

INFLUENCE OF FREEZING AND ULTRASOUND APPLICATION ON DRYING OF MEAT

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ABSTRACT

Dry-cured meat products are of great importance in the food industry. Meat structure is very prone to suffer case-hardening during drying and, as a consequence, natural convection conditions must be used. However, this fact increases the operation time and the energy consumption. The process can be intensified by introducing some additional energy sources e.g. power ultrasound. Moreover, a large amount of the raw material used to produce dried meat products is previously frozen and this fact can also affect the drying rate. Thus, the main goal of this work was to evaluate the feasibility of the power ultrasound application in convective drying of meat, evaluating the influence not only on drying kinetics but also on quality parameters such as rehydration ability or texture.

For this purpose, fresh and previously fast and slow frozen meat samples were dried without and with (21.7 kHz; 20.5 kW/m³) ultrasound application. After, the dried samples were rehydrated in water (25 °C). A diffusion model was used to quantify both drying and rehydration kinetics. The texture of rehydrated samples were measured by a penetration test.

The results obtained showed that the previous freezing influenced the drying and the rehydration kinetics. The application of ultrasound during drying of both frozen and fresh meat increased the drying rate.

RESUMEN

Los productos cárnicos crudo-curados son de gran importancia en la industria alimentaria. Sin embargo, la carne es un producto muy propenso a sufrir encostramiento durante el secado lo que obliga a utilizar condiciones de convección natural. Estas condiciones aumentan el tiempo de operación y el consumo de energía. Para la intensificación del proceso, se pueden utilizar fuentes de energía adicionales como por ejemplo, los ultrasonidos de potencia. Por otro lado, una parte importante de la materia prima utilizada para producir productos cárnicos crudo-curados es previamente congelada y este hecho puede afectar a la velocidad de secado. Por lo tanto, el objetivo principal de este trabajo fue estudiar la viabilidad de la aplicación de ultrasonidos de potencia en el secado convectivo de carne evaluando no sólo la influencia en la cinética de secado, sino también, en parámetros de calidad como la capacidad de rehidratación o la textura.

Para ello se realizaron experiencias de secado de tres tipos muestras de carne, frescas, congeladas convencionalmente y congeladas rápidamente, con (21,7 kHz; 20,5 kW/ m³) y sin la aplicación de ultrasonidos. Posteriormente, se estudió el

proceso de rehidratación (25 °C). Para cuantificar tanto la cinética de secado y rehidratación se utilizó un modelo difusivo. También se determinó la dureza de las muestras rehidratadas mediante ensayos de punción.

Los resultados obtenidos mostraron que la congelación influyó en la cinética de secado y de rehidratación. La aplicación de ultrasonidos durante el secado de la carne congelada y fresca aumentó significativamente la velocidad de secado.

RESUM

Els productes carnis cru-curats són de gran importància en la indústria alimentària. No obstant això, la carn és un producte molt propens a patir encrostant durant l'assecat el que obliga a utilitzar condicions de convecció natural. Aquestes condicions augmenten el temps d'operació i el consum d'energia. Per a la intensificació del procés, es poden utilitzar fonts d'energia addicionals com ara els ultrasons de potència. D'altra banda, una part important de la matèria primera utilitzada per produir productes carnis cru-curats és prèviament congelada i aquest fet pot afectar la velocitat d'assecat. Per tant, l'objectiu principal d'aquest treball va ser avaluar la viabilitat de l'aplicació d'ultrasons de potència en l'assecatge convectiu de carn avaluant no només en la influència en la cinètica d'assecat, sinó també en paràmetres de qualitat com la capacitat de rehidratació o la textura.

Per això, es van realitzar experiències d'assecatge de tres tipus mostres de carn, fresques, congelades convencionalment i congelades ràpidament, amb (21,7 kHz; 20,5 kW / m³) i sense l'aplicació d'ultrasons. Posteriorment, es va estudiar el procés de rehidratació mitjançant immersió de les mateixes en aigua (25 °C). Per quantificar tant la cinètica d'assecat i rehidratació es va utilitzar un model difusiu. També es va determinar la dureza de les mostres rehidratades mitjançant assaigs de punció.

Els resultats obtinguts van mostrar que la congelació va influir en la cinètica d'assecat. L'aplicació d'ultrasons durant l'assecat de la carn congelada i fresca va augmentar significativament la velocitat d'assecat.

INTRODUCTION

Hot air drying is widely used for centuries to preserve food products. It allows their availability regardless the season of the year (Chen et al, 2008). During convective drying, moisture content of the product is reduced which leads to slow down its chemical and microbiological deterioration extending the shelf life. Moreover, volume and weight of the product decreases significantly resulting in lower costs and making easy the transport and the storage of the dried products comparing to the fresh ones (Mujumdar et al., 2000).

Unfortunately drying also presents some important drawbacks being one of them related with the energy consumption. According to Chen et al. (2008) the dehydration processe count up for 25% of the industrial energy consumption. Moreover, the long process time needed and the high temperatures used during drying process is linked not only to the high consumption of energy but also to the low quality of the final product. Thus, convective drying leads to a series of changes such as shrinkage, color changes, oxidation or loss of texture and nutritional functional properties (Vega-Galvez et al., 2009). All this changes are directly related with the drying technique applied, the temperature used (Heras-Ramirez et al., 2012) and the drying time. Pretreatments or the use of additional energy sources during drying such as infrared radiation (Rastogi, 2012), microwave (Li et al., 2011) or power ultrasound (Cárcel et al., 2012) can overcome these quality and energy problems by reduction of drying time as well as the drying temperature.

Microwaves or infrared radiation are thermal techniques to intensify drying process that include the risk of product overheating (Riera et al., 2011). On the contrary, the application of power ultrasound in gas-solid system don't significantly affect the sample temperature. Acoustic waves, vibrating with a frequency between 18-500kHz, produce mostly mechanical effects, such as the fast compression and expansion of the material and the micro-channels creation. These effects makes the exit of water from the inner part of product easier without introducing high amount of thermal energy during drying (Riera et al., 2011, Nowacka et al., 2012). Moreover, strongly attached water molecules can be removed by cavitation phenomena induced by power ultrasound (Soria et al., 2010). Comparing to other methods, the use of power ultrasound can be included as a non-thermal way of processing and an environmental friendly, energy saving technology (Gallego- Juarez, 2010).

There are two main methods of applying power ultrasound during drying. When there is close contact between product and ultrasound source, called direct-contact application, and, when ultrasound is applied through the air,

called air-borne application. It is known that the second one is less efficient when energy yields are considered but it has lower heating effect and better adaptability to convective driers. That is why air-born application is more investigated and better developed than direct-contact one (Ozuna et al., 2014; Schössler et al., 2012).

Dried products are generally rehydrated before use. The main goal of rehydration is to achieve similar characteristics to fresh material. That is why many studies have been carried out concerning the rehydration behavior of some dried foodstuff for example broccoli (Femenia et al., 2000), apples (Bilbao-Sáinz et al., 2005), mushrooms (García-Pascual et al., 2005), pasta (Cunningham et al., 2007), tomatoes (Goula and Adamopoulos, 2009), chicken (Schmidt et al., 2009) or pork meat (Uengkimbuan et al., 2006). Nowadays consumers are more aware of quality of products. That is why it is important that rehydrated product have the highest quality possible. Unfortunately, rehydration is not exactly a reverse process of dehydration. During drying and pretreatment some damage to the cell structure is made. Therefore, rehydration ability can indicate the level of structure changes produced by drying (Bilbao-Sáinz, et al., 2005). Dry-cured meat products are of great importance in Spain. However, meat is very prone to suffer case-hardening during drying, developing an external dried layer that makes the exit of internal moisture difficult. As a consequence, low quality products are obtained. To avoid this phenomenon, the drying of meat usually takes place under natural convection or very slight forced conditions that makes the drying a very slow process that consume an important amount of energy. In this sense, the application of power ultrasound can improve mass and heat transport intensifying the drying process.

Nowadays, a large amount of raw material used to produce dried meat products is previously frozen. This fact could affect internal structure of meat, and thus, influence the drying process.

Therefore, the main goal of this work was to assess the influence of the previous freezing and the application of ultrasound in the drying kinetics of meat as well as on quality parameters such as rehydration and texture.

MATERIAL AND METHOD

Raw material

The meat used for the experiments was *Porcine Longissimus Dorsi* which was purchased in a local supermarket (Valencia, Spain). The samples were chosen as homogeneous as possible. For this, the meat used was always from the same supplier and the shelf life date was in all cases of six days. Samples correspond with the central part of muscle and were chosen with similar color. Sliced portions, mechanically cut with a slicer, were stored at 5 °C until processing (no more than 4 hours). Then, slab samples of 6 x 35 x 60 mm were obtained from the central part of the slices with a knife avoiding fatty areas. The samples were divided into three batches. One of them was directly used for drying experiments (M). The two others were frozen before drying experiments. Of the two, the first one was frozen using a conventional freezer at -20 °C for at least 12 h (FM). During freezing, samples were wrapped in a waterproof plastic film to avoid partial dehydration. The last batch was frozen using a blast chiller until -35°C for 15 min (FFM)

Drying process

All three batches of meat samples, fresh (M), slowly frozen (FM) and fast frozen (FFM), were dried using an air velocity of 1 m/s, to limit case hardening of samples, and at 40°C, which can be considered a moderate drying temperature. It should be underline that frozen samples were introduced directly into the drier to avoid the influence of leaching due to the defrosting process on the initial moisture content of samples. The drying experiments were carried out without (AIR) and with (ULS) ultrasound applications. In this last case, a specific electric power of 50 W was applied to the transducer, which means a power density of 20.5 kW/m³. For each run, six samples (93.8 ± 5.3 g) were randomly placed in a sample holder assuring the uniform flow of drying air around them and a uniform ultrasound application. Sample weight was automatically recorded at 5 min intervals during the whole drying process. In all cases, drying was carried out until a loss of 50% of the initial mass of the sample was reached. All drying conditions were performed at least in triplicate to limit the influence of the natural variability of meat. The moisture of meat samples was measured following standard methods 950.46 (AOAC, 1997). Thus, the moisture content was obtained by measuring the difference of weighting between fresh or frozen samples and the same meat samples dried at 105°C until they achieved constant weight (24 h approximately).

Airborne ultrasonic dryer

Drying experiments were carried out in an ultrasonically assisted air drier (Diagram 1.), already described in the literature (Cárcel et al., 2011). In the drying system, two PID control algorithms allowed the temperature and the velocity of the air to be controlled and registered. The drier is equipped with a pneumatic system, allowing samples to be weighed automatically at pre-set drying times. The drying chamber is constituted by an aluminium cylinder (internal diameter 100 mm, height 310 mm, and thickness 10 mm). This is driven by a piezoelectric composite transducer that consists of an extensional piezoelectric sandwich element together with a mechanical amplifier (Mulet et al., 2011). This device is able to generate a high-intensity ultrasonic field in the air medium, reaching an average sound pressure level of 154.3 dB in stagnant air conditions.

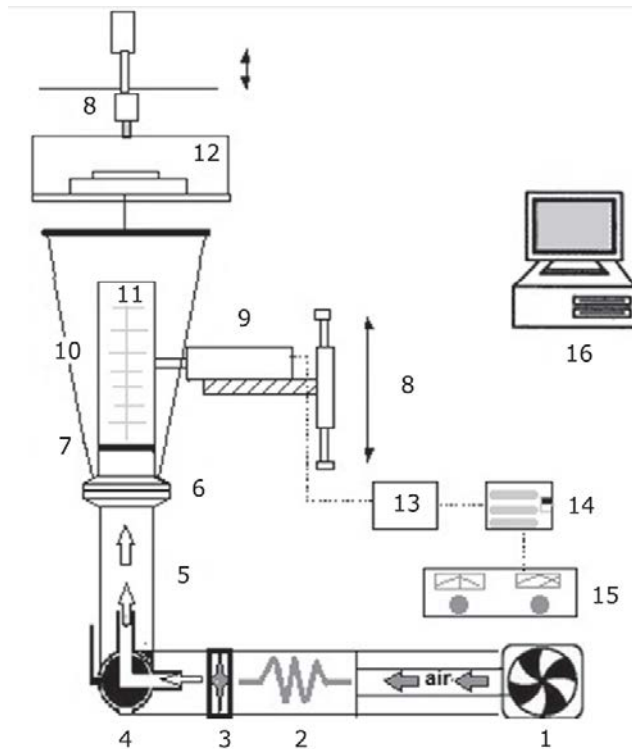


Diagram 1. Diagram of the ultrasonic assisted dryer. 1. Fan. 2. Heating unit. 3. Anemometer. 4. Three-way valve. 5. Thermocouple. 6. Sample loading chamber. 7. Coupling material. 8. Pneumatic system. 9. Ultrasonic transducer. 10. Vibrating cylinder. 11. Sample holder. 12. Balance. 13. Impedance matching unit. 14. Digital power meter. 15. High power ultrasonic generator. 16. PC. (Gamboa-Santos et al., 2014)

Rehydration process

Rehydration process of dried pork was carried by immersing 6 meat samples in distilled water which were in constant movement at temperature of $25 \pm 1^\circ\text{C}$. Weight changes were measured during rehydration to determine the rehydration kinetics. For that purpose, samples were removed from water at regular time intervals, superficially dried using paper towels and weighted on laboratory balance. The weight change of samples was calculated from Eq.1.

$$\Delta M_t^0 = \frac{M_t - M_0}{M_0} \quad (1)$$

Where ΔM_t^0 is the net weight change (kg water/kg dried meat), M_t is the weight of sample (kg) at time t (s), M_0 is the initial weight of the dried meat (kg). After reading the weight samples were returned to the bath for next period of time. Process was repeated until obtaining a constant weight.

Drying and rehydration modelling

First order kinetic modelling

In order to do a first evaluation of the kinetics of the drying process, an experimental model based in a first order equation was used (Equation 2)

$$W = W_i \cdot e^{(m \cdot t + n)} \quad (2)$$

where W is the moisture content of the sample (kg water / kg dry matter); W_i is the initial moisture content (kg water / kg dry matter); t is the drying time (s); m and n are the parameters of the model. The factor m offers an estimation of the drying velocity and includes the effect of any variable on the drying kinetics.

Diffusive modeling

In a second phase, a theoretical diffusion model was used to mathematically describe not only drying kinetics but also rehydration kinetics. For an infinitive slab geometry, the equation of this model is shown in Eq (3),

$$\frac{\partial W_p(x,t)}{\partial t} = D_w \left(\frac{\partial^2 W_p(x,t)}{\partial x^2} \right) \quad (3)$$

where W_p is the local moisture content (kg water / kg dry matter); t is time (s); D_e is effective diffusivity (m^2 / s); x is the transport moisture direction (m).

In order to solve Eq. (3) following assumptions were considered: the initial moisture content was the same in whole sample, the volume of the sample remained constant during drying or rehydration (no shrinkage/swelling phenomena were considered) and the external resistance to water transfer

was negligible. The Equation 4 is the analytical solution used, which takes all of the above assumptions into consideration.

$$\psi(t) = \frac{W(t) - W_e}{W_0 - W_e} = \left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{\left(\frac{D_w (2n+1)^2 \pi^2 t}{4L^2} \right)} \right] \quad (4)$$

The fitting of the model to both drying kinetics and rehydration kinetics were performed by solving an optimization problem. This optimization problem consisted of finding the value of the effective diffusivity minimizing the average squared difference between the experimental values of the average moisture content and the values calculated with the model. Solving the problem of optimization was performed using the Solver tool of Microsoft Excel™ spreadsheet (Microsoft Corporation, Seattle, USA), which applies the method of Generalized Reduced Gradient (GRG).

The goodness of fit was evaluated by calculating the percentage of explained variance (%VAR, Eq (5)) (Berthouex et al., 1994).

$$\%VAR = \left[1 - \frac{S_{xy}^2}{S_y^2} \right] \cdot 100 \quad (5)$$

Texture measurement

Texture of rehydrated samples was assessed from the determination of the maximum penetration force. It was measured using a Texture Analyzer (TAX-T2i, Stable Micro System, United Kingdom), equipped with a 2 mm flat cylinder probe (SMS P/2 N). The experiment was carried out using a cross-head speed of 1 mm/s and a strain of 75%. For each sample, penetration tests were carried out in 15 different points following a preset pattern. Four meat samples were analyzed for each replication of the different drying condition tested. That means, that a total number of texture measurement of 1080 (6 drying conditions x 3 replicates x 4 samples x 15 texture determinations) were carried out. It is important to underline that measurement of texture was performed on two samples from upper level and two from lower level of sample holder. Hot air was passing first by the lower level of sample holder than the upper one which means that the samples from the lower level received dried air and the ones from upper level were dried with an air with higher moisture content.

Statistical analysis

The results were statistically analyzed using analysis of variance (ANOVA, $p < 0.05$) and the significance of differences between treatments was established from the least significant difference test (LSD Least Significant Difference) using the program Statgraphics Centurion XVI.

RESULTS AND DISCUSSION

Drying process and modeling

Drying experiments were performed with fresh (M), slow (FM) and fast (FFM) frozen samples of pork tenderloin. The initial moisture content of samples was 2.9 ± 0.08 kg water/kg dry matter (d.m.) not founding significant differences between moisture content of fresh and frozen samples.

The experimental results obtained showed an initial delay in the drying kinetics of FM and FFM samples that can be attributed to the fact that at the beginning of drying, these samples were frozen (Figure 1A). Thus during this first stage of drying, the moisture content of samples increased due to the condensation of water on the frozen meat surface. However, few minutes after, this additional moisture was removed and then, the drying rate of FM samples appeared to be higher than M samples. In the case of FFM, the drying rate was slower than the observed for M samples.

The application of ultrasound during drying accelerated the process kinetics for M samples as well as for FM and FFM (Figure 1B). In the case of both types of frozen samples (FM and FFM), ultrasound also accelerated the thawing stage. As in the case of AIR drying experiments and after the thawing stage, the drying rate of FM-ULS samples appeared to be higher than observed for M-ULS ones. Similarly, FFM-ULS samples showed similar drying kinetics to M-ULS samples. This fact can be attributed to the difference of size of ice crystals formed during freezing process. Thus, the fast freezing process induced the formation of many small ice crystals, which are homogeneously distributed mostly at intercellular levels within muscle limiting the cellular damage. On the contrary, during slow freezing process big ice crystals are formed that destroy cell membranes and cause damage in muscle proteins. As a consequence, it is easier to remove the water from broken structures and then drying time is shorter (Yuan et al., 2015).

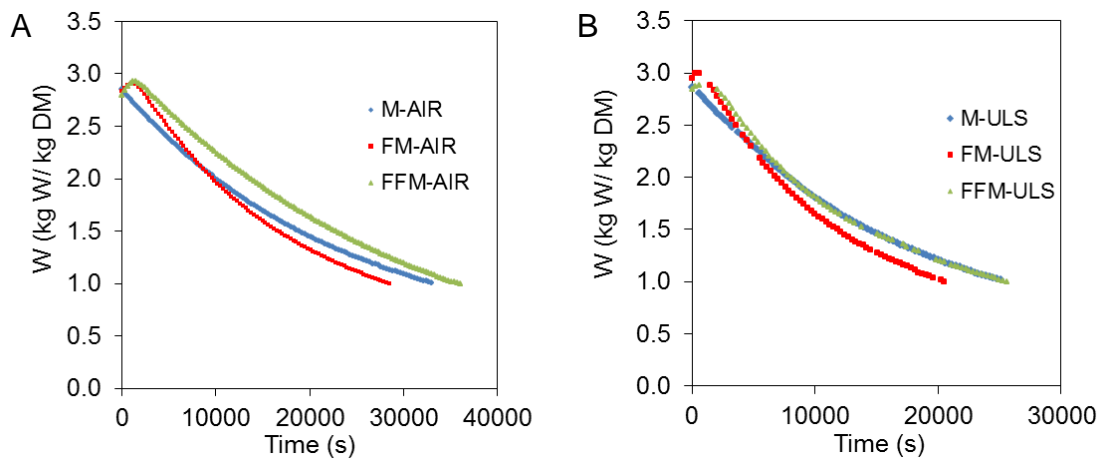


Figure 1. Experimental moisture content evolution of fresh (M), slow frozen (FM) and fast frozen (FFM) meat during drying (40°C, 1 m/s) without ultrasound application (A) and with ultrasound application (B; 20.5 kW/m³; 21.7 kHz).

The total drying time needed to achieve a final moisture content of 1 kg water/kg dry matter was 15.7 % lower for FM samples than for M ones in case of AIR assisted drying. The FFM samples showed the highest drying time of the three type of samples studied (Table 1). Thus, the drying time of FFM-AIR samples was 25.3% higher than FM-AIR ones being these differences significant ($p > 0.05$).

The application of ultrasound during drying accelerated the operation. Thus, in the case of M samples, drying time was 31.4% lower for ultrasonically assisted dried samples than for conventionally dried ones. In the case of FM samples, this difference was 39% and a 27.7% for FFM one. All of these differences were significant ($p < 0.05$) (Table 1).

Similarly than for AIR samples, among the drying experiments carried out with ultrasound application, FM-ULS samples showed the shortest drying process while the FFM-ULS samples needed the longest time.

It is known that ultrasound provoke a series of effects which affect both internal and external resistance to mass transfer (Mulet et al., 2011). Thus, application of ultrasound significantly reduced the total time of drying of the three kinds of samples used. The differences of the impact observed among batches tested can be attributed to the different kind of pretreatment applied. As mentioned before, the different size of crystals created during the fast and the conventional freezing had a different impact in meat structure that can affect the drying rate. This also can affect the influence of ultrasound application on drying rate and it can explain why FM samples were dried faster than other two.

Table 1. Total drying time to achieve a moisture content of 1 kg water/kg dry matter of fresh (M) slow frozen (FM) and fast frozen (FFM) meat dried without (AIR) and with (ULS) ultrasound application

Experiment Code	Total drying time (h)
M-AIR	9 ± 1 ^a
FM-AIR	8 ± 1 ^b
FFM-AIR	10 ± 1 ^a
M-ULS	7 ± 1 ^b
FM-ULS	5.7 ± 0.6 ^c
FFM-ULS	7.8 ± 0.3 ^b

The initial water condensation on the surface of frozen samples delay the start of drying process. This delay it can considered as a tempering time and it can be estimated as the time needed to the samples to achieve the initial moisture content again. Thus, an effective drying time (t_e) can be calculated as the total drying time minus this delay period (Table 2). As can be seen in Table 2, for the AIR drying experiments, this effective drying time for both FM and FFM samples was about 10% smaller than the total drying time. In the case of ULS experiments this difference was reduced below 8%.

Moreover, the t_e of FM samples was 60% smaller for ULS dried samples than for AIR ones. Similar results were obtained for FFM samples. Therefore, the effects produced by ultrasound not only can reduce mass transfer resistance but also heat transfer resistance reducing this tempering period.

On the other hand, taking under consideration the effective drying time only, it can be observed that M-AIR and FFM-AIR samples show similar drying times. It can be assumed that fast freezing pretreatment did not significantly affected meat structure and then no significant influence on effective drying time of FFM-AIR sample was observed.

On the contrary, the conventional freezing process significantly reduced the effective drying time of meat samples. As stated before, the slow freezing can contribute to the formation of big ice crystals that can broke meat fibers and/or produce some cellular damage that make the water movement inside samples easier. As a result effective drying time of FM-AIR sample is the shortest of all other samples.

Considering ULS application, a significant reduction of effective drying time can be observed. In the case of FFM sample this reduction is about 25.3% and for FM sample it is 42.4%. As it was leased above during slow drying

process many damages to the meat structure occur. Therefore US influence on FM samples can be higher.

Table 2. Effective drying time to achieve a moisture content of 1 kg water/kg d. m. of fresh (M) slow frozen (FM) and fast frozen (FFM) meat dried without (AIR) and with (ULS) ultrasound application

Experiment Code	Effective drying time, t_e (h)
M-AIR	9 ± 1^a
FM-AIR	7.3 ± 0.8^b
FFM-AIR	9 ± 1^a
M-ULS	7 ± 1^b
FM-ULS	5.3 ± 0.6^c
FFM-ULS	7.2 ± 0.3^b

a, b, c: the same letters show homogeneous groups.

Drying Modelling

First order kinetic modelling

A first attempt to quantify the influence of the previous freezing of meat and the ultrasound application during drying in drying kinetics was made by fitting the natural logarithm of the dimensionless moisture content evolution in time to a linear behavior (Equation 2). In the case of M samples this linear relationship was observed for all drying time. In the case of FM and FFM samples, only the effective drying period was considered (Figure 2).

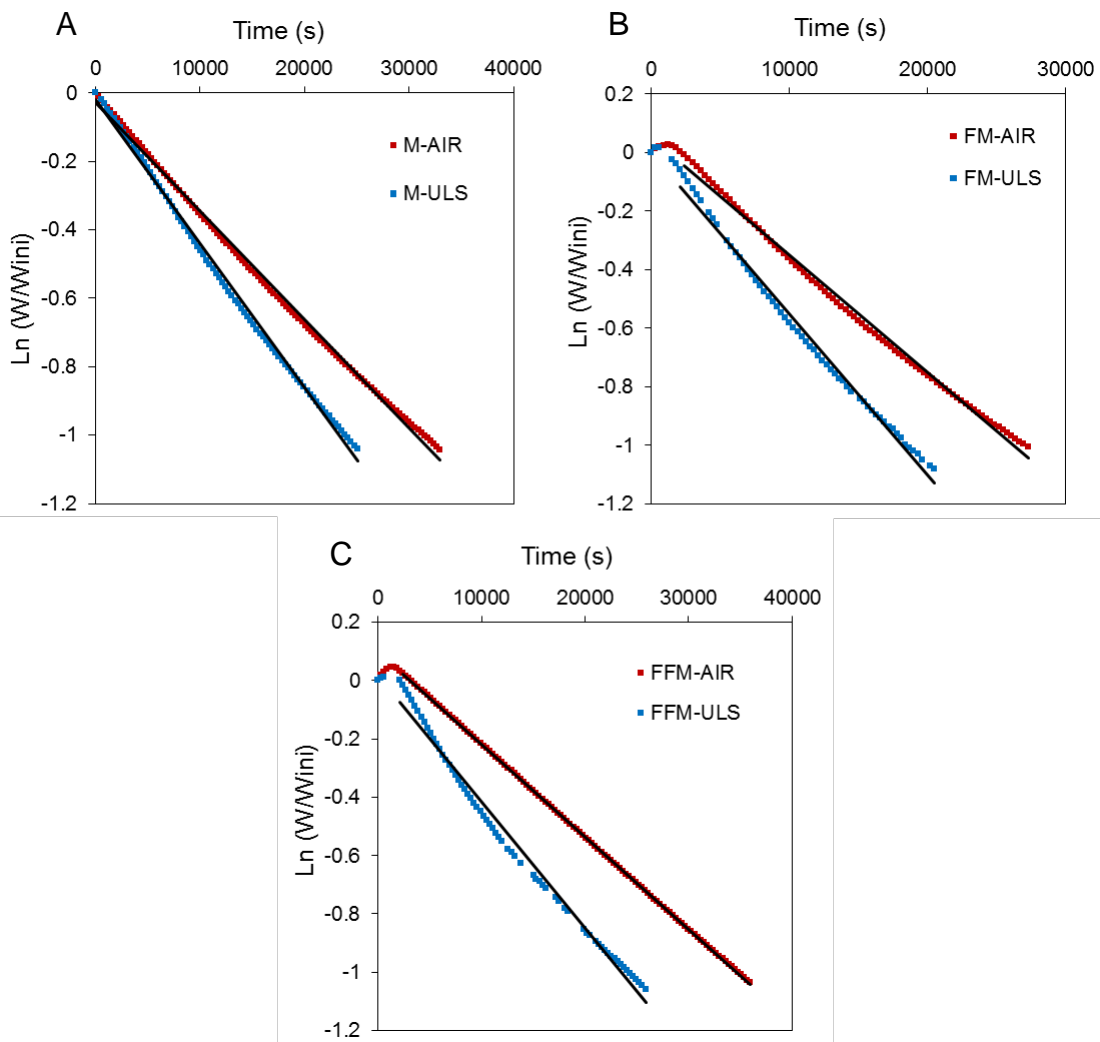


Figure 2. Natural logarithm of the ratio moisture content at drying time and initial moisture content versus drying time for fresh ((M) - graph A), slow frozen ((FM) - graph B) and fast frozen meat ((FFM) - graph C) drying with (ULS) and without (AIR) ultrasound application

As can be observed in Figure 2, the linear relationship can be used as a roughly first approach of drying kinetics. The slope of natural logarithm of the dimensionless moisture versus time was an indicator of the drying rate (Table 3). Accordingly the AIR dried experiments, the values obtained for the FM samples, were higher than the ones obtained for M and FFM samples being these last two quite similar.

Considering the application of ultrasound during drying, for the three samples, M, FM as well as FFM, it was observed higher values of slope than those obtained in AIR drying conditions. The influence of ultrasound was a little higher for FM samples than for M and FFM samples.

These modelling results agreed with those observed from the comparison of the effective drying time (Table 2). The fast frozen limited the influence of frozen in the meat structure and then drying rate was similar than the one observed for fresh meat. The slow freezing could affect sample structure accelerating the drying process.

Table 3. Slope of the linear relationship between natural logarithm of the moisture and initial moisture content of sample and drying time for fresh (M) slow frozen (FM) and fast frozen (FFM) meat dried without (AIR) and with (ULS) ultrasound application

Experiment Code	Slope (10^{-5})
M-AIR	3.1 ± 0.4^a
M-ULS	4.2 ± 0.6^b
FM-AIR	4.1 ± 0.3^b
FM-ULS	6 ± 1^c
FFM-AIR	3.2 ± 0.4^a
FFM-ULS	4.1 ± 0.4^b

a, b, c: the same letters show homogeneous groups.

In any case, the effects produced by ultrasound both inside meat samples and at the interface meat-air contributed to accelerate the drying. The high variability of raw matter can partially mask the influence of the variables considered. Therefore, more research is needed to better establish their influence on the process.

Diffusive modelling

As stated before, the first order kinetics model is just a rough approaches to the experimental drying kinetics. A more deep work of modelling was carried out from the fitting of the diffusive model described in material and methods section (Equation 3). The percentage of explained variance obtained was in the order of 98 %. This slightly low value can be attributed not only to some assumptions considered in the model, such as consider the external resistance negligible, but also the high natural variability of the meat. In any case, it can be considered as adequate and make possible the comparison between treatments.

As can be seen in Table 4, the value of effective diffusivity identified for FM-AIR samples was 38.8% higher than those identified for M-AIR samples and 9.0% higher than for FFM-AIR sample. These data can confirm the influence of the previous freezing of the sample and the differences between freezing treatments

In the case of ULS assisted drying experiments, the identified effective diffusivity increased compared to AIR experiments. However this impact was dependent for the type of sample. Thus, for FM samples and M samples, the identified D_e was 24.9% and 30.2% respectively higher than the identified in AIR experiments. On the contrary for FFM, it was only 4.4% higher.

Table 4. Effective diffusivity (D_e) identified and percentage of variance explained (%VAR) by the fitting of diffusive model to experimental drying kinetics of fresh (F), slow frozen (FM) and fast frozen (FFM) meat samples. $\Delta D_e\%$ indicates the increase of D_e produced by US application.

Sample	AIR		ULS		$\Delta D\%$
	D_e ($10^{-10} \text{ m}^2/\text{s}$)	%VAR	D_e ($10^{-10} \text{ m}^2/\text{s}$)	%VAR	
M	3.7 ± 0.6^a	97.9 ± 0.4	4.9 ± 0.4^{ab}	97.5 ± 0.5	30.2
FM	5.2 ± 0.1^b	97.9 ± 0.8	6.5 ± 0.1^c	99 ± 1	24.9
FFM	5 ± 1^{ab}	97.6 ± 0.9	5 ± 2^{ab}	98.6 ± 0.7	4.4

a, b, c: the same letters show homogeneous groups.

Rehydration of the dried samples and modeling

The experiments of rehydration were carried out with the samples obtained in the different drying experiments. The moisture content of the dried samples at the beginning of rehydration experiments was in a relatively narrow range ($\pm 5\%$) (Table 5), which contributes to the representativeness of the results. The small differences were due to the difficulty to stop drying process at the same level of moisture loss.

Table 5. Moisture content of the samples at the beginning of rehydration experiments (kg water/ kg d.m.)

Sample	X_w	
	AIR	ULS
M	0.9 ± 0.1	0.8 ± 0.1
FM	0.8 ± 0.2	0.9 ± 0.7
FFM	0.9 ± 0.1	0.8 ± 0.1

The lower values of rehydration time were obtained for FM samples (Table 6). In the case of AIR dried samples, it was 22.8% and 74.8% smaller than M and FFM samples respectively. In the case of samples ultrasonically assisted dried, these differences were 31.8% and 8.6% respectively (Figure 3).

Regarding the influence of ultrasound application during drying in the rehydration time, it was different for M and FM samples than for FFM ones. Thus, the rehydration time of M-ULS and FM-ULS samples was 11.4% and 3.8% greater than those needed for M-AIR and FM-AIR samples respectively being these differences not significant ($p < 0.05$). On the contrary, FFM-AIR dried samples needed a rehydration time 55.0% higher than FFM-ULS samples.

It is known that rehydration is dependent on the degree of cellular and structural disruption. That is why the difference between three differently pretreated samples might have occurred. The slow freezing of FM can greatly affect the meat structure making easy not only drying of samples but also rehydration. In this case the application of ultrasound during drying had a low influence on structure because the damages produced by freezing were quite important. Therefore, the rehydration time of FM-AIR and FM-ULS samples were similar. On the other hand, the fast freezing of FFM samples preserved better the natural structure of meat. Then, in this case the influence of ultrasound application during drying was significant and its influence on rehydration time was more evident.

Table 6. Rehydration time to achieve stable weight of fresh (M), slow frozen (FM) and fast frozen (FFM) meat dried without (AIR) and with (ULS) ultrasound application.

Sample	Time of rehydration (h)	
	AIR	ULS
M	8 ± 1	9 ± 1
FM	7 ± 2	7 ± 1
FFM	11.5 ± 0.3	7.4 ± 0.6

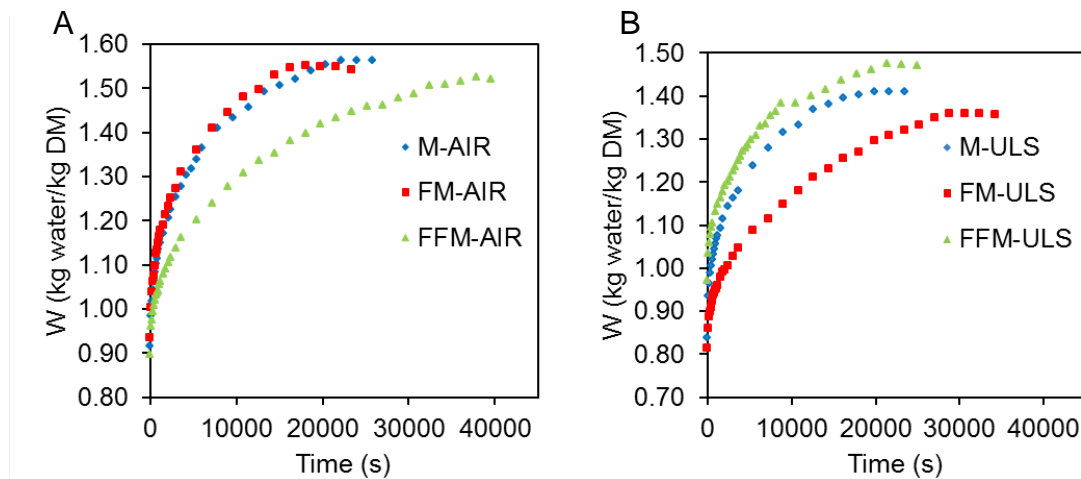


Figure 3. Experimental moisture content evolution of fresh (M), slow frozen (FM) and fast frozen (FFM) dried (40 °C; 1m/s; with (ULS) and without (AIR) ultrasound application) meat during rehydration (25°C).

After rehydration, the final moisture content of all samples was not significantly different (Table 7). As stated before, the moisture content of fresh samples was 2.87 ± 0.08 kg water/kg d.m. This means that rehydrated samples only achieved the $48\% \pm 3$ of the initial moisture content of meat, independently of the drying method used.

Table 7. Moisture content of the samples at the end of rehydration experiments (kg water/ kg d.m.)

Sample	AIR	ULS
	X_w	X_w
M	1.9 ± 0.1	1.9 ± 0.1
FM	1.9 ± 0.3	1.9 ± 0.1
FFM	2.0 ± 0.1	1.9 ± 0.1

Modelling rehydration kinetics.

Rehydration kinetics were modelled, as in case of drying, by applying a diffusion model without considering the external resistance to mass transfer. Taking into account the high variability of samples, the model fitted adequately ($\% \text{VAR} > 97\%$) to the experimental data (Table 8).

Table 8. Effective diffusivity identified by fitting the diffusive model to the rehydration kinetics of meat and percentage of explained variance (%VAR) by the model. $\Delta D_{er}\%$ indicates the increase of D_{er} due to the application of US during drying.

Sample	AIR		ULS		$\Delta D_{er}\%$
	D_{er} (10^{-10} m ² /s)	% VAR	D_{er} (10^{-10} m ² /s)	% VAR	
M	5 ± 1^a	96.7 ± 0.4	0.70 ± 0.01^c	99.0 ± 0.8	-86.6
FM	30 ± 1^b	99.7 ± 0.2	25 ± 16^b	99.3 ± 0.3	-18.9
FFM	5.79 ± 0.01^a	99.6 ± 0.1	30 ± 11^b	98.3 ± 0.9	418.1

a, b, c: the same letters show homogeneous groups.

The identified value of D_{er} was similar for M-AIR and FFM-AIR samples. This fact will confirm the slight effects that fast freezing pretreatment caused on meat structure. On the other hand, the D_{er} identified for FM-AIR samples was 553.1% higher than obtained for M-AIR and FFM-AIR samples that will show the greater damage to the meat structure that the slow freezing process could induce.

Taking under consideration the results obtained for rehydration modelling of M-ULS data it can be observed that application of ultrasound affected the structure of the meat which made the rehydration process slightly difficult than for the M-AIR samples. That is why D_{er} for this samples have negative value. In case of FM experiments, as it was mentioned before, the main damage to the meat structure was made during freezing process so the application of ultrasound did not have a significant influence on the rehydration rate. On the contrary, the identified D_{er} for FFM-ULS samples increased 418% compared to FFM-AIR samples. It can be said that combination of fast freezing pretreatment and application of ultrasound during drying process significantly improved the rehydration of samples.

Texture

The hardness of the rehydrated meat samples was measured by computing the maximum penetrating force. Test was performed to evaluate not only the effect of the freezing pretreatment and the application of ultrasound during drying in the texture of rehydrated samples but also the position of the sample on the sample holder during drying experiments (Figure 4).

In general, the rehydrated M-AIR samples showed higher average values of hardness than FM-AIR and FFM-AIR samples, regardless of sample position during drying. In case of ULS assisted drying, FFM-ULS samples had higher average values of hardness than the M-ULS and FM-ULS samples (Table 9).

However, in both cases these differences were not statistically significant ($p < 0.05$) (Figure 4A).

The application of ultrasound during drying significantly increased the hardness of rehydrated sample (Figure 4B). Thus, the maximum penetration force of FFM-ULS samples placed in the upper and in the lower position of sample holder was 24.9% and 31.8% higher than FFM-AIR samples respectively (Table 9). For FM samples, the value was 27.7% and 19.7% higher in the ultrasonically assisted samples, and for M samples, it was 10.3% higher for the upper position and 15.1% for lower one.

The results also showed that samples which were placed in the lower position of sample holder during drying presented a significantly ($p < 0.05$) higher maximum penetration force than those placed in the upper position (Figure 4C). Thus, in the case of M-AIR samples, the maximum force was 9.0% higher in the lower position than in the upper position (Table 9). In the case of FM-AIR and FFM-AIR samples, this difference was 21.2% and 10.04% respectively. As regard the ultrasonically assisted dried samples the differences were 13.2%, 13.7% and 16.1% for M-ULS, FM-ULS and FFM-ULS samples respectively (Table 9). Samples placed at the lower position received directly a dry drying air while samples placed in the upper position received an air with a higher moisture content due to it contains the moisture eliminated at the lower position samples. Then, the dry air could produce some casehardening phenomenon in the lower samples that produced harder samples after rehydration.

Table 9. Hardness (F max) of rehydrated meat samples previously dried with (ULS) and without (AIR) application of ultrasound. Average values and standard deviation

Sample	F max (N)	
	Upper level (1)	Lower level (2)
M-AIR	4.3 ± 0.5 ^a	4.7 ± 0.3 ^{ab}
M-ULS	4.8 ± 0.1 ^b	5.4 ± 0.8 ^c
FM-AIR	3.7 ± 0.4 ^a	4 ± 1 ^a
FM-ULS	4.7 ± 0.2 ^b	5.3 ± 0.3 ^c
FFM-AIR	3.9 ± 0.1 ^a	4.2 ± 0.4 ^a
FFM-ULS	4.8 ± 0.2 ^b	5.6 ± 0.4 ^c

a, b, c: the same letters show homogeneous groups.

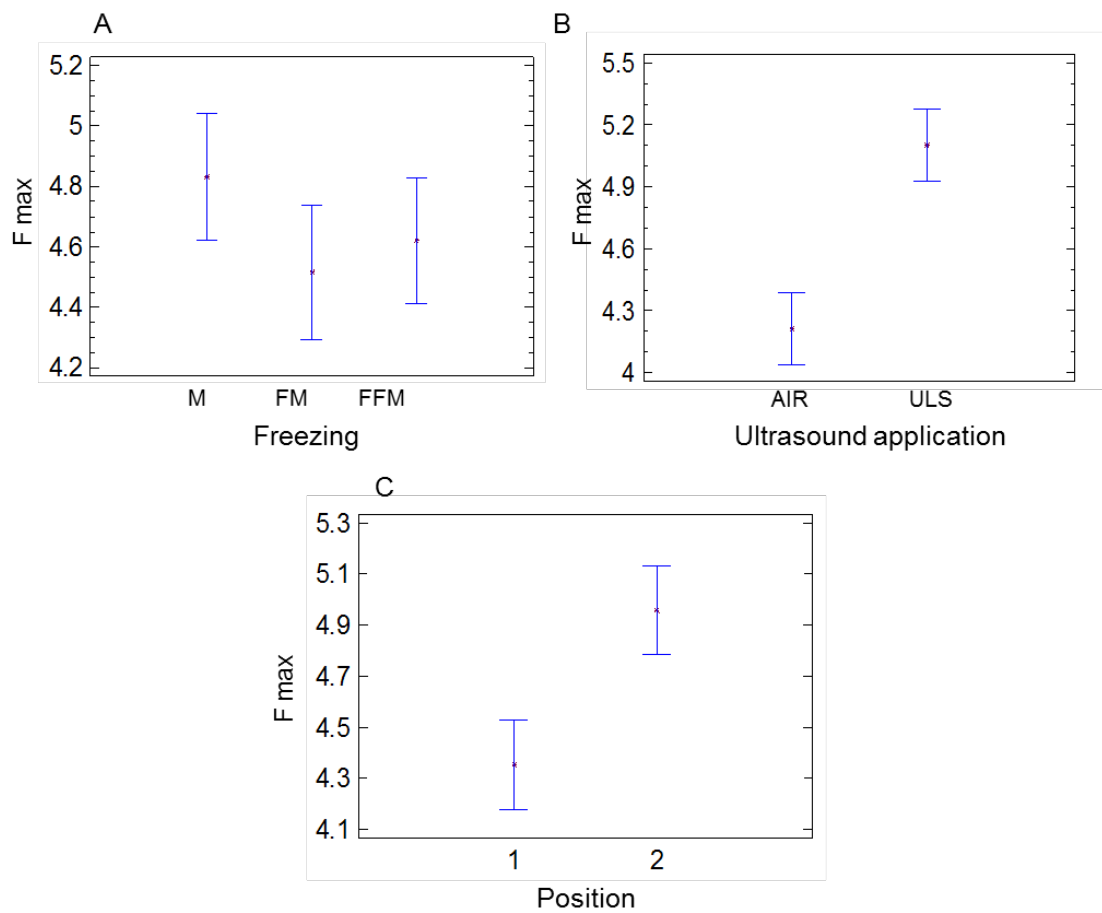


Figure 4. Mean values of maximum force (Fmax (N)), and LSD (Least Significance Difference) intervals ($p < 0.05$) of rehydrated M, FM and FFM samples previously dried with (ULS) and without (AIR) application of ultrasound. Figure 4A represent values dependent on different pretreatment, 4B shows values dependent on application of ultrasound and 4C represent values dependent on position of the sample on the sample holder during drying.

CONCLUSIONS

The freezing pretreatment and the ultrasound application during drying significantly affected not only drying kinetics of meat but also the rehydration rate. Thus, the slow freezing samples showed the faster drying and rehydration rate. That drying of fast freezing samples was quite similar than fresh meat samples indicating that the slow freezing did not significantly affect meat structure. The ultrasound application increased effective diffusivity of drying and rehydration, particularly in the case of fast freezing samples. There was no significant difference in texture of rehydrated samples regardless the freezing of meat. The ultrasound application during drying produced slightly harder samples than samples dried without ultrasound application. Results obtained in this work underline that air-borne ultrasonic application during convective drying of pork loins is a promising technology to increase drying rate and the later rehydration process.

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