Analysis of ultrasound-assisted convective heating/cooling process: Development and application of a Nusselt equation

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ABSTRACT

In this study, the convective heating/cooling process assisted by US irradiation is analyzed with the aims of developing a new convective heat transfer correlation. Heat transfer experiments were conducted with different copper machined geometries (cube, sphere and cylinder), fluid velocities (0.93–5.00 × 10⁻³ m/s), temperatures (5–60 °C), and US intensities (0–6913 W/m²) using water as heat transfer fluid. The Nusselt (Nu) equation was obtained by assuming an apparent Nu number in the US-assisted process, expressed as the sum of contributions of the forced convection and cavitation-acoustic streaming effects. The Nu equation was validated with two sets of experiments conducted with a mixture of ethylene glycol and water (1:1 V/V) or a CaCl₂ aqueous solution (30 g/L) as immersion media, achieving a satisfactory reproduction of experimental data, with mean relative deviations of 17.6 and 17.8%, respectively. In addition, a conduction model with source term and the proposed correlation were applied to the analysis of US-accelerated heating kinetics of dry-cured ham reported in literature. Results demonstrated that US improves heating of ham slices because of the increased heat transfer coefficients and the direct absorption of US power by the foodstuff.

1. Introduction

Food process operations frequently involve heating or cooling stages between fluids and solid materials, where conduction and convection represent the dominant heat transfer mechanisms. To improve processes, new methods and technologies have been proposed for enhancing heat exchange while reducing energy losses. Ultrasound (US) is a promising non-thermal food processing technology which has been recognized as an effective tool for intensifying heat transfer in different processes such as air drying, cooling, freezing, and blanching, increasing the efficiency of the processes while improving the quality of the final product [20,11,33,1,43,37,36].

Ultrasound is a cyclic sound pressure wave with frequencies above 18 kHz; however, it is very often applied in the frequency range of 20–100 kHz for process intensification [12]. When these waves propagate in fluids, cavitation and acoustic streaming are generated enhancing heat transfer [2,25]. Acoustic cavitation involves the formation, growth, oscillation, and collapse of gas bubbles due to alternate compression and rarefaction cycles, [32,7,3]. Cavitation effects and collapse of bubbles near solid–liquid interfaces can reduce the local flow resistance and enhance the heat transfer rate by disruption of the boundary fluid layers [28]. Besides, US can also generate high-speed unidirectional flow of these tiny bubbles producing momentum gradients and fluid currents, phenomenon known as acoustic streaming. These streams enhance heat transfer by improving mixing of the liquid phase [24,25].

Empirical correlations obtained by fitting experimental data are widely used to calculate heat transfer coefficients in several applications [35,34,40,26,23]. These models are selected depending on process characteristics, including flow regime, geometrical arrangement, and the range of dimensionless numbers (Reynolds, Prandtl, Grashof, etc.) in which they were developed. For natural and forced convection processes, the US irradiation has been demonstrated to enhance heat transfer coefficients [27,4,39,30]; however, only a few correlations incorporating its effect have been developed [5,19,8]. These relationships might be helpful to analyze the effect of US irradiation for process design and optimization or for the development of new applications as demonstrated in selected studies. For example, Kiani and Sun [21] predicted that freezing time of potato samples could be shortened by applying US irradiation and using a previously reported Nu equation in the heat transfer model. Thus, the development of additional applications for US irradiation in convective heat transfer processes is deeply tied to the understanding of the functional relationships between
Nomenclature

\( A, B, C, D, E \) parameters for \( Nu \) equation
\( a, b, c, d, e \) parameters for \( Nu \) equation
\( A \) solid surface area (m\(^2\))
\( A_n \) \( n \)-th coefficient of the analytical solution to conduction equation
\( B_i \) Biot number (dimensionless)
\( C_{p0} \) specific heat (J/kg/\( ^\circ \)C)
\( D \) conductive heat transfer coefficient (W/m\(^2\)/\( ^\circ \)C)
\( f \) fraction of the US power absorbed by the fluid
\( F \) flow rate (m\(^3\)/s)
\( G_j \) transfer function (\( j = 1, 2, 3, 4 \))
\( h \) convective heat transfer coefficient (W/m\(^2\)/K)
\( I \) US intensity (W/m\(^2\))
\( k \) thermal conductivity (W/m/\( ^\circ \)C)
\( K_j \) process gain (\( j = 11, 12, 13, 21, 22 \))
\( L \) characteristic length for conduction (m)
\( L_c \) characteristic length for convection (m)
\( M_i \) magnitude of the step input (\( i = 1, 2, 3 \))
\( Nu \) Nusselt number (dimensionless)
\( P \) Power (W)
\( Q \) heat irradiated by the US (W/m\(^2\))
\( Pr \) Prandtl number (dimensionless)
\( r \) radial coordinate (m)
\( R \) ratio between convection and irradiation effects of US leading to a rise of solid temperature
\( Re \) Reynolds number (dimensionless)
\( S \) vessel surface (m\(^2\))
\( t \) time (s)
\( T, T_0 \) Solid temperature: local and average, respectively \((^\circ \)C\))
\( U \) global heat transfer coefficient (W/m\(^2\)/K)
\( v \) velocity (m/s)
\( V \) Volume (m\(^3\))
\( x \) averaged variable
\( X \) denotes an arbitrary input
\( Y \) denotes an arbitrary response
\( z \) axial coordinate (m)

Greek symbols

\( \alpha \) thermal diffusivity (m\(^2\)/s)
\( \beta \) geometry factor for average temperature (dimensionless)
\( \delta \) length-to-diameter ratio in finite cylinder
\( \epsilon \) volume fraction occupied by the fluid
\( \phi \) geometry factor for internal heat transfer coefficient (dimensionless)
\( \lambda_n \) \( n \)-th eigenvalue of the analytical solution (dimensionless)
\( \lambda \) Biot number (dimensionless)
\( \sigma \) emitting surface area of the transducer (m\(^2\))
\( \tau \) time constant (\( j = 1, 2 \))

Subscripts

\( app \) apparent
\( av \) average
\( i \) denotes the interface solid-fluid
\( s \) denotes the solid
\( ss \) denotes the steady-state solution
\( US \) for US-assisted process
\( 0 \) denotes an initial state
\( 0, 1 \) denotes the inlet and outlet stream, respectively
\( \infty \) denotes the fluid

process variables and the creation of experimental protocols to achieve these tasks. Therefore, this study aims to analyze the convective heating/cooling process assisted by US irradiation. To fully achieve this objective the following topics are covered: (i) the modeling of convective/cooling process assisted by US irradiation. To fully achieve this task. Therefore, this study aims to analyze the convective heat transfer as an input-response process, (ii) the development and validation of a new convective heat transfer correlation and (iii) the use of the proposed correlation to the analysis of the US-accelerated heating kinetics of dry-cured ham.

2. Methods and materials

2.1. Experimental setup

The effect of US application on convective heat transfer was evaluated with copper machined geometries immersed in a fluid. A copper billet (\( k = 406 \) W/m/\( ^\circ \)C, \( C_p = 385 \) J/kg/\( ^\circ \)C, \( \rho = 8941 \) kg/m\(^3\)) was machined into a cube (0.02 m side), sphere (0.02 m diameter) and cylinder (0.03 m length and 0.02 m diameter). The US-assisted cooling/heating was carried out in an ultrasonic bath (Model P 70H, Elmasonic, Germany) operated at a frequency of 37 kHz and a maximum input power of 880 W. The ultrasonic bath consists of a rectangular stainless-steel tank of internal dimensions 100 mm \( \times \) 137 mm \( \times \) 505 mm (depth \( \times \) width \( \times \) length) fitted with four piezoelectric transducers located under the bottom of the tank. A single fine drill hole (1 mm diameter) was performed in each machined geometry allowing a thermocouple (type K, TP870, Extech Instruments, United States) to seat tight into it. The drill hole was performed in perpendicular direction at the center of the square and circular faces in the cube and cylinder geometries, respectively, while it was performed perpendicular to surface in sphere solid. The drill hole depth was fixed to reach the solid centroid (0.01 m in cube and sphere and 0.015 m in cylinder). Thermal paste (MGZ-NDSC-N15M-R1, Cooler Master, China) was used to fill air gaps in drill holes allowing a more efficient transfer of heat between the thermocouple and the copper solid. The thermocouple and the machined copper geometries were kept at a fixed position by using a stainless-steel sample holder during the experiments with the centroid of the solids

### Table 1
Factors and levels evaluated in the present experiment.

| Experiment set | Objective                                      | Medium | Geometry \((x_1)\)                  | Fluid temperature \((\rm^\circ \)C, \(x_2)\) | Fluid velocity \((\times 10^2 \) m/s, \(x_3)\) | Ultrasound power level \((\%\, x_4)\) | Factorial design \((L_1 \times L_2 L_3 L_4)\) | Number of treatments |
|----------------|-----------------------------------------------|--------|-----------------------------------|---------------------------------------------|------------------------------------------|---------------------------------|---------------------|-------------------|
| 1              | Development of heat transfer correlation       | Water  | Cube, sphere, cylinder            | 5, 15, 30, 45, 60                            | 0.93, 1.86, 5.00                        | 0, 30, 100                     | \(3 \times 5 \times 3 \times 3\) | 135               |
| 2              | Model validation                              | EGW    | Cube, sphere                       | -5, 0                                       | 1.86                                     | 0, 100                         | \(2 \times 2 \times 1 \times 2\) | 8                 |
| 3              | Model validation                              | CCW*   | Sphere, cylinder                   | -5, 0, 5                                    | 1.86                                     | 0, 30, 100                     | \(2 \times 3 \times 1 \times 3\) | 18                |

1 EGW: Ethylene glycol and water (1:1 V/V).
2 CCW: CaCl\(_2\) aqueous solution (30 g/L).
located 25 mm above the transducer surface. Here, the cube was placed with one of its faces parallel to the ultrasonic bath bottom while the cylinder was placed in horizontal position. The temperature of the sample was recorded every second by a data logger (EA10, Extech Instruments, United States). US irradiation was started before immersing the copper geometries into the bath. A bath circulator (ECO 10, SEV-PREND, México) was used to control the temperature of the cooling/heating medium. Experiments without US irradiation were also performed for comparison purposes. Each experiment was carried out by triplicate. Heat transfer experiments were performed by using three immersion fluids as follows:

1. Water was initially used for the development of a new experimental convective heat transfer correlation for US-assisted heating/cooling processes.
2. An ethylene glycol–water mixture (1:1 V/V) and a CaCl$_2$ aqueous solution (30 g/L) were further tested as heat transfer media to validate the prediction capabilities of developed correlation.

The factors and levels evaluated in this study are summarized in Table 1. A total of 135 treatments (405 experiments) were conducted to develop heat transfer correlation, while 26 treatments (78 experiments) were performed to validate the proposed model.

2.2. Determination of ultrasonic power

A calorimetric procedure was used to determine the ultrasonic power. This procedure assumes that the mechanical energy generated by the ultrasound waves is transformed to heat. The dissipated ultrasonic power ($P$) was calculated from the rate of temperature increase as

$$P = \rho_\infty C_{p,\infty} F \frac{dT}{dt}$$ ...

Where $\rho_\infty$ and $C_{p,\infty}$ are the density and heat capacity of the fluid, $\epsilon$ is the volume fraction occupied by the fluid, $V$ is the volume and $t$ is the time. The applied ultrasonic intensity ($I$) was determined from the calculated power as [18, 19, 42, 29, 33]

$$I = \frac{P}{\sigma}$$ ...

where $\sigma$ is the emitting surface area of the transducer.

2.3. Theory

2.3.1. Heat transfer model

The following equations describe the energy interchange between a solid of arbitrary shape and a surrounding fluid contained in a vessel with continuous flow, ideal mixing, and US power source (Fig. 1):

$$\frac{d(\rho_\infty C_{p,\infty} V \Theta_1)}{dt} = \rho_\infty C_{p,\infty} F \Theta_1 - \rho_\infty C_{p,\infty} F \Theta_1 + \int V dV + US(\Theta - \Theta_i)$$ ...

$$\frac{d(\rho_s C_p(1 - \epsilon)V T i)}{dt} = hA(\Theta_1 - \Theta_{i1}) + (1 - f)P$$ ...

$$hA(\Theta_1 - \Theta_{i1}) = DA(T_i - T)$$ ...

$$T_i = \Theta_{i1}$$ ...

Where $\rho$, $C_p$, $A$, $V$, $\epsilon$, $f$, $F$, $h$, $D$, $U$, $S$, $\Theta$, and $T$ are the density, specific heat, solid area, volume (solid plus fluid), volume fraction occupied by the fluid, fraction of the US power absorbed by the fluid, flow rate, convective heat transfer coefficient (fluid to solid surface heat transfer), conductive heat transfer coefficient (heat transfer from the surface to inside), global heat transfer coefficient (heat transfer between surrounding media and vessel), vessel surface, surrounding temperature, fluid temperature and average solid temperature, respectively; the subscripts $\infty$, $s$, $i$, 0 and 1 denote the fluid, the solid, the fluid–solid interface, the fluid, and the solid, respectively.

![Fig. 1. Experimental setup for studying the ultrasound-assisted convective heating/cooling process. (1) Ultrasonic generator, (2) stainless-steel tank, (3) machined copper solid, (4) transducer, (5) thermocouple, (6) data logger.](image-url)
interface, the inlet stream and the outlet stream, respectively. According to Eq. (3), the rate of energy accumulation by the fluid is equal to the sum of the rate of energy inflow, \( \rho_w C_{pw} \Phi \), the rate of energy outflow, \( \gamma_{as} C_{pw} \Phi \); its rate of US power absorption, \( P_r \); and rate of energy exchange between the vessel and the surrounding medium, \( \dot{\theta}(\Theta_1, \Theta_2) \). On the other hand, Eq. (4) is a volume-averaged heat transfer equation expressing the rate of energy accumulation by the solid as the sum of the rate of energy exchange between the fluid and solid surface, \( h(\Theta_1, \Theta_2) \); and its rate of US power absorption, \( (1-f)P \). Eq. (5) represents the heat transfer continuity at the interface, that is, the energy flux transferred from the fluid to the solid surface by convection, \( h(\Theta_1, \Theta_2) \), equal to energy flux leaving the fluid–solid interface inward by conduction, \( DA(T; T) \). Finally, Eq. (6) represents the thermal equilibrium condition. The combination of Eqs. (4), (5) and (6) yields

\[
\frac{d(\rho_w C_{pw}(1-\varepsilon)V)}{dt} = HA(\Theta_1 - T) + (1-f)P
\]

(7)

with

\[
\frac{1}{H} = \frac{1}{h} + \frac{1}{1}
\]

(8)

where \( H \) is an overall heat transfer coefficient grouping convection and conduction mechanisms. The internal heat transfer coefficient \( D \) is a function of the thermal conductivity and the effective film thickness where the heat conduction takes place [38,6] (Appendix A). If internal resistance to heat transfer is negligible \((D \gg h)\) then \( H = h \). The volume-averaged temperature is defined as

\[
T = \frac{\int_T T dV}{\int dV}
\]

(9)

where \( T \) represents the temperature distribution within the solid. The average temperature can be estimated as shown in the Appendix A.

The model considers that the system is subjected to an ultrasound irradiation \( P \), split between the fluid and solid phases according to fraction \( f \).

Eqs. (3) and (7) can be arranged as follows by assuming that \( \rho, C_p, V \) and \( \varepsilon \) do not change during process

\[
\frac{d\theta_1}{dt} + \Theta_1 = K_{11} \theta_0 + K_{12} P + K_{13} \theta
\]

(10)

\[
\frac{d\Theta_1}{dt} + T = K_{12} \Theta_1 + K_{22} P
\]

(11)

\[
\begin{align*}
K_{11} &= \frac{1}{US} \\
K_{12} &= \frac{f}{\rho_w C_{pw} F + US} \\
K_{13} &= \frac{US}{\rho_w C_{pw} F + US}
\end{align*}
\]

\[
\begin{align*}
K_{21} &= 1 \\
K_{22} &= \frac{1-f}{HA}
\end{align*}
\]

(12)

\[
\begin{align*}
\tau_1 &= \rho_w C_{pw} \varepsilon V \\
\tau_2 &= \frac{\rho_w C_{pw} (1-\varepsilon) V}{HA}
\end{align*}
\]

(13)

Eqs. (10) and (11) can be rewritten in terms of deviation or perturbation variables to represent the change around a nominal operating point (a method commonly used in control engineering); thus, their initial conditions become zero. The application of Laplace transform to resulting model yields

\[
\Theta_1(s) = \frac{K_{11}}{\tau_1 s + 1} \Theta_0(s) + \frac{K_{12}}{\tau_1 s + 1} P(s) + \frac{K_{13}}{\tau_1 s + 1} \Theta(s)
\]

(15)

\[
T′(s) = \frac{K_{21}}{\tau_2 s + 1} \Theta(s) + \frac{K_{22}}{\tau_2 s + 1} P(s)
\]

(16)

where the apostrophe indicates the Laplace transform is applied to a deviation variable. The combination of Eqs. (15) and (16) produces

\[
T′(s) = G_1(s) \Theta_0(s) + G_2(s) P(s) + G_3(s) \Theta(s) + G_4(s) P(s)
\]

(17)

\[
G_i(s) = \frac{K_{1i}}{\tau_1 s + 1} \quad \text{for } i = 1, 2, 3; \quad G_i(s) = \frac{K_{2i}}{\tau_2 s + 1}
\]

(18)

According to Eq. (17), the solution is the sum of the output response of a first order system, \( G_i(s) \), and three series of two first order systems, \( G_i(s) \ (i = 1, 2, 3) \). The transfer functions involved in Eq. (17) have the general forms

\[
Y(s) = \frac{K}{\tau_2 s + 1}
\]

(19)

\[
Y(s) = \frac{K}{\tau_1 s + (\tau_2 s + 1)}
\]

(20)

The transient step responses of magnitude \( M \) for Eqs. (19) and (20) are, respectively,

\[
Y(t) = KM(1 - e^{-t/T})
\]

(21)

\[
Y(t) = KM \left[ 1 - \left( \frac{t \tau_2}{\tau_1 - \tau_2} \left( \frac{1}{\tau_2} - \frac{1}{\tau_1} \right) \right) \right]
\]

(22)

Therefore, the required solution is

\[
T = T_0 + (K_{21} K_{11} M_1 + K_{12} K_{22} M_2 + K_{13} K_{M} M_3) \times ...
\]

(23)

\[
1 - \left( \frac{t \tau_2}{\tau_1 - \tau_2} \left( \frac{1}{\tau_2} - \frac{1}{\tau_1} \right) \right) + K_{22} M_2 (1 - e^{-t/c})
\]

with

\[
M_1 = \Theta_0 - \Theta_1; \quad M_2 = P; \quad M_3 = \theta - \Theta_1
\]

(24)

Eq. (23) reaches the steady-state solution

\[
T_{ss} = T_0 + (K_{21} K_{11} M_1 + K_{12} K_{22} M_2 + K_{13} K_{M} M_3)
\]

(25)

The terms \( K_{21} K_{11} \) (C/C), \( K_{22} K_{12} \) (C/W) and \( K_{22} K_{13} \) (C/C) represent the steady-state gains for inputs \( \Theta_0 \), \( P \) and \( \theta \), respectively. They indicate the expected change in solid temperature per unit change in inputs.

2.3.3. Negligible dynamic of the fluid phase

The dynamic of the fluid phase described by Eq. (10) can be neglected when \( \Theta_0 = \Theta_1 \). That is, the amount of heat transferred to the surrounding medium is much smaller than the fed energy \((US \ll \rho_w C_{pw} F, K_{11} \rightarrow 1, K_{13} \rightarrow 0)\), the ultrasound irradiation absorbed by the liquid phase is negligible in comparison with the fed energy \((f \ll \rho_w C_{pw} F, K_{12} \rightarrow 0)\), and the residence time of the liquid is very small \((\varepsilon V \ll F, \tau_1 \rightarrow 0)\). Thus, Eq. (23) reduces to

\[
T = T_0 + (K_{21} M_1 + K_{22} M_2) (1 - e^{-t/\tau_2})
\]

(26)

Eq. (10) can be also neglected if the following three conditions are satisfied: (1) the fluid phase has reached a steady-state temperature with inputs \( \Theta_0 \), \( P \) and \( \theta \); (2) the solid is not initially submerged in the fluid; (3) the fluid-to-solid mass ratio is large enough to allow for a negligible change of the fluid temperature.

2.3.3. Evaluation of the ultrasound power absorbed by the solid

Kiani et al. [18] proposed the following model to describe the heat transfer within a solid sphere immersed in a fluid

\[
\frac{\partial T}{\partial t} = \frac{\alpha_1}{r^2} \left( \rho \frac{\partial T}{\partial r} \right)
\]

(27)

Eq. (27) was solved by using the boundary condition

\[
-k \frac{\partial T}{\partial r} = h(T_s - \Theta_1) + Q
\]

(28)

According to Eq. (28), the energy flux transferred from surface into
the solid by conduction results from the sum of the energy transferred towards the solid surface by convection from the fluid and the heat irradiated by the US (Q). The proposed solution under negligible internal resistance to heat transfer and initial homogeneous distribution of temperature within the solid is (the solution is presented with the nomenclature of current study)

\[
T = T_0 + \left( K_{21} M_1 + \frac{Q}{R} \right) (1 - e^{-\frac{t}{\tau}})
\]  
(29)

Comparison of Eqs. (26) and (29) reveals that

\[
QA = (1 - f) P
\]

Thus, Eq. (29) is, in fact, the solution of

\[
d(\rho C_p V (1 - e)) \frac{dT}{dt} = \h A (\Theta_s - T) + QA
\]

That is, Eq. (31) is equivalent to Eq. (7) under negligible dynamics of the liquid phase and negligible internal resistance to heat transfer (\(H = h\)), but the forcing input is Q. However, geometry effects still can be included in Eq. (7) in the internal heat transfer coefficient (D) if internal resistance to heat transfer cannot be neglected. Please notice that using an intensive property as a forcing input can lead to potential physical errors in the model solution. In this case, for example, the power delivered by the US transducer (QA) can be adjusted by changing the solid surface (A) and could be increased beyond the technical specifications of the equipment. Thus, the form of Eq. (7) should be preferred over Eq. (31), even if they are mathematically equivalent.

Kiani et al. [18] developed a procedure to evaluate the heating effect of US at the surface of the sphere. The authors considered that after US irradiation, for the solid in thermal equilibrium with the fluid, the heat generated at the surface of the sphere will cause the temperature of the sphere to rise (\(\Theta_s = T \at t = 0\)). Thus, the heating effect is calculated as:

\[
(1 - f) P = QA = \rho C_p V \Delta T_{el} / \Delta t
\]

\(\Delta T_{el}\) is the temperature increase caused by the US. The authors used a circulator bath (10 -C) to avoid the effect of heat generated by the fluid. In addition, the temperature measurement was performed for a short time (10 s) to allow neglecting the heat transfer between the solid and the fluid. No further analysis is presented to test the validity of the assumptions.

Eqs. (3) and (7) can describe the experimental setup used by Kiani et al. [18]. According to Eq. (25), the US irradiation causes both a direct (K_{21}, ultrasound power absorbed by the solid) and indirect (K_{22}, energy transfer trough fluid) rise of solid temperature. The steady-state ratio between indirect and direct contributions is

\[
R_{us} = K_{21} K_{12} / K_{22} = \frac{HAf}{(1 - f) \rho C_p P + US}
\]

However, under unstable-state conditions, the ratio between these contributions will change according to time constants \(\tau_1\) and \(\tau_2\). The time-averaged ratio during a certain operation time is

\[
[R] = \frac{K_{21} K_{12}}{K_{22}} \int_0^t \frac{1}{1 - (1 - e^{-\tau_1})} \left( \frac{dT}{dt} \right) dt
\]

Thus, the US power absorbed by the solid corrected for the convective effects is

\[
(1 - f) P = \frac{1}{1 + (R)^0} C_p V (1 - e) \frac{dT}{dt}
\]

For negligible dynamics of the fluid phase (the liquid has reached a steady-state temperature while applying US irradiation before the solid is submerged, \(\Theta_s \neq T \at t = 0\)), then

\[
R = \frac{K_{21} M_1}{K_{22} M_2} = \frac{HA (\Theta_s - T_0)}{\left( 1 - f \right) P}
\]

Here, the value of R remains constant along process because the terms K_{21} M_1 and K_{22} M_2 have the same dynamics according to Eq. (26).

### 2.4. Development of a heat transfer correlation for the US-assisted process

Heat transfer between a sphere and a fluid is very often represented in terms of the Nusselt, Reynolds and Prandtl numbers by the equation [17]:

\[
Nu = 2 + aRe^d Pr^c
\]

\[
Nu = \frac{hL}{k_w}
\]

\[
Re = \frac{\rho V L}{\mu}
\]

\[
Pr = \frac{C_p \mu}{k_w}
\]

where all properties are evaluated at the film temperature. For non-spherical solids the length for convection is considered as the diameter of a sphere with the same surface as the given solid [16].

US might affect the flow turbulence of a fluid surrounding a solid because the cavitation and acoustic-streaming effects [14,3], enhancing the Reynolds number and thus the Nusselt number for an US-assisted process. Therefore, it is proposed in this study that an apparent Nusselt number (\(Nu_{app}\)) in an US-assisted process can be written as the sum of contributions of the forced convection (\(Nu\)) and cavitation/ acoustic-streaming (\(Nu_{US}\)) effects,

\[
Nu_{app} = Nu + Nu_{US}
\]

where

\[
Nu_{US} = AR_{US}^p Pr^c
\]

where \(R_{US}\) is a function of the US irradiation intensity or power. Eq. (42) lacks the number 2 on the left-hand side found in Eq. (37) because the natural convection limit of heat transfer between the fluid and a submerged sphere is already considered in this last equation. The \(R_{US}\) number can be seen as the effect of US application on fluid turbulence. The following expression is proposed to relate \(R_{US}\) with the ultrasound intensity or power levels

\[
Re_{US} = D \left( \frac{P}{P_{ref}} \right)^E
\]

where

\[
Nu_{app} = 2 + aRe^d Pr^c + A \left( \frac{P}{P_{ref}} \right)^B Pr^c = 2 + aRe^d Pr^c + d \left( \frac{P}{P_{ref}} \right)^r Pr^c
\]

where \(d = AD^p\) and \(e = EB\). If \(e = C\) (the ultrasound does not change the effect of Prandtl on heat transfer coefficient), then

\[
Nu_{app} = 2 + \left( aRe^d + d \left( \frac{P}{P_{ref}} \right)^r \right) Pr^c
\]

On the other hand, if \(C = 0\) (the ultrasound does not interact with \(Pr\) and \(Re\) to affect heat transfer coefficient), then

\[
Nu_{app} = 2 + aRe^d Pr^c + d \left( \frac{P}{P_{ref}} \right)^r
\]

Eq. (46) is similar to that empirically proposed by Kiani et al. [19] to describe the effect of US irradiation on heat transfer coefficients, but with parameter \(e = 1\).
Heat transfer coefficient \((h)\) can be estimated from the plot of \(T\) versus \(t\) by fitting Eq. (26) to experimental data. Heat transfer coefficient values were expressed in terms of the Nusselt number. The thermophysical properties \((\rho_p, C_p, \mu_p, \kappa_w\) and \(\kappa_a\) \()\) of water, the mixture of ethylene glycol and water (1:1 \(V/V\)) and the CaCl\(_2\) aqueous solution (30 g/L) were calculated according to data provided by Choi and Okos [9], Flick [15] and Conde [10], respectively. Finally, \(Nu_{app}\) correlations were fitted to experimental \(Re\) and \(Pr\) numbers as well as the US irradiation term to determine their unknown coefficients \((a, b, c, d, \text{ and } e)\).

### 2.5. US-accelerated mild heating of dry-cured ham

Conteras et al. [11] applied power US to intensify heat transfer during the mild thermal treatment of dry-cured ham immersed in water. Experiments were conducted by packing the dry-cured ham slices (0.2 m \(\times\) 0.1 m \(\times\) 0.02 m) from two main muscles (Biceps femoris and Semimembranosus) in polyamide/polyethylene films. Heating experiments were performed in an ultrasound bath (15 L, 20 kHz, \(P = 600\) W) at different temperatures (40, 45 and 50°C). Bath temperature was externally controlled with a circulator by recycling the water at a flow rate of 3.5 L/min. Ham composition ranged from 2.4 to 16.2% in fat (wet basis) and 2.8–8.6% in salt content (wet basis), with an average moisture content of 52% (wet basis). Central temperature of sample was acquired with a type-T thermocouple. The thermal history of Semimembranosus muscle is considered in this study.

Mild heating of dry-cured ham was modeled by using the unsteady-state conduction equation

\[
\frac{\partial(\rho_p C_p T)}{\partial t} - \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \frac{(1-f)P}{\rho \varepsilon V} \text{ for } -L \leq z \leq L
\]

(47)

\[
-k \frac{\partial T}{\partial z} = h(T - \Theta_i) \quad \text{for} \quad z = L, t > 0
\]

(48)

Eq. (47) includes a source term which considers that product may increase its temperature because of the absorbed US power. Heat transfer along \(x\) and \(y\) directions was neglected because of process conditions and product dimensions (the relative difference between 1D and 3D solutions at product centroid was lower than 0.1% at any time, as estimated from the analytical solution to conduction equation without source term). The heat transfer model developed in section 2.3.1 was not further used in this part of the study because the evaluation of average temperature in a flat slab shaped product with internal resistance to heat transfer requires at least temperature from two locations, as shown in the Appendix A, and only the center location was available. The equations reported by Choi and Okos [9] were used to describe the variability of product density, specific heat, and thermal conductivity with temperature (with an average wet basis composition of 9.3% for fat, 5.7% for salt, 52% for water and 33% for protein). Heat transfer coefficient was calculated with the Nusselt correlation (45). Eqs. (47) and (48) lack an analytical solution under variable properties and thus were numerically solved by the method of lines, that is, the original PDE is transformed to a set of ODEs by only discretizing the spatial derivatives. Heat transfer model was used to both simulate the central temperature of dry-cured ham and to evaluate the fraction of the US power absorbed by the product with a uniform distribution of initial temperature. The temperature-averaged values of heat transfer coefficient, thermal conductivity and thermal diffusivity \((\alpha_t = k/\rho c_p)\) of product along process were estimated according to

\[
x_p = \int_{0}^{L} x dT \int_{0}^{P} \frac{\partial T}{\partial z} \text{d}z \bigg| \Theta_i - T_0
\]

(49)

where \(x\) represents the averaged variable \((h, k, k_p/\rho_c P)\). Finally, the values \(k_p\) and \(k_w\) were used to estimate a Biot number representative of the whole process.

\[
Bi_p = \frac{k_p L}{k_w}
\]

(50)

### 2.6. Statistical analyses

Robust nonlinear regression and statistical analyses were performed with the Matlab software and its Statistic Toolbox 7.3 (Matlab R2010a, MathWorks Inc., Natick, MA, USA). The fitness quality of the proposed models was quantified by the determination coefficient \((R^2)\) and mean relative deviation \((\text{MRD})\) while the statistical significance of nonlinear parameter estimates was evaluated through their 95% confidence intervals.

### 3. Result and discussion

#### 3.1. Development and validation of a new Nusselt equation

Heat transfer coefficients estimated for each experiment were in the ranges of 368.6–1887 (14.4 \(\leq Nu \leq 89.5\)), 562.1–2508.5 (22.2 \(\leq Nu \leq 95.7\)) and 499.0–1386.8 (16.4 \(\leq Nu \leq 107.1\)) W/m\(^2\)/°C for the 0, 30 and 100% ultrasound power levels, while corresponding Reynolds and Prandtl numbers were in the ranges of 15.2–215.2 and 4.3–8.5, respectively. Heat transfer coefficients were fitted by assuming a negligible amount of US power absorbed by the machined copper geometries, that is, \(K_{22} = 0\) in Eq. (26), and negligible internal resistance to heat transfer \((D \gg h, H \approx h)\). The ratio of the contributions of convection and US-irradiation mechanisms to solid heating can be estimated with Eq. (36) by assuming the energy absorbed by the solid is proportional to its volume fraction, that is, \(1-f \approx 1\). In this case, convection mechanism contributes between the 87 and 98% of the observed temperature rise (a worst case scenario for a fixed \(h\) value of 420 W/m\(^2\)/°C, a value below the lowest end of those obtained in the process conducted with US). The lowest contribution of convection occurs at the highest US power level setting (100%) and the lowest temperature difference between the solid and fluid (5°C). The contribution of convection mechanism to heat transfer in the lowest limit increases to 91 and 93% for the cases where the temperature difference increases to 10 °C or the US power level is decreased to the 30% while the US power setting or temperature difference are left unchanged, respectively. Thus, the assumption of a negligible amount of US power absorbed by the solid allows to simplify the problem without incurring in a significant error. According to Incropera et al. [17], the assumption of uniform temperature distribution within the solid is reasonable if Biot number is lower than 0.1. As example, the highest expected Biot number for the sphere is about 0.044 \((k_s = 406 \text{ W/m/°C, } R = 0.01 \text{ m, } h = 1800 \text{ W/m}^2/\text{°C})\); thus, it is not necessary to perform temperature measurements of the solid at its surface. The highest error caused by neglecting heat conduction in the estimation of convective heat transfer coefficient is about the 1.5%, as calculated with geometry parameters in Table A1 and Eq. (A10). The effect of neglecting heat conduction and ultrasound irradiation on solid heating are not additive as the contribution of ultrasound irradiation maximizes for low \(h\) values while temperature profiles would be accentuated at high \(h\) values.

Developed theory allows to analyze the experiment designed by Kiani et al. [18] to evaluate the US power absorbed by the solid. In this case, the contribution of convection and US-irradiation mechanisms to solid heating is not constant. An average contribution of convection and US-irradiation mechanisms to heat transfer during a certain time can be estimated with Eq. (34). For a 10 s operation, convection mechanism still contributes between the 15 and 30% of the observed temperature rise in the experiment designed by Kiani et al. [18], as estimated by available data \((h = 800 \text{ W/m}^2/\text{°C spheres diameters of 0.01 and 0.02 m, flow rates of } 2.50 \times 10^{-3} \text{ and } 1.67 \times 10^{-5} \text{ m}^3/\text{s})\) and some assumed values \((U = 0 \text{ W/m}^2/\text{°C, } f = e)\). Thus, Eq. (34) represents a valuable tool to analyze experimental conditions if the amount of US power absorbed
describe heat transfer data in US-assisted processes (Fig. 2, Table 2), with a decreasing dependency on Reynolds number as the US power increases (parameter \( b \) becomes smaller). In this case, the \( Nu \) dependency on \( Pr \) number \((c = 0.4)\) was obtained from Whitaker [41], as our set of experimental data did not cover a wide \( Pr \) range to allow for a significant estimation of the related parameter \((p > 0.05)\). According to Fig. 3, US application at the 30% setting (319 W, 4611 W/m²) caused a significant increase of Nusselt numbers (and thus, heat transfer coefficient) in comparison with experiments conducted without US for \( Nu \leq 50 \) \((h \geq 1000 \text{ W/m}²/°C, \text{symbols appear above reference line})\). Above this limit, the effect of US becomes negligible on heat transfer. These experiments were performed with the highest fluid velocity \((5 \times 10^{-3} \text{ m/s})\), corresponding to a Reynolds numbers higher than 100. A further increase of the US power level to the 100% setting (478 W, 6914 W/m²) did not enhance heat transfer beyond the levels observed for the lower 30% setting (Fig. 3b). Therefore, US application at a high-power setting or in combination with a high fluid velocity does not improve heat

Table 2

| \( P \) (%) | \( 1-f \) | \( a^* \) | \( b^* \) | \( R^2 \) | MRD (%) |
|-----------|------|------|------|------|--------|
| 0         | 0    | 1.11 | 0.64 | 0.68 | 6.70   |
| 30        | 0    | 4.02 | 0.40 | 0.54 | 4.98   |
| 100       | 0    | 10.77| 0.17 | 0.11 | 6.95   |

*Parameters were estimated for Eq. (36) with \( c = 0.4\). Results are presented as the parameter estimate \( \pm 95\% \) confidence interval.

A preliminary fit of Eq. (37) to experimental Nusselt numbers obtained at the three US power levels demonstrated its inadequacy to

Fig. 2. Fitted versus experimental Nusselt number at different ultrasound power levels.

Fig. 3. Effect ultrasound power settings on the experimental Nusselt numbers.

Fig. 4. Effect of Reynolds number on the experimental Nusselt numbers for ultrasound-assisted cooling-heating of cube, sphere or cylinder copper solids immersed in water ([5 to 60 °C) at different fluid velocities and ultrasound irradiation levels. The 30 and 100% US settings correspond to irradiation intensities of 4611 and 6913 W/m², respectively.
Kiani et al. [22] reported a linear increase of heat transfer coefficient along duty cycle from 0 to 70%, achieving a constant value thereafter; that is, US application has a limited potential to enhance heat transfer. Delouei et al. [13] investigated the impact of ultrasonic vibration on pressure drop and heat transfer enhancement on inlet turbulent flows. These authors showed that increasing Reynolds numbers leads to diminishing returns in heat transfer enhancements by US. Therefore, the existing interactions between the characteristic velocity of the acoustic field and the flow velocity are critical parameters controlling the ability of US irradiation to improve heat transfer.

Experimental data for the US-irradiated process at the 30% level were fitted to estimate parameters \( d \) and \( e \) in Eqs. (45) and (46) (Table 3). The constant \( e \) was not significantly different from 1 (\( p > 0.05 \)), and thus was set to this value during a subsequent regression procedure. The proposed \( Nu \) equations achieved a satisfactory reproduction of experimental data as shown in Fig. 5. The prediction capabilities of these correlations were further tested with experimental data from sets 2 and 3 (Table 1) and compared with the model proposed by Kiani et al. [19]. Here, the models were tested in the ranges 9.1 \( \leq \text{Re} \leq 18.4 \) and 23.5 \( \leq \text{Pr} \leq 34.5 \) for the mixture of ethylene glycol and water and 12.9 \( \leq \text{Re} \leq 29.9 \) and 11.2 \( \leq \text{Pr} \leq 18.8 \) for the CaCl\(_2\) aqueous solution. Both the \( Nu \) equation developed by Kiani et al. [19] and Eq. (45) achieved a satisfactory reproduction of these data, with MRD ranging from 18 to 24% (Figs. 6 and 7), while Eq. (46) showed a significant deviation of the experimental behavior when the CaCl\(_2\) aqueous solution was used as immersion medium (Table 4).

### Table 3

| Case | \( d^* \) | \( e^* \) | \( R^2 \) | MRD (%) |
|------|-----------|-----------|----------|---------|
| \( C = c \) | 5.45 ± 0.81 | 1.00 | 0.51 | 5.06 |
| \( C = 0 \) | 11.44 ± 1.66 | 1.00 | 0.52 | 5.01 |

*Parameters were estimated for Eq. (44) by using constants \( a \) and \( b \) for an ultrasound power of 0% in Table 2. Results are presented as the parameter estimate ± 95% confidence interval. †Parameter was not statistically different from 1 during an initial fitting procedure and thus was further fixed during regression.*

3.2. Effect of US on mild thermal treatment of dry-cured ham

The experimental and modeled heating kinetics of dry-cured ham are presented in Fig. 8. The heating rate predicted by the simulation was slower than that the experimental one, with an especially notable lag at the lowest temperature (8.4% \( \leq \text{MRD} \leq 20% \)). Averaged heat transfer coefficients and thermal conductivities of solid ranged from 378 to 392 W/m\(^2\)/°C and from 0.416 to 0.420 W/m/°C, resulting in Biot numbers between 9.10 and 9.33, increasing with temperature in all cases (Table 5). Identified Biot numbers correspond to a heat transfer process dominated by both conduction and convection mechanisms. The US-assisted heating process was also simulated by assuming a negligible external resistance to transfer in comparison with a non-irradiated process (Fig. 4).
corresponds to the estimation of the US source term (1- US power absorbed by the solid, 1- Fig. 8. heat transfer (or strictly conduction-controlled process,
cesses in different media.
Prediction capabilities of heat transfer correlation for ultrasound-assisted pro
Table 4
Prediction capabilities of heat transfer correlation for ultrasound-assisted pro-
cesses in different media.
| Medium       | Heat transfer correlation | MRD (%) | R² |
|--------------|---------------------------|---------|----|
| EGW          | Proposed (C = C)          | 18.2    | 0.90 |
| EGW          | Proposed (C = 0)          | 26.2    | 0.89 |
| EGW          | Kiani et al. [19]         | 24.7    | 0.93 |
| CCW          | Proposed (C = C)          | 23.6    | 0.81 |
| CCW          | Proposed (C = 0)          | 31.2    | 0.21 |
| CCW          | Kiani et al. [19]         | 23.7    | 0.85 |

EGW: Ethylene glycol and water (1:1 V/V); CCW: CaCl₂ aqueous solution (30 g/L)

The proposed heat transfer model was further fitted to experimental data to estimate the source term (the fraction of the US power absorbed by the solid) while using the Nusselt equation (47) to estimate h (red line in Fig. 8). The estimated fraction of the US power absorbed by the solid ranged from 0.008 at 50 °C to 0.037 at 40 °C (Table 5), that is, the effect of US irradiation on product temperature increase is higher at the lowest temperature. The value of 1-f roughly approximates the volume fraction of food in the water bath (≈ 0.027). The averaged thermal properties of product, heat transfer coefficient and Biot number remained practically unchanged during the estimation of 1-f (Table 5). The addition of the US source term to conduction equation allowed a precise reproduction of heating kinetics of ham (2.6% ≤ MRD ≤ 7.7%), reducing the initial deviation between experimental and simulated data observed at the lowest tested temperature.

4. Conclusions

The convective heating/cooling process assisted by US irradiation was analyzed allowing the formulation of a new Nusselt equation showing a good agreement with experimental data. The conduction model with source term jointly with the proposed heat transfer correlation were successfully applied to the analysis of the US-accelerated heating kinetics of dry-cured ham, allowing a new interpretation of the US effect in these results. Theoretical results could be helpful in design experiments for appraising the US power absorbed by products and its dependence on other variables thus opening the needs for further investigations.

CRediT authorship contribution statement

T. Martínez-Ramos: Investigation, Methodology, Software, Visualization, Writing - review & editing. E. Corona-Jiménez: Investigation, Funding acquisition, Project administration, Writing - review & editing.
Table 5

| Simulation (case 1) | Simulation (case 2) |
|---------------------|---------------------|
| $\theta_1$ | $h_{\text{aw}}$ | $k_{\text{aw}}$ | $a_{\text{aw}} \times 10^7$ | $b_{\text{aw}}$ | $R^2$/MRD | $h_{\text{aw}}$ | $k_{\text{aw}}$ | $a_{\text{aw}} \times 10^7$ | $b_{\text{aw}}$ | $R^2$/MRD |
| 40 | 378.3 | 0.416 | 1.21 | 9.10 | 0.70/20.1 | 0.93/11.3 | 377.7 | 0.415 | 1.20 | 9.11 | 3.74 ± 0.53 | 0.97/7.65 |
| 45 | 385.0 | 0.417 | 1.21 | 9.22 | 0.96/8.83 | 0.99/3.08 | 384.0 | 0.416 | 1.21 | 9.23 | 1.73 ± 0.15 | 1.00/2.56 |
| 50 | 391.7 | 0.420 | 1.22 | 9.33 | 0.97/8.36 | 0.98/7.41 | 391.0 | 0.418 | 1.21 | 9.35 | 0.76/20.1 | 0.93/11.3 |

Simulations conducted by assuming a negligible US power absorbed by the solid, $1/f = 0$. Case 1: $h$ from Nu correlation, Eq. (45). Case 2: Negligible external resistance to heat transfer ($h \to \infty$, $Bi \to \infty$). Unit: $\theta_1$ in °C; $h_{\text{aw}}$ in W/m²/°C; $k_{\text{aw}}$ in W/m/°C; $a_{\text{aw}}$ in m²/°C; MRD in %.

I.I. Ruiz-López: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing - original draft.

Déclaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. . Appraisal of internal heat transfer coefficient and dominant mechanism for heat transfer

The internal heat transfer coefficient $D$ is often represented as [38,6]

$$D = \frac{h}{\phi L}$$

(A1)

where $\phi$ is a geometrical factor evaluated from the analytical solution to unsteady-state conduction equation assuming negligible interfacial resistance and infinite volume of the liquid phase. The analytical solution for unsteady-state conduction equation has the general form

$$\frac{T - T_{\text{aw}}}{T_0 - T_{\text{aw}}} = \sum_{n=1}^{\infty} A_n \exp \left( -\frac{\lambda_n^2 \alpha t}{L^2} \right)$$

(A2)

where $T_0$ and $T_{\text{aw}}$ represent the initial and steady-state temperatures, respectively, $\alpha$ is the thermal diffusivity, $A_n$ represents a series coefficient, $\lambda_n$ is an eigenvalue of the solution, and $L$ is the characteristic length for conduction. The time-derivative to the first term of Eq. (A2) is

$$\frac{dT}{dt} = \frac{\lambda_n^2 \alpha}{L^2} (T - T_{\text{aw}})$$

(A3)

where $\lambda_1$ is the first eigenvalue of the analytical solution. On the other hand, Eqs. (4), (5), (6) and (A1) can be combined and expressed as follows by assuming (1) no US irradiation ($P = 0$), (2) a conduction-controlled process ($T_1 = T_{\text{ss}}$) and (3) constant properties ($\rho, C_p, V$ and $\varepsilon$).

$$\frac{dT}{dt} = -\frac{k_c A}{\phi L \rho C_p (1 - \varepsilon) V} (T - T_{\text{aw}})$$

(A4)

Combination of Eqs. (A3) and (A4) produces

$$\phi = \frac{aL}{\lambda_1}$$

(A5)

where $a = A_1/(1 - \varepsilon) V$ is the specific surface of solid. Table A1 summarizes expressions for $a$, $\lambda_1$ and $\phi$ in common geometries. The ratio between convective and conductive resistances to heat transfer can be estimated from the Biot number,

$$Bi = \frac{hL}{k_c}$$

(A6)

The assumption of uniform temperature distribution within the solid is reasonable if $Bi < 0.1$ [17]. In this case, it is not necessary to perform multiple temperature measurements of the solid since the center or surface temperatures can be taken as the average value $T$.

However, if $Bi > 0.1$, then a parabolic approximation of the temperature inside the product can be assumed,

$$\psi = \psi_c + (\psi_s - \psi_c) \frac{r^2}{\rho_c}$$

(A8)

where $\psi_{\text{centroid}}$ and $\psi_{\text{surface}}$ represent the dimensionless temperatures at centroid and surface of solid, respectively. The mean dimensionless temperature can be obtained by volume averaging Eq. (A8) to obtain

$$\frac{T - T_{\text{aw}}}{T_0 - T_{\text{aw}}} = \frac{2}{3 + \beta} \frac{1}{\rho_c} + \frac{1 + \beta}{3} \frac{1}{\rho_{\text{surface}}}$$

(A9)

where $\beta$ takes the values 0, 1 and 2 for the flat slab, infinite cylinder, and sphere geometries, respectively. The solutions for cube and finite cylinder can be obtained from Eq. (A8) by applying the superposition principle.

Finally, an expression to evaluate the error in the estimation of

Table A1

| Geometry          | Specific area (a) | First squared eigenvalue ($\lambda_1^2$) | $\phi - aL/\lambda_1^2$ |
|-------------------|-------------------|----------------------------------------|-------------------------|
| Flat slab         | 1/L               | $\pi^2/4$                               | 4/$\pi^2$               |
| Infinite cylinder | 2/L               | (2.4048)$^2$                           | 2/(2.4048)$^2$          |
| Sphere            | 3/L               | $\pi^2$                                | (86$^2 + 4)/(\pi^2 + 2$  |
| Finite cylinder   | $2 + 1/6$       | $2\pi^2/(4\pi^2)^2 + (2.4048)^2$      | (2.4048)$^2$/$\pi^2$   |
| Cube              | 3/L               | $3\pi^2/4$                             | 4/$\pi^2$               |

$\delta$ is the length-to-diameter ratio in finite cylinder.
convective heat transfer coefficient when neglecting conductive resistance to heat transfer (that is, by taking \( H \approx h \)) can be obtained by combining Eqs. (8), (A1) and (A6),

\[
\varepsilon(\%) = 100 - \frac{\phi \beta_i}{\phi \beta_i + 1}
\]

References

[1] C. Alvarez, S. Ospina, C.E. Orrego, Effects of ultrasound-assisted blanching on the processing and quality parameters of freeze-dried guava slices, J. Food Process. Preserv. 43 (2019), e14288.

[2] C. Bartoli, F. Balligli, Effects of ultrasonic waves on the heat transfer enhancement in subcooled boiling, Exp. Therm Fluid Sci. 35 (2011) 423–432.

[3] O. Bulliard-Sauret, J. Berindei, S. Ferrouillat, L. Vignal, A. Memponteil, C. Poncet, N. Gondrexon, Heat transfer intensification by low or high frequency ultrasound: thermal and hydrodynamic phenomenological analysis, Exp. Therm Fluid Sci. 104 (2019) 258–277.

[4] O. Bulliard-Sauret, S. Ferrouillat, L. Vignal, A. Memponteil, N. Gondrexon, Heat transfer enhancement using 2 MHz ultrasound, Ultrasounds sonochim. 39 (2017) 262–271.

[5] C. Gai, X. Hua, S. Liang, X. Li, Augmentation of natural convective heat transfer by acoustic cavitation, Front. Energy Power Eng. Chin. 4 (2010) 313–318.

[6] K. Castillo-Santos, L.I. Ruiz-Lopez, G.C. Rodriguez-Jimenes, J. Carrillo-Ahumada, M.A. García-Alvarado, Analysis of mass transfer equations during solid-liquid extraction and its application for vanilla extraction kinetics modeling, J. Food Eng. 192 (2017) 36–44.

[7] X. Cheng, M. Zhang, B. Xu, B. Adhikari, J. Sun, The principles of ultrasound and its application in freezing related processes of food materials: A review, Ultrasounds sonochim. 27 (2015) 576–585.

[8] S.-W. Chen, C.-F. Liu, H.-J. Lin, P.-S. Ruan, Y.-T. Su, Y.-C. Weng, J.-R. Wang, J.-D. Lee, W.-K. Lin, Experimental test and empirical correlation development for heat transfer enhancement under ultrasound vibration, Appl. Therm. Eng. 143 (2018) 639–649.

[9] Y. Choi, M.R. Okos, Thermal properties in liquid foods, Food Eng. Process Appl. 1 (1986) 93–101.

[10] M.R. Conde, Properties of aqueous solutions of lithium and calcium chlorides: formulations for use in air conditioning equipment design, Int. J. Therm. Sci. 43 (2004) 367–382.

[11] M. Contreras, J. Benedito, J. Bon, J.V. García-Pérez, Accelerated mild heating of Brassica oleracea, Ultrasonics Sonochemistry 60 (2020), 104733.

[12] R. Roohi, E. Abedi, S.M.B. Hashemi, K. Marxzek, J.M. Lorenzo, F.J. Barba, Ultrasound-assisted bleaching: Mathematical and 3D computational fluid dynamics simulation of ultrasound parameters on microbubble formation and cavitation structures, Innovative Food Sci. Emerg. Technol. 55 (2019) 66–79.

[13] Y. Tao, D. Li, W.S. Chai, P.L. Show, X. Yang, S. Manickam, G. Xie, Y. Han, Comparison between airborne ultrasound and contact ultrasound to intensify air drying of blackberry: heat and mass transfer simulation, energy consumption and quality evaluation, Ultrasounds sonochim. 72 (2021), 105151.

[14] Y. Tian, P. Zhang, Z. Zhu, S.W. Sun, Development of a single/dual-frequency orthogonal ultrasound-assisted rapid freezing technique and its effects on quality attributes of frozen potatoes, J. Food Eng. 226 (2020), 110112.

[15] J. Wang, J. Duan, X. Wang, M. Zheng, Saturated boiling heat transfer under ultrasound, Int. Commun. Heat Mass Transfer 115 (2020), 104515.

[16] J. Wen, H. Zhan, L. Li, D. Zhang, Experimental investigation and development of new corelation for flow boiling heat transfer in mini-channel, Int. J. Therm. Sci. 129 (2018) 209–217.

[17] S. Whitaker, Forced convection heat transfer correlations for flow in pipes, past flat plates, single cylinders, single spheres, and for flow in packed beds and tube bundles, AIChE Journal 18 (2) (1972) 361–371.

[18] Y. Xin, M. Zhang, B. Adhikari, Ultrasound assisted immersion freezing of broccoli (Brassica oleracea L. var. botrytis L.), Ultrasounds sonochim. 21 (2014) 1728–1735.

[19] Z. Zhu, P. Zhang, S.W. Sun, Effects of multi-frequency ultrasound on freezing rates and quality attributes of potatoes, Ultrasounds sonochim. 60 (2020), 104733.