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Accelerated mild heating of dry-cured ham by applying power ultrasound in a liquid medium

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ABSTRACT

Mild thermal treatments could be considered a feasible technique with which to improve the texture of dry-cured ham. This study explores the feasibility of using power ultrasound (PuS) to intensify heat transfer during the mild thermal treatment of dry-cured ham immersed in a liquid medium. For that purpose, a temperature controlled ultrasonic bath was used to avoid the water temperature rise due to cavitation during ultrasonic application, which could mask the actual effect of ultrasound in heat transport mechanisms. Experiments were carried out using dry-cured ham slices (thickness 2 cm), which were heated at different temperatures (40, 45, 50 ºC) with (PuS) and without (conventional mechanical stirring, CV) ultrasonic assistance. Temperature was monitored in the two main muscles of the ham (*Biceps femoris* and *Semimembranosus*) and in different positions of the slice. A model that considered heat transfer entirely controlled by conduction was chosen for describing heating kinetics and quantify the influence of temperature and ultrasonic application in the apparent thermal diffusivity.

The heat conduction model proposed was adequate to describe both CV and PuS heating kinetics (VAR >98.6%). Ultrasound application sped up the heat transfer by increasing the apparent thermal diffusivity up to 51%, but the higher the temperature, the lower the ultrasonic intensification. The apparent thermal diffusivities identified for the slices were satisfactorily validated (VAR> 98.4%) in independent experiments with ham cylinders. Therefore, PuS could be considered as an effective technology for the purposes of accelerating the heat transfer, thus shortening the heating time of dry-cured ham slices immersed in a liquid medium.

Key-words: dry-cured ham, heat transfer, thermal treatment, ultrasound, conduction, apparent thermal diffusivity.

1. INTRODUCTION

Cured meat products requiring a long period of curing sometimes present defective texture at the end of the processing. Especially in dry-cured ham, some intrinsic factors like low pH (García-Rey, García-Garrido, Quiles-Zafra, Tapiador, & Luque de Castro, 2004), high water content (Ruiz-Ramírez, Arnau, Serra, & Gou, 2006) or high proteolytic activity (Garcia-Garrido, Quiles-Zafra, Tapiador, & Luque De Castro, 1999) as well as processing factors like the use of low salt concentrations (Ruiz-Ramírez et al., 2006) or the use of excessive high temperatures during curing (Arnau, Guerrero, & Gou, 1997) can provoke soft and pasty textures. These texture defects diminish the quality of the final product (Schivazappa et al., 2002), causing rejection by the consumer. In this context, some authors have addressed different ways of improving defective textures at the end of the elaboration process of dry-cured ham. Garcia-Gil et al. (2014) stated that dry-cured ham slices subjected to high pressure treatment (500 MPa) tended to be harder than control ones, while Fulladosa, Serra, Gou, & Arnau (2009) claimed that high pressure processing (600 MPa) increased the hardness of restructured dry-cured ham. Moreover, corrective mild thermal treatments have also been addressed. Thus, Gou, Morales, Serra, Guàrdia, & Arnau (2008) affirmed that a 10-day ageing at 30 ºC could be a useful means of reducing the problems associated with soft dry-cured hams with no effect on the product flavor. Morales, Arnau, Serra, Guerrero, & Gou (2008) assessed textural changes in dry-cured ham pieces by means of mild thermal treatments during different times and temperatures, but only the thermal treatment at 30 ºC for 7 days decreased the softness in *Biceps femoris* muscle. Some of the main drawbacks of these previous studies are the high cost of high- pressure treatments and the long time period required to improve the dry-cured ham texture when using mild thermal treatments. Therefore, the search for intensification methods in order to shorten the processing times of mild thermal treatments could be an interesting cost-effective option.

In recent years, power ultrasound (PuS) has emerged as an interesting method for process intensification in several engineering applications. Ultrasonic waves have been used to overcome heat and mass transfer limitations. Many studies have proven the enhancement of heat transfer under the influence of ultrasonic vibrations, most of which focused on heat transfer convection (Legay, Gondrexon, Le Person, Boldo, & Bontemps, 2011). Additionally, the ultrasound-assisted intensification of heat exchangers has been addressed, revealing that the overall heat transfer coefficient is always higher under ultrasonic conditions (Gondrexon et al., 2015; Legay, Le Person, Gondrexon, Boldo, & Bontemps, 2012). This improvement in heat transfer is mainly due to acoustic cavitation, acoustic streaming and fluid particle oscillations. Basically, the cavitation and microagitation produced by ultrasound in the liquid medium are responsible of reducing heat transfer resistance by increasing fluid turbulence.

As regards the application of ultrasound in the food sector, it has been formerly used in sterilization (Piyasena, Mohareb, & McKellar, 2003), extraction (Ahmad-Qasem et al., 2013; Jadhav, Gogate, & Rathod, 2009; Tiwari, 2015), filtration (Masselin et al., 2001), drying (Fan, Zhang, & Mujumdar, 2017; Musielak, Mierzwa, & Kroehnke, 2016; Santacatalina, Guerrero, Garcia-Perez, Mulet, & Cárcel, 2016) or freezing (Zheng & Sun, 2006) to increase the efficiency or shorten the processing times. In these applications, ultrasound was used to intensify mass transfer, heat transfer or both phenomena simultaneously. Thus, as examples of mass transfer intensification, Ozuna, Cárcel, Walde, & Garcia-Perez (2014) shortened the drying time for salted cod by up to 50% (20 ºC, 20.5 kW/m^3), while Santacatalina, Contreras, Simal, Cárcel, & Garcia-Perez (2016) sped up the drying process of apple by up to 80% (-10 ºC, 32 kW/m^3). As far as the coupling of ultrasonic waves in heat transfer processes is concerned, it has been used in both cooling and heating processes. As to cooling, Li & Sun (2002) reported that acoustic energy could lead to a noticeable increase in the freezing rate of potato and Delgado, Zheng, & Sun (2009) also showed that the application of ultrasound could increase the freezing efficiency of apples. Regarding heating, although several applications of PuS-assisted heating in gas and liquid medium have been studied (Chemat, Zill-E-Huma, & Khan, 2011; Rodríguez et al., 2018), research into the ultrasonically-assisted heating of solid foods is scarce in the literature, particularly the heating of ready-to-eat products. Therefore, there exists a need to investigate the behavior of the product during heating and test whether the additional acoustic energy during the heat treatment leads to a shortening of the heating time. In this context, the objective of this study was to explore the feasibility of using PuS to intensify heat transfer during the mild thermal treatment of dry-cured ham in a liquid medium.

2. MATERIALS AND METHODS

2.1. Raw material

Dry-cured ham slices (20.4±1.2 cm length, 2.0±0.1 cm thick) were purchased at a local supplier's from deboned commercial pieces and immediately vacuum packaged in plastic film and stored at 4 ºC until treated. Additionally, cylinders were taken from different slices of ham, 4±0.2 cm thick and also purchased from a local supplier, using a household tool, further split into two identical cylindrical pieces (2 cm in diameter and 2.0±0.2 cm in height), one of them was treated and the other one was kept as control in order to assess the impact of the heating in the textural properties. Afterwards, the samples were vacuum-packed in plastic film of polyamide/polyethylene (oxygen permeability of 50 cm3/m2/24h at 23 ºC and water permeability of 2.6 g/m2/24h at 23 ºC and 85% RH, Sacoliva® S.L., Spain) and stored at 4 ºC. The extracted cylinders were randomly distributed in the slice without muscle distinction.

Fat, salt and moisture contents were determined in ham slices and cylinders. Fat and moisture contents were analyzed following AOAC procedures 991.36 and 950.46, respectively (AOAC, 1997), and salt content was analyzed using a Chloride Analyzer equipment (Chloride Meter 926L, Ciba Corning, U.K.) following the process described by de Prados, García-Pérez, & Benedito (2015). All the analyses were performed in triplicate. A wide range of dry-cured ham samples of differing composition was selected. Thus, the fat content ranged from 2.4 to 16.2% (wet basis) and the salt content varied from 2.8 to 8.6% (wet basis). The average moisture content in both slices and cylinders was 52±6% (wet basis).

2.2. Heat treatments: Conventional (CV) and Ultrasonically-assisted (PuS)

Heat treatments were carried out in a stainless steel 15 L ultrasonic bath (ATG15160, ATU, Spain) using water as the heating medium. The bath was provided with a temperature control system (Figure 1). Temperature control was based on recycling the water bath using the available upper and lower connections. The upper connection was used to keep the water level in the tank constant. Thus, the output water stream was driven to a reservoir tank (5 L) provided with a circulating thermostat (Digiterm TFT-200, Selecta, Spain), which kept the liquid in agitation as well as impelling it (3.5 L/min) through a plate heat exchanger (EL852, Mas Malta Cervecera, Spain). As the cooling liquid, a solution of glycol (40% v/v) provided by a refrigerated circulating bath (1190s, Refrigerator Circ, US) was used in the heat exchanger. The output water stream of the heat exchanger was introduced into the water bath using its lower connection, closing the water circuit loop. An ON-OFF control was implemented by acting through the working time of the circulating thermostat of the water reservoir tank. For that purpose, a Pt-100 sensor was connected to a process controller (E5CK, Omron, Japan) which acted on the circulating unit.

Ultrasonically-assisted (PuS) and conventional (CV) heat treatments were performed using the experimental set-up shown in Figure 1. In PuS experiments, the ultrasonic generator (GAT600W ATU, Spain) supplied an electric power of 600 W and 20 kHz to the transducers and the heating system of the circulating thermostat was only activated at the beginning until water temperature reached the set point. Afterwards, the heater was switched off and due to the heat generation linked to ultrasonic cavitation, the chiller was switched on (set point -2 ºC). Thus, passing the water through the heat exchanger allowed reducing the additional heat generated by cavitation. In CV experiments, a mechanical stirrer (D91126, Heidolph Instruments, Germany) provided with a pitched blade impeller (diameter 75 mm) was placed into the ultrasonic bath (360 rpm) in order to increase the turbulence and ensure temperature homogeneity. In addition, the heating system was set to the target temperature of the experiment and the chiller was switched-off since there did not exist heat generation. As already mentioned, in both PuS and CV experiments, the actuator in the control loop was the circulating thermostat of the water reservoir tank. This experimental set up allowed an accurate control of the temperature in the water bath for both PuS and CV experiments.

Samples were placed at 4 cm from the bottom of the ultrasonic bath, using a basket as a holder (Figure 1). For ham slices, the temperature was measured in both *Semimembranosus* (SM) and *Biceps femoris* (BF) muscles, following the scheme shown in Figure 2. Thus, in each muscle, two type-T thermocouples were placed at 1 (center of the slice; X=0, Figure 2) and 0.5 cm from the surface (X=0.5, Figure 2), these points coinciding with the total (L) and half (L/2) characteristic dimension of the slice, respectively. Type-T thermocouples (0.5 mm in diameter) were inserted into a hypodermic needle in order to make its location easier. In order to minimize the water and air entrance into the package, a silicon strip (3x3x2 mm, CHA-475, CYH Sistemas, Spain) was placed over the puncture point before the hypodermic needle was pricked. In addition, two type-K thermocouples were stuck onto the surface of the slice with adhesive tape. In the case of ham cylinders, on the other hand, only a Type-T thermocouple was placed at the geometrical center. Thermocouples were connected to a PC through a data logger (34970A, Agilent, U.S.A) using the RS-232 interface.

PuS and CV heating treatments of ham slices were carried out at different bath temperatures (40, 45 and 50 ºC). Every heating condition was tested in triplicate at least. Thus, the total number of experiments carried out was 18 (2 ultrasound application x 3 temperatures x 3 replicates). The range of temperatures was chosen based on previous experiments to avoid dry-cured ham cooked flavor but inducing textural changes. In every case, experiments were extended until a temperature 5 ºC lower than the pre-set temperature of the water bath was reached in the center of the slice or cylinder. The temperature was monitored and logged every 20 s during the heating treatments. Each heating condition was tested at least three times.

2.3. Modelling

Modelling was used to compute the influence of the process variables (ultrasound application, temperature and type of muscle) on the overall heating process of ham slices. For that purpose, a diffusive model that considered heat transfer to be entirely controlled by conduction was chosen, assuming that the sample surface temperature reached equilibrium with the water temperature instantaneously and therefore, considering negligible the external resistance to heat transfer. No additional external resistance was assigned to the plastic film. Ham was supposed to be homogeneous and isotropic, with negligible contraction and constant apparent thermal diffusivity. In addition, due to the average slice shape (length 20±1, thickness 2±0.1 and width 10±1 cm), the samples were assumed to behave as infinite slab bodies in terms of heat transfer. Thus, the conduction equation (Eq. 1) (Holman, 1986) used is written as follows:

$$T_{(x,t)} = T_\infty + \left(T_0 - T_\infty\right)\left(2\sum_{n=0}^{\infty}\frac{(-1)^n}{\beta_n L}e^{-\alpha\beta_n^2 t}\cos(\beta_n x)\right) \qquad (1)$$

where T_0 is the initial temperature (refrigeration temperature, 5±2 °C) of dry-cured ham, T_∞ is the water bath temperature (40, 45 or 50 ºC, depending on the experiment tested), βn are the eigenvalues calculated as $\beta_n = (2n+1)\frac{\pi}{2L}$, L is the half-thickness of the slice (m), α is the apparent thermal diffusivity (m^2/s), t is the time (s) and x is the axial direction (m).

The apparent thermal diffusivity (α) was identified by fitting Eq. 1 to the temperature evolution during heating in two different positions of the slice, x=0 and x=L/2 (Figure 2), and for both SM and BF muscles. The identification was carried out by minimizing the sum of the squared differences between the experimental and calculated temperatures. For that purpose, the solver optimization tool available in Microsoft Excel 2016 was used. The goodness of the fit was assessed by calculating the percentages of explained variance (VAR, Eq. 2) and the mean relative error (MRE, Eq. 3),

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

$$MRE(\%) = \frac{\sum_{i=1}^{N} \left| \frac{T_{ei} - T_{ci}}{T_{ei}} \right|}{N} \tag{3}$$

where S_{xy} and S_y are the standard deviations of the estimation and the sample, respectively, T_{ei} and T_{ci} are the experimental and calculated temperatures and N is the number of experimental data. An MRE below 10% could be considered an adequate fit, such as reported by Garau, Simal, Femenia, & Rosselló, 2006 and Park, Vohnikova, & Brod, 2002.

Additionally, dry-cured ham cylinders were used for model validation. In this way, ham cylinders were heated at 50 ºC, assisted with PuS. The cylinders were selected for validation for the purpose of checking the robustness of the model regardless of the shape of the dry-cured ham used. Moreover, the apparent thermal diffusivity identified using PuS treatments of ham slices at 50 ºC were used to simulate the temperature evolution in the center of finite cylinders (diameter 2 cm, height 1.7±0.3 cm). The corresponding diffusive model is shown in Eq. 4 (Holman, 1986),

$$T_{(x,r,t)} = T_\infty + \left(T_0 - T_\infty\right)\left(2\sum_{n=0}^{\infty}\frac{(-1)^n}{\beta_n L}e^{-\alpha\beta_n^2 t}\cos(\beta_n x)\right)\left(2\sum_{n=1}^{\infty}\frac{e^{-\alpha\lambda_n^2 t}}{\lambda_n R J_1(\lambda_n R)}J_0(\lambda_n r)\right) \quad (4)$$

where λ_n are the eigenvalues calculated as $\lambda_n / J_0(\lambda_n R) = 0$, R is the cylinder radius (m), J_1 and J_0 are the Bessel functions of the first kind of order 1 and 0, respectively and r is the radial direction (m).

In order to validate the diffusive model, experimental and simulated temperatures were compared and VAR and MRE (Eqs. 2 and 3, respectively) were computed.

2.4. Statistical analysis

A two-way analysis of variance (ANOVA) was performed in order to assess the influence of processing factors (temperature: 40, 45 and 50 ºC and heating treatment: CV and PuS) on the identified apparent thermal diffusivity. In addition, a one-way ANOVA was used to study the effect of both the type of muscle (BF and SM) on the apparent thermal diffusivity, as well as that of the positions, x=0 and x=L/2, on the kinetic parameter. In every case, a significance level of 95% was considered. The statistical analysis was performed using Statgraphics Centurion XVI (Statpoint Technologies Inc., Warrenton, VA, USA).

2.5. Textural properties

The textural properties of dry-cured ham cylinders were measured using a TA-XT2 texturometer (SMS, Godalming, UK) provided with a load cell of 50 kg. A flat 75 mm diameter aluminum plunger (SMS P/75) was used to carry out the stress-relaxation test. The samples were compressed to 25 % of their original height parallel to the fiber bundle direction at a crosshead speed of 1 mm/s and afterwards, the probe was held for 90 s to monitor relaxation. The measurement were done at constant temperature (4±1 ºC). The experimental data were recorded and processed with Exponent Lite 6.1.4.0 software (SMS, Godalming, UK). Thus, hardness was computed from the force versus time profiles as the maximum force achieved during compression and the level of force decay (Y) logged during relaxation was calculated as follows:

$$Y = (F_0 - F_{90}) / F_0 \qquad (6)$$

where F0 is the maximum force during compression (N) and F90 is the force recorded at the end of the stress-relaxation test (90 s). The difference between treated and control samples was calculated for every texture parameter in order to quantify the changes in the texture of dry-cured hams after the heat treatment.

3. RESULTS AND DISCUSSION

3.1. Heating kinetics

The heating kinetics of CV and PuS experiments on BF muscle are shown in Figure 3. For every temperature studied, the heat treatment was considered to have ended when the target temperature (5 ºC below the water bath temperature) was reached in the center of the sample. The CV heating kinetics presented in Figure 3A revealed the typical shape of a heat transfer process controlled by conduction: there exists a short latency period, less noticeable at 50 ºC, followed by an exponential increase in the temperature and, finally, the kinetic tends towards an asymptotic value. As expected, the bath temperature during the heating of dry-cured ham influenced the heating kinetics in CV experiments. The higher the water temperature, the higher the product temperature for a particular treatment time. Thus, higher temperatures shortened the time needed to reach a specific temperature. As an example, to reach 25 ºC in the center of the product, 6.7±0.4, 5.7±0.2 and 4.4±0.1 minutes were needed when the bath temperature was 40, 45 and 50 ºC, respectively (Figure 3A). This occurs because the increase in the temperature gradient between the product and the medium leads to an increase in the driving force for heat transfer, resulting in a larger heat flow. However, the application of PuS during dry-cured ham heating partially modified the effect of the water temperature on heating kinetics. As can be observed in PuS experiments (Figure 3B), the time needed to reach 25 ºC was similar at every temperature tested, 3.5±0.4 min, a shorter time than either of the CV experiments, indicating that the heat transfer process was affected by PuS. The same tendency was observed in SM muscle.

To assess the influence of PuS on heating kinetics for the different heating temperatures, CV and PuS heating kinetics were compared at every temperature tested (Figure 4 shows heating kinetics for SM muscle). CV heat treatments presented a gradual, smooth temperature increase, while instabilities, sharp fluctuations in temperature, were observed in PuS heating kinetics; this was probably due to cyclic compressions and expansions produced by ultrasound at microscopic level in the material (Cárcel, García-Pérez, Benedito, & Mulet, 2012). For every temperature studied, the heating kinetics were faster when PuS was applied (Figure 4), demonstrating that PuS application exerted a great influence on the shortening of the heating time. However, how much shorter varied depending on the temperature used. Thus, for SM muscle, the time differences between CV and PuS treatments at the end of the experiments carried out at 40, 45 and 50 ºC were 6.4±0.5, 4.7±1.1 and 4±0.6 min, respectively. These results confirmed that the higher the temperature, the milder the influence of PuS on the heating time. Thereby, a time saving of 35% was obtained when comparing PuS and CV experiments performed at 40 ºC, while the percentage was only 21% at 50 ºC. The same behavior was noticed for BF muscle. This could be ascribed to the fact that, at high temperatures, the mechanical energy supplied to the medium by PuS is practically negligible compared with the thermal energy introduced into the medium by hot water. This observation is coherent with results found by García-Pérez, Rosselló, Cárcel, De la Fuente, & Mulet (2006) studying hot air drying, where the effect of ultrasound on mass transfer during drying lessened as the temperature increased.

The application of ultrasound in meat processing and the consequent time-saving has been the subject of prior research. Pohlman, Dikeman, Zayas, & Unruh (1997) found remarkable advantages as regards how fast beef was cooked in the presence of ultrasound, reducing the cooking time by half. Additionally, Miles, Morley, & Rendell (1999) reported that acoustic application shortened the defrosting time: the thawing times of *Semitendinosus* beef muscle were considerably shorter using ultrasound (from 32 to 66% shorter, depending on the PuS frequency and intensity used) compared to conventional thawing at a constant temperature of 25 ºC.

The effect of PuS on heat transfer, as well as the predominant heat transfer phenomena taking place, will be analyzed in the subsequent modelling section.

3.2. Modelling of the heating kinetics

Table 1 shows the apparent thermal diffusivity (α) and apparent thermal diffusivity variation (Δα) between PuS and CV experiments carried out at 40, 45 and 50 ºC on SM and BF muscles. As expected, after fitting the conduction model (Eq. 1) to the experimental heating kinetics, it was observed that the position (x=0; x=0.5; Figure 2) of the thermocouple in the sample did not have a significant ($p>0.05$) influence on the apparent thermal diffusivity. For that reason, the average apparent thermal diffusivity of both sensor positions for every heating condition is reported in Table 1. The conduction model used was an accurate means of describing the heating kinetics of dry-cured ham under the different conditions tested, providing percentages of explained variance higher than 98.6% and mean relative errors lower than 6% (Table 1). The close fit between experimental and calculated data indicated that the hypothesis considered, whereby the product surface instantaneously reaches water bath temperature, was adequate (heat transfer entirely controlled by conduction). Thus, mechanical agitation in CV experiments, as well as cavitation and liquid microturbulence in PuS experiments, minimized the effect of external resistance to heat transfer, which became negligible compared to the internal kind. The accuracy of the model proposed for describing the heating kinetics of SM muscle (x=0) is plotted in Figure 5, where experimental data and calculated curves are compared at every temperature tested. Most of the studies dealing with ultrasound-assisted heating found in the literature only focus on heat convection and consider as negligible the influence of power ultrasound on thermal diffusivity, which is considered as a constant parameter dependent on the product properties. The importance of internal mass transport resistance has been evidenced in convective drying of solid foods assisted by PuS, where a coupled heat and mass transfer exists (Musielak et al., 2016). In this study, the modelling of heating kinetics (Table 1 and Figure 5) demonstrated that the heating of dry-cured pork ham under these experimental conditions was entirely controlled by conduction. This is also supported by the temperature measurement taken on the product surface (Figure 2), which evidenced that product temperature rapidly reaches (0.8±0.4 min) the water temperature in both CV and PuS experiments.

From the CV experiments, statistically similar values of α were found at every heating condition tested (Table 1), regardless of the temperature and the type of muscle considered. However, in the PuS experiments, the bath temperature significantly affected ($p<0.05$) the apparent thermal diffusivity. Consequently, in the BF muscle, the lower the temperature tested, the higher the α, reaching the greatest value at 40 ºC (1.86±0.3 x10^{-7} m^2/s). A similar tendency was observed for the SM muscle. As for the influence of muscle factor on the apparent thermal diffusivity of the PuS experiments, the comparison between BF and SM heated at the same temperature showed that α was smaller for the SM muscle in every case, but such differences were not statistically significant ($p>0.05$).

Additionally, the apparent thermal diffusivity was used to analyze the effect of PuS application on heat transfer. Thus, the average apparent thermal diffusivity in CV experiments was 1.1±0.1 x10^{-7} m^2/s, which was significantly ($p<0.05$) lower than in PuS experiments (1.4±0.2 x10^{-7} m^2/s). Singh (1982) found a α of 1.38 x10^{-7} m^2/s in smoke ham for temperatures ranging from 40 to 65 ºC, a value lying between those found in CV and PuS experiments in the present study. For either of the temperatures tested, ultrasound application during heating involved a significant ($p<0.05$) increase in the kinetic parameter. The apparent thermal diffusivity variation, $\Delta\alpha=(\alpha_{PuS}-\alpha_{CV})/\alpha_{CV}$, increased by between 9 and 51% in the presence of acoustic waves (Table 1). The reported results revealed that power ultrasound application implied a significant improvement in conduction heat transfer, which has not been previously reported. Ultrasonic intensification could be explained by considering that the alternating expansions and contractions produced by ultrasonic vibration facilitate molecular heat transport, resulting in higher thermal conductivity. In addition, the vibration of solid particles at microscopic level could also bring about an increase in temperature by particle friction; although this could be considered as internal heat generation, which is included in the model as an unknown factor affecting the apparent thermal diffusivity. The improvement in α produced by PuS (Δα) in both muscles was reduced as the bath temperature rose, indicating that, as previously mentioned, ultrasound was more effective at low temperatures (Table 1). In ultrasound assisted drying and blanching processes, the influence of temperature on ultrasonic intensification was similar to the present study, the influence of PuS being more marked at the lowest temperatures. In this sense, Lespinard, Bon, Cárcel, Benedito, & Mascheroni (2015) reported an improvement of 205% in the convective heat transfer coefficient (h) when PuS was applied at a blanching temperature of 90 ºC, while at 60 ºC it rose up to 599%. As previously explained, this could be linked to the proportion of acoustic and thermal energy compared to the total energy introduced into the medium. In such a way, higher temperatures supplied a greater thermal energy to the water bath, affording less relevance to PuS energy.

3.3. Model validation

As indicated in section 2.3, the heat transfer model was validated by the PuS-assisted heating of 18 cylinders of dry-cured ham at 50 ºC. The cylinders were randomly taken without considering the relevance of the muscle in order to check the robustness of the model to further describe the heating of whole slices. For that purpose, the average apparent thermal diffusivity previously identified in slices of both SM and BF muscles heated at 50 ºC within PuS experiments was used and the heating of the cylinders was simulated through Eq. 4. As an example, Figure 6 shows the experimental and simulated heating kinetics of one dry-cured ham cylinder. The average explained variance and mean relative error of every validation experiment were 99% and 4%, respectively, indicating a good fit of the model to the experimental data. This indicated that the proposed model and the obtained apparent thermal diffusivity values were robust and could be used to predict the heating behavior of dry-cured ham slices.

3.4. Textural properties

In order to quantify the influence of the treatment on dry-cured ham texture, stress-relaxation tests were carried out in the cylinders heated at 50 ºC. Thus, the increment of textural parameters was calculated as the difference between the treated samples and their controls. In every experiment, the hardness variation was positive, indicating that dry-cured ham became harder after the heat treatment. The average enhancement of hardness was 15.2±4.4 N, which is in concordance with the hardness variation reported by Contreras, Benedito, Bon, & Garcia-Perez (2018) when heating ham with hot air at the same temperature (treatment times ranged from 18 to 24 minutes). Force decay was also measured in order to evaluate the elasticity of the treated ham. Thus, the average variation of the force decay for treated samples regarding the control ones was of -0.078±0.057, which indicated an improvement in ham elasticity since the smaller the force decay, the larger the elasticity (Garcia-Gil et al., 2014).

4. CONCLUSIONS

This study illustrates the feasibility of applying power ultrasound to accelerate the heating kinetics of dry-cured ham. The improvement in the heat transport produced by ultrasound was noticeable from the shortening of the heating time. The ultrasonic effect on heating experiments was greater at low temperatures, increasing the apparent thermal diffusivity by up to 51%. Modelling revealed that ultrasonic intensification mainly focused on the enhancement of heat conduction. Therefore, ultrasonic technology could be considered a feasible technique with which to speed up the heat transfer processes of dry-cured ham in a liquid medium and the conduction model employed could be useful to predict the ultrasound assisted heating behavior of sliced dry-cured ham.

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FIGURE CAPTIONS

Figure 1. Scheme of the temperature controlled ultrasonic bath. 1, Circulating thermostat; 2, Water reservoir tank; 3, Plate heat exchanger; 4, Ultrasonic bath; 5, Basket sample holder; 6, Ultrasonic transducers; 7, Refrigerated circulating bath; 8, Process controller; 9, Ultrasonic generator and amplifier.

Figure 2. Scheme of thermocouple location on ham slices (thickness 2 cm) during thermal treatment.

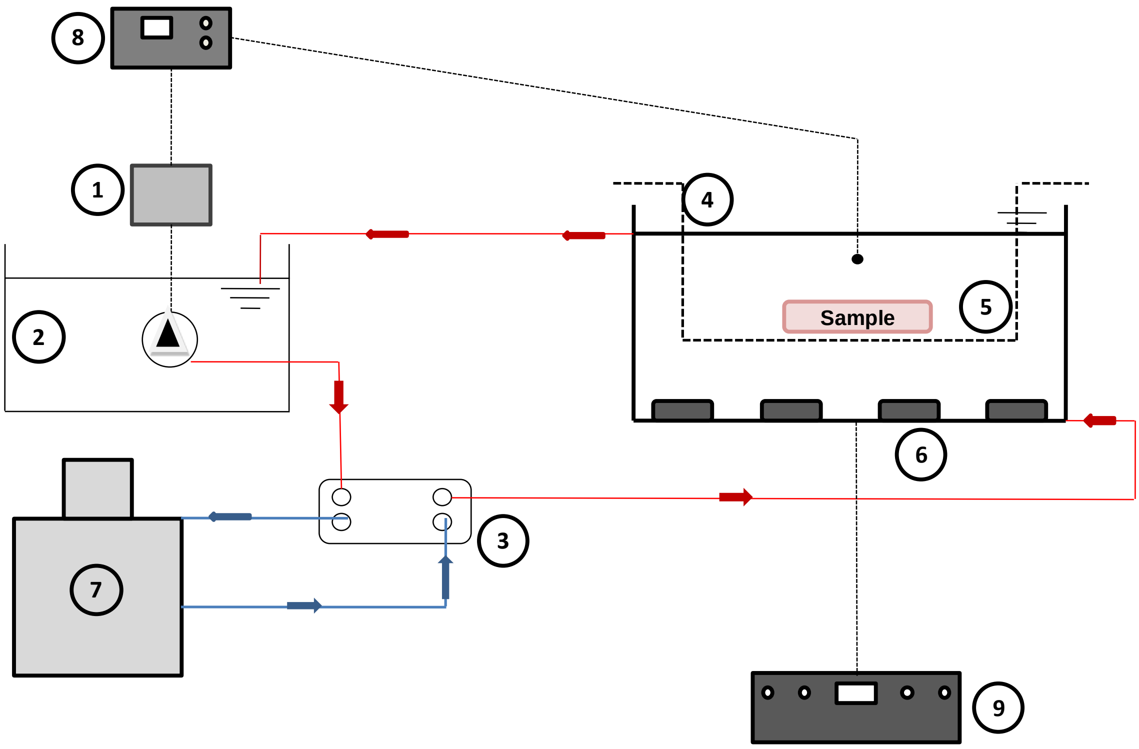
Figure 3. Heating kinetics of dry-cured ham slices (x=0) in BF muscle at different temperatures (3A: Conventional heating (CV); 3B: Ultrasonically-assisted heating (PuS).

Figure 4. Heating kinetics of dry-cured ham slices (x=0) in SM muscle at different temperatures (CV: Conventional heating; PuS: Ultrasonically-assisted heating).

Figure 5. Experimental and modeled PuS heating kinetics of dry-cured ham slices in SM muscle (x=0) at different temperatures (5A: 40 ºC; 5B: 45 ºC; 5C: 50 ºC).

Figure 6. Experimental and simulated heating kinetics of a dry-cured ham cylinder heated at 50 ºC and PuS-assisted.

Table 1. Apparent thermal diffusivity (α) and its variation (Δα) between CV and PuS experiments carried out at 40, 45 and 50 ºC in SM and BF muscles.



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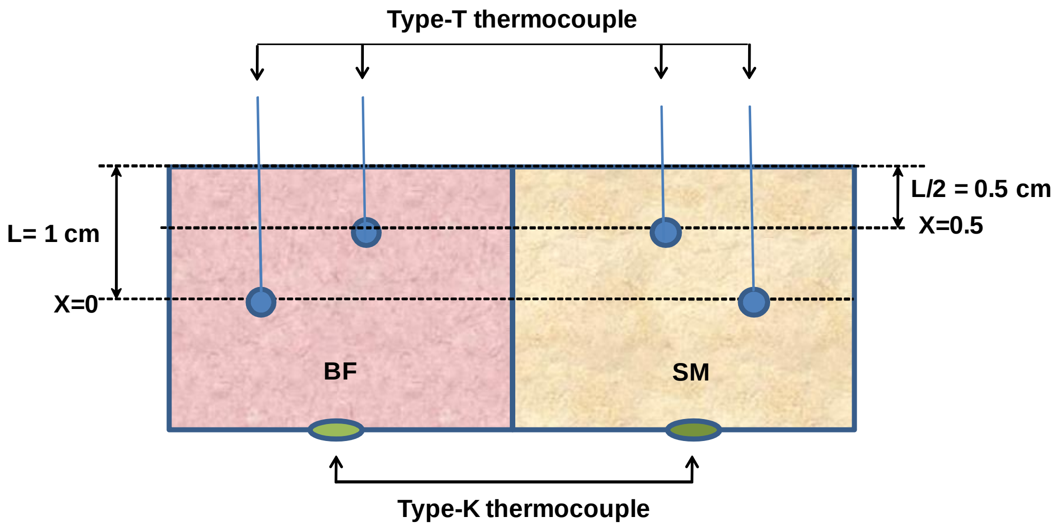

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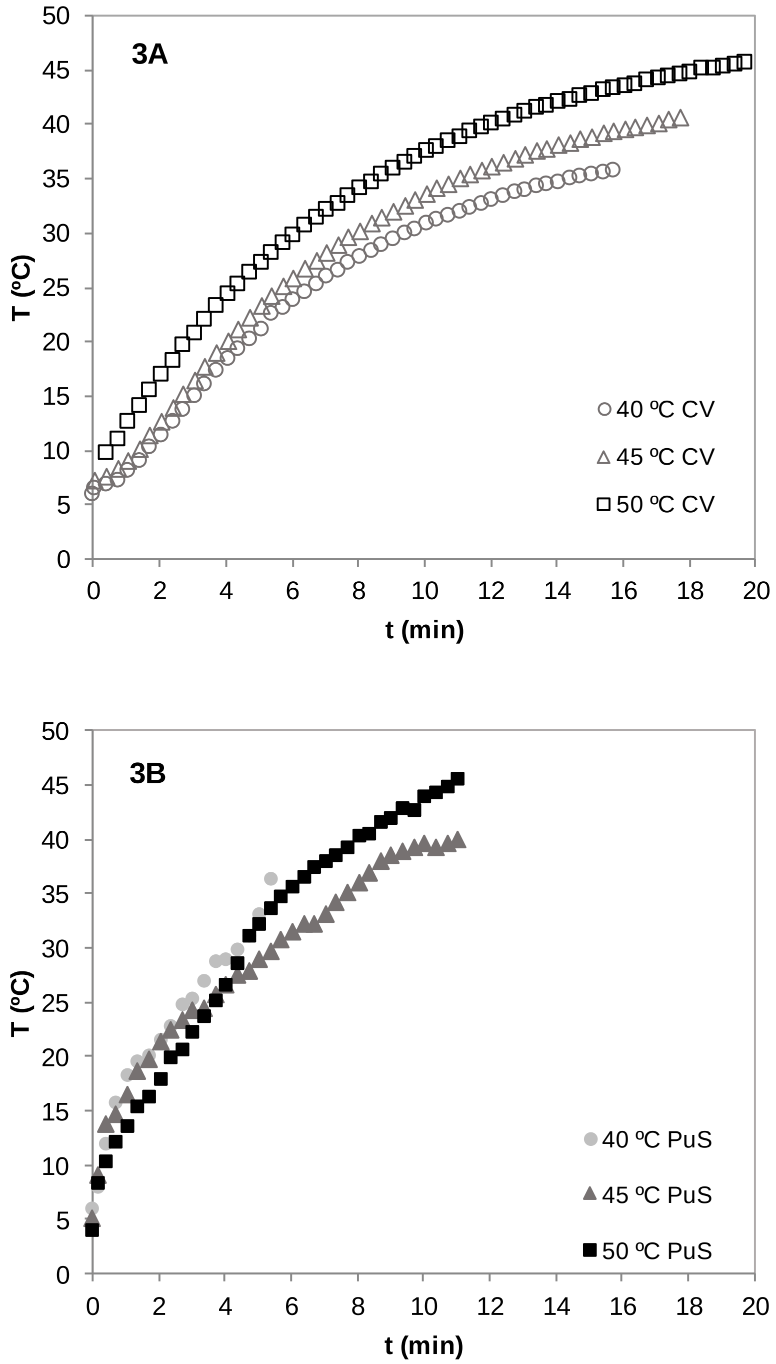


Figure 3. Heating kinetics of dry-cured ham slices (x=0) in BF muscle at different temperatures (3A: Conventional heating (CV); 3B: Ultrasonically-assisted heating (PuS).

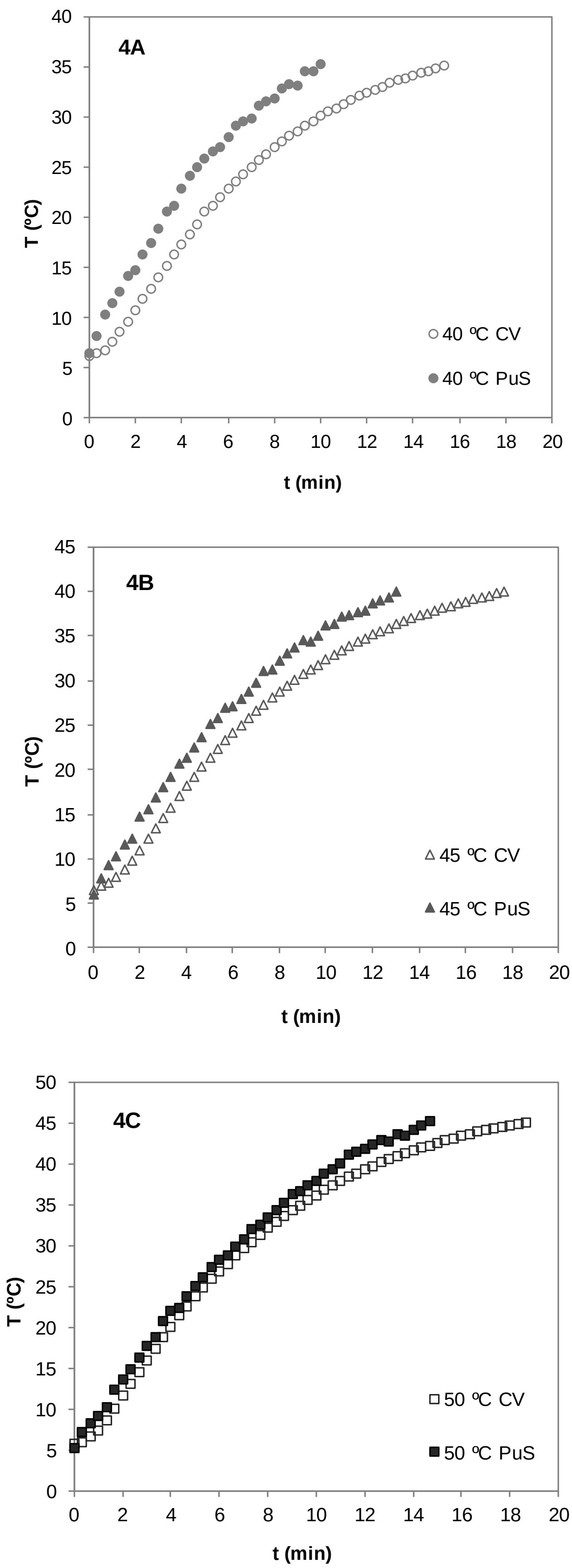
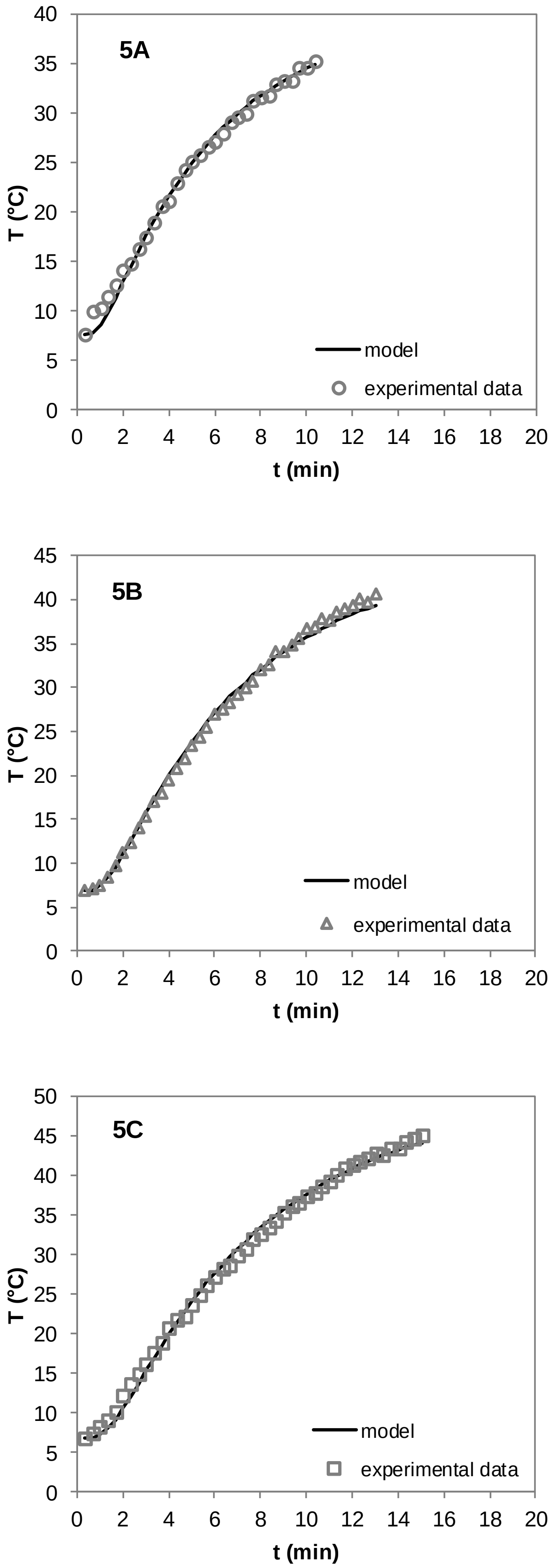


Figure 4. Heating kinetics of dry-cured ham slices (x=0) in SM muscle at different temperatures (CV: Conventional heating; PuS: Ultrasonically-assisted heating).



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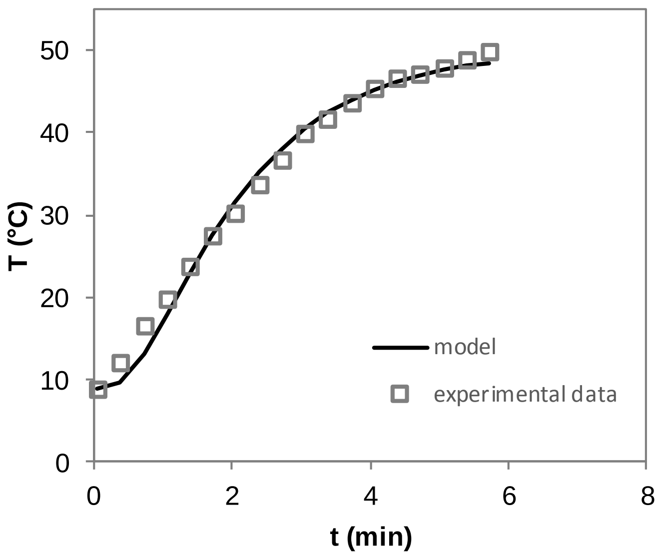

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Table 1. Apparent thermal diffusivity (α) and its variation (Δα) between CV and PuS experiments carried out at 40, 45 and 50 ºC in SM and BF muscles.

T (ºC)	Muscle	PuS			CV			Δα (%)
		α (10^{-7} m^2/s)	VAR (%)	MRE (%)	α (10^{-7} m^2/s)	VAR (%)	MRE (%)	
40	**SM**	1.35 ± 0.2^{C}	99.16	3.98	0.98 ± 0.08^{A}	99.38	4.08	38
45	**SM**	1.41 ± 0.3^{C}	99.39	2.09	1.23 ± 0.3^{ABC}	99.19	2.28	15
50	**SM**	1.10 ± 0.1^{AB}	99.22	4.67	1.10 ± 0.1^{A}	99.58	5.21	9
40	**BF**	1.86 ± 0.3^{c}	98.83	5.74	1.23 ± 0.4^{a}	99.75	5.12	51
45	**BF**	1.56 ± 0.2^{bc}	98.64	4.86	1.2 ± 0.3^{ab}	98.98	4.97	30
50	**BF**	1.34 ± 0.2^{ab}	99.03	5.81	1.11 ± 0.1^{a}	99.52	5.90	21

Δα was calculated as $(\alpha_{PuS}-\alpha_{CV})/\alpha_{CV}$. VAR (%) is the explained variance and MRE (%) the percentage of mean relative error. Superscripts in capital letters (A, B, C) and lowercase letters (a, b, c) show homogeneous groups established from LSD (Least Significance Difference) intervals ($p<0.05$) obtained by multifactor ANOVA (temperature and treatment time as factors) for α of SM and BF muscle heating experiments, respectively.