ULTRASONICALLY ASSISTED LOW-TEMPERATURE DRYING OF DESALTED CODFISH

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Abstract

Low-temperature drying (LTD) constitutes an interesting means of dehydrating foodstuffs, thus preserving the quality of the product. Power ultrasound (US) generates several mechanical effects that could help to shorten the long drying times associated with LTD. In this work, the feasibility of using US in LTD of desalted cod was assessed.

For this purpose, desalted cod slices (50x30x5 mm) were dried (2 m/s) at different temperatures (10, 0 and -10ºC) without (AIR) and with (AIR+US, 20.5 kW/m^3) US application. Afterwards, the dried samples were rehydrated in distilled water (25°C). A diffusion model was used to describe both drying and rehydration kinetics. The color and hardness of both dried and rehydrated cod samples were also measured.

The application of US increased the drying rate at every temperature tested, shortening the drying time by 16% at 0ºC and up to 60% at -10ºC. The ultrasonically assisted dried samples presented a rehydration rate which was slightly lower than that of those that had been conventionally dried, but they were harder and whiter, which is more suited to consumer preferences. Therefore, power ultrasound could be considered an affordable technology with which to accelerate LTD of desalted cod, providing high quality dried products.

Keywords: Ultrasound; Dehydration; Rehydration; Texture; Color

1. Introduction

Dried and salt-cured cod (*Gadus morhua*) is a highly-appreciated product due to its high nutritional value (high protein and low fat content) and its particular sensory properties. It is mainly produced in Norway and Iceland and primarily consumed in the Southern European countries, such as Spain and Portugal (Martínez-Álvarez and Gómez-Guillén, 2013; Oliveira, Pedro, Nunes, Costa, and Vaz-Pires, 2012). The high salt concentration of this product (approximately 20% w/w) prevents its degradation but limits its direct consumption; for this reason salted cod must be desalted (Ozuna, Puig, Garcia-Perez, and Cárcel, 2014a), a process that takes approximately 24h. This slow salt diffusion constrains the consumption of salted cod for both domestic use and the catering industry. In addition, the desalting converts the cod into a highly perishable product (Fernández-Segovia, Escriche, Fuentes, and Serra, 2007) and, in fact, the fish must be either immediately consumed, chilled or frozen (Lauritzsen et al., 2004). Therefore, it could be interesting to explore alternative preservation methods, such as drying, that ensure both the desalted product's stability and the retention of the sensory attributes (Andrés, Rodríguez-Barona, and Barat, 2005). The desalted and dried cod may be used as an ingredient in prepared foods, such as instant meals or ready-to-use products, due to its low salt content and rehydration ability.

Convective drying constitutes a traditional dehydration method for foodstuffs (Garcia-Perez, Ozuna, Ortuño, Cárcel, and Mulet, 2011). The use of high air temperatures accelerates the drying kinetics, but causes chemical and physical changes that can affect the quality traits of the dried product (Soria et al., 2010). Consumer demand for high quality products has encouraged research into alternative techniques to minimize quality degradation during processing. In this sense, low temperature drying (LTD) could be an interesting method. However, the long drying times linked to LTD could limit its use on an industrial scale.

Power ultrasound (US) has been used to speed up the convective drying of several foodstuffs (Cárcel, Garcia-Perez, Riera, and Mulet, 2011; Gallego-Juárez et al., 2007; Garcia-Perez et al., 2011), mainly by introducing mechanical energy. The ultrasonic waves generate alternating expansions and contractions when travelling across a medium, which have a similar effect to that found in a sponge when it is repeatedly squeezed and released (Gallego Juárez et al., 2007). This mechanical stress helps the water move from the inner parts of the product to the surface and could create microscopic channels that reduce the internal resistance to mass transfer (Gallego-Juárez, 2010). Moreover, in solid/gas systems, the application of US also produces oscillating velocities, micro-streaming and pressure variation at the interfaces, which reduce the boundary layer and, as a consequence, improve water movement from the solid surface to air. Therefore, US could help to reduce both the external and the internal mass transfer resistance without introducing a significant amount of thermal energy during drying (Cárcel et al., 2011). In this sense, the feasibility of US application during the LTD process of different products, such as apple (Santacatalina et al., 2014, Garcia-Perez, Cárcel, Riera, Rosselló, and Mulet, 2012), salted cod (Ozuna, Cárcel, Walde, and Garcia-Perez, 2014b), green peas (Bantle and Eikevik, 2011), carrot or eggplant (Garcia-Pérez et al., 2012) has been proved. More research has been done on analyzing the effect of US on the drying kinetics than on the product quality (Pingret, Fabiano-Tixier, and Chemat, 2013). Therefore, the aim of this work was to evaluate the feasibility of using US in LTD of desalted cod, analyzing not only drying and rehydration kinetics but also quality parameters, such as color and texture.

2. Materials and methods

2.1. Raw material and sample preparation

A homogeneous batch of salted cod (*Gadus morhua*) was provided by a local supplier (Carmen Cambra S. L., Spain). The pieces of salted cod averaged 1.5±0.25 kg.

Parallelepiped-shaped samples (50x30x5 mm) were obtained from the central part of the cod loin using a sharp knife and, afterwards, were wrapped in plastic waterproof film and kept refrigerated at 2±1ºC (maximum storage time 120 h) until the desalting process took place. For that purpose, the slices of salted cod were immersed in water (70 g cod/L water) of low mineral content (Cortes S.A., Spain) at 4±1ºC for 24 h. After desalting, the surface water was removed with tissue paper. Then the samples were wrapped in plastic waterproof film and separated into three batches. Two of them were kept in refrigeration at 2±1ºC (maximum storage time 4 h) until the drying experiments were conducted (samples dried at 0 and 10ºC). The third (samples dried at -10ºC) was frozen by placing samples at -18±1ºC until processing (at least 72 h).

The moisture and the NaCl content of the cod samples were measured before and after desalting following standard methods 950.46 and 971.27, respectively (AOAC, 1997). Thus, the moisture content was obtained by the difference of weighting between salted or desalted cod samples and the same cod samples dried at 105ºC until they achieved constant weight (24 h approximately). For the NaCl measurement, approximately 0.5 g of ground sample was placed into 100 mL of distilled water and homogenised at 9500 r.p.m. for 5 min with an ultra-turrax mod. T25 provided with a dispersion tool mod. S25N-18G (IKA Labortechnik, Janke & Kunkel GMBH & Co, Staufen, Germany). The chloride content of the extract was determined in triplicate using a chloride meter (Ciba Corning, mod. 926. L; Halstead, Essex, United Kingdom). Thus, the average value of the moisture content of desalted cod was 4.42±0.02 kg water/kg dry matter of desalted cod (dmdc) and the NaCl content was 0.023±0.001 kg NaCl/kg dmdc.

2.2. Drying experiments

Drying experiments were carried out in a convective drier with air recirculation (Figure 1), already described in the literature (Garcia-Perez et al., 2012). The system provides an automatic temperature and air velocity control. Moreover, an ultrasonically activated cylindrical radiator generates a high intensity ultrasonic field (155 dB) in the drying chamber. Drying experiments were conducted using a constant air velocity (2 m/s) at three different temperatures (10, 0 and -10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3) US application. Drying kinetics were obtained by weighing samples at preset times (interval of 15 min) and considering the initial moisture content. In every case, the initial mass load was of 138.7±6.9 g (10 cod slices) and the relative humidity of drying air was maintained below 10±3% during the whole drying process.

The drying experiments were replicated at least three times for each drying condition tested and extended until samples lost 65±3% of the initial weight. After drying, the moisture content of the samples was also measured following standard method 950.46 (AOAC, 1997). Finally, the dried samples were vacuum-sealed and stored in refrigeration (0±1ºC; maximum storage time 4 days) until the quality analyses (rehydration, color and texture) were carried out.

2.3. Modeling of drying kinetics

A diffusion model was used to describe the drying kinetics. The mass transport was considered to be one-dimensional due to the fact that sample thickness (5 mm) was 1/6 (30 mm) and 1/10 (50 mm) shorter than the other dimensions. Thus, the approach of considering the samples as infinite slabs can be considered as appropriate (Garau, Simal, Femenia, and Rosselló, 2006). Assuming the effective moisture diffusivity as constant and the solid to be isotropic and homogeneous, the diffusion equation (equation 1) is written as follows:

$$\frac{\partial W_p(x,t)}{\partial t} = D_{ed}\left(\frac{\partial^2 W_p(x,t)}{\partial x^2}\right) \tag{1}$$

where W_p is the local moisture (kg water/kg dmdc), t is the time (s), D_{ed} is the effective moisture diffusivity (m^2/s) during drying and x represents the characteristic mass transport direction in the slab geometry (m).

In order to solve equation (1), the following assumptions were considered: solid symmetry, uniform initial moisture content and temperature, constant shape during drying and negligible external resistance to mass transfer. The analytical solution of the diffusion equation, expressed in terms of the average moisture content, is shown in equation (2) (Crank, 1975).

$$W(t) = W_e + (W_0 - W_e)\left[2\sum_{n=0}^{\infty}\frac{1}{\lambda_n^2 L^2} e^{-D_{ed}\lambda_n^2 t}\right] \tag{2}$$

where, λ_n are the eigenvalues calculated as $\lambda_n L = (2n+1)\frac{\pi}{2}$, W is the average moisture content (kg water/kg dmdc), L the half-thickness of the sample (m) and subscripts 0 and e represent the initial and equilibrium state, respectively.

The diffusion model was fitted to the experimental drying kinetics in order to identify the effective moisture diffusivity. The identification was carried out by minimizing the sum of the squared differences between the experimental and the calculated average moisture content. For that purpose, the Generalized Reduced Gradient (GRG) optimization method, available in Microsoft Excel™ spreadsheet (Microsoft Corporation, Seattle, WA, USA) was used. The goodness of the fit was determined by calculating the percentage of explained variance (VAR, equation 3).

$$VAR = \left[1 - \frac{S_{xy}^2}{S_y^2}\right]\cdot 100 \tag{3}$$

where S_{xy} and S_y are the standard deviation of the estimation and the sample, respectively.

2.4. Rehydration experiments

The rehydration capacity was determined by immersing the dried cod samples in distilled water at 25±1ºC. In order to obtain the rehydration kinetics, the samples were taken out of the bath at preset times, blotted with tissue paper to remove the surface water and weighed. The rehydration tests were carried out in triplicate for each drying condition considered, using 10 samples (16.5±1.5 g) of dried cod in each run. The experiments were extended until the difference in sample weight between two consecutive measurements (60 min) was lower than 0.5 g, assuming that this point was close to the equilibrium weight. The rehydration kinetics were modeled using the same diffusion model described in section 2.3. for the drying kinetics. In this case, W_0 represents the moisture content of the dried samples and W_e the equilibrium moisture content of the rehydrated samples and the term D_{ed} was replaced by D_{er} to differentiate the effective moisture diffusivity (m^2/s) during drying and rehydration.

2.5. Color

The color of both dried and rehydrated cod samples was determined by measuring the CIE L*a*b* color coordinates (Bai, Sun, Xiao, Mujumdar, and Gao, 2013) using a colorimeter (Minolta CM-2500d, Konica Minolta Optics, Inc., Japan), provided with a standard illuminant D65, an observation angle of 10° and calibrated using a standard white. In every case, the measurements were carried out directly on the sample surface, in triplicate and at room temperature (20±1ºC). Thus, for each type of dried sample, a minimum of 90 color measurements were carried out. The overall color difference (ΔE, equation 4) was computed as the difference between AIR+US (L*, a*, b*) and AIR (L_0*, a_0*, b_0*) samples. In the case of the rehydrated samples, ΔE indicates the color difference between the rehydrated samples (L^*, a^*, b^*) and the desalted cod before drying (L_0^*, a_0^*, b_0^*).

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \quad (4)$$

2.6. Texture

The hardness of both dried and rehydrated cod samples was measured using a Texture Analyzer (TAX-T2, Stable Micro System, Godalming, United Kingdom) with a load cell of 25 kg. The penetration tests were conducted with a 2 mm flat cylinder probe (SMS P/2N), at a crosshead speed of 1 mm/s and a strain of 75% (penetration distance 3.5 mm). The hardness was characterized as the maximum penetration force achieved. In each sample, the penetration tests were carried out at 16 points following a preset pattern. For each drying run, at least three dried and three rehydrated samples were analyzed. Because each drying conditions was tested by triplicate, this means that nine dried and nine rehydrated samples was used to assess the hardness in each case.

2.7. Statistical analysis

Analyses of variance (ANOVA) ($p<0.05$) were carried out and LSD (Least Significant Difference) intervals were estimated using the statistical package, Statgraphics Centurion XVI (Statpoint Technologies Inc., Warrenton, VA, USA), in order to assess the significance of the influence of the different operating conditions (temperature and US application) on the identified D_{ed} and D_{er}, as well as on the color and hardness of both the dried and rehydrated samples.

3. Results and discussion

3.1. Drying experiments

The drying kinetics of desalted cod without (AIR) and with (AIR+US) ultrasound application are shown in Figure 2. In both AIR and AIR+US, the lower the drying temperature, the longer the drying time. Thus, in AIR experiments, 69% less time was needed for drying at 10ºC (18.1±1.9 h) than at -10ºC (57.7±5.9 h). It should be noted that at 0 and 10ºC, the water was removed from the solid matrix by evaporation. On the contrary, at -10ºC, water removal took place by sublimation due to the fact that the water remains frozen during drying; therefore, under these conditions it could be considered as atmospheric freeze drying (AFD) (Claussen, Ustad, Strommen, and Walde, 2007).

The application of US increased the drying rate at every temperature tested (Figure 2). The shortening of the drying time depended on the temperature being higher at -10ºC (60%) than at 0 and 10ºC (16 and 29%, respectively). As observed in Figure 2, the influence of temperature on AIR+US drying kinetics was less remarkable than in AIR experiments. Thus, the difference in drying time between the AIR experiments carried out at -10 and 10ºC was 39.6 h, while this difference was only 10.2 h in the case of AIR+US experiments. Using the same US device, Ozuna et al. (2014b) succeeded in shortening the drying time by between 35 and 54% when US was applied during the drying of salted cod (from -10 to 20ºC). In the case of apple drying, and under similar experimental conditions (from -10 to 10ºC), Santacatalina et al. (2014) found time savings of between 60 and 77%. Likewise, Garcia-Perez et al. (2012) reported drying time reductions of around 70% in the drying of carrot and eggplant at -14°C. Bantle and Hanssler (2013) reduced the drying time by over 90% when drying salted codfish at 10ºC using a commercial ultrasonic plate-like emitter (20kHz; DN 20/200, Sonotronic, Karnsbald, Germany), but considering only the initial drying period (until samples reached a moisture content of 45%). Schössler, Jäger, and Knorr (2012) reported that, when freeze-drying red bell pepper cubes using a contact ultrasonic system, the drying time was shortened by 11.5%.

3.2. Modeling of drying kinetics

The proposed model was adequate for describing the drying kinetics of desalted cod slices at 0 and 10ºC, obtaining percentages of explained variance (VAR) of over 99% (Table 1). The goodness of the fit at 0 and 10ºC is illustrated in Figure 2, where the similar trend of the experimental and calculated moisture content can be observed. On the contrary, a lower VAR value (98.5%) was found in the experiments carried out at -10ºC, probably because the samples remain frozen during drying. Under these conditions, the water is removed by sublimation and two layers can be found in the product: a frozen inner core and a dry outer layer. Therefore, the product is not homogeneous, as is assumed in the diffusion model.

At the drying temperatures tested, the fit of the diffusion model was poorer when US was applied. This is probably due to the fact that US application partially modifies the mechanisms of mass transport that could affect the relationship between internal and external mass transport resistance, meaning that diffusion was not the only mechanism controlling mass transfer, as assumed in the model.

In any case, in the proposed model, any effect on the drying rate was included in the D_{ed}. Therefore, this parameter can be used to compare and assess the overall effect of the different conditions tested (temperature and/or US application) on the drying rate. In the case of temperature, the higher the air drying temperature applied, the higher the identified D_{ed} (Table 1). The application of US during LTD of desalted cod also involved a significant ($p<0.05$) increase in the D_{ed} at the three temperatures studied (Table 1). This influence of US on the identified diffusivities were similar to those reported by Ozuna et al. (2014b) for US-assisted drying kinetics of salted cod at temperatures between 20 and -10ºC. The mechanical stress caused by the alternating compressions and expansions (sponge effect) produced by US could improve the internal diffusion of moisture (Gallego-Juárez et al., 2007). Moreover, this stress could create microscopic channels that help to make the movement of the water towards the product surface easier (Gallego-Juárez, 2010). At the solid-air interface, US produces alternating pressures and microstirring that could also help to speed-up the convective moisture transport.

As can be observed in Table 1, the increase in D_{ed} produced by US application was significantly ($p<0.05$) larger in the experiments conducted at -10ºC (123.5%) than in those carried out at 0 and 10ºC (17.4 and 35.4%, respectively). As stated before, while evaporation was responsible for the water removal at 0 and 10ºC, at -10ºC it took place through sublimation which can be assumed to be atmospheric freeze drying. This makes the outer porous dry layer developed during this kind of drying more prone to the ultrasonic effects than the more compact structure developed during drying by evaporation at 0 and 10ºC. In this sense, Ozuna, Gómez, Riera, Cárcel, and Garcia-Perez, (2014c) observed that the product porosity influences the extension of the ultrasound effects during drying. Thus, highly porous materials present higher values of impedance, closer to the surrounding air, than materials with a hard and closed-compact structure. The fact that the coupling of the air-porous structure is better makes easier the ultrasound transmission and helps ultrasound effects to be more intense (Ozuna et al., 2014c).

3.3. Rehydration experiments

Since rehydration potential is an important quality attribute for products that need to be reconstituted before consumption, the influence of the drying method on the rehydration kinetics of dried samples (0.54±0.07 kg water/kg dmdc) was experimentally determined. The results obtained showed that the AIR samples dried at -10ºC rehydrated significantly ($p<0.05$) faster than those dried at 10 and 0ºC (Figure 3). Thereby, the average rehydration time for AIR samples dried at 0 and 10ºC was 22.0±0.9 h, while for AIR samples dried at -10ºC it was 8.7±0.3 h. The moisture content reached at the end of the rehydration process was also significantly ($p<0.05$) higher for samples dried at -10ºC (3.05±0.44 kg water/kg dmdc) than for those dried at 10 and 0ºC (2.61±0.24 and 2.41±0.10 kg water/kg dmdc, respectively). These results could be explained by the fact that drying at -10ºC leads to a minimum shrinkage and a highly porous structure (Stawczyk, Li, Witrowa-Rajchert, and Fabisiak, 2007). So, the high porosity makes it easier for water to enter the dried matrix.

The application of US during drying did not significantly ($p<0.05$) affect the moisture gain rate during the rehydration of samples dried at 0 and 10ºC (Figure 3). On the contrary, for samples dried at -10ºC, US application slightly reduced the rehydration rate and the final moisture gain. US could affect the microstructure of cod samples, provoking ruptures in the cod fibers and causing the formation of wider spaces between myofibrils (Ozuna et al., 2014c). The extension of these effects were enough to modify the rehydration capacity of cod slices dried at -10ºC, but not for those dried at 0 and 10ºC. It is likely that this is due to the combined impact of freezing and US application on the structure of the samples dried at -10ºC, which results in a softer and more unstructured matrix where the water intake and its retention during the rehydration process is more difficult. In this sense, Nowacka, Wiktor, Śledź, Jurek, and Witrowa-Rajchert (2012) reported that a short ultrasonic pretreatment of apple cubes before drying reduced their moisture content after 60 minutes of rehydration due to changes in the product's microstructure. However, Schössler et al. (2012) reported no differences in the rehydration characteristics of the US assisted freeze-dried red bell pepper in comparison with those conventionally freeze-dried, probably due to the lower efficiency of the contact ultrasonic system used in this work.

The experimental rehydration kinetics were also modeled, taking Equation 2 into account. A satisfactory description (VAR>98%) (Table 2) of the rehydration kinetics was only obtained for AIR dried samples at 0 and 10ºC (Figure 3). In samples dried at -

10ºC, mechanisms other than diffusion, and probably linked to the high porosity and bulk water input, could be involved.

The D_{er} identified for samples dried at 0 and 10ºC was similar (Table 2). At these temperatures, US application during drying caused a slight but not significant ($p<0.05$) increase in the D_{er}. However, the D_{er} identified for AIR samples dried at -10ºC was five times greater than that identified for those dried at 0 and 10ºC. In this case, AIR+US samples dried at -10ºC showed a significantly ($p<0.05$) lower D_{er} than AIR samples.

3.4. Color

3.4.1. Dried samples

The average values of the color coordinates of desalted cod before drying were 63.7±1.9 for L*, -3.85±0.52 for a* and 0.95±0.78 for b*. In general terms, as can be observed in Table 3, the drying increased the value of the three coordinates. AIR dried samples at 0 and 10ºC showed higher a* and b* coordinates and lower L* than those dried at -10ºC. These results suggest that the moisture removal by evaporation (0 and 10ºC) caused a yellowing (higher b*) and a darkening (lower L*), while the removal by sublimation (-10ºC) leads to brighter and whiter samples. According to Asli and Morkore (2012), cod should preferably have a high lightness value (L*-value), as the color white is considered positive by consumers. Bjorkevoll, Reboredo, and Fossen (2014) also associated high quality with a whiter and less yellow surface in the sensory evaluation of the heavy salted cod. However, Lauritzsen et al. (2004) reported that the reduction in the water content causes changes in the color of the fish. Brás and Costa (2010) reported an increase in both the lightness (L*) and yellowness (b*) of the cod caused by drying, which was more marked as drying progressed.

The application of US during drying only significantly ($p<0.05$) affected the L* coordinate for samples dried at -10ºC, reducing their lightness as compared with AIR samples. Moreover, the overall color difference (ΔE) between samples dried without (AIR) and with (AIR+US) (Table 3) showed negligible differences in the case of samples dried at 0 and 10ºC due to the fact that, as reported by Francis and Clydesdale (1975), ΔE values lower than 2 are not detected by the human eye. On the contrary, the ΔE obtained for the samples dried at -10ºC was significantly ($p<0.05$) higher; this indicated that, at this drying temperature, US application caused a meaningful color difference. This was probably due to the slight thermal effect generated by US on the sample's surface, which could be more marked in this case and bring about a little darkening.

3.4.2. Rehydrated samples

The drying temperature did not affect the color of the rehydrated samples (Table 4) and no significant ($p<0.05$) differences were found for samples previously dried at -10, 0 or 10ºC. In a similar way, US application during drying did not cause noticeable changes in the color coordinates of the rehydrated samples (Table 4).

In this case, ΔE was calculated by considering the desalted cod prior to drying as reference. In general terms, the dried and rehydrated cod samples did not recover the color of the desalted samples, the ΔE ranging from 8.8 to 11.7 (Table 4).

3.5. Texture

3.4.1. Dried samples

The initial hardness of the desalted cod was 1.55±0.53 N. Therefore, the drying process provoked a hardening of the samples (Figure 4), regardless of the drying conditions used. For the AIR samples, the hardness was dependent on the drying temperature (Figure 4), so, the lower the air temperature, the harder the dried cod sample. No influence of the air drying temperature on the hardness was observed in the case of AIR+US samples. However, when comparing ultrasonically assisted dried samples with those conventionally dried, it was observed that the AIR+US samples dried at 0 and 10ºC were significantly ($p<0.05$) harder than the AIR ones (Figure 4). This fact could be attributed to the successive compression and expansion cycles of the material produced by US, which could affect cod proteins thus causing a hardening of the samples. At -10ºC, the hardening of AIR and AIR+US samples was similar. The previous freezing step and the fact that water removal occurred by sublimation could provoke changes in the sample's structure that may mask the structural US effect.

3.4.2. Rehydrated samples

In general, both the drying and the later rehydration process produced samples that were slightly harder than the initial desalted cod (1.55±0.53 N), but their final hardness depended on the drying temperature and US application. Thus, in the case of AIR samples, the effect of drying temperature on rehydrated samples was to the opposite of that found in dried samples; so, the higher the air temperature, the harder the rehydrated sample (Figure 5). As regards the application of US, the rehydrated AIR+US samples dried at 0 were significantly ($p<0.05$) harder than AIR samples (Figure 5). The textural changes caused by US application could be linked to the denaturation of proteins (Lee and Feng, 2011). In the case of samples dried at 10ºC, no significant ($p<0.05$) differences were observed between AIR and AIR+US, which could be explained by the fact that the shorter drying time at 10ºC prevented a lengthy action of US on the internal structure. In the case of -10ºC experiments, the effects of freezing on structure can mask the effects of ultrasound.

4. Conclusions

The application of US during the low temperature drying of desalted cod improved the drying rate at every temperature tested, but it was particularly noticeable when drying took place at -10ºC, which is when water removal took place by sublimation. As far as quality attributes are concerned, the cod dried at -10ºC rehydrated faster and gained more water than that dried at higher temperatures. Moreover, these samples were brighter, whiter and slightly softer than those dried at 0 and 10ºC. US application slightly reduced the rehydration rate and increased the sample's hardness, but allowed whiter samples to be obtained, which are usually preferred by consumers. Therefore, power ultrasound could be considered an interesting technology to speed-up the low temperature drying of desalted cod without greatly affecting the quality of the obtained product.

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Figure captions

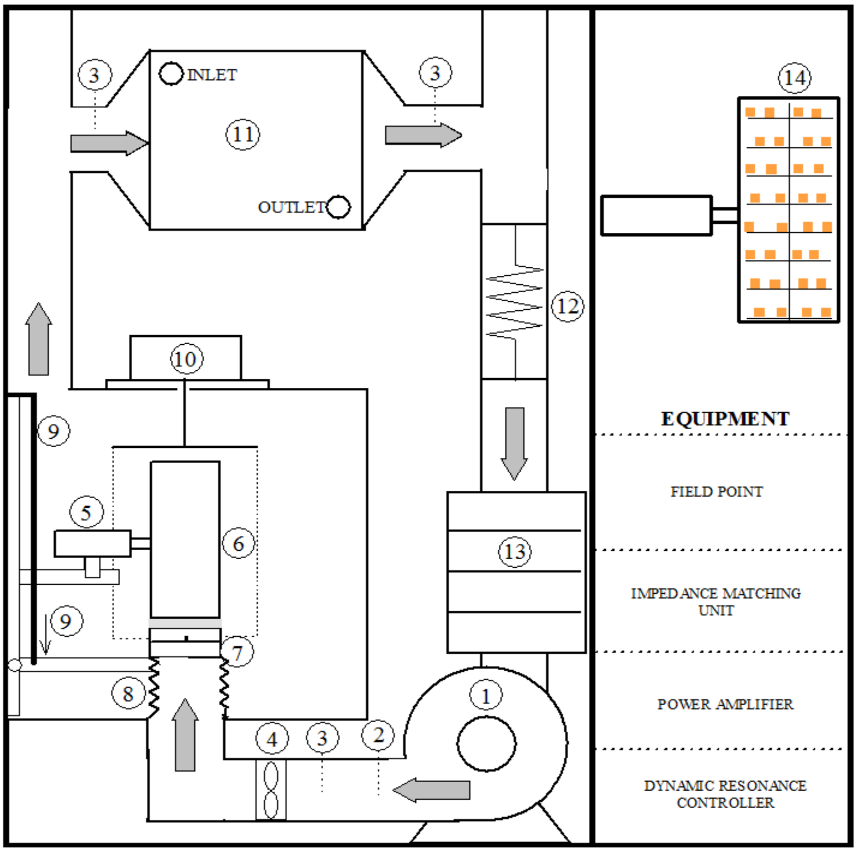
Figure 1. Diagram of the ultrasonically assisted convective dryer: 1, fan; 2, Pt-100; 3, temperature and relative humidity sensor; 4, anemometer; 5, ultrasonic transducer; 6, vibrating cylinder; 7, sample load device; 8, retreating pipe; 9, slide actuator; 10, weighing module; 11, heat exchanger; 12, heating elements; 13, desiccant tray chamber; 14, details of the sample load on the trays.

Figure 2. Experimental and calculated (diffusion model) drying kinetics (2 m/s) of desalted cod at different temperatures (-10, 0 and 10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application.

Figure 3. Experimental and calculated (diffusion model) rehydration kinetics of desalted and dried cod (2 m/s) at different temperatures (-10, 0 and 10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application.

Figure 4. Hardness of desalted and dried cod at different temperatures (-10, 0 and 10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application. Average values ± LSD intervals ($p<0.05$) are plotted. Different letters show significant differences according to LSD intervals ($p<0.05$).

Figure 5. Hardness of rehydrated cod previously desalted and dried at different temperatures (-10, 0 and 10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application. Average values ± LSD intervals ($p<0.05$) are plotted. Different letters show significant differences according to LSD intervals ($p<0.05$).



INLET
OUTLET
EQUIPMENT
FIELD POINT
IMPEDANCE MATCHING UNIT
POWER AMPLIFIER
DYNAMIC RESONANCE CONTROLLER
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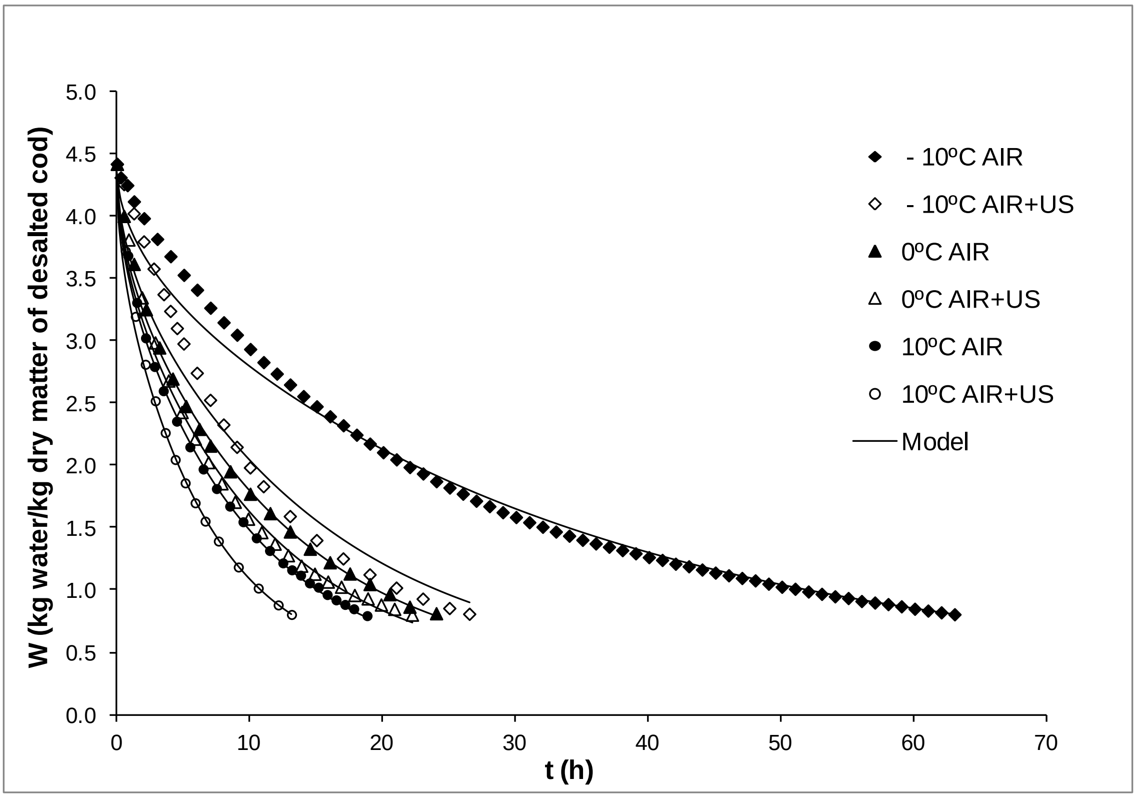
Figure 1



W (kg water/kg dry matter of desalted cod)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
t (h)
- 10ºC AIR
- 10ºC AIR+US
0ºC AIR
0ºC AIR+US
10ºC AIR
10ºC AIR+US
Model

Figure 2

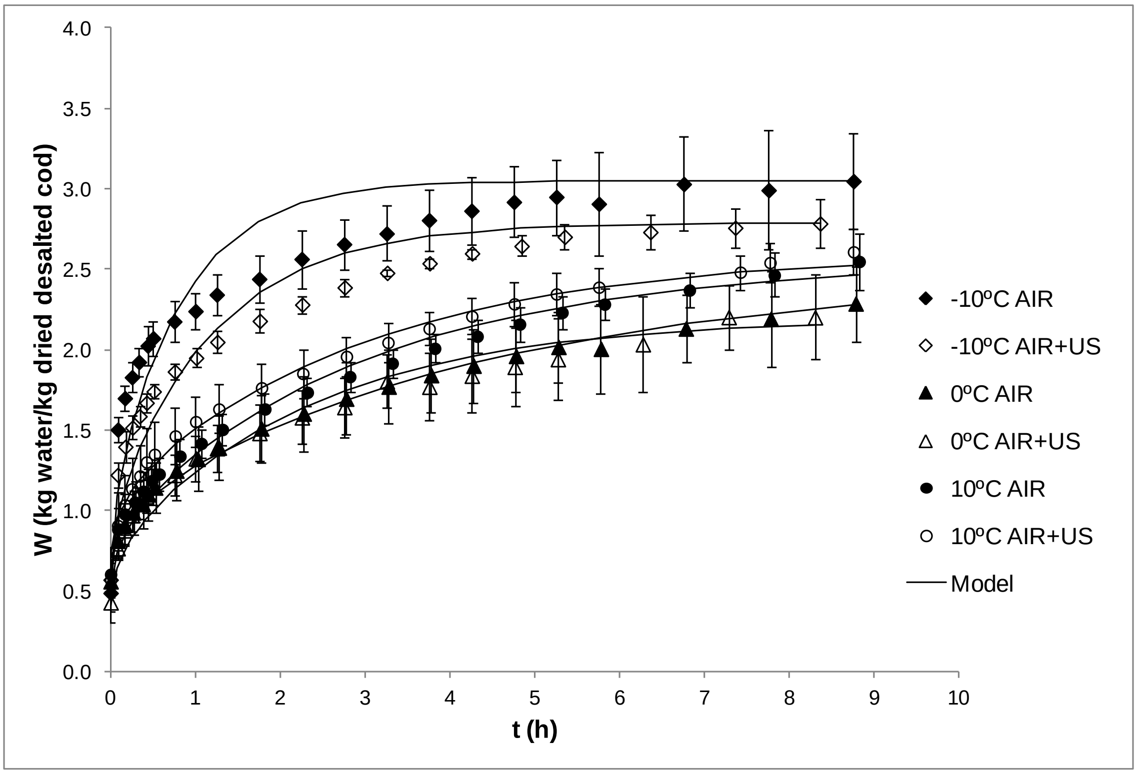

W (kg water/kg dried desalted cod)
t (h)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
-10ºC AIR
-10ºC AIR+US
0ºC AIR
0ºC AIR+US
10ºC AIR
10ºC AIR+US
Model

Figure 3

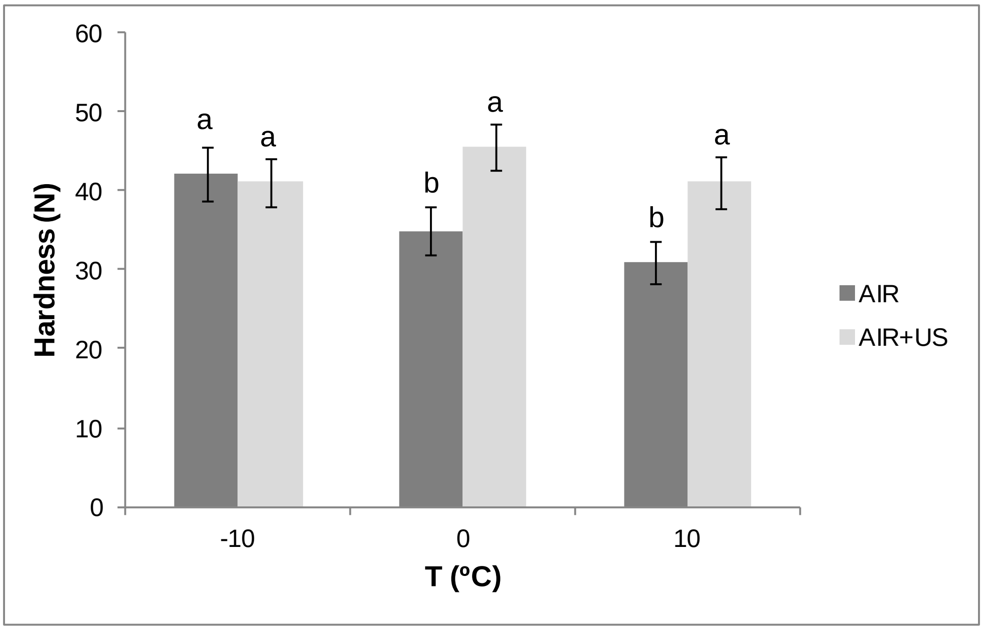


Figure 4

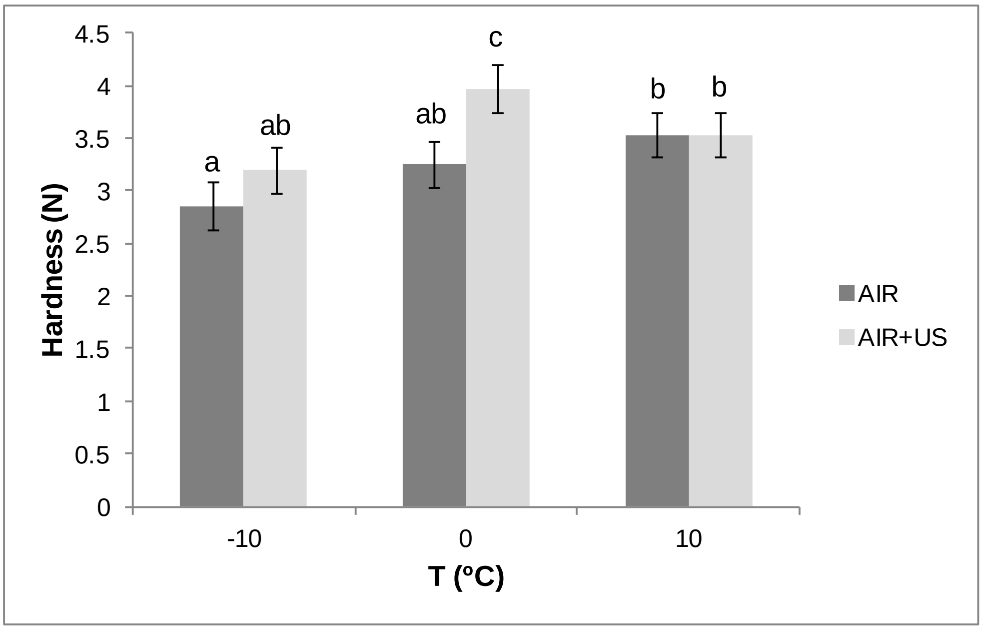


Figure 5

Table 1. Effective moisture diffusivity (D_{ed}) for the drying kinetics of desalted cod at different temperatures (10, 0 and -10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application. Average values ± standard deviation are shown. VAR (%) is the percentage of explained variance. ΔD_{ed} shows (in percentage) the increase in effective moisture diffusivity produced by ultrasonic application.

	AIR		AIR+US		
T (ºC)	D_{ed} (10^{-11} m^2/s)	VAR (%)	D_{ed} (10^{-11} m^2/s)	VAR (%)	ΔD_{ed} (%)
10	7.77 ± 0.62^{e}	99.7	10.51 ± 0.33^{f}	99.1	35.4
0	5.65 ± 0.35^{c}	99.3	6.63 ± 0.09^{d}	99.2	17.4
-10	2.17 ± 0.20^{a}	98.5	4.84 ± 0.60^{b}	94.4	123.5

Superscript letters (a, b, c, d, e, f) show homogeneous groups established from LSD (Least Significance Difference) intervals ($p < 0.05$).

Table 2. Effective moisture diffusivity (D_{er}) for the rehydration kinetics of desalted cod dried at different temperatures (10, 0 and -10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application. Average values ± standard deviation are shown. VAR (%) is the percentage of explained variance.

	AIR		AIR+US	
T (ºC)	D_{er} (10^{-10} m^2/s)	VAR (%)	D_{er} (10^{-10} m^2/s)	VAR (%)
10	1.99±0.66^{a,b}	99.1	2.26±0.87^{a,b}	97.5
0	1.89±0.52^{a}	98.3	2.34±0.58^{a,b}	95.5
-10	9.93±4.35^{c}	86.7	5.60±2.17^{b}	94.3

Superscript letters (a, b, c) show homogeneous groups established from LSD (Least Significance Difference) intervals ($p< 0.05$).

Table 3. CIELab (L*, a*, b*) color coordinates for desalted cod dried at different temperatures (10, 0 and -10ºC), without (AIR) and with (AIR+US, 20.5 kW/m^3, 21 kHz) ultrasound application. Average values ± standard deviation are shown. ΔE represents the overall color differences between AIR+US and AIR samples.

		-10ºC	0ºC	10ºC
L*	AIR	79.9±4.4^{a}	57.9±4.1^{c}	54.1±2.3^{c,d}
	AIR+US	67.0±4.3^{b}	55.3±4.2^{c,d}	55.9±5.0^{d}
a*	AIR	-1.2±0.4^{m}	-1.0±1.3^{m}	-0.1±1.2^{n}
	AIR+US	-0.9±0.5^{m}	-1.0±0.8^{m}	-1.0±1.0^{m}
b*	AIR	13.6±3.0^{x}	16.1±3.0^{y}	16.1±2.9^{y}
	AIR+US	12.6±2.6^{x}	15.8±2.6^{y}	15.6±3.0^{y}
ΔE	AIR+US vs AIR	12.9	2.6	2.1

Superscript letters (a, b, c, d), (m, n) and (x, y) show homogeneous groups, established from LSD (Least Significance Difference) intervals (p<0.05) for L*, a* and b*, respectively.