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INTENSIFICATION OF HEAT TRANSFER DURING MILD THERMAL TREATMENT OF DRY-CURED HAM BY USING AIRBORNE ULTRASOUND

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Abstract

The application of power ultrasound (PuS) could be used as a novel technology with which to intensify thermal treatments using hot air. Mild thermal treatments have been applied to improve the soft texture of dry-cured ham caused by defective processing. In this regard, the aim of this study was to assess the kinetic intensification linked to the application of airborne PuS in the mild thermal treatment using hot air of dry-cured ham. For this purpose, vacuum packed cylindrical samples (2.52±0.11 cm in diameter and 1.90±0.14 cm in height) of dry-cured ham were heated using hot air at different temperatures (40, 45, 50 ºC) and air velocities (1, 2, 3, 4, 6 m/s) with (22.3 kHz, 50 W) and without PuS application. Heat transfer was analyzed by considering that it was entirely controlled by conduction and the apparent thermal diffusivity was identified by fitting the model to the heating kinetics. The obtained results revealed that PuS application sped up the heat transfer, showing an increase in the apparent thermal diffusivity (up to 37%). The improvement in the apparent thermal diffusivity produced by PuS application was greater at high temperatures (50ºC) but negligible at high air velocities (6 m/s). Heating caused an increase in the hardness and elasticity of dry-cured ham, which would correct ham pastiness defects, while the influence of PuS on such textural parameters was negligible.

Keywords; Temperature; air velocity; ultrasound; heat transfer; modelling

1. Introduction

Dry-cured ham is highly appreciated by consumers due to its high quality, which is defined by a typical flavour, colour, composition and texture [1]. Therefore, texture is one of the most important sensory attributes of dry-cured ham, which greatly influences consumer acceptability [2]. Two of the main textural problems in this product are excessive softness and pastiness [3,4]. These defects are related to a short processing time and low salt content, which are linked to the fact that companies rush to obtain the final product in the shortest possible time as well as to the tendency to reduce the final NaCl content according to the Global Strategy on Diet, Physical Activity and Health of the World Health Organization (WHO).

One of the strategies reported in the literature to correct the softness and pastiness of dry-cured ham, obtaining a harder texture, has been the use of mild thermal treatments. Morales et al. [5] evaluated textural changes when submitting small, packaged dry-cured ham cross sections to 30 ºC for 168 h, observing that the softness decreased in *Biceps femoris* muscles while the texture in the *Semimembranosus* muscle and other physicochemical parameters, such as moisture, water activity and proteolytic index, remained unaffected. On the other hand, Gou et al. [6] investigated the effect of a 10-day ageing process at 30 ºC on the soft texture of whole dry-cured ham pieces elaborated with different raw meat pHs and salting times. These authors reported that the ageing at temperatures of around 30 ºC could be useful for the purposes of decreasing the incidence of soft textures in dry-cured ham without affecting the product flavor. However, the mild thermal treatments tested by Morales et al. [5] and Gou et al. [6] required a long processing time, which is a significant drawback for industrial applications. Therefore, temperatures higher than 30 ºC should be tested to evaluate whether the expected textural changes can be produced in shorter times. However, higher temperatures could damage quality characteristics of dry-cured ham, such as flavor and appearance. To minimize these unfavourable effects, the use of more efficient heat transfer processes should be investigated.

Process intensification aims to improve traditional technologies and to develop new ones to achieve a higher yield, a notable reduction in equipment size, lower energy usage and increased product quality and processing safety [7,8]. Among other new technologies, power ultrasound (PuS) emerges as a feasible technology for improving heat transfer processes. Legay et al. [9] reported an exhaustive review of ultrasonic applications in liquid medium to improve heat transfer processes, such as boiling, melting and solidification. Basically, the cavitation and microagitation produced by ultrasound in the liquid medium are the responsible of reducing heat transfer resistance by increasing fluid turbulence. In addition, the application of PuS in fluids provokes an increase in its temperature due to cavitation and molecule friction [10,11], which also accelerates the heating processes. Thus, ultrasonic water baths or sonotrode-type systems could be useful for the heating intensification necessary to reduce the soft texture of dry-cured hams, by immersing the packaged samples in a liquid medium, such as water. However, at industrial level, the use of hot water would involve large amounts of energy and water consumption. Furthermore, these systems could lead to the contamination of samples, since the plastic bags where dry-cured ham pieces are packaged could be perforated due to the water micro jets produced by ultrasonic cavitation. In order to overcome liquid media handicaps, hot air treatments could be an interesting alternative for correcting the soft texture of cured hams through mild thermal treatments. Heat transfer in air medium is limited by its lower external convection coefficient compared to liquid medium. Thereby, the application of airborne PuS could be considered a relevant strategy for process intensification. Multiple applications of ultrasonically-assisted heating in liquid media exist [12], but no references have been found in the literature of using airborne PuS for heating applications in food materials. Most of the references found in the literature pertaining to the use of airborne PuS in food applications refer to mass transfer processes and particularly to food drying. In this regard, Garcia-Perez et al. [13] already reported the feasibility of using PuS for improving heat transfer during the hot air drying of grape stalks. Similarly, Bantle et al.

[14] confirmed that high intensity airborne ultrasound is a promising technology for enhancing the heat transfer coefficient and thus, reducing the drying time of salted codfish convective drying. In the same way, silica gel regeneration, which is essentially a drying process, has been improved by ultrasound application due to the fact that it leads to a more uniform energy distribution and, hence, achieves a greater efficiency of utilization [15,16].

Therefore, the main aim of this study was to assess the kinetic improvement linked to the application of airborne PuS in the hot air mild thermal treatment of dry-cured ham. In addition, the influence of the thermal treatment in the textural changes induced in the hams was also analysed.

2. Materials and methods

2.1. Raw material

For the heating experiments, dry-cured ham slices from Large White breed pigs provided by the IRTA-Research&Technology-Food&Agriculture Institute (Monells, Girona) were used. From the slices, cylindrical samples were taken from the *Biceps femoris* and *Semimembranosus* muscles using a household tool. Each cylinder (2.52±0.11 cm in diameter and 4.00±0.14 cm in height) was split into two equal size portions (half of the height), one half was used as control and the other half was vacuum packaged (PA/PE bags with water permeability smaller than 5 $g/m^2/d$ at 23 ºC and 85% RH, Sacoliva® S.L., Spain). Packaged ham cylinders were kept in refrigeration (4±2 ºC) until heating experiments were performed.

2.2. Heating treatments

Heating experiments were carried out in an air-forced heater (Figure 1), which was described in detail by Riera et al. [17]. The air flowed from the fan to the heating chamber, passing through an electrical resistance that warmed it up to the desired temperature. Air velocity and temperature were measured in a PID control loop by an anemometer (Wilh. Lambrecht GmbH, Göttingen, Germany) and a Pt-100 sensor, respectively. The heating chamber consisted of a vibrating aluminum cylinder attached to a piezoelectric transducer (22.3 kHz). Samples were placed within the vibrating cylinder hung on a sample holder, similar to that used by Garcia-Perez et al. [18]. In the PuS experiments, ultrasonic waves were transmitted from the walls of the heating chamber to the air, finally reaching the sample.

Two different sets of experiments were carried out to test the influence of the air temperature (#1) and flow rate (#2).

- The first set (#1) was conducted at different air temperatures (40, 45, 50 ºC), constant air velocity (2 m/s) and without (AIR, 0 W) and with (AIR+PuS, 50 W) PuS application. The temperature range was chosen in order to accelerate textural changes without imparting cooking flavors and appearance to the ham.
- The second set (#2) was performed at different air velocities (1, 2, 3, 4, 6 m/s), constant air temperature (50 ºC) and without (0 W) and with (50 W) PuS application.

Heating treatments were finalized when the temperature in the center of the sample (Target temperature, Tt) was 5 ºC under the air temperature. Every different heating condition was tested in triplicate at least. Thus, the total number of experiments carried out in the first set was 18 (3 temperatures x 2 ultrasound application x 3 replicates) and 30 in the second set (5 air velocities x 2 ultrasound application x 3 replicates). The evolution of the temperature in all the experiments was monitored in the center of the sample by using a type-T thermocouple (Class I, TCDirect, Spain). Furthermore, the air temperature was measured at the inlet and outlet of the heating chamber by using a type-K thermocouple (TCDirect, Spain).

2.3. Modelling of the heating kinetics

Modelling was used to quantify the effect of air temperature, air velocity and PuS on the kinetics of the heating process. For that purpose, a mathematical model was used that considered heat transfer to be entirely controlled by conduction, assuming that the sample surface temperature instantaneously reached equilibrium with the air temperature. The material was supposed to be homogeneous and isotropic, with constant effective thermal diffusivity. In addition, due to the cylindrical shape, the samples of dry-cured ham were considered as a finite cylinder as regards heat transfer. Thus, the conduction equation (Equation 1) [19] used is written as follows:

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

where T_0 is the initial temperature (°C) of dry-cured ham, T_∞ is the air heating medium temperature (ºC), β_n are the eigenvalues calculated as $\beta_n=(2n+1)\frac{\pi}{2}$, L is the half-thickness of the cylinder (m), α is the apparent thermal diffusivity (m^2/s), t is the time (s), x is the axial direction (m), λ_n are the eigenvalues calculated as $\lambda_n / J_0(\lambda_n R)=0$, R is the cylinder radius (m), J_υ is the Bessel function of the first kind of order υ and r is the radial direction (m). The model was solved by taking (i) only the first term or (ii) the first 50 terms of both summations. The aim behind this strategy is to check the accuracy of both strategies in the estimation of the thermal diffusivity and the accuracy of fit of the model [20].

In Eq. 1, thermal diffusivity is assumed to be an apparent kinetic parameter, which includes not only conduction phenomena, but also others linked to effects that were not considered, such as convection and radiation from the vibrating cylinder walls.

Apparent thermal diffusivity (α) was identified by fitting Eq. 1 to heating kinetics, defined as the evolution of the temperature in the center of the cylinder, T(0,0,t). The identification was carried out by minimizing the summatory of squared differences between the experimental and calculated temperature. The Solver optimization tool available in Microsoft Excel 2016 was used for this purpose. The goodness of the fit was assessed by calculating the percentages of explained variance (VAR, Equation 2) and the mean relative error (MRE, Equation 3),

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

$$\mathrm{MRE}(\%)=\frac{\sum_{i=1}^{N}\frac{\left|T_{ei}-T_{ci}\right|}{T_{ei}}}{N}\cdot 100 \qquad (3)$$

where S_{xy} and S_y are the standard deviation of the estimation and the sample, respectively, T_{ei} and T_{ci} are the experimental and calculated temperature and N is the number of experimental data.

2.4. Textural properties

The textural properties of dry-cured ham cylinders from the first set of experiments (#1) were measured using a TA-XT2 texturometer (SMS, Godalming, UK) provided with a load cell of 50 kg. Stress-relaxation tests were carried out at constant temperature (4±1 ºC) using a flat 75 mm diameter aluminum plunger (SMS P/75). 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 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(t) logged during relaxation was calculated as follows:

$$Y(t) = \frac{F_0 - F(t)}{F_0} \quad (6)$$

where F_0 is the maximum force during compression (N) and F(t) is the force recorded after t seconds of relaxation. Y was calculated at 2 s of the relaxation period and at the end of the stress-relaxation test (90 s). In order to quantify the changes in the texture of dry-cured hams after the heating treatment, the difference between control and treated samples was calculated for every textural parameter.

2.5. Statistical analysis

In order to evaluate if the operating conditions studied (temperature, air velocity and PuS) had a significant influence on the thermal diffusivity, an analysis of variance (ANOVA) ($p<0.05$) was carried out, and the least significant difference (LSD) intervals were estimated using the statistical package Statgraphics Centurion XVI (Statpoint Technologies Inc., Warrenton, VA, USA). ANOVAs were performed considering the thermal diffusivity as a dependent variable and the air temperature, air velocity and the heating treatment (AIR or AIR+PuS), as well as their interactions, as factors. Additionally, the influence of the heating conditions on the ham textural properties were also compared by means of ANOVA and LSD intervals.

3. Results and discussion

3.1. Heating kinetics

3.1.1. Effect of air temperature

The heating kinetics of packaged dry-cured ham cylinders at different air temperatures are shown in Figure 2. The common effect of air temperature on air-forced heating for foodstuffs is illustrated in the aforementioned figure; so, as extensively described in the literature [21,22], the higher the air temperature, the higher the product temperature for a particular treatment time. Additionally, air temperature had a relevant effect on the necessary heating time, which, as mentioned in section 2.2, was defined as what was required to reach the target temperature in the center of the product (5 ºC less than the air temperature). As can be observed in AIR experiments, the higher the air temperature used, the longer the heating time (Figure 2, A). Therefore, heating times ranged from 19±0.8 min at 40 ºC to 25±0.9 min at 50 ºC. In this context, the application of PuS during dry-cured ham heating partially modified the effect of air temperature on heating kinetics. Thus, in AIR+PuS experiments, the heating time was similar at every temperature tested (Figure 2, B). This evidenced a larger improvement in the heat transfer as the temperature increased. It should be mentioned that the use of PuS had no significant (p>0.05) influence on the temperature of the output air of the heating chamber, which demonstrates that no additional air heating was produced by the ultrasonic field.

If AIR and AIR+PuS heating kinetics are compared (Figure 3), the shortening of the heating time produced by ultrasonic application was of only 15% at 40 ºC, while at 50 ºC it was 31% shorter, which showed the effect of the interaction between temperature and the application of PuS. Similarly, previous results reported for other airborne PuS applications found that ultrasound had a greater effect on mass transfer at high than at low air temperatures. On the contrary, in hot air drying, Garcia-Perez et al. [23] suggested that the ratio of the energy provided when PuS was applied at high temperatures was lower than at low temperatures due to the already existing high thermal energy in the medium and, consequently, the effect on water transport linked to ultrasound was reduced. In heating experiments, the thermal energy gradient produced by the temperature difference is the driving force of the heat flow, which increases as the temperature rises. Therefore, any improvement in heat transfer coefficients will have a bigger impact on the heat flow at high than at low temperatures . This could explain the fact that PuS has a greater effect on heating treatments at high than at low air temperatures.

3.1.2. Effect of the air velocity

The heating kinetics of packaged dry-cured ham were carried out at five different air velocities (1, 2, 3, 4 and 6 m/s) and 50 ºC. In AIR experiments, it was found that the higher the air velocity, the faster the heating kinetics (Figure 4, A). Thus, the heating time was shortened from 38±5 to 12±1 min when the air velocity increased from 1 to 6 m/s. This might occur because the increase in air velocity led to a reduction in the boundary layer thickness and, consequently, to a decrease in the external resistance to heat transfer [24–26].

The application of PuS buffered the effect of the air velocity on the heating kinetics. As observed in Figure 4 B, fairly similar heating times were found for air velocities higher than 1 m/s. This fact revealed a meaningful effect of ultrasound on external resistance to heat transfer. Yao et al. [27] reported that the mechanical vibration induced by PuS reduced the thickness of the boundary layer on the gas-solid interface, lessening the external resistance to heat transfer. For process intensification purposes, AIR+PuS experiments were only markedly faster than AIR ones at low air velocities; so, the ultrasonic effect was blurred as the air velocity increased. Thus, for example, the heating times of the experiments carried out at 1 m/s were 38±5 and 20±5 minutes for AIR and AIR+PuS, respectively; whereas at 6 m/s, the heating time in AIR experiments was 12±1 contrasted with the 15±3 minutes in AIR+PuS ones. This might be ascribed to some facts; firstly, to the negative effect of high air flow rates on the ultrasonic field, which would reduce the acoustic energy available at high air velocities, such as was suggested by Garcia-Perez et al. [18]. Secondly, the negligible effect of ultrasound at high air velocities could be explained by assuming that there is no effect of ultrasound on heat conduction, its influence being restricted to the heat convection. This has been reported in liquid media applications where cavitation [28] increases the liquid temperature in the interface apart from rising turbulence and pressure variations [29], leading to a reduction in the external resistance to heat transfer. Modelling will help to gain knowledge about the effect of PuS on heat transfer, as well as the predominant phenomena (conduction or convection).

3.2. Modelling of the heating kinetics

The heating kinetics of dry-cured ham cylinders processed at different temperatures (40, 45 and 50 ºC), air velocities (1, 2, 3, 4 and 6 m/s), and without and with PuS application were modelled using Eq. 1, described in section 2.3. Table 1 shows the thermal diffusivity and statistical parameters computed when the conduction model was solved by taking the first 50 terms of both summations. The conduction heat transfer model considered did not provide an optimal fit of the experimental data since the explained variance percentages were under 99% and mean relative errors over 10% in every case (Table 1). A very poor fit was obtained when only the first term of both summations was considered, which involved an average increase in the MRE up to values close to 30% and a reduction in the VAR down to figures close to 50%. Statistical data shown in Table 1 illustrate that assumptions considered in the model did not adequately match the process behaviour. Therefore, the hypothesis that assumes that heat transfer was entirely controlled by conduction, neglecting any resistance linked to heat convection in the interface, did not correspond to the process characteristics. As presented in the previous section, the influence of heat convection should not be neglected due to the fact that the increase in the air velocity involved the shortening of the heating time, which was especially meaningful in AIR experiments. As a consequence, the apparent thermal diffusivity identified by fitting Eq. 1 to the heating kinetics should be considered an overall heat transport coefficient including the kinetic coefficients linked to both the external and the internal resistance to the heat transfer.

Therefore, more realistic models have to be developed considering both internal and external heat transfer resistance. The resolution of joint convection+conduction models involves larger computing requirements and should be the subject of future studies since modelling was not the main aim of the present piece.

In the interval of temperatures analysed, the values of apparent thermal diffusivity obtained ranged from 4.1 x10^{-8} m^2/s at 40 ºC without PuS application to 5.8 x10^{-8} m^2/s at 50 ºC with PuS application. The use of only the first term of the summations in Eq. 1 leads to an underestimation of the thermal diffusivity, i.e. for AIR experiments at 40ºC; this approach reduces the thermal diffusivity from 4.1x10^{-8} to 2.43x10^{-8} m^2/s. Slightly lower values of thermal diffusivity were identified by Rinaldi et al. [29] during pork loin cooking at 100 ºC (0.7 x10^{-8} m^2/s) and 140 ºC (4.1 x10^{-8} m^2/s) and by Ayadi et al. [20] while cooking turkey ham at 90 ºC (1.98 x10^{-8} m^2/s). As can be observed in Figure 5, the apparent thermal diffusivity in AIR experiments was not affected by temperature. It seems to be consistent with the literature, since thermal diffusivity is a characteristic property of the material and should not be modified by air temperature if it does not lead to any textural-structural sample modification. However, the opposite behaviour was observed in AIR+PuS experiments, since the higher the air temperature, the higher the apparent thermal diffusivity; this was reflected in the ANOVA through the significant (p=0.0403) interaction between the factors, treatment type (AIR and AIR+PuS) and air temperature. In addition, the application of PuS led to an increase in the apparent thermal diffusivity at every temperature tested, compared to AIR treatments. In particular, the higher the temperature (50 ºC), the greater the improvement in transport phenomena brought about by PuS application, achieving a ratio $\alpha_{AIR+PuS}/\alpha_{AIR}$ of 1.4 at 50ºC. The increase in the apparent thermal diffusivity could either be associated with the reduction in both internal and external resistance to heat transfer or merely with the reduction in the external one. As already mentioned [27], the main effects of ultrasound on external resistance to heat transfer could be linked to cavitation [28], which increases the turbulence thus reducing the external resistance to heat transfer. Additionally, the compressions and expansions provoked by ultrasound in the solid may induce a possible increase in heat conduction mechanisms and, consequently, in the thermal diffusivity.

As regards the experiments carried out at different air velocities, the increase in air velocity provoked a significant (p=0.0011) increase in the apparent thermal diffusivity in the case of AIR experiments (Figure 6). Moreover, the lowest figures of the explained variance were found in experiments conducted at 1 m/s (Table 1), which confirmed a better fit of the model at high air velocities due to the reduction in the external resistance to heat transfer, which made conduction phenomena predominant over convection. The trend in thermal diffusivity was towards an asymptotic value when the air velocity increased, reflecting an almost negligible influence of the convective flow for air velocities higher than 4 m/s. The explained variance did not reach values higher than 99 % nor mean relative errors of under 10 %, probably because the influence of the plastic bag was not considered, and this acted as an additional external resistance to heat transfer regardless of the air flow rate used. As for AIR+PuS experiments, it was found that the greater increase in the apparent thermal diffusivity produced by air velocity appeared from 1 to 2 m/s (42%), whereas for the rest of the air velocities tested, it remained practically constant.

When AIR and AIR+PuS experiments were compared, it could be observed in Figure 6 that apparent thermal diffusivity was always higher for experiments with ultrasound application. Nevertheless, the higher the air velocity, the smaller the difference between AIR and AIR+PuS treatments. Thus, at 6 m/s, both treatments exhibited very similar apparent thermal diffusivity. As mentioned in section 3.1.2, this could be explained by the disruption of the ultrasonic field by the high air flow rates which made it difficult for the acoustic energy to reach the sample [25] or because ultrasound was not capable of increasing heat conduction rates.

3.3. Dry-cured ham texture

In order to quantify the influence of the air temperature during the heating treatment on dry-cured ham texture, stress-relaxation tests were carried out. Thus, the increase in textural parameters was calculated as the difference between the treated samples and their controls. When comparing ultrasonically assisted heated samples with those conventionally heated, it was observed that the influence of PuS application on Δhardness was not significant ($p>0.05$, data not shown); therefore, to study the influence of temperature, the average for AIR and AIR+PuS experiments was considered. As can be observed in Figure 7, the heating induced an increase in the sample hardness since every hardness variation (Δhardness) estimated was positive, regardless of the heat treatment applied. Similarly, Morales et al. [5] reported an increase in *Biceps femoris* muscle hardness after a thermal treatment at 30 ºC for 168 h. Moreover, air temperature significantly ($p=0.0263$) influenced Δhardness, thus, similar values for this parameter were found at 40 and 45 ºC (6.3 N), and a marked increase (up to 15.4 N) was observed at 50 ºC (Figure 7). This change could be linked to a modification in the protein matrix, since, during heating, the different meat proteins denature and structural changes, additional to what is provoked by salting during curing, occur [31]. Cell membrane destruction [32], the transversal and longitudinal shrinkage of meat fibers [31] and the aggregation of the globular heads of myosin [5] were some of the changes that could take place. Moreover, as the heating temperature rose, such changes become intensified.

Another textural parameter measured was the force decay (Y), which is inversely related to the material elasticity. Thus, the greater the elasticity of the material, the smaller the force decay during the relaxation period. A similar pattern was found for the variation between the treated and control samples in terms of the force decay at 2s (Y(2)), and the final one (Y(90)). The variation in both parameters was significantly ($p=0.001$ for Y(2) and $p=0.013$ for Y(90)) affected by temperature, but no effect of PuS application was found. Thus, both ΔY(2) and ΔY(90) were similar at 40 and 45 ºC and were reduced at 50 ºC (Figure 8). In the same way, Gou et al. [6] found that after a 10-day ageing of dry-cured ham at 30 ºC, Y(90) values decreased compared with the same time of ageing performed at 18 ºC. Besides that, the results obtained for force decay matched the one found for the variation in hardness, which confirmed that the heated dry-cured ham texture was dependent on the heating temperature. Thereby, the negative $\Delta Y(90)$ figures found at 50 ºC corresponded to an increase in the ham elasticity. As the loss of elasticity is the main trait of the pastiness defect in dry-cured ham [33], short thermal treatments such as those shown in this study could be useful for reducing textural defects prior to the commercialization of the product.

4. Conclusions

This study evidenced the influence of different operating variables (air velocity and temperature) on the heating kinetics of dry-cured ham during mild thermal treatments. In every air velocity-temperature condition tested, the application of airborne PuS increased the apparent thermal diffusivity. However, the magnitude of PuS effects depended on the air velocity and temperature; thus, ultrasound was more effective at high air temperatures and low air velocities. Besides, the heating process provoked an enhancement of the dry-cured ham texture, since it became harder. Therefore, airborne power ultrasound, which could be considered a feasible technique with which to shorten the heating time of dry-cured ham and improve its texture, is emerging as an alternative to hot water treatments.

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Figure captions

Table 1. Apparent thermal diffusivity (α) and statistical parameters obtained from modelling the heating kinetics of dry-cured ham at different air temperatures (40, 45 and 50 °C) (constant air velocity of 2 m/s), and at different air velocities (1, 2, 3, 4 and 6 m/s) (constant air temperature of 50 °C), without (AIR) and with (AIR+PuS) PuS application. VAR (%) is the percentage of explained variance and MRE (%) the percentage of mean relative error.

Figure 1. Scheme of ultrasonically assisted air-forced heater.

Figure 2. Heating kinetics of dry-cured ham at different air temperatures (40, 45, and 50 °C) (constant air velocity of 2 m/s). A: without PuS application (AIR). B: with PuS application (AIR+PuS).

Figure 3. Heating kinetics of dry-cured ham at different air temperatures (40 and 50 °C) without (AIR) and with (AIR+PuS) PuS application.

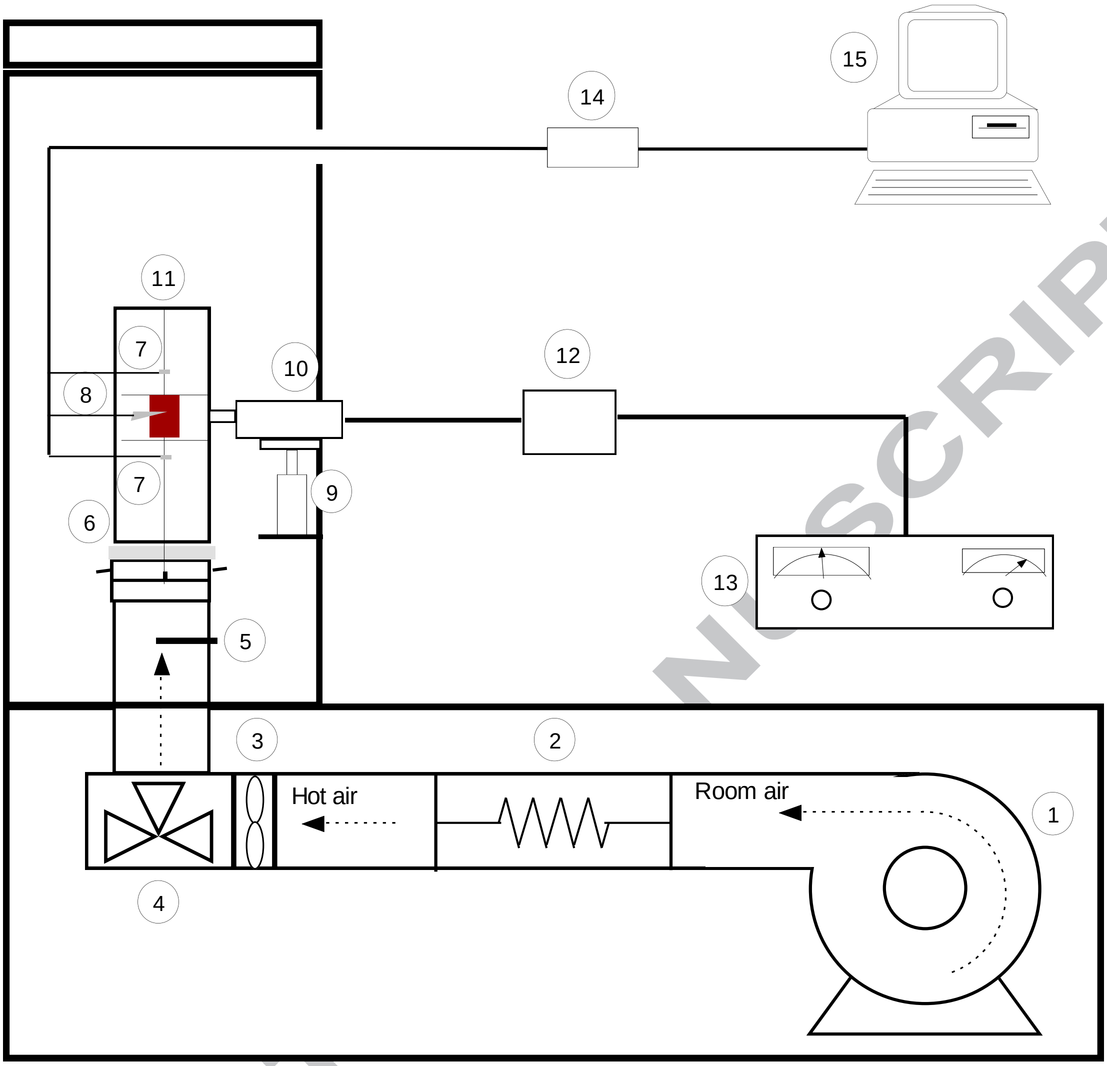
Figure 4. Heating kinetics of dry-cured ham at different air velocities (1, 2, 3, 4 and 6 m/s) (constant air temperature of 50 ºC). A: without PuS application (AIR). B: with PuS application (AIR+PuS).

Figure 5. Apparent thermal diffusivity of dry-cured ham heated at different air temperatures (40, 45, and 50 °C) (constant air velocity of 2 m/s) without (AIR) and with (AIR+PuS) the application of PuS. Letters show homogeneous groups established from LSD intervals (95%).

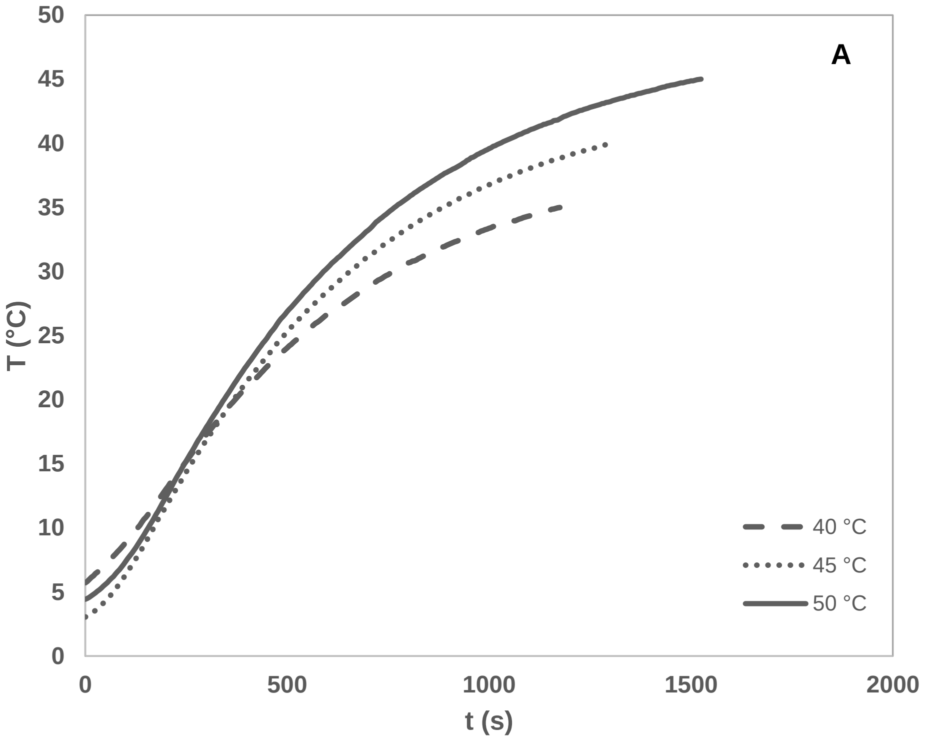
Figure 6. Apparent thermal diffusivity (α) of dry-cured ham heated at different air velocities (1, 2, 3, 4 and 6 m/s) (constant air temperature of 50 ºC) without (AIR) and with (AIR+PuS) the application of PuS. Letters show homogeneous groups established from LSD intervals (95%).

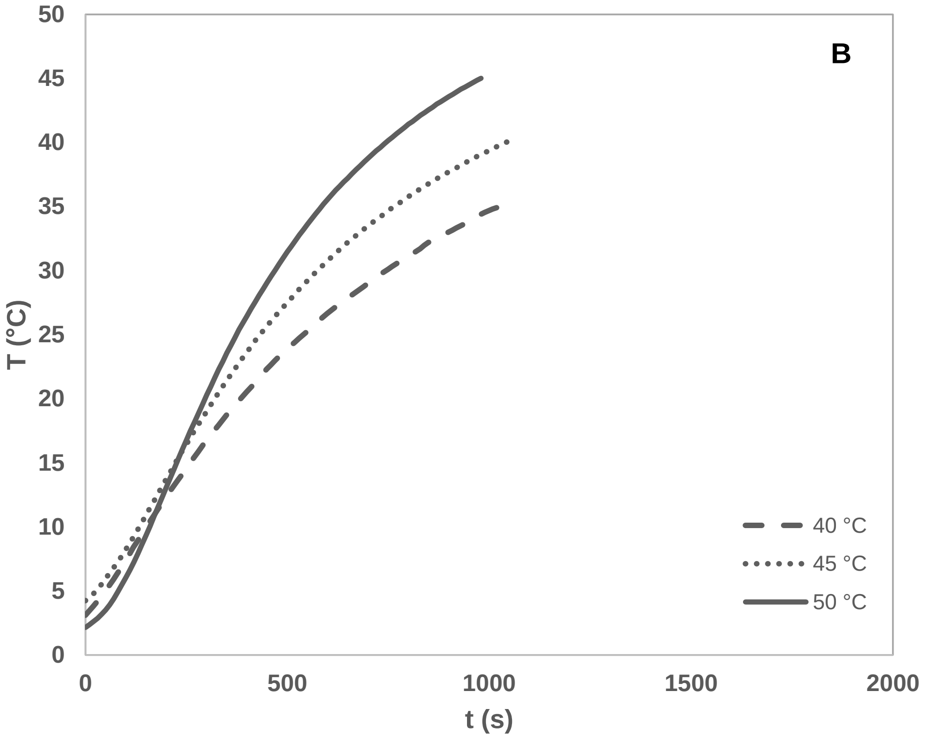
Figure 7. Hardness variation of dry-cured ham heated at 40, 45 and 50 °C at 2 m/s. Average values for AIR and AIR+PuS experiments. Error bars show LSD intervals (95%).

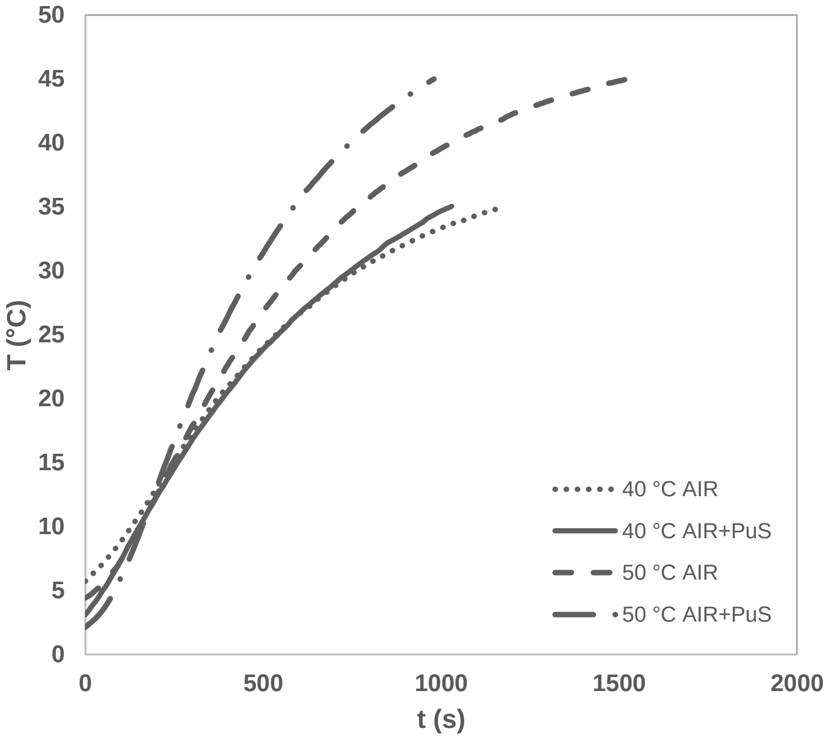
Figure 8. Force decay variation, ΔY(90), of dry-cured ham heated at 40, 45 and 50 °C at 2 m/s. Average values for AIR and AIR+PuS experiments. Error bars show LSD intervals (95%).

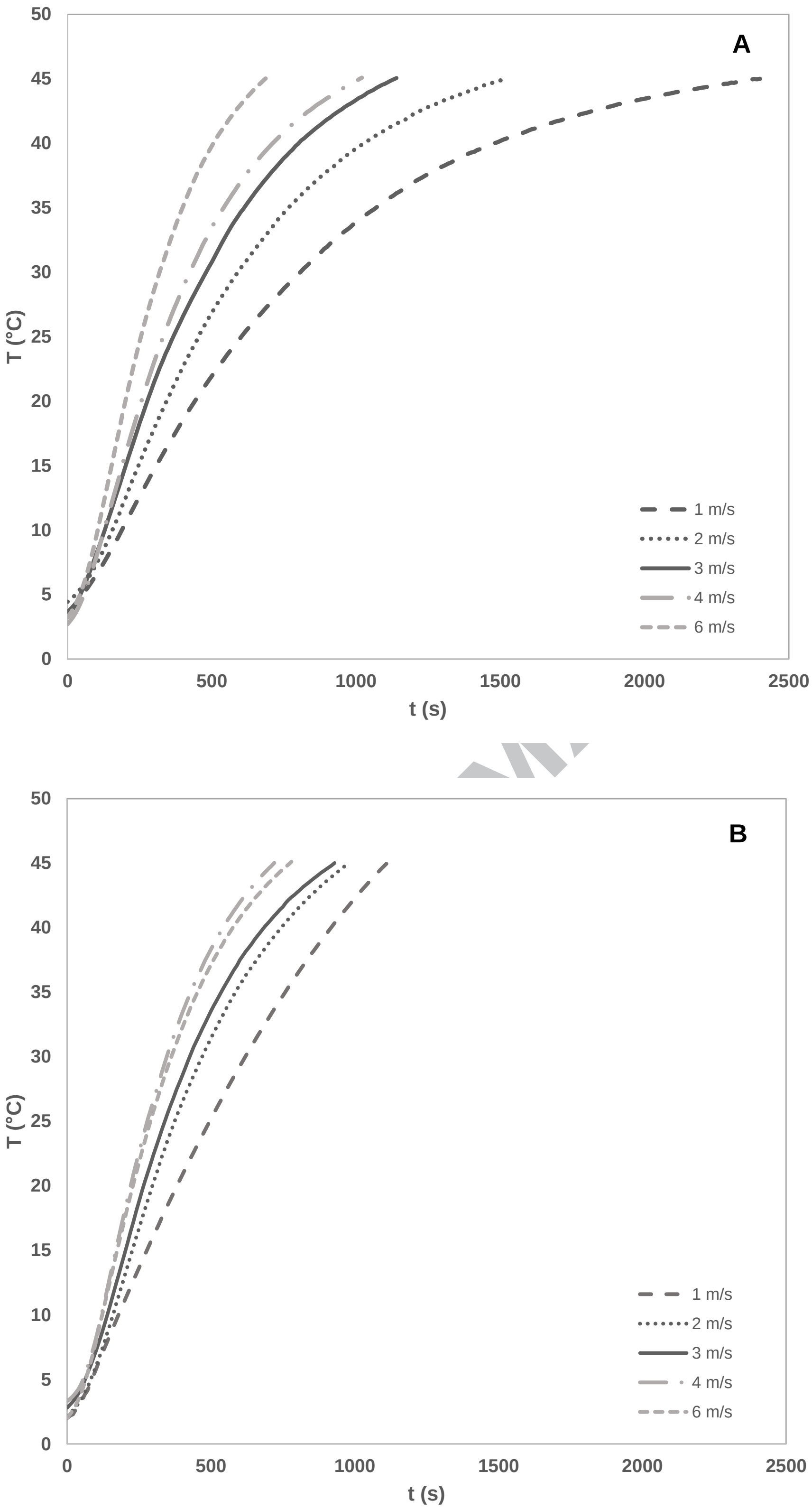


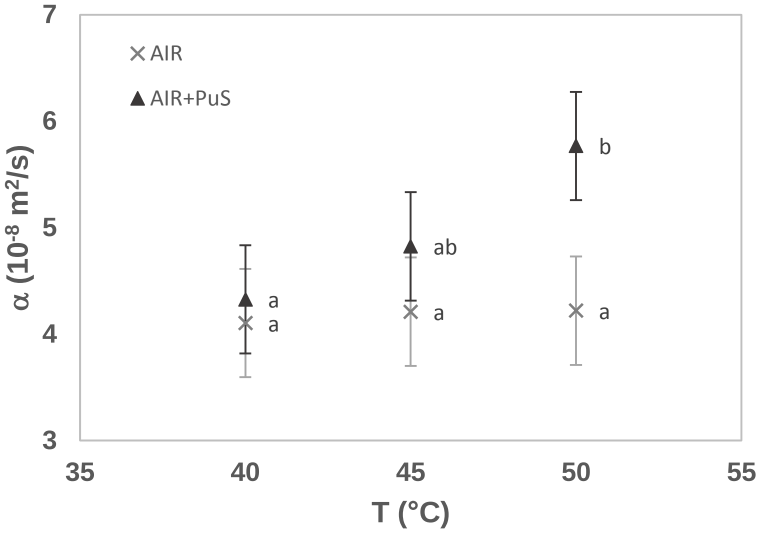
1. Fan, 2. Electrical resistances, 3. Anemometer, 4. 3-Way valve, 5. Pt-100, 6. Heating chamber, 7. Type-K thermocouples, 8. Type-T thermocouple, 9. Pneumatic moving arms, 10. Ultrasonic transducer, 11. Vibrating cylinder, 12. Impedance matching unit, 13. High power ultrasonic generator, 14. Data logger, 15. PC

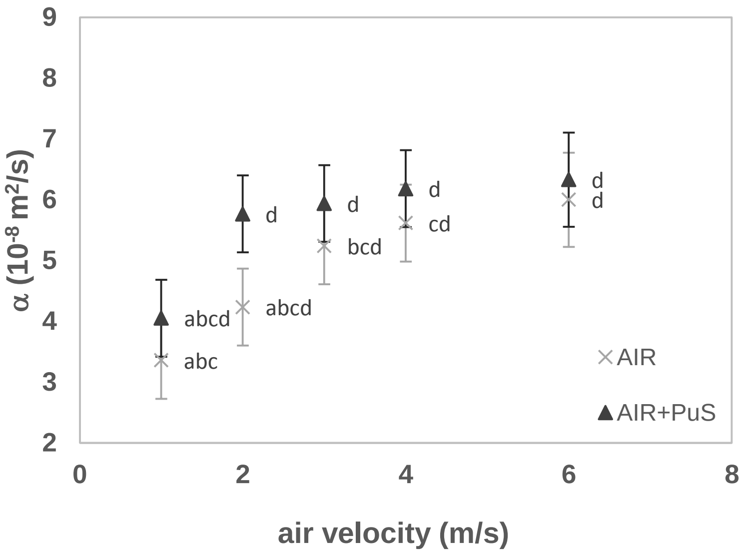

A
T (°C)
t (s)
0
5
10
15
20
25
30
35
40
45
50
0
500
1000
1500
2000
40 °C
45 °C
50 °C

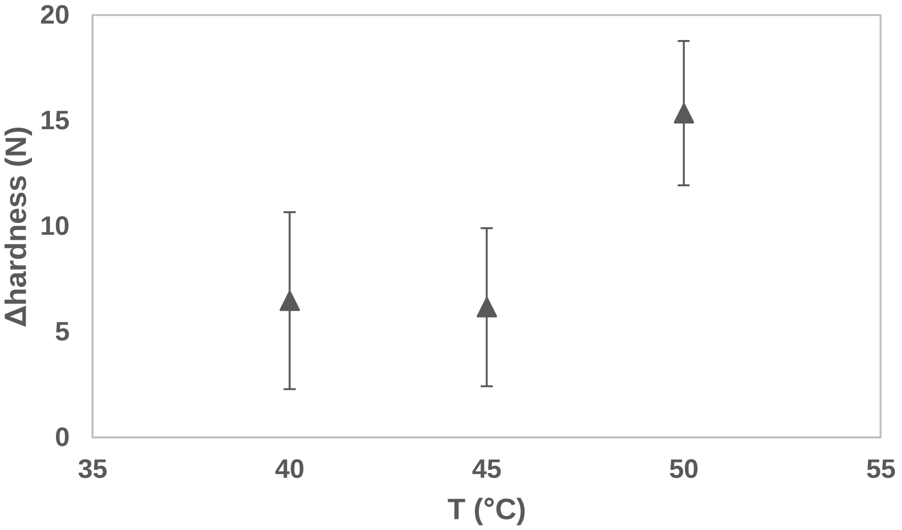

B
T (°C)
t (s)
0
5
10
15
20
25
30
35
40
45
50
0
500
1000
1500
2000
40 °C
45 °C
50 °C


T (°C)
50
45
40
35
30
25
20
15
10
5
0
t (s)
0
500
1000
1500
2000
40 °C AIR
40 °C AIR+PuS
50 °C AIR
50 °C AIR+PuS


A
T (°C)
0
5
10
15
20
25
30
35
40
45
50
t (s)
0
500
1000
1500
2000
2500
1 m/s
2 m/s
3 m/s
4 m/s
6 m/s
B
T (°C)
0
5
10
15
20
25
30
35
40
45
50
t (s)
0
500
1000
1500
2000
2500
1 m/s
2 m/s
3 m/s
4 m/s
6 m/s


× AIR
▲ AIR+PuS
α (10^{-8} m^2/s)
T (°C)
7
6
5
4
3
35
40
45
50
55
a
a
ab
a
b
a


α (10^{-8} m²/s)
9
8
7
6
5
4
3
2
0
2
4
6
8
air velocity (m/s)
abcd
abc
d
abcd
d
bcd
d
cd
d
d
× AIR
▲ AIR+PuS


20
15
10
5
0
Δhardness (N)
35
40
45
50
55
T (°C)

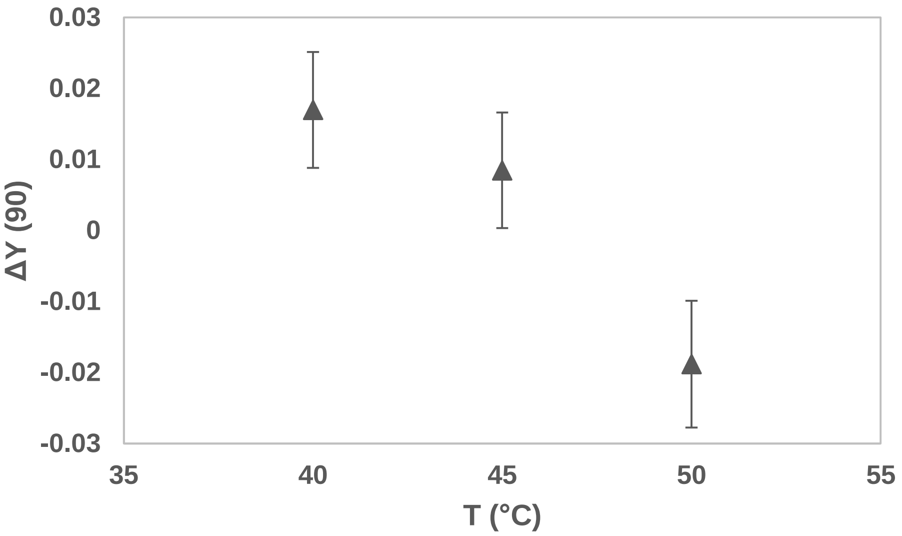

0.03
0.02
0.01
0
-0.01
-0.02
-0.03
ΔY (90)
35
40
45
50
55
T (°C)

Table 1. Apparent thermal diffusivity (α) and statistical parameters obtained from modelling of heating kinetics of dry-cured ham at different air temperatures (40, 45 and 50 °C) (constant air velocity of 2 m/s), and at different air velocities (1, 2, 3, 4 and 6 m/s) (constant air temperature of 50 °C), without (AIR) and with (AIR+PuS) PuS application. VAR (%) is the percentage of explained variance and MRE (%) the percentage of mean relative error.

		Apparent thermal diffusivity (α) ($\times 10^{-8}$ m^2/s)	**VAR (%)**	**MRE (%)**
AIR	**40 °C**	4.1	91.3	12.6
	45 °C	4.2	93.9	16.4
	50 °C	4.2	94.3	18.1
AIR+PuS	**40 °C**	4.3	92.9	12.7
	45 °C	4.8	92	14.5
	50 °C	5.8	94.6	15.5
AIR	**1 m/s**	3.4	91.7	17.5
	2 m/s	4.2	94.3	22.5
	3 m/s	5.2	94.2	15.2
	4 m/s	5.6	95.7	13.3
	6 m/s	6.0	94.7	13.5
AIR+PuS	**1 m/s**	4.1	93.5	14.2
	2 m/s	5.8	94.6	15.5
	3 m/s	5.9	96.8	11.9
	4 m/s	6.2	97.7	12.1
	6 m/s	6.3	95.8	17.9

Data showed in this table were computed by taking the first 50 terms of both summations in Eq. 1.

Highlights

- Power ultrasound (PuS) sped-up the heat transfer, increasing the apparent thermal diffusivity (α) up to 37 %
- The improvement of α by PuS application was larger at high temperatures (50 ºC)
- The effect of PuS application at high air velocities (6 m/s) was negligible
- Heating improved dry-cured ham hardness and elasticity