated with UAOD and next dried convectively, as well as for samples after pure convective drying (CV). It may result from long drying time and high sugar intake. The smallest colour change between fresh and dried product was observed for convectively dried samples with ultrasound enhancement (CVUS). This positive effect follows from shortening the drying time. Nevertheless, the differences in ΔE values for samples processed in other programs than CVUS are very small, and it is difficult to judge which drying program was the best and which the worst. For this reason differences between particular tristimulus parameters were assigned and presented in Fig. 3c.

Colour values presented in Fig. 3c reveal that dried products had higher values of L^*, a^*, and b^* than the fresh ones. It implies that the colour of the obtained after drying products is surely brighter (ΔL^*>0) and more saturated (Δa^*, Δb^* >0) in comparison to the fresh material. This kind of changes in material colour are usually acceptable and prove that browning reactions (enzymatic or non-enzymatic) did not proceed to an excessive degree. In ultrasonically assisted convective drying (CVUS, OD-CVUS, UAOD-CVUS) Δa^* is noticeably higher compared to CV drying, which means that colour shifts tored shades.

Water activity (a_w) is one of the most important quality parameters informing about product microbiological stability, and thus on its safety state. Basically, a microbiologically safe biomaterial is characterised by the water activity of less than 0.6, so that almost all microorganisms (bacteria, yeast, mold etc.) are significantly reduced and most of negative processes (browning, oxidation, Maillard reaction etc.) are inhibited. Fresh fruits and vegetables are characterised by extremely high a_w and therefore they are highly perishable and need to be processed immediately after being harvested. The water activity of products tested in our experiment was lower than 0.4 on average, and therefore it can be stated that these products were safe and stable.

4. CONCLUSIONS

The positive effect of ultrasound enhancement during osmotic dehydration was found for both tested agents i.e. fructose and sorbitol. The highest values of WL and SG were gained after ultrasonically aided osmotic dehydration in fructose solutions.

Some differences in dehydration kinetics were found. Dehydration was more efficient for fructose solutions as higher values of WL and SG were achieved compared to d-sorbitol.

Although the ultrasound accelerated evidently the process of convective drying, the benefit from OD or UAOD in kinetics of CV or CVUS drying was imperceptible. Nevertheless, positive influence of ultrasound on the quality of obtained products was observed. Samples processed with ultrasound assistance revealed smaller water activity and their colour was better preserved compared to those dehydrated/dried without ultrasound enhancement.

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SYMBOLS

a	activity
Cp	concentration, % w/w
I	intensity, W/m^2
L, a, b	tristimulus colour values, 1
m	mass of sample, kg
MC	moisture content, kg/kg

MR	moisture ratio
P	power, W
SG	solid gain, kg/kg
s	solid matter, kg
T	temperature, K
t	time, min
v	velocity, m/s
WL	water loss, kg/kg

Greek symbols

ΔE	overall colour change

Superscripts

*	CIE*Lab* colour space tristimulus coordinates

Subscripts

a	air
db	dry basis
eq	equilibrium
i, 0	initial
m	moisture
OD	osmotic dehydration
s	dry matter
t	at time *t*
US	ultrasounds
w	water

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