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Simulation and parametric sensitivity evaluation for ohmic heating of chicken breast

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Abstract

The objective of the present study is to assess the global sensitivity (using Response Surface Methodology) of chicken meat and cooking medium temperatures during ohmic heating against uncertainties in chicken meat properties (specific heat capacity, thermal conductivity, and electrical conductivity), the concentration of the salt solution, applied voltage, and surrounding air temperature, as well as the heat transfer coefficient to the air. To achieve this, a mechanistic model for ohmic heating of chicken meat in salt solution was developed by coupling heat transfer, laminar fluid flow, and electric field. The numerical solution was carried out using COMSOL Multiphysics® v5.6. The developed model's accuracy was validated by comparing the experimental data obtained at two different voltages (120 and 180V) and salt concentrations (0.2 and 0.4%) of the heating solution. The model predictions were in good agreement with experimental data. According to the results, special care should be given during ohmic heating of meat samples to avoid under-processing that may occur on sample surfaces. From the sensitivity analysis, chicken electrical conductivity, applied voltage, and brine concentration are the main factors affecting the chicken core and surface temperatures, as well as heating rate. On the other hand, properties related to the surrounding air (overall heat transfer coefficient and temperature) had no significant impact on neither chicken temperature nor its heating rate.

Keywords: Joule heating; meat; COMSOL; response surface; CFD

1. Introduction

Thermal processing is an essential step for many food products (particularly meat and meat products). Several processing methods, such as frying, grilling, roasting, blanching, etc., were used and studied for many years (Ferreira et al., 2016; Naveena et al., 2014; F. A. P. Silva et al., 2016; Song et al., 2017; Yao et al., 2020). These cooking methods, particularly those that cause browning on the meat surface, such as frying and grilling, help with the development of the desired taste and flavour in meat (Mottram, 1998). However, they may cause serious health issues such as cancer, especially in the case of over processing or intense browning (de Verdier et al., 1991). Furthermore, non-uniform heat transfer during cooking leads to undesired nutritional and sensorial changes in the product. Heat transfer in these traditional methods is accomplished by receiving heat from an external source and then gradually transferring it to the product via convection, conduction, or radiation (Kanjanapongkul, 2017; Varghese et al., 2014). During the sequential transfer of heat, a significant amount of energy is lost to achieve the desired temperature at the chicken core to obtain safe meat. Nevertheless, volumetric heating methods (microwave (MW) and ohmic heating (OH)) may be preferred as alternative techniques to reduce energy consumption during food processing (Goullieux & Pain, 2014).

MW and OH are known as the two of the most efficient techniques in terms of the amount of energy required for food cooking or thermal treatments.

Because the supplied energy is directly converted to heat in the food, they are called "volumetric heating", and the heating rate in MW and OH is less dependent on thermal conduction and convection. There is no need to heat the cooking medium (the surrounding air, cooking equipment, etc.), which can be considered another key factor for reduced energy consumption during OH (Goullieux & Pain, 2014; Jun & Sastry, 2005) and why more energy should be consumed in conventional heating techniques compared to volumetric ones, particularly OH (Sakr & Liu, 2014).

Abbreviations

MW	Microwave heating
OH	Ohmic heating
RSM	Response surface methodology
RC	Regression coefficient
SRC	Standardised regression coefficient
n	Total number of samples observation
t	Time (s)
g	Gravitational acceleration ($m.s^{-2}$)
μ	Dynamic viscosity (Pa.s)
σ	Electrical conductivity ($S.m^{-1}$)
ρ	Density ($kg.m^{3}$)
c_p	Specific heat capacity ($kJ.(kg°.C)^{-1}$)
k	Thermal conductivity ($W.(m°.C)^{-1}$)
s	Standard deviation
u	Velocity ($m.s^{-1}$)
P	Pressure (Pa)
T	Temperature (°C)
U	Heat transfer coefficient ($W.(m^{2}.°C)^{-1}$)
X	Independent variables for a regression model
V	Voltage (V)
Z	Dependent variables for a regression model
Q_e	Heat generated by ohmic heating (W)
β	Regression coefficient

Subscripts

air	Surrounding air
b	Brine
c	Chicken
P	Predicted
E	Experimental
c,75°C	Chicken core heating to 75°C
min,75°C	Minimum temperature of chicken heating to 75°C
min,110s	Minimum after 110 s of ohmic heating

Volumetric heating methods are far more efficient than traditional methods, and OH is even more energy-efficient than MW. The energy efficiency of OH is nearly 90%, compared to 50% for MW (Akkara & Kayaardı, 2014). There are also some disadvantages of OH, and maybe the most important one is the non-uniform heating possibility compared to traditional methods. This is commonly experienced when particulate foods are heated because the heating medium has heterogeneous electrical properties (Shim et al., 2010). The potential survival of foodborne pathogens due to insufficient thermal treatments may eventually cause some public health issues.

Food products (chicken meat in our case) should be cooked until the slowest heating point (the centre of the food piece for traditional cooking methods) reaches temperatures of 63-71°C at the very least (Dominguez-Hernandez et al., 2018), but higher temperatures are unquestionably better for food safety. Because studies showed that two pathogens, Campylobacter and Salmonella, can present at high loads in the gastrointestinal tract of birds. They also appear in many health problem reports about chicken meat safety (Rouger et al., 2017). To ensure a safe process that achieves Salmonella inactivation, it is recommended to heat the cold spot of chicken meat to 70-85°C (Silva & Gibbs, 2012). But even worse than Salmonella, C. jejuni may survive on chicken breast meat after 10 minutes of heating in boiling water (de Jong et al., 2012). Moreover, it has been established that the cold spot does not always appear in the geometrical centre of the product during OH (Choi et al., 2020; Salengke & Sastry, 2007) and foodborne pathogens can survive in those spots for a long time (Shin et al., 2020). That is why it is critical to understand the heating behaviour of chicken meat during OH and the factors that influence it.

OH has been extensively researched for a variety of different foods or food systems (Goullieux & Pain, 2014; Khodeir et al., 2021; Kim et al., 2020; Turgut et al., 2021; Varghese et al., 2014). However, studies on the OH of chicken are primarily focused on the determination of electrical properties and some pre-treatment options (Patel et al., 2018; Sarang et al., 2007, 2008; Tulsiyan et al., 2008). To fully comprehend the process, a modelling study is required to reveal the cooking of chicken meat with OH. Even though some studies on theoretical modelling of OH related to heat treatments on liquids, solids and simple solid/liquid mixtures have previously done (Albuquerque et al., 2019; Choi et al., 2020; Engchuan et al., 2014; Guo et al., 2017; Jiang et al., 2010; Jun & Sastry, 2005; Marra et al., 2009; Salengke & Sastry, 2007; Shim et al., 2010; Ye et al., 2004; Zell et al., 2008), on the primary concern of these studies were the model development. On the other hand, knowing the most efficient factors of a system and the relative impact of model inputs on outputs is crucial for many engineering, design, and process control applications. Some studies about the effect of electrical and physical qualities of foods and system parameters on OH efficiency and heating patterns of materials can be found in the literature (Choi et al., 2020; Goullieux & Pain, 2014; Varghese et al., 2014). But these studies investigate the effect of individual parameters (such as electrical conductivity, salt concentration, etc.) at a time which is not sufficient to have an idea about the complicated transfer mechanisms during OH. So far as we know, there is not any study in the literature about (i) the OH of chicken meat and temperature change during the process, and (ii) sensitivity evaluation of system parameters in combination for OH.

Thus, the current study aims to (i) develop and validate a mechanistic model for OH of chicken meat, and (ii) conduct a sensitivity analysis for selected model inputs by comparing their relative impacts on the time and temperature (tc,75°C, Tmin,110s and tmin,75°C). These will be detailed in the following sections: the detailed information about the experimental studies is given in Section 2; modelling strategies, governing equations, and sensitivity analysis are presented in section 3; simulation results and evaluations are discussed in Section 4.

2. Materials and methods

2.1. Sample preparation and system settings

Chicken breast meat (skinless and boneless) was acquired at a local store on the day of the experiments. Before the OH treatment, the chicken meat was sliced into rectangular prisms (5x5x3 cm, see Figure 1) and maintained at room temperature for about 15-20 minutes. Although preliminary trials revealed that fibre orientation had no important effect on temperature during OH, special care was given to keep the fibre direction parallel to the electric current (along the x-axis) for all samples.

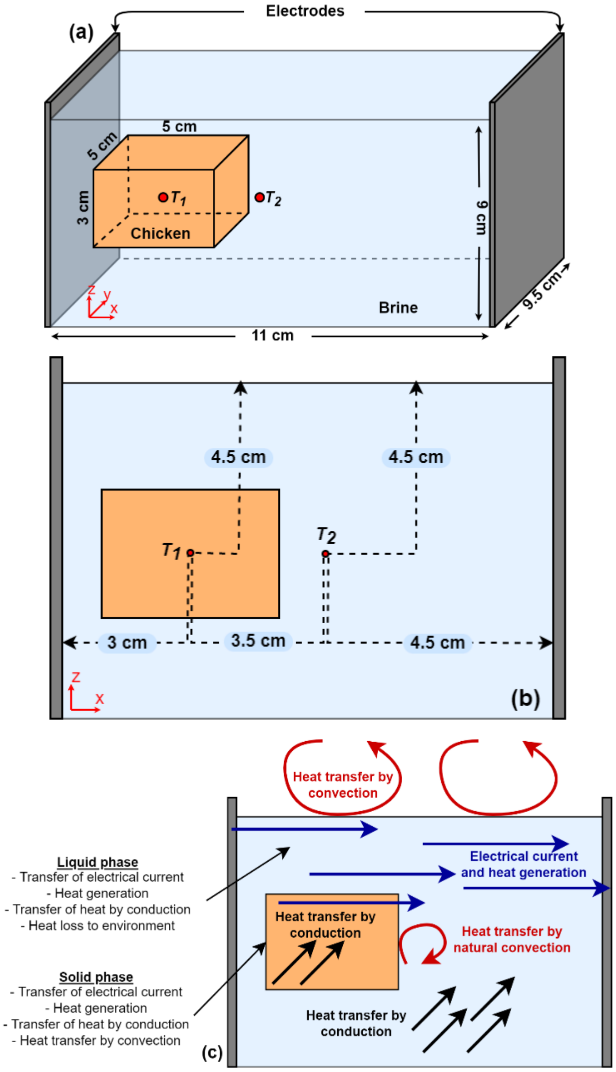

Figure 1. Schematic representation of ohmic cell and chicken meat with thermocouple positions in (a) 3D and (b) 2D domains and (c) considered transport mechanisms of different phases.

Experiments were carried out with a static lab-scale ohmic heater (BCH Ltd., Lancashire, UK) built up with a W500 grade polyethylene rectangular cell with variable size adjustments and two titanium electrodes (Pedersen et al., 2016). Ohmic cell dimensions were adjusted to 9.5x11 cm. The height of the heating medium, including the meat piece and brine, was approximately 9 cm during experiments. The OH unit can supply alternating current, at a maximum of 230 V (60 Hz, sinusoidal). Temperature was monitored and captured every 5 s using a data logger (TC-08, Pico Technology Ltd., Cambridgeshire, UK) and two K-type thermocouples (T_1 located in the sample centre (at 4.5 cm from the top surface) and T_2 was located 6.5 cm away from the first electrode to measure brine temperature (Figure 1).

2.2. Electrical conductivity of brine

Brine was prepared using deionized water and salt at various concentrations and temperatures ranging from 3-90°C. Their electrical conductivities were measured using a conductivity meter (LF323, Mobro Instruments, Welheim, Germany). The relationship between the electrical conductivity of brine (S.m-1), salt concentration (cb, %, w/v) and the temperature was explained using Eq. 1 which is given in Table 1 (R2=0.9932, adjusted R2=0.9929).

Table 1. Model input parameters, corresponding values, and units.

Parameter	Value	Unit	Source
Density			
chicken meat (ρ_c)	1070	kg.m^{-3}	[a]
Specific heat capacity			
chicken meat ($c_{p,c}$)	2800	J.(kg.°C)$^{-1}$	[b]
Thermal conductivity			
chicken meat (k_c)	0.45	W.(m.°C)$^{-1}$	[c]
Electrical conductivity			
chicken meat (σ_c)	0.665	S.m^{-1}	[d]
brine (σ_b)	Eq. 1	S.m^{-1}	Measured
Heat transfer coefficient			
air (U)	5	W.(m^2.°C)$^{-1}$	[e]

- Eq. 1: $a+\frac{b}{[\{1+\exp((c-T_b)/d)\}\{1+\exp((e-c_b)/f\}]}$, a=−0.229, b=11.6, c=3.43 x 10^2, d=0.74, f=0.386
- [a]: Alters & May (1963), [b] McKetta (1995), [c]: Geankoplis (2003), [d]:Sarang et al. (2008), [e]: Marra et al. (2009)
- COMSOL built-in material properties for liquid water were used for the properties of brine except for electrical conductivity.

2.3. Preliminary studies

Two preliminary experiments were carried out to test the effects of sample size, electrical field strength, and salt concentration before developing the mechanistic model and conducting the sensitivity analysis. The independent variables in the first experiment were voltage and sample size, with constant brine concentration. For the second experiment, applied voltage and brine concentration were chosen as independent variables. The full factorial design method was used for both trials. According to the findings, the size variation of chicken meat for the studied range had no significant effect on the temperature profile ($p>0.05$, data not shown). Therefore, it was not considered as a variable within the present study. On the other hand, the effect of voltage was significant ($p\leq0.05$). The statistical evaluation of the second preliminary experiment was made to assess the changes in voltage (120 and 180V) and brine concentration (0.2 and 0.4%, w/v). Eight experiments were carried out using these factors at two levels, with two replicates for each combination. The resulting data were compared with the expected temperature profile of OH for model validation.

3. Modelling of transport phenomena

3.1. Model description and assumptions

The mechanistic model for the OH of chicken meat in the brine was developed by considering heat transfer, fluid flow (natural convection) and electrical current for energy generation during OH process. The model equations (gathered from various sources) are presented in detail in section "3.2. Governing equations". Moreover, a schematic representation of the three-dimensional model domain and the transfer phenomena are presented in Figure 1. The considered phenomena and assumptions are listed as follows:

- Heat transfer through conduction in solid and liquid phases, and through convection in brine (due to natural convection) and brine/air interface were considered.
- During OH, heat is generated in the material because of the electric current passing through the medium (de Alwis & Fryer, 1990). Thus, the heat generation term related to OH was included in the model.
- The water evaporation from the upper surface of the ohmic cell was neglected.
- The flow mechanism for brine was assumed to be natural convection.
- Particularly for chicken meat, any significant mass transfer and change in electrical properties of the sample were not observed even during boiling at 100°C (Sarang et al., 2007). Thus, mass transfer and electric conductivity change for chicken were not included in the model.
- The voltage applied between two electrodes. Other surfaces were insulated.
- Heat loss from external boundaries was considered.

3.2. Governing equations

The heat transfer within chicken and brine is described by Eq. 2 (Bird et al., 2000), except for the velocity term (**u**) which is equal to zero for the domain with chicken meat (Figure 1).

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p (\mathbf{u} \cdot \nabla) T = k \nabla^2 T + Q_e \tag{2}$$

where ρ is density (kg.m^3), c_p is specific heat capacity (kJ.(kg°.C)$^{-1}$), k is thermal conductivity (W.(m°.C)$^{-1}$), T is the temperature (°C), t is time (s) and Q_e represents the heat generated by OH (W) and it is described by Eq. 3 (de Alwis & Fryer, 1990).

$$Q_e = \sigma |\nabla V|^2 \tag{3}$$

where σ is the electrical conductivity of materials (S.m^{-1}) and V represents the voltage applied to the system (V). The electrical potential distribution can be computed using the Laplace equation (Eq.4).

$$\nabla \cdot \sigma \nabla V = 0 \tag{4}$$

The equations for continuity and momentum are described in Eq. 5 and Eq. 6, respectively (Bird et al., 2000).

$$\nabla \mathbf{u} = 0 \tag{5}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \boldsymbol{u} = -\nabla P + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g} \tag{6}$$

where μ is the dynamic viscosity (Pa.s), P is pressure (Pa) and **g** is the gravitational acceleration (m.s^{-2}).

3.3. Boundary and initial conditions

The initial temperature of the surrounding air (Tair) and the chicken meat was ≈22°C, and the brine temperature at the beginning of OH was 10°C.

Convective heat transfer from the external surfaces was defined as follows (Eq. 6).

$$-k_b \nabla T_b = U(T_b - T_{air}) \tag{6}$$

where U is the overall heat transfer coefficient describing the rate of heat loss from brine to air (W.(m^2.°C)$^{-1}$); b, c and air are subscripts indicating brine, chicken and air, respectively.

Regarding fluid flow, the non-slip boundary condition for all external surfaces was applied except for the top surface, where the open-boundary condition is considered.

3.4. Model solution and validation

The partial differential equations considered for the OH model were solved using COMSOL Multyphysics® (version 5.6). The model parameters/variables used were presented in Table 1. The 3D model geometry was built and meshed using COMSOL software. Mesh sensitivity analysis was done by performing a series of simulations with increasing mesh density until it has no impact on the simulation results (Kumar & Dilber, 2006). To accomplish this, five meshes with 21258, 41591, 102901, 195019, and 491510 elements were tested (Figure 2). After visual inspection, the one with 195019 elements was used for further simulations. The model was validated against the experimental data and the standard error of estimate (SEE) was calculated as the goodness of the prediction measure (Eq. 8).

$$SEE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_P - T_E)^2} \tag{8}$$

where n is the total number of samples, T_P and T_E are the predicted and measured temperatures, respectively. After validation, it was concluded that the model has satisfactory performance to be used in the sensitivity analysis.

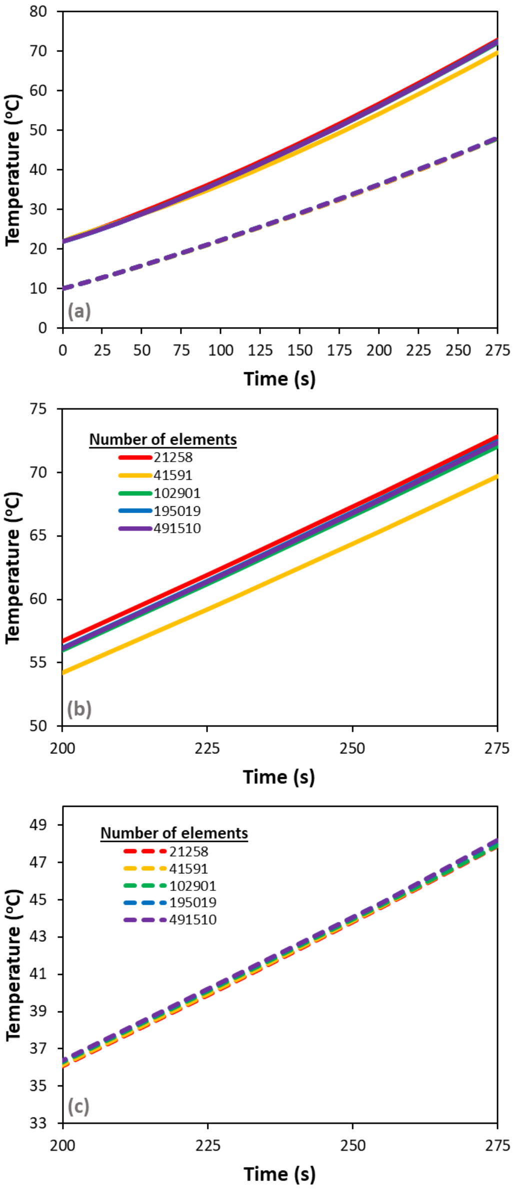

Figure 2. OH model sensitivity of (a) T_1 and T_2 up to 275 s, (b) T_1 between 200-275 s and (c) T_1 between 200-275 s against mesh density.

3.5. Statistical evaluation of sensitivity

Sensitivity analysis is the examination of the relative impact of various input parameters on the final model output, and two methodologies, local and global, are commonly used (Saltelli, 2002). Although local sensitivity analyses are easier and faster to execute, a global sensitivity method supplies more detailed and realistic information about the studied parameters since several input variables in combination are in consideration. So, the global sensitivity analysis was designed using response surface methodology (RSM), and the standardised regression coefficients (*SRC*) were identified using multiple linear regression to be used for parameter ranking. All the statistical analyses, including preliminary studies, RSM and regression for sensitivity measurements, were conducted using R programming language over the RStudio IDE (Version 1.1.383, RStudio Inc., Boston, MA).

3.6. Response surface methodology

RSM was used to design the sensitivity analysis. The independent variables were applied voltage (X_1), brine salt content (X_2), electrical conductivity, thermal conductivity, and specific heat capacity of chicken meat (X_3, X_4, X_5, respectively), convective heat transfer coefficient of air (X_6), and ambient temperature (X_7). Table 2 shows the levels of the independent variables. For the experimental design with 7 independent variables with 3 levels each, the Box-Behnken method was used, and 57 simulations (total number of independent factor combinations) were run, including one simulation as the central point (without replication since no uncertainty of the model predictions is expected for an input combination). The time required ($t_{c,75°C}$) to heat the chicken core temperature (T_1) to 75°C, the minimum temperature of the chicken after 110 s of OH treatment (the time right after the minimum $t_{c,75°C}$ all simulations) ($T_{min,110s}$) and the time required to increase the cold spot temperature of chicken meat to 75°C during OH ($t_{min,75°C}$) were evaluated as output (dependent) variables.

Table 2. Box-Behnken design parameters of sensitivity analysis and their corresponding values.

Independent variables (X_i)	Unit	Minimum value	Nominal value	Maximum value
V	V	140	150	160
c_b	%, w/v	0.20	0.30	0.40
σ_c	$S.m^{-1}$	0.49	0.66	0.83
k_c	$W.(m.°C)^{-1}$	0.34	0.45	0.56
$c_{p,c}$	$kJ.(kg.°C)^{-1}$	2.70	2.80	2.90
U	$W.(m^2.°C)^{-1}$	2	5	8
T_{air}	°C	20	25	30

3.7. Analysis of regression

The sensitivity of complicated models is commonly assessed using regression analysis. It provides the sensitivity ranking based on the regression coefficients (*RC*) (Eq. 9). *RC*s are numerical values that indicate the direction and magnitude of a change in model response to an input. However, due to unit differences and variances in the magnitudes of input parameters, a standardisation step is mostly required (Hamby, 1994). As a result, *SRC*s become a natural sensitivity measure when the input-output data is properly fitted with a linear model (Borgonovo & Plischke, 2016) (Eq. 10).

$$Z = \beta_0 + \sum_{i=1}^{7} \beta_i X_i \qquad (9)$$

$$SRC_i = \beta_i \frac{s_i}{s_Z} \qquad (10)$$

where Z is the dependent variable, β_o is the intercept, β_i is the regression coefficient, and s_i and s_z are the standard deviations of the model inputs and outputs, respectively. The coefficient of determination (R^2) was used to assess the model accuracy.

4. Results and discussion

4.1. Temperature profile and model validation

A good mechanistic model should be able to accommodate real-world changes. The most common and widely recognised method to test a model's validity is to compare the model predictions with experimental data. In the presented study, the temperature history of chicken meat and brine (as a function of time for T_1 and T_2, please see Figure 1) was obtained experimentally and used for validation. The validation results are shown in Figure 3, and a good agreement between model predictions and experimental temperatures was obtained for all studied conditions. Particularly for chicken core temperature, the model performed better compared to the other positions (e.g., in brine). The best result was obtained for the chicken core temperature at 120V-0.2% brine concentration, with the lowest *SEE* of 0.56 (Figure 3a). It was then followed by the temperature predictions for the chicken core at 180V-0.2% chicken, for the brine at 20V-0.4%, and for the chicken core at 120V-0.4% in increasing order of *SEE*, which were 0.79, 1.18, and 1.24, respectively. Although there is an acceptable deviation after 90 s for brine temperature at 180V/0.2% salt concentration of brine (especially at the end of the process) (Figure 3b), the mathematical model performed sufficiently. For chicken core temperature, the *SSE* ranged from 0.56 to 1.46, indicating that the model developed is good enough to be used for further sensitivity analysis.

It is well known that to ensure the microbiological efficiency of heat treatments, special attention should be paid to the cold spot of heated mediums/materials from an engineering and food safety standpoint. Because the cold spot temperature of food material should be chosen as a target (Silva & Gibbs, 2012; Zell et al., 2010). For conventional heat treatment methods, the cold spot is searched for at the geometrical centre of the material (Marra et al., 2009; Zell et al., 2008), implying that the cooking/heating time of the chicken meat should be determined according to the temperature history of the centre. However, as seen in Figures 4 and 5, the cold spot may not occur in the centre of the food for OH, but rather towards the edges, in contrast to traditional methods. Because the electrical conductivity of the liquid medium was lower than that of food for the examined range of salt content in our study, its temperature increased much slower than that of meat which is in agreement with the other studies (Marra et al., 2009; Salengke & Sastry, 2007; Zell et al., 2008).

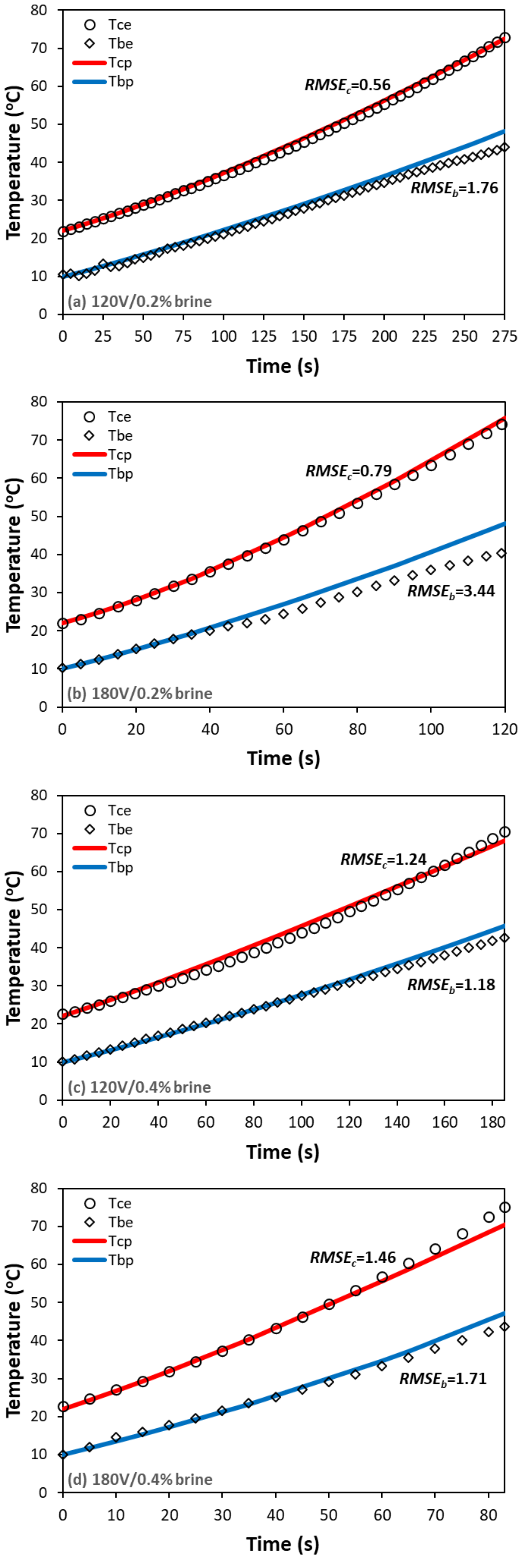

Figure 3. Comparison between predicted and measured temperature profiles for validation (chicken core and brine temperatures (T_1 and T_2 in Figure 1); *b*, *c*, *e* and *p* subscripts are brine, chicken, experimental and predicted, respectively; (a) 120V/0.2% brine, (b) 180V/0.2% brine, (c) 120V/0.4% brine, (d) 180V/0.4% brine).

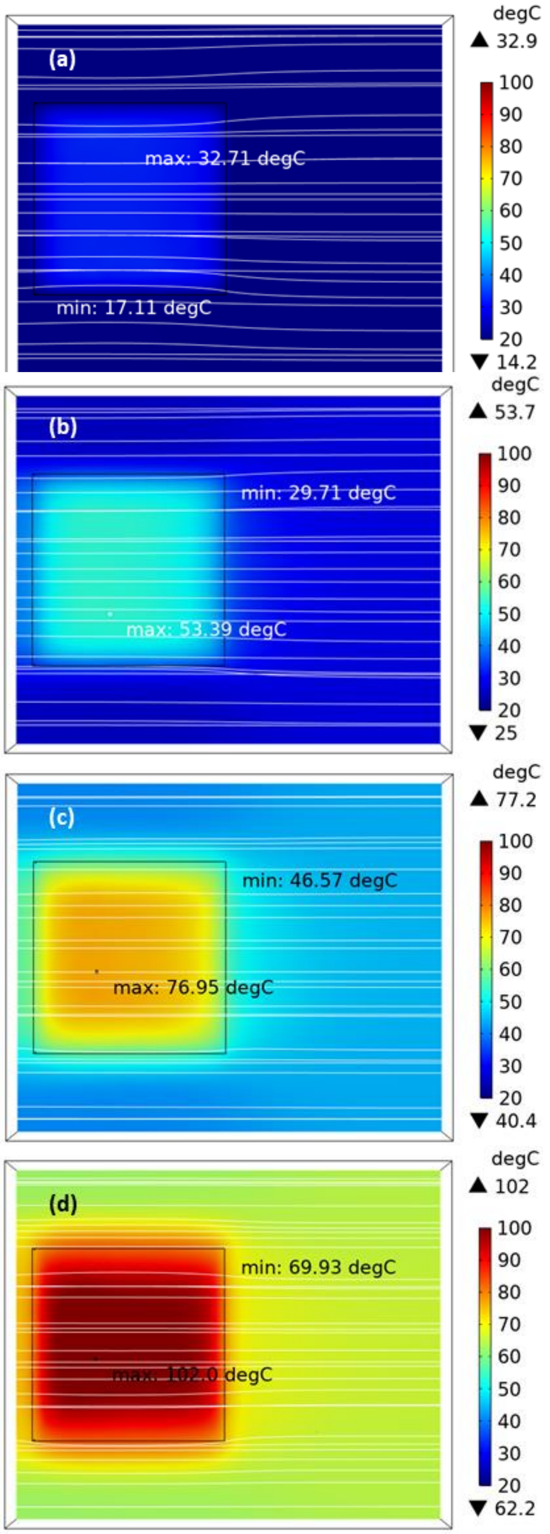

Figure 4. Temperature distribution and electrical field streamlines (A.cm^{-2}, coloured white) in ohmic cell (xz plane) at (a) 30 s, (b) 80 s, (c) 130s and (d) 180 s of heating (V=160V, c_b=0.3%, σ_c=0.665 S.m^{-1}, $c_{p,c}$=2.8 kJ.(kg.°C)$^{-1}$, k_c=0.45 W.(m.°C)$^{-1}$, U=2 W.(m^2.°C)$^{-1}$, T_{air}=20°C).

The amount of electric current passing through the food item changes proportionally to its electrical conductivity (Singh & Heldman, 2014). The electrical conductivity of chicken meat piece (0.49-0.83 s.m^{-1}) in the simulations was higher than brine (ranging between 0.21-0.52, 0.30-0.67, and 0.44-0.91 S.m^{-1}, respectively for 0.2, 0.3, and 0.4% salt concentration and temperatures ranging between 10-40°C). So the electric current primarily passes through the chicken piece, resulting in higher heating rates compared to brine. The electrical field density streamlines and temperature distribution around the chicken meat in Figure 4 can be used to verify that phenomenon, which is known as the "shadow effect" in OH. It is described as temperature heterogeneities in a mixture (especially in unmixed batch systems) caused by interactions between materials with varying electrical conductivities (Goullieux & Pain, 2014). This temperature difference between the chicken and the surrounding brine causes the occurrence of a colder region around the chicken piece (Figures 4 and 5). Despite the movement of the brine in the ohmic cell due to natural convection (Figure 6), the temperature difference along the ohmic chamber maintains its presence in variable degrees under different system conditions (Figure 5).

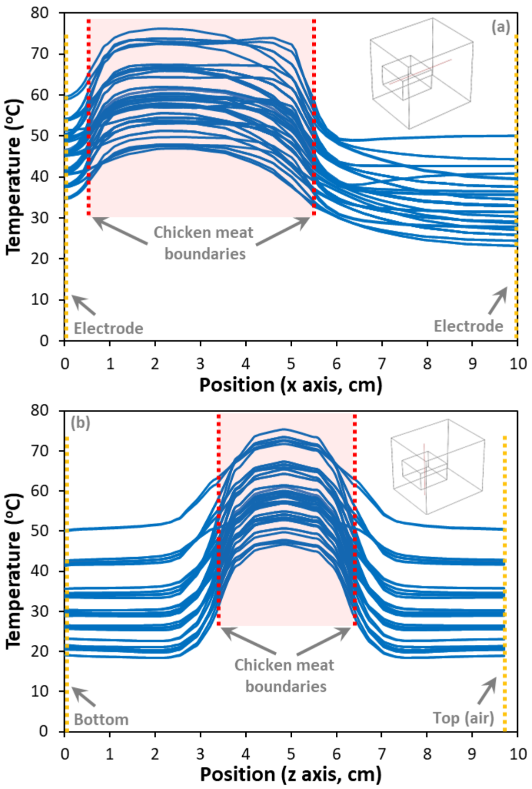

Figure 5. Temperature profiles in brine and chicken sample (a) along the x-axis (parallel to electric current) and (b) along the z-axis (perpendicular to electric current) for all combinations (57 runs RSM design) of independent variables at the end of 110 s of ohmic heating.

4.2. Sensitivity assessment and parameter ranking

As previously stated, the magnitude of *RC*s shows the effect of independent variables on each dependent response, whilst the sign indicates a positive (+) or negative (-) relation between an input parameter and the subsequent response. However, because of the variations in the range of independent variables, it is not appropriate to compare their effects using *RC*s. That is why *SRC*s, represent the expected change of dependent variables (in standardised units of s_i) against the change in each independent variable (in standardised units of each sz) where each unit corresponds to one standard deviation (Siegel et al., 2022), are given in Table 3 to compare and rank the relative effects of studied variables on specified outputs.

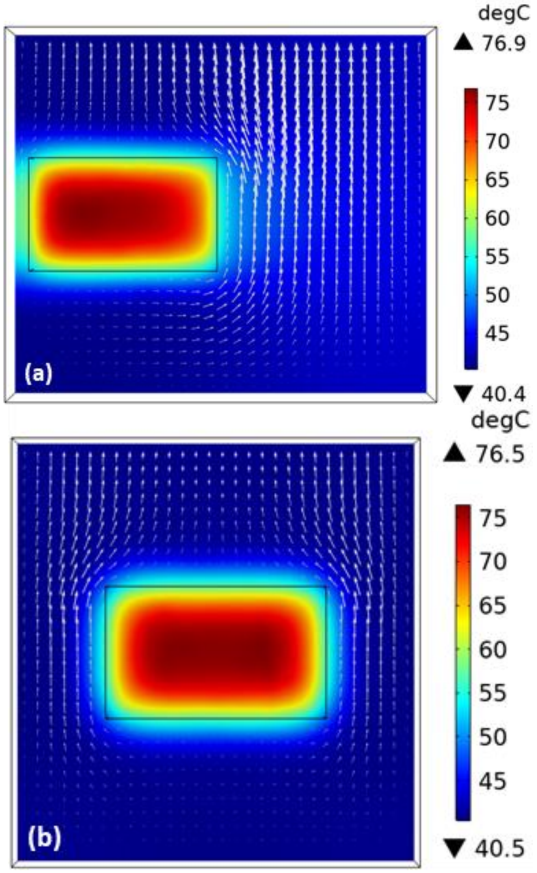

Figure 6. Temperature profile and velocity field (white arrows) in brine and chicken meat for (a) xy plane (parallel to electric current) and (b) yz plane (perpendicular to electric current) at the end of 130 s of ohmic heating (V=160V, c_b=0.3%, σ_c=0.665 S.m^{-1}, $c_{p,c}$=2.8 kJ.(kg.°C)$^{-1}$, k_c=0.45 W.(m.°C)$^{-1}$, U=2 W.(m^2.°C)$^{-1}$, T_{air}=20°C).

The findings show that the most important and statistically significant ($p \leq 0.001$) inputs on $t_{c,75°C}$ are σ_c, c_b, V and $c_{p,c}$ with the decreasing impact order. Only $c_{p,c}$ exhibits a positive correlation with $t_{c,75°C}$, showing that as the specific heat capacity of the chicken meat increases, so does the time necessary to heat the chicken's core temperature to 75°C. Concerning the most effective parameters on $t_{c,75°C}$, they are σ_c, c_b and V, and these factors are all related to the performance of the OH system. Other independent factors, such as chicken thermal conductivity, overall heat transfer coefficient of air, and surrounding air temperature, had no significant impact on $t_{c,75°C}$ ($p > 0.10$). As a result, the electrical properties of the heating material are expected to have a strong influence on heat transfer. The electrical conductivity of chicken meat and applied electrical potential have almost equal impact on $t_{c,75°C}$ with the salt concentration of brine. Because the higher salt concentration increases ion concentrations in solution and electrical conductivity, the efficacy of OH increases.

Table 3. *SRC*s of developed models for evaluation of $t_{c,75°C}$, $T_{min,110s}$, $t_{min,75°C}$ sensitivity.

	$t_{c,75°C}$		$T_{min,110s}$		$t_{min,75°C}$	
Rank	R^2=0.97		R^2=0.97		R^2=0.92	
1	σ_c^{****}	-0.60	c_b^{****}	+0.88	c_b^{****}	-0.74
2	c_b^{****}	-0.55	V^{****}	+0.43	V^{****}	-0.64
3	V^{****}	-0.54	σ_c^{****}	+0.12	σ_c^{****}	-0.32
4	$c_{p,c}^{****}$	+0.12	k_c^{ns}	+0.03	$c_{p,c}^{ns}$	+0.02
5	k_c^{ns}	+0.02	$c_{p,c}^{ns}$	-0.01	k_c^{ns}	-0.02
6	U^{ns}	+0.00	T_{air}^{ns}	+0.00	U^{ns}	+0.00
7	T_{air}^{ns}	+0.00	U^{ns}	+0.00	T_{air}^{ns}	+0.00

**** $p \leq 0.001$, *** $p \leq 0.01$, $^{**}p \leq 0.05$, * $p \leq 0.10$, ^{ns} not significant.

The significant input parameters and their rank order are the same for Tmin,110s and tmin,75°C. cp,c is not a significant parameter for Tmin,110s and tmin,75°C, as well as kc, U and Tair (p>0.10). As a result, any parameter related to the air does not have an important impact on OH at the studied range. However, the parameters related to the electrical features are still important. Because the cold spot of the material does not always appear at the core of the material during OH. But according to our findings, it should be looked for in the regions close to the edges, more specifically at the corners. Because when the electrical conductivity of the samples is greater than the surrounding medium, which is brine in our study, electric current tends to move and pass through the meat more than the brine. This causes a faster temperature increase in the chicken. However, since the brine temperature is still lower and there is ongoing heat transfer between the meat surface and the brine, chicken surfaces have lower temperatures than the chicken core.

Regarding the signs of the statistically significant ($p \leq 0.001$) SRCs, they are all positive for $T_{min,110s}$ and negative for $t_{min,75°C}$. This means that as the magnitude of these input variables increases, the minimum temperature of the chicken after 110 s ($T_{min,110s}$, the minimum temperature for chicken meat after 110 s of OH). On the other hand, the time required ($t_{min,75°C}$) to increase the cold spot temperature of chicken meat to 75°C during OH decreases if the applied voltage level and brine electrical properties are higher.

5. Conclusion

In the present study, a mechanistic model for ohmic heating of chicken in the salt solution was developed, and heat transfer was coupled with momentum and electric current. The model predictions were validated against the experimental results at the different voltage (120 and 180V) and brine salt concentration (0.2

and 0.4%, w/v) levels. According to the model predictions, extra attention should be paid to the interface between meat and the brine during ohmic heating where cold spots developed in contrast to standard heating methods.

According to the sensitivity analysis, ohmic heating-related variables (electrical conductivity of chicken, applied voltage, and brine concentration, so its conductivity) were the most important variables affecting chicken core and surface temperatures and their heating rates. Moreover, the specific heat capacity of chicken meat was also important for the chicken core heating rate. Properties related to the surrounding air (overall heat transfer coefficient and temperature) had no significant effect in any case. This indicates that conduction and convection have limited effect during ohmic heating of chicken meat, and it is mainly dominated by Joule heating.

In the current study, ohmic heating was only considered for a single chicken meat piece in salt solution. However, the existence of multiple pieces in the solution, variations in the piece's shape and size of the ohmic heater, the addition of other food particles such as vegetables, beans, etc., and the use of other formulations like sauces instead of a simple salt solution may cause changes in the electrical field distribution and resulting heating patterns. As a result, future research into more complex cooking media may be beneficial.

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