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Predicting optimal flipping conditions during burger pan cooking with a numerical model

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ABSTRACT

This study analyzes the influence of the number of flips on the cooking performance of burgers by heating contact using results from both experimental test and computational simulation. The analysis employs a previously developed multiphysics model that accounts for heat and moisture transfer as well as product deformation. The turning process was simulated considering two heat sources representing the cooking pan that are alternately activated and deactivated to heat either surface of the product. Furthermore, a set of experiments were carried out to validate the model outcomes recording data of temperature at the center and upper surface of the burger, weight loss, and shrinkage at different number of flips. When performing only one flip, great moisture expelling was observed at the top surface, while multiple flips facilitates moisture retention, reducing cooking losses and shrinkage since it allows for a reduction in cooking time to reach the desired temperature. However, more than five flips do not significantly improve these effects.

1. Introduction

The tenderness and juiciness of cooked meat primarily depend on moisture migration during cooking, which is in turn related to the structural changes that occur in this process (Tornberg, 2005). Most of the water contained in meat is bulk water, retained by capillary forces that are much greater than gravitational force, resulting in minimal drip loss in raw whole meat (Tornberg, 2013). When meat is cooked, there is a decrease in its water retention capacity due to the denaturation of proteins and the subsequent contraction of the connective tissue network.

The transport of water due to the contraction pressure resulting from the heating of the protein matrix has been described using the Flory-Rehner theory of rubber elasticity (van der Sman, 2007; Ahmad et al., 2015; Chapwanya and Misra, 2015; Nelson et al., 2020). This theory describes convective water transport through Darcy's law, considering that the pressure is due to the elasticity of the solid matrix of the porous material and results from the sum of two components: osmotic pressure and pressure due to the elastic deformation of the cross-linked protein network. When the temperature increases, both terms become unbalanced, resulting in the expelling of excess fluid from the meat (Mathijssen et al., 2023). Therefore, the variation in water content in the meat is directly proportional to the difference between the instantaneous water content and the water holding capacity. However, although most meat cooking models take into account the contraction of the protein network to explain the movement of moisture during cooking, they do not explicitly consider the shrinkage of the solid matrix, with the exceptions of some studies (Zorrilla and Singh, 2003; Dhall and Datta, 2011; Moya et al., 2021; Hernández-Alhambra et al., 2024).

The coupling of these moisture transport mechanisms with heat transfer during the cooking of burgers has allowed the development of numerical models capable of evaluating the influence of pan or grill temperature on: the temperature distribution inside meat burgers (Dagerskog, 1979; Pan et al., 2000; Zorrilla and Singh, 2003), the time required to reach the desired center temperature of the product (Oroszvári et al., 2005), the hardness or chewiness of the burgers (Erdogdu et al., 2005) and the cooking losses (Hernández-Alhambra et al., 2024).

Typically, these models have been implemented and validated in double-sided pan fryers (Oroszvári et al., 2005) or double-sided clamshell grills (Pan et al., 2000; Zorrilla and Singh, 2003; Erdogdu et al., 2005), or exceptionally in a single-faced grill without considering

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product flipping (Rocca-Poliméni et al., 2019; Hernández-Alhambra et al., 2024). However, home-cooked burger preparations often involve contact with a hot surface on one side of the burger, requiring it to be flipped. The influence of the timing and frequency of flipping on moisture loss and, therefore, on the juiciness of the product at the end of the cooking has not been considered in cooking models, except for a few exceptions, such as the work by Thiffeault (2022), which addresses it exclusively from the perspective of heat transfer; the model by Moya et al. (2021), which predicts the flipping time to achieve a similar beef color profile on both sides; or those of Ou and Mittal (2007) and Dalvi-Isfahan (2023), in which the inactivation of pathogenic microorganisms during single-sided pan frying of frozen burgers with flipping are described, and the influence of the flipping interval on microbial inactivation is assessed.

Cooking the burger by only one side heating will primarily result in product shrinkage, especially at the bottom. Therefore, the situation will be different from that described by Oroszvári et al. (2006) in simultaneous double-side heating, in which the stress created by the shrinkage at the bottom and at the top generates a pressure gradient that causes water to flow towards the center of the burger and then a parallel flow along the surface of the fryer towards the circumference of the burger. Heat transfer will also be different since the layers near the surface quickly reach the boiling point of water, but the core remains at lower temperature. When flipped, the temperature of the freshly cooked side decreases as heat is conducted from this area towards the center, although there are also heat losses due to water evaporation on the surface and convection towards the surrounding air. The overall effect is that the surface cools, and the center heats up, resulting in temperature uniformity. Additionally, repeated flips accelerate the cooking process by reducing the excess of heat from the side in contact with the hot surface and preventing excessive cooling of the upper side. However, these observations, that some expert chefs have pointed out (McGee, 2004; Myhrvold et al., 2011), have not been incorporated into meat cooking models. These models could address the question of how many flips and at what intervals a burger with a given thickness should be turned when cooked at a certain pan temperature to minimize cooking time while keeping it as tender as possible.

Taking these considerations into account, a combined computational and experimental strategy has been used in this work with the aim of: (i) assessing the influence of the number and timing of flips on the evolution of temperature, moisture loss and product shrinkage. (ii) establishing the optimal flipping conditions to minimize cooking time, burger moisture loss and toughness. To achieve these goals, a numerical model (Hernández-Alhambra et al., 2024) that incorporates moisture transport, heat transfer, and deformation in a porous medium has been adjusted to simulate flips. Computational results were validated by comparing them with experimental data obtained using a domestic induction hob equipped with sensors able to monitor temperature and weight loss. After validation, the model was able to predict the necessary cooking flips and times to reach a minimum temperature at the center of the product of 160 °F (71.1 °C). Subsequently, the texture parameters, moisture content, cooking losses, and shrinkage of the burgers cooked under these conditions were compared.

2. Materials and methods

2.1. Burger preparation

Burgers were crafted from the center section of beef loin (*Longissimus dorsi* muscle). The meat was passed through a 3 mm grinder plate. A manual burger press with a 100 mm diameter was employed to shape the meat into cylindrical pieces, each weighing 180 g and measuring 20 mm in thickness. The burgers were individually kept refrigerated at 4 °C in LDPE zip bags for less than 48 h, and then tempered at 20 °C in an isothermal chamber (MIR-153 Incubator, Sanyo, Osaka, Japan) before cooking.

2.2. Cooking procedure

Burgers were placed in a 210 mm diameter multilayer pan (steel-aluminum-steel) coated with a Teflon platinum layer and individually cooked at 215 °C using an induction hob equipped with an automatic temperature control system (frying sensor BOSCH PXY675DW4E/01 model, BSH, Munich, Germany). The burgers were added to the pan when the pan temperature measured by a surface K type RS PRO thermocouple (RS, London, UK), located 30 mm from the edge of the pan, indicated that the goal temperature was reached with a deviation of ±3 °C. The central bottom pan temperature was also measured by a K type 1.5 mm-diameter thermocouple located in a hole made for this purpose. The burgers were cooked without adding oil and were not pressed on the top surface during cooking. Figs. 1a and 1d show the experimental setup. In order to fully understand the different mechanisms involved and to validate the model, three scenarios have been analyzed:

1. Tests conducted with only 1 flip at two different time instants: 340 s and 453 s, corresponding with 1/2 and 2/3 of the total cooking time (680 s), respectively.
2. Tests applying 3, 5, and 7 flips at regular intervals until 680 s.
3. Tests performed with 1, 3, 5 and 7 flips to reach 71.1 °C at the center point of the burger.

The evolution of the temperature in the center of the burgers was measured during the tests by one penetration *T* type, 1.5 mm-diameter thermocouple connected to a data logger (TC-08 Series, Farnell Components, Barcelona, Spain). The average temperature on the top surface of the burgers was determined by capturing images evenly using an infrared thermal camera (875-2 model, Testo, Lenzkirch, Germany). The power supplied by the induction hob control system and the measured temperatures were monitored with LabTech v6.0.1.5 software (ConnectWise, Tampa, Florida, USA). The weight of the burgers was measured during the cooking with a balance (DS30K0.1 L, Kern & Sohn, Balinger-Frommern, Germany) positioned beneath the induction hob. The weight data, taken with a precision of 0.1 g, were monitored every 5 s using the KERNBC4 software.

2.3. Cooking loss and shrinkage

Cooking loss has been considered as the percentage of fluids lost during cooking (which may contain water, protein, fat, and minerals). It has been calculated by the difference in weight between the raw burger and the cooked burger, immediately after removing it from the pan. It has been expressed as a percentage relative to the raw weight. The shrinkage of the burgers was determined in two ways: (a) During cooking, the percentage reduction in the surface area of the upper side was quantified by digitally analyzing images taken with a mobile phone placed parallel to the pan. These images were subsequently processed using the publicly available ImageJ software (Fig. 1b). (b) Shrinkage was also measured by determining the percentage reduction in the volume of the burgers after cooking and cooling at room temperature for 30 min (selected to achieve constant weight). An HF-2000 electronic balance (A&D Company, Tokio, Japan) and the principle of Archimedes (Yan et al., 2008) were used for this purpose (Fig. 1c). A perforated metal tray was suspended from the balance, and its weight was measured in the air and after being immersed in the solvent (water). The burger was placed on the tray, and the combined weight was measured in the air and in the solvent. Immersing the dish in the solvent was done consistently to the same level in all measurements. These measurements were conducted with the raw burger and after cooking and cooling it. The volume of the burgers was calculated using the following expression:

$$V = \frac{(W_{air} - w_{air}) - (W_s - w_s)}{\rho_s} \tag{1}$$

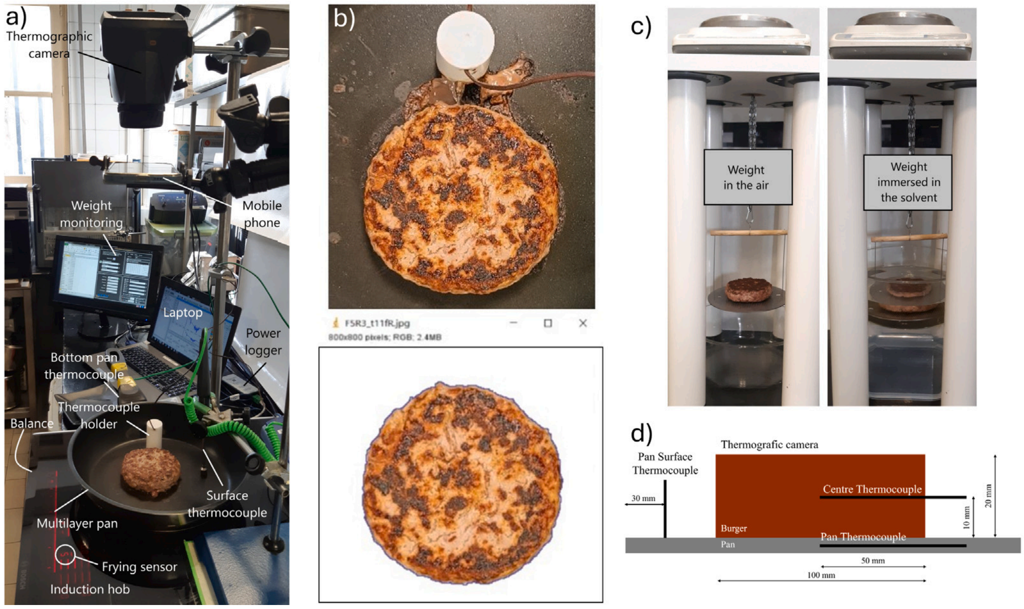


Fig. 1. (a) Experimental setup for temperature, weight loss and shrinkage measurement during the cooking process. (b) Digital image analysis for measuring shrinkage of the upper surface area of the burger. (c) Experimental system for measuring changes in the volume of the burger. (d) Schematic representation of the different thermocouples' positions.

where W_{air} [kg] and W_s [kg] are the weights of the sample in air and in the solvent respectively, while w_{air} [kg] and w_s [kg] are the weights of the dish in air and in the solvent, respectively and ρ_s [kg/m^3] is the density of the solvent. As a result, $(W_{air} - w_{air}) - (W_s - w_s)$ [N], is the buoyant force.

2.4. Moisture content

Four samples were taken from the center of each burger to analyze moisture using a cylindrical punch (20 mm in diameter). Each of these samples was further divided into three pieces: a lower one (3 mm in height), an upper one (3 mm in height), and a central one. The upper zone has been designated as the one that had the first contact with the pan. Three burgers were used for the raw state and for each cooking condition. The moisture content of the meat sections (12 replicates) was analyzed according to AOAC Method 950.46 (AOAC, 2002).

2.5. Texture

The impact of cooking conditions on the textural characteristics of the burgers was determined using a Texture Analyzer TA-XT2i Plus (Stable Micro System, Godalming, England). Texture profile analysis (TPA) were carried on for 25 mm × 25 mm × 20 mm cuboids extracted from the burgers after conditioning them to room temperature. The double-compression tests were performed using a cylindrical flat-probe (50 mm diameter), and a 30 kg load cell acting at 1 mm s^{-1} up to 50% compression with a trigger force of 0.049 N. Twenty replicates were analyzed for each condition. The graph of force (N) versus time (s) was automatically recorded and the hardness (maximum force during the first cycle of compression), springiness (distance of height during second compression by the first compression distance), cohesiveness (ratio between the area under the second curve to that of the first curve), and chewiness (the product of hardness × cohesiveness × springiness) parameters of each sample was calculated by the instrument software. Shear tests were also carried out using a Warner-Blatzler blade acting at 1 mm s^{-1} up to a distance of 35 mm with a trigger force of 0.049 N. The force of the first peak (force at which the blade begins penetration), the maximum shear force and work of shearing (total area under the curve) were determined from the force-time plot.

2.6. Statistical analysis

One-way ANOVA with post-hoc Tukey HSD (Honestly Significant Difference) was used to interpret the differences between texture parameters. The null hypothesis is that there is no significant difference between these parameters regardless of the cooking conditions. Statistical analysis was performed using the Statistical Package for Social Sciences v.26 (SPSS Inc, Chicago, IL, USA). Differences were considered significant at $p < 0.05$.

3. Finite element model

The process of pan-frying burgers can be considered as a flow and mass transport problem in a deforming solid matrix during thermal processing. In this study, a 2D axisymmetric model incorporating the fundamental equations to account for these phenomena was implemented in the COMSOL Multiphysics 5.3a software. Following Hernández-Alhambra et al. (2024) the three group of equations solved are:

Mass transfer. The equation governing water liquid transport inside the solid is:

$$\frac{\partial c_w}{\partial t} + \nabla \cdot \boldsymbol{n}_w = 0 \tag{2}$$

where c_w [mol/m^3] is the water concentration and the flux $\boldsymbol{n}_w = \boldsymbol{n}_{w,G} - D_{wT}\nabla T$ [mol/(m^2 s)] defined as the flux due to the temperature gradient, being D_{wT} [kg/(m s K)] the temperature diffusivity, and the flux with respect to a stationary observer:

$$\boldsymbol{n}_{w,G} = -D_w \nabla c_w + c_w \cdot \vec{v}_{s,G} \tag{3}$$

D_w [m^2/s] is the diffusivity due to the water concentration gradient and $\vec{v}_{s,G}$ [m/s] is the velocity of the solid due to matrix deformation obtained from the deforming finite element mesh.

Energy conservation. Assuming thermal equilibrium between the solid matrix and the water, the energy balance equation can be written as:

$$\rho_{eff} C_{p,eff} \frac{\partial T}{\partial t} + \boldsymbol{n}_{w,G} \cdot \nabla (C_{p,w} T) = \nabla \cdot \left(k_{eff} \nabla T\right) \tag{4}$$

The burger effective density ρ_{eff} [kg/m^3], specific heat $C_{p,eff}$ [kJ/(kg K)], water specific heat $C_{p,w}$ [kJ/(kg K)], and thermal conductivity

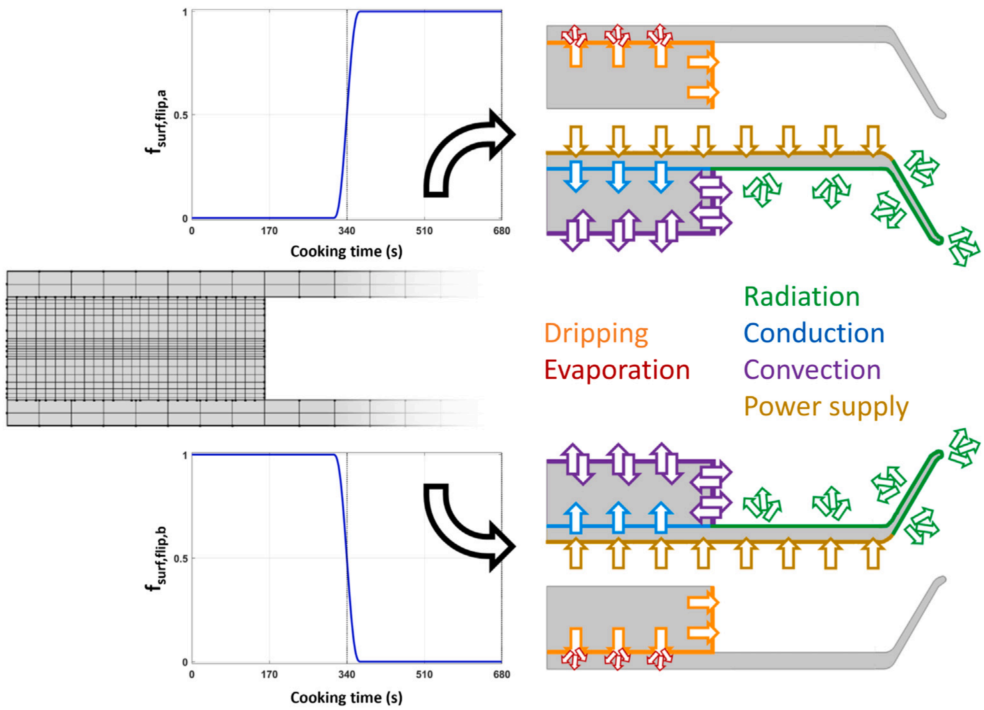


Fig. 2. Mass and heat transfer boundary conditions applied in the contour of the burger and the pan governed by the two step functions to simulate the flipping process. The diagrams have been duplicated to arrange those related to heat and mass transfer boundary conditions.

k_{eff} [W/(m K)], are obtained as a function of temperature (T [K]) and composition (Hernández-Alhambra et al., 2024).

Conservation of linear momentum. Neglecting body forces and inertia effects, the equation simplifies to the quasi-static equilibrium:

$$\nabla \sigma = 0 \tag{5}$$

in which, considering a saturated medium, the symmetric Cauchy stress tensor can be expressed as the sum of the partial solid stress and the fluid swelling pressure.

In the model, the geometry of both the multilayered pan with a diameter of 210 mm and 5 mm thickness and the product with a diameter of 100 mm and 20 mm thickness was considered. The different domains were meshed with rectangular elements using quadratic approximation for mass transfer, temperature and deformation. A mesh sensitivity analysis was carried out to establish the optimum mesh size which showed the stabilization of the solution. The number of nodes and elements for the selected model mesh were 746 and 658, respectively (see Fig. 2).

3.1. Flipping process

To reproduce the process of turning the burger over, two pans were modeled following the work of Moya et al. (2021) when neglecting the action of gravity in water diffusion. Moreover, in terms of solid mechanics, deformation along the burger thickness is also not significant (Hernández-Alhambra et al., 2024) and the burger can be assumed to be confined between the two pan surfaces. The effect of the lower and upper pan domains represented in Fig. 2 on the cooking process is activated or deactivated by multiplying the related boundary conditions with a specific function that can be defined as:

$$f_{surf,flip} = \begin{cases} 1 & \text{for } t_{act} \le (t \mod 2\tau) < \tau \\ 0 & \text{for } \tau \le (t \mod 2\tau) < 2\tau \end{cases} \tag{6}$$

Here, t_{act} is the time instant when the boundary condition activates, $t \mod 2\tau$ gives the position within the current period (2τ), being mod the mathematical operation that finds the remainder when one number is divided by another, and 2τ the period or time of cooking the two burger sides. An smoothed version of this function is provided by the software, allowing up to two continuum derivatives. The two step functions shown in Fig. 2 govern the boundary conditions when the burger is subjected to one flip.

3.2. Initial and boundary conditions

Mass transfer. Uniform water concentration is considered at the beginning of the simulation c_{w0} = 44085 mol/m^3. The boundary condition for the liquid water equation consists of evaporation and drip fluxes. The magnitude of the evaporation flux is given by the mass transfer coefficient h_m [m/s] multiplied by the vapor density difference between the surface $\rho_{v,surf}$ [kg/m^3] and the boundary $\rho_{v,amb}$ [kg/m^3].

$$n_{w,surf,e} = h_m \left(\rho_{v,surf} - \rho_{v,amb}\right) f_{surf,flip} \tag{7}$$

Dripping occurs when surface moisture concentration is larger than the water holding capacity. Therefore, the drip loss is the total moisture flux reaching the surface minus the evaporation flux (Dhall and Datta, 2011):

$$n_{w,surf,d} = \left(\boldsymbol{n}_w \cdot \boldsymbol{N} - n_{w,surf,e}\right) f_{surf,flip} \tag{8}$$

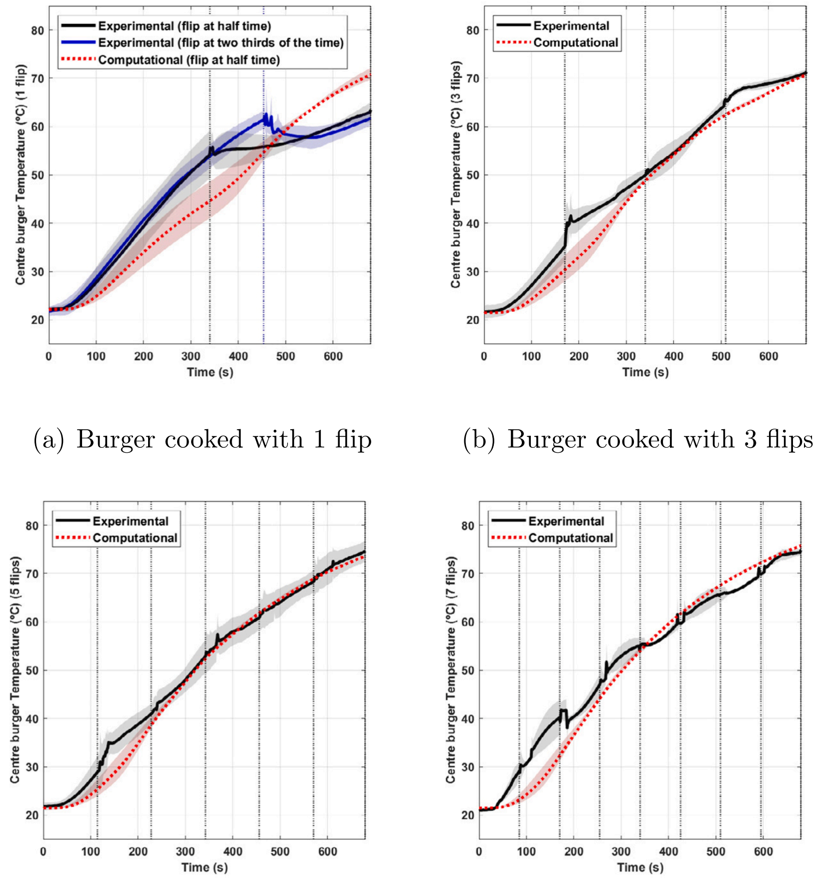
where $\boldsymbol{N}$ is a unit normal vector to the surface.

Energy equation. An initial temperature condition of T^o_{pan} = 25 °C was considered on the pan and a uniform temperature for the burger of 23.4 °C was set to match the real initial temperature of the samples. The heat transfer between the two surfaces in contact can be expressed as:

$$q_{surf,cont} = H_c \left(T_{pan} - T_{surf}\right) f_{surf,flip} \tag{9}$$

To simulate the experimental procedure, a power control was implemented in the model in order to regulate the heat power required to increase the temperature of the pan (Hernández-Alhambra et al., 2024). The heat flux applied at the bottom surface of the pan is:

$$q_{surf,ind} = \begin{cases} \frac{\kappa}{A}(T^o_{pan} - T^*_{pan}) f_{surf,flip} & \text{if} \quad (T^o_{pan} - T^*_{pan}) < W_{max}/\kappa \\ (W_{max}/A) f_{surf,flip} & if \quad (T^o_{pan} - T^*_{pan}) \ge W_{max}/\kappa \end{cases} \tag{10}$$



(a) Burger cooked with 1 flip (b) Burger cooked with 3 flips

(c) Burger cooked with 5 flips (d) Burger cooked with 7 flips

Fig. 3. Central temperature evolution for different number of flips: (a) one, (b) three, (c) five, and (d) seven flips. The vertical lines indicate the flipping times.

where κ = 84 W/K is a control parameter, A is the pan surface [m^2], T^*_{pan} is the goal temperature and W_{max} = 2200 W is the maximum induction hob power. The cooking process starts when the pan has reached the goal temperature T^*_{pan} = 215 °C as in the experiment, so the first 175 seconds of the simulation were used to heat the pan up to this temperature. Henceforth, computational results will be displayed omitting this time period.

Since the burger is assumed to be water-saturated throughout the cooking process (with no gas phase present), evaporation only occurs at the boundary in contact with the pan (Fig. 2). The heat flux representing the energy absorbed by the evaporating water is:

$$q_{surf,evap} = \sigma_{evap}\, \bar{\rho}_w\, L_{evap}\, e\, f_v(T_{surf})\, f_{surf,flip} \tag{11}$$

where $\sigma_{evap} = 1.604 \cdot 10^{-3}$ 1/s is the evaporation rate constant, $L_{evap} = 2.26{\cdot}10^6$ J/kg is the water latent heat of vaporization, $e = 1{\cdot}10^{-3}$ m is the assumed thickness of the liquid water layer and $f_v = \frac{1}{1+e^{0.107(-T_{surf}+121)}}$ is a sigmoid function (Hernández-Alhambra et al., 2024).

The convective heat flux expressed as:

$$q_{surf,conv} = h(T_{amb} - T_{surf})\, f_{surf,flip} \tag{12}$$

considers a surrounding air temperature T_{amb} = 25 ^{o}C and a convection coefficient h = 5 W/(m^2 K).

Conservation of linear momentum. As previously mentioned, since deformation along burger thickness is neglected, normal displacements at its top and bottom surfaces are constrained throughout the simulation:

$$\boldsymbol{u} \cdot \boldsymbol{N} = 0 \tag{13}$$

Moreover, displacements perpendicular to the axisymmetric axis are also impeded.

4. Results and discussion

4.1. Temperature, weight loss and shrinkage evolution

Fig. 3 represents the temperature evolution measured with the thermocouple initially placed at the geometric center of the burger, considering the different experimental cooking scenarios. Due to the shrinkage of the burger, there will be moments at which this thermocouple will be displaced from the point of minimum temperature. However, since the thickness change is less than 1.5 mm (experimentally determined with a caliper), this effect will not be significant. At the turn over instant for the samples only flipped once (Fig. 3a), the temperature evolution exhibit a slowdown effect (for samples flipped at 340 s) and even a slight decrease (for samples flipped at 453 s). At the end of the cooking process, practically the same temperature was reached regardless of the moment when the flip was performed (63.5 ± 1.3 °C for samples flipped at 340 s and 61.7 ± 1.6 °C for samples flipped at 453 s).

From these results, it can be inferred that the evolution of the core temperature changes minimally with more than one turn as was also found by Thiffeault (2022). The deceleration in temperature rise after the first turn for the samples flipped only once could be attributed to the moisture dynamics within the product. As the cooking progressed without turning the product, liquid water in the upper surface became visually apparent, as depicted in Fig. 4. After flipping, this water

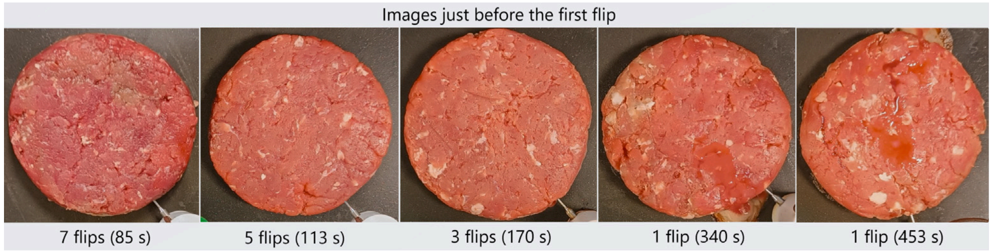


Fig. 4. Movement of water towards the upper surface of the burger.

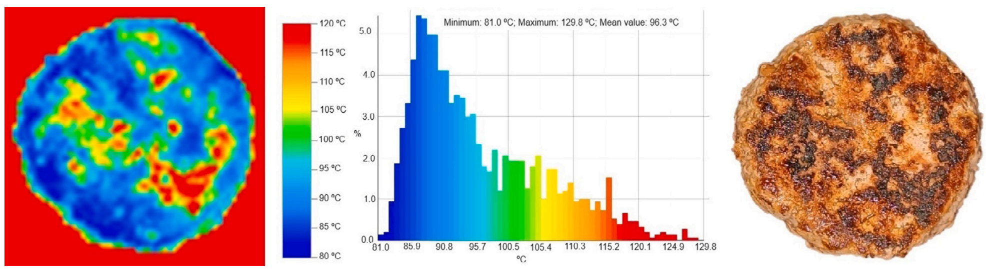


Fig. 5. Thermographic image and histogram of the burger region showing the existence of nearly a 50 °C temperature difference between points on the upper surface of the burger (illustrative example after the fifth and final flip at $t = 567$ s).

evaporates upon contact with the hot pan, consuming a significant amount of heat. Consequently, the heating rate of the burger is reduced, so that at the end of the cooking process (680 s), the center of the patty does not reach 71.1 °C. This temperature is considered the minimum for ground meats to enhance food safety (USDA, 2016).

When analyzing the temperature using the infrared thermal camera just after the turn over, as can be seen in Fig. 5, a non uniform temperature distribution was found at the top surface of the samples. This is a clear indication that the evolution of the contact between the pan and the burger is not entirely perfect.

In Fig. 6 the evolution of the mean, maximum and minimum experimental temperatures are shown. Frequently flipping the burger conducts to lower temperature differences between both sides, leading to greater temperature uniformity. These findings align with the results of earlier studies, which concluded that a more even temperature distribution by increasing the number of flips results in a reduction in the time required to achieve a $12 - log$ reduction in the *Salmonella* serotypes populations at the center point of the burger (Dalvi-Isfahan, 2023), and in an increase in the cooked fraction for a given cooking time (Thiffeault, 2022).

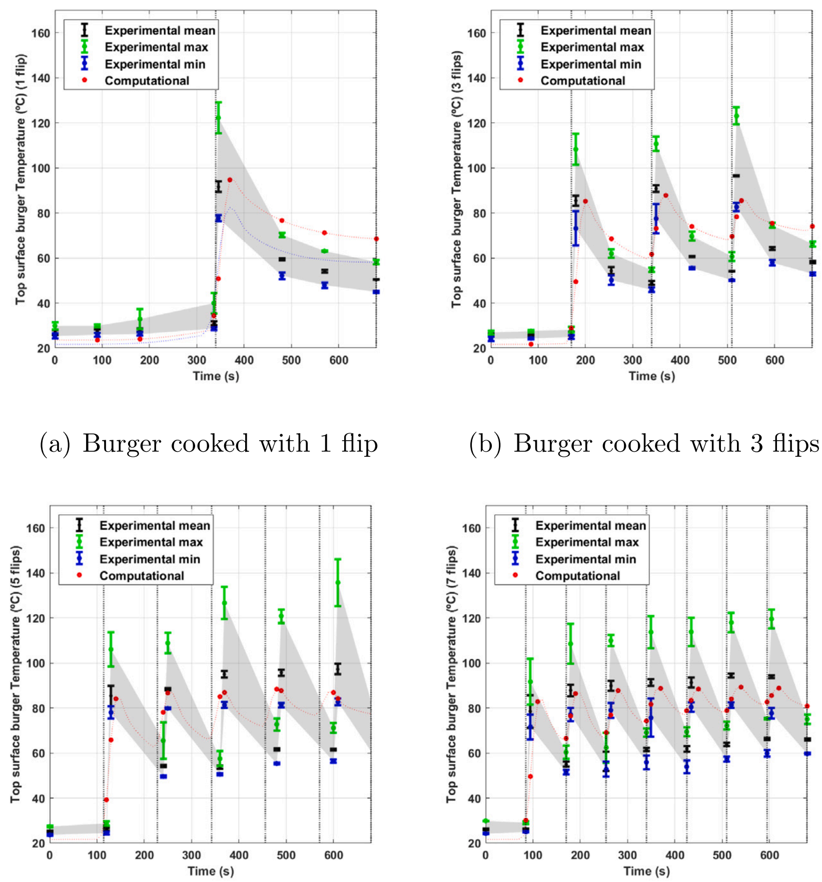
Analyzing the weight loss evolution, a single flip exhibited a clear increase in the slope (Fig. 7a) possibly associated with the evaporation of water displaced towards the upper surface upon contact with the pan. Consequently, the weight loss at the end of the cooking process was: $16.30 \pm 1.49\%$ for one flip at 340 s and $18.79 \pm 1.12\%$ for one flip at 453 s. The change in the rate of weight loss after flipping was not found in a previous study that modeled double-sided pan cooking of 19 mm thick steaks (Moya et al., 2021). This may be due to the doneness levels being very rare, rare, and done, corresponding to core temperatures of 30, 44, and 57 °C, respectively, which implied shorter flipping times than those in this study.

Keeping a cooking time of 680 s, if the number of flips was increased (Figs. 7b, 7c and 7d), the weight loss followed a linear trend over time with final values of $17.44 \pm 1.21\%$ for 3 flips, $18.55 \pm 1.45\%$ for 5 flips, and $19.35 \pm 0.49\%$ for 7 flips. The fact that the weight loss increases with the number of flips is consistent with the greater uniformity in temperature inside the product when it is flipped repeatedly, and is in line with the findings of Dalvi-Isfahan (2023). This is due to the heat transfer towards the interior by the upper surface that has just been in contact with the pan.

During the cooking process a visually perceptible reduction in size of the burgers is observed (Fig. 8). The evolution of the burger shrinkage, calculated from the area of the upper surface, is shown in Fig. 9.

At the end of the cooking, the surface retraction was: $21.74 \pm 1.72\%$ and $23.53 \pm 1.66\%$ for one flip at $1/2$ and $2/3$ of the total cooking time, respectively. The shrinkage calculated as a change in volume also with only one flip is $24.35 \pm 1.05\%$. The volume reduction for one flip at $2/3$ of the total cooking time was $27.07 \pm 1.17\%$, a significantly higher value than that obtained when flipping earlier, in accordance with the results obtained for weight loss. This is attributed to the previously mentioned phenomenon of increased meat juice emergence on the upper surface of the burger before flipping. The shrinkage calculated as volume change is greater than that determined from the upper area of the burger, as the values encompass the additional retraction that burgers experience during cooling after cooking. The shrinkage shows higher values than moisture loss, indicating that not all the retraction could be considered as a function of moisture content (Barbera and Tassone, 2006; Dhall and Datta, 2011; Hernández-Alhambra et al., 2024). Furthermore, its evolution does not follow the linear trend of moisture loss since the rate of shrinkage slows down towards the end of the cooking process, consistent with the findings of Pan and Singh (2001), who reported that the rate of volume decrease reduces when the temperature exceeds 70 °C once protein denaturation has already taken place.

At the end of the cooking, the surface retraction was: $23.04 \pm 0.77\%$, $25.22 \pm 3.12\%$, and $24.25 \pm 1.11\%$ for 3, 5 and 7 flips, respectively; finding no significant differences between cooking conditions ($p > 0.05$). These data represent a reduction in diameter (assuming that the circular shape has not been lost) between 13.03% and 15.23 %. These values are in line with the studies of Oroszvári et al. (2006), Zorrilla and Singh (2003), where the diameter shrinkage at the end of cooking was approximately 12% for frozen meat burgers cooked in a double-sided pan fryer at 163–177 °C until the core temperature reached 72 °C. Some authors use thickness as another parameter to quantify the changes in the dimensions of burgers (Dhall and Datta, 2011; Pan and Singh, 2001). However, in this work, it was not used due to the difficulty of quantifying it accurately because the changes it undergoes



(a) Burger cooked with 1 flip (b) Burger cooked with 3 flips

(c) Burger cooked with 5 flips (d) Burger cooked with 7 flips

Fig. 6. Evolution of temperature in the top surface for different number of flips: (a) one, (b) three, (c) five, and (d) seven flips. The vertical lines indicate flipping times.

Table 1
Moisture content, texture parameters, weight and cooking losses, and shrinkage (as volume change) of burgers cooked with different number of flips until the final core temperature was 71.1 °C.

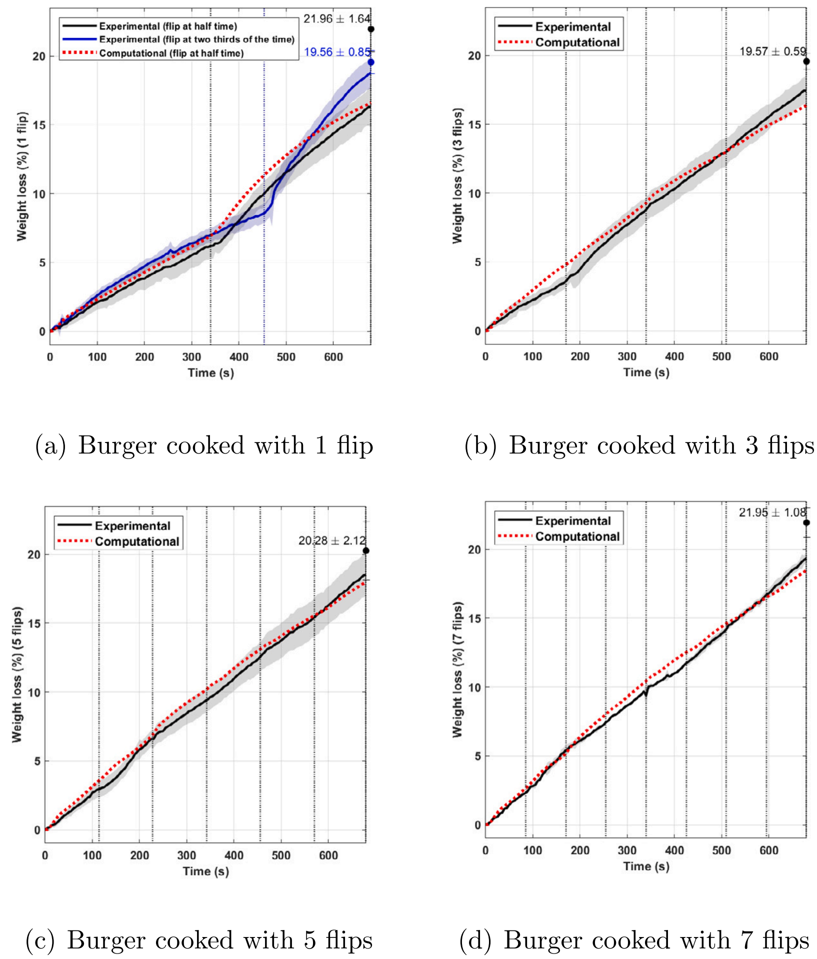
Parameters		Cooking conditions			
		1 flip - 800 s	3 flips - 680 s	5 flips - 603 s	7 flips - 603 s
Moisture content (%)	Upper region	61.42 ± 1.76^{a}	64.85 ± 1.30^{b}	64.18 ± 1.55^{b}	64.82 ± 1.12^{b}
	Central region	68.32 ± 0.81^{a}	70.51 ± 0.58^{b}	70.09 ± 0.86^{b}	72.35 ± 0.57^{c}
	Lower region	61.77 ± 1.58^{a}	64.73 ± 1.01^{bc}	63.89 ± 1.63^{b}	66.16 ± 0.95^{c}
Weight loss (%)		19.55 ± 0.93^{c}	17.44 ± 1.21^{b}	14.76 ± 0.68^{a}	13.24 ± 0.63^{a}
Cooking loss (%)		21.45 ± 1.34^{c}	19.39 ± 1.72^{b}	15.15 ± 2.41^{a}	14.24 ± 0.74^{a}
Shrinkage (%)		26.17 ± 0.12^{c}	24.80 ± 0.37^{c}	21.72 ± 1.10^{b}	18.56 ± 0.76^{a}
TPA parameters	Hardness (N)	107.60 ± 5.46^{a}	108.43 ± 7.72^{a}	101.57 ± 4.40^{ab}	92.00 ± 8.18^{b}
	Springiness	0.66 ± 0.05^{a}	0.68 ± 0.03^{ab}	0.71 ± 0.03^{b}	0.66 ± 0.03^{a}
	Cohesiveness	0.64 ± 0.02^{b}	0.61 ± 0.02^{a}	0.63 ± 0.01^{ab}	0.62 ± 0.02^{a}
	Gumminess (N)	66.60 ± 8.25^{a}	68.14 ± 8.16^{a}	62.22 ± 5.77^{a}	51.41 ± 6.80^{b}
	Chewiness (N)	44.28 ± 6.54^{a}	46.63 ± 5.64^{a}	44.40 ± 4.65^{a}	36.27 ± 3.70^{b}
Shear test parameters	First peak (N)	16.36 ± 3.81^{a}	14.06 ± 1.65^{a}	13.14 ± 3.47^{a}	12.49 ± 3.20^{a}
	Maximum Shear force (N)	34.74 ± 13.04^{a}	30.41 ± 5.77^{a}	30.19 ± 6.95^{a}	24.32 ± 10.84^{a}
	Work of shearing (N mm)	517.37 ± 157.23^{a}	484.37 ± 69.56^{a}	412.06 ± 67.15^{a}	409.24 ± 101.26^{a}

Data are expressed as means ± standard deviations.
Values followed by different letters within the same row indicate significant difference ($p < 0.05$) between cooking conditions.

are not uniform across all radial positions, with greater thickness in the center than at the edges. In the literature, data have been found regarding the influence of the burger diameter and cooking temperature on shrinkage (Oroszvári et al., 2005), but to our knowledge, there is no previous studies on the impact of the number of turns on burger shrinkage. The shrinkage calculated as a change in volume also exhibited a slight increase with the number of flips: 24.35 ± 1.05%, 24.79 ± 0.37%, 25.61 ± 1.46%, and 28.14 ± 1.21% for 1, 3, 5 and 7 flips, respectively.

4.2. Textural quality and moisture content

The textural attributes of burgers play a crucial role in determining consumer acceptance. Therefore, the influence of the number of flips on the texture of the burgers was examined. In Table 1, the moisture content, weight and cooking losses, shrinkage (calculated from volume changes), and texture parameters of burgers cooked with 1, 3, and 5 flips until the central temperature reached 71.1 °C are presented. These data reflect that burgers cooked with only one flip retain a



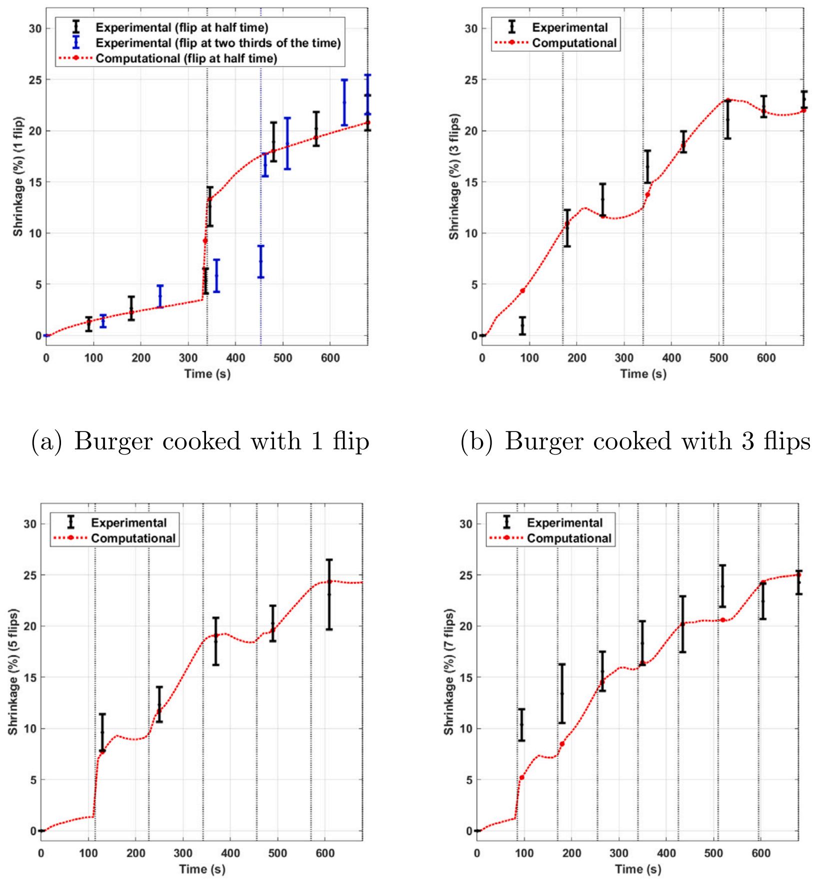
(a) Burger cooked with 1 flip (b) Burger cooked with 3 flips

(c) Burger cooked with 5 flips (d) Burger cooked with 7 flips

Fig. 7. Evolution of weight loss for different number of flips: (a) one, (b) three, (c) five, and (d) seven flips. The vertical lines indicate flipping times and dots indicate the value of the discontinuous weight loss.

Fig. 8. Final appearance of the burger as a function of the number of flips applied during cooking.

lower amount of water ($p < 0.05$) than those cooked with a higher number of flips, and this occurs for all the three studied regions (upper, central, and lower). Additionally, there are no significant differences in moisture between 3 and 5 flips ($p > 0.05$). For each cooking condition, the central zone has a moisture content closer to that of the raw burger (74.49 ± 0.78%) than the outer zones, with no noticeable differences between the upper and lower zones. The weight loss, cooking loss, and shrinkage, decrease as the number of flips increases, due to the reduction in cooking time. These differences in the moisture content of the burgers were not reflected in the textural parameters obtained in the shear tests, as there are no significant differences in either the first peak force, the maximum shear force, or the work of shearing. However, the parameters obtained with the double compression test show that the hardness, gumminess and chewiness of the burgers slightly decrease as the number of flips increases and the time decreases. It has been described that, the hardness, cohesiveness, springiness, and chewiness of burgers increase with cooking time (Vu et al., 2022). The rise in hardness is primarily associated with the denaturation of myosin and actin, resulting in the contraction of the protein matrix and the expulsion of moisture. However, the results suggest that burgers cooked for a longer duration (1 flip - 800 s), retaining lower moisture content, and experiencing greater shrinkage, exhibit similar hardness and chewiness to those cooked with 3 flips (680 s). Some studies show that the hardness determined by TPA of burgers ceases to increase with the degree of cooking at core temperatures between 60 and 71 °C (Barbosa et al., 2022). During the TPA tests, the release of meat juice from the burgers was observed during compression, followed by its reabsorption when the force ceased (Fig. 10), indicating that the meat behaves similarly to a sponge. Through the compression test, not only the resistance offered by the structure of the protein matrix itself was measured, but also the resistance to the flow exerted by the juice occupying the pores. The outward flow resistance of water from the burger is lower for samples with lower moisture, and this effect has a sufficient impact on hardness to partially balance the compression resistance of the protein structure. Recent studies have concluded that the juiciness perception of beef burgers is negatively correlated



(a) Burger cooked with 1 flip

(b) Burger cooked with 3 flips

(c) Burger cooked with 5 flips

(d) Burger cooked with 7 flips

Fig. 9. Evolution of shrinkage for different number of flips: (a) one, (b) three, (c) five, and (d) seven flips. The vertical lines indicate when it is time to flipping the burger.

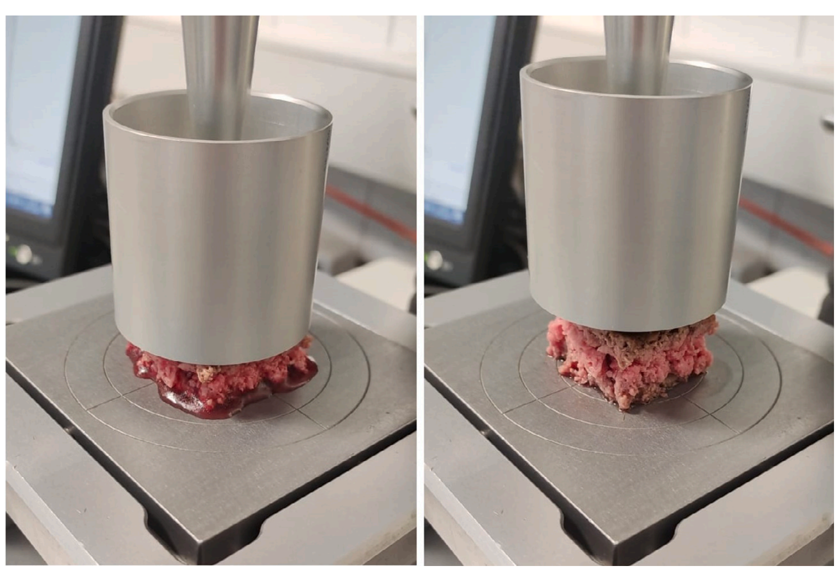


Fig. 10. Experimental setup for the texture profile analysis test.

with cooking loss and positively correlated with the amount of serum released from the food matrix during mastication (Warner, 2017; Zhang et al., 2024). Thus, from a sensory point of view, increasing the number of flips, involves better quality in terms of hardness and juiciness.

4.3. Model validation

In order to prepare the model to assist in the study, the different experimental cooking scenarios were assessed to validate its predictive capabilities. Taking the set of model parameters described

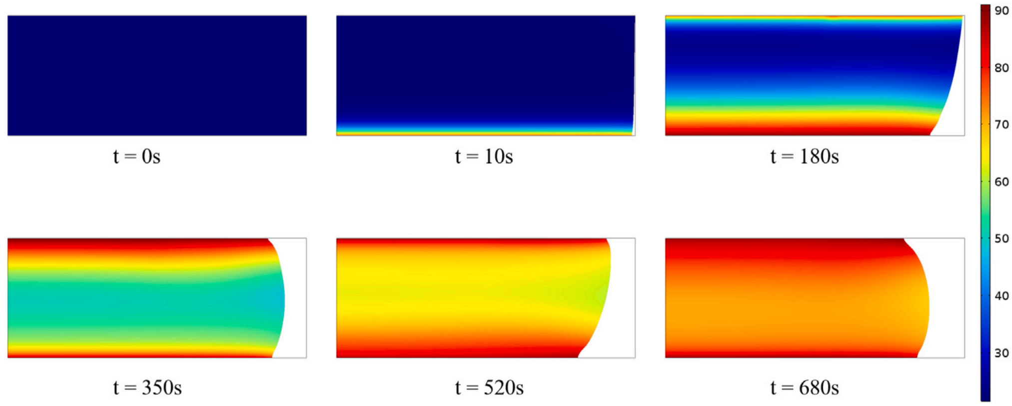


Fig. 11. Evolution of the burger temperature and deformation at the beginning of the experiment ($t = 0$ s), $t = 10$ s, $t = 180$ s (or 10 s after the first flip), $t = 350$ s (or 10 s after the second flip), $t = 520$ s (or 10 s after the third flip) and at the end of the process ($t = 680$ s).

Table 2
Root Mean Square Error (RMSE) and relative error for the model predictions of the three variable evolution.

	1 flip (340 s)	3 flips	5 flips	7 flips
RMSE central temperature	5.29 °C	2.26 °C	1.66 °C	3.12 °C
RMSE weight loss	1.30%	1.00%	1.01%	0.93%
Maximum shrinkage absolute error	2.97%	1.91%	1.85%	5.11%

in Hernández-Alhambra et al. (2024), the central and top temperature, weight loss and shrinkage evolution were compared with the real tests. These results have been included in the previous figures (Fig. 3, Fig. 6, Fig. 7 and Fig. 9). To enhance clarity in the representation, only the model prediction for samples flipped at 340 s is depicted. Root Mean Square Error (RMSE) and relative error for the model predictions of the three variable evolution are presented in Table 2.

When looking at the central temperature evolution for only one flip, the model underestimate the temperature until the turn over and clearly overestimate it at the end of the experiment. The root mean squared error (RMSE) between the two curves was 5.29 °C. The central temperature predicted by the model for different numbers of flips is also shown in Fig. 3. An interval region has been added to the computational curves to represent the uncertainty in the thermocouple position during placement in the experimental tests (estimated at ±1 mm). As observed, the model results fall within the range of values obtained experimentally.

When comparing the model predictions of the top temperature, since the observed non-uniformities cannot be reproduced by the axisymmetric model, the histogram shown in Fig. 5 was used to obtain the average upper surface temperature as well as the maximum and minimum values. Fig. 6 represents in continuous line the evolution of the temperature at the top surface provided by the computational model. As can be observed, results fit better within the experimental minimum and maximum temperatures when the number of flips is increased.

In Fig. 11 the temperature distribution and the deformation predicted by the model is represented at six time points during the cooking process. The time points of 180 s, 350 s and 520 s were selected 10 s after the turn over. When looking at the central region, high temperature gradients can be observed, which, in some cases, result in discrepancies with the experimental data due to the previously mentioned localization effect of the thermocouple.

The model is also able to capture the evolution of weight loss providing better predictions for increasing number of flips (Fig. 7). As shown in Table 2, the RMSE between the predicted weight loss and the experimental samples flipped only once at 340 s was 1.30%. RMSE values between the predicted and experimental values for the water loss were 1.00%, 1.01% and 0.93% for 3, 5 and 7 flips, respectively.

Since shrinkage was measured experimentally only at certain time points, in Fig. 9 those values represented as the mean and standard deviation are compared with the continuous shrinkage predicted by the model. In Table 2 the maximum absolute error made by the computational simulation is presented. These error values appear in the early stages of the cooking process and may be due to the method used for determining shrinkage, which compares a 3D geometry to an idealized 2D model.

4.4. Optimal flipping conditions

Finally, the question of how much time is needed to reach a safe temperature to ensure that harmful bacteria and pathogens present in raw meat are effectively killed motivated the third scenario of computational testing. In this scenario, the simulations were conducted until a temperature of 71.1 ° C was achieved at the center point of the burger at the end of the cooking process, regardless of the number of flips. Through a trial and error process using the results of the previous scenarios, it was determined that cooking the burgers with only one flip required a total cooking time of 800 s. In the case of three flips, 680 s were needed, while a cooking time of 603 s was required for both five and seven flips to achieve this safe temperature, with flips occurring at regular intervals.

The simulations were extended to include different combinations of final cooking time and number of flips, with them being equally spaced. A total of 38 simulations were conducted and values of central temperature, weight loss and shrinkage at the end of the cooking process as a function of the total cooking time and number of flips were fitted with polynomial surfaces. Different orders for these polynomials were tested and those requiring the fewest parameters were selected to achieve a fitting goodness greater than 0.99. Fig. 12 shows these surfaces.

The equation of the fitted surface representing the central temperature as a function of the total time and number of flips is:

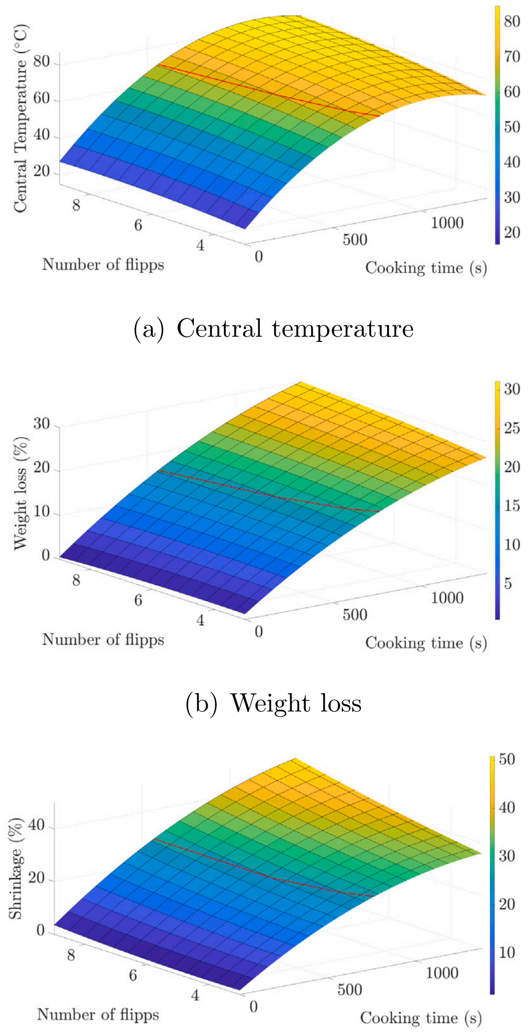
$$\text{Central temperature} = a_{00} + a_{10}t + a_{01}n + a_{20}t^2 + a_{11}nt + a_{02}n^2 \tag{14}$$

where the coefficient values are: $a_{00} = 16.89$ ^{o}C, $a_{10} = 0.09478$ ^{o}C/s, $a_{01} = 2.635$ ^{o}C/flip, $a_{20} = -4.532 \cdot 10^{-5}$ ^{o}C/s^2, $a_{11} = 0.0007901$ ^{o}C/(flip s) and $a_{02} = -0.1637$ ^{o}C/flip^2. The goodness of the fit was $R^2 = 0.9944$.

For the final weight loss of the product, the fitted surface is:

$$\text{Weight loss} = b_{00} + b_{10}t + b_{01}n + b_{20}t^2 + b_{11}nt + b_{02}n^2 \tag{15}$$

the coefficient values are: $b_{00} = 0.5254$, $b_{10} = 0.02703$ %/s, $b_{01} = 0.3719$ %/flip, $b_{20} = -7.517 \cdot 10^{-6}$ %/s^2, $b_{11} = 0.000519$ %/(flip s) and $b_{02} = -0.04146$ %/flip^2. The goodness of the fit was $R^2 = 0.9975$.



(a) Central temperature

(b) Weight loss

(c) Shrinkage

Fig. 12. Representation of the response surface predicted by the model for the central temperature, weight loss and shrinkage as a function of the number of flips and cooking time. The red line indicates a temperature of 71.1 °C at the central point.

The shrinkage at the end of the cooking process was fitted by:

$$\text{Shrinkage} = c_{00} + c_{10}t + c_{01}n + c_{20}t^2 + c_{11}n\,t + c_{02}n^2 \tag{16}$$

being the coefficients: $c_{00} = 3.194$, $c_{10} = 0.04068$ %/s, $c_{01} = -0.7833$ %/flip, $c_{20} = -1.44 \cdot 10^{-5}$ %/s^2, $c_{11} = 0.001383$ %/(flip s) and $c_{02} = 0.09135$ %/s^2. Although the goodness of this fit, $R^2 = 0.9467$, is lower than the initial goal established for the surfaces, this function was kept to maintain the same number of parameters.

In Fig. 12 a red line has been superposed in the three surfaces indicating a temperature of 71.1 °C at the center of the burger. Analyzing the response surfaces, it can be inferred that increasing the number of flips reduces the total cooking time required to reach the desired central point temperature, with less weight loss and shrinkage. This behavior reaches an asymptote with no apparent benefit beyond 5 flips.

5. Conclusions

As demonstrated, the computational model incorporating the flipping action accurately predicts the temperature, weight loss, and shrinkage evolution of beef burgers. However, when flipping occurs at advanced cooking times, leading to water surfacing on the upper side of the burger, the predictive accuracy decreases, particularly in central temperature prediction.

Experimental results comparing burgers cooked to reach the same final central temperature indicate that cooking time is significantly reduced with 3 or more flips. This allows burgers to retain more moisture, resulting in lower cooking losses and shrinkage. Therefore, it is highly recommended to perform multiple flips during burger cooking, and performing more than 5 flips does not significantly improve results in terms of time.

Extrapolating these results to other cooking conditions should be approached cautiously. However, it is anticipated that these conclusions may hold for various pan temperatures, as previous studies (Hernández-Alhambra et al., 2024) have shown that the temperature profile remains consistent across a range of pan temperatures (between 215 °C and 140 °C), with the exception of a thin layer of the burger near the outer surface. Hence, the cooking times required to achieve the final temperature are unlikely to differ significantly from those presented here. Conversely, for thinner burgers where cooking is more uniform, the distinctions between a single flip and multiple flips may not be as noticeable.

CRediT authorship contribution statement

E. Hernández-Alhambra: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation. **P. Guiu:** Writing – original draft, Methodology, Investigation, Data curation. **A. Ferrer-Mairal:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **M.A. Martínez:** Supervision, Methodology, Investigation, Conceptualization. **B. Calvo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **J. Grasa:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M.L. Salvador:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration 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.

Data availability

Data will be made available on request.

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References

Ahmad, S., Khan, M.A., Kamil, M., 2015. Mathematical modeling of meat cylinder cooking. LWT Food Sci. Technol. 60, 678–683. http://dx.doi.org/10.1016/j.lwt.2014.10.061.

Barbera, S., Tassone, S., 2006. Meat cooking shrinkage: Measurement of a new meat quality parameter. Meat Sci. 73, 467–474. http://dx.doi.org/10.1016/j.meatsci.2006.01.011.

Barbosa, A.D., Alexandre, B., Tondo, E.C., da Silva Malheiros, P., 2022. Microbial survival in gourmet hamburger thermally processed by different degrees of doneness. Int. J. Gastron. Food Sci. 28, 100501. http://dx.doi.org/10.1016/j.ijgfs.2022.100501.

Chapwanya, M., Misra, N., 2015. A mathematical model of meat cooking based on polymer-solvent analogy. Appl. Math. Model. 39, 4033–4043. http://dx.doi.org/10.1016/j.apm.2014.12.015.

Dagerskog, M., 1979. Pan-frying of meat patties i. a study of heat and mass transfer. In: Lebensmittel Wissenschaft Und Technologie. vol. 12, pp. 217–224.

Dalvi-Isfahan, M., 2023. Mathematical modeling for investigating the effect of single-sided flipping on moisture, fat content, and safety of hamburger patty. J. Food Process Eng. 46, http://dx.doi.org/10.1111/jfpe.14450.

Dhall, A., Datta, A.K., 2011. Transport in deformable food materials: A poromechanics approach. Chem. Eng. Sci. 66, 6482–6497. http://dx.doi.org/10.1016/j.ces.2011.09.001.

Erdogdu, F., Zorrilla, S., Singh, R., 2005. Effects of different objective functions on optimal decision variables: A study using modified complex method to optimize hamburger cooking. In: LWT Food Sci. Technol. vol. 38, pp. 111–118. http://dx.doi.org/10.1016/j.lwt.2004.05.010.

Hernández-Alhambra, E., Guíu, P., Cabeza-Gil, I., Ferrer-Mairal, A., Martínez, M., Calvo, B., Grasa, J., Salvador, M., 2024. Towards domestic cooking efficiency: A case study on burger pan frying using experimental and computational results. J. Food Eng. 363, 111783. http://dx.doi.org/10.1016/j.jfoodeng.2023.111783.

Mathijssen, A.J.T.M., Lisicki, M., Prakash, V.N., Mossige, E.J.L., 2023. Culinary fluid mechanics and other currents in food science. Rev. Modern Phys. 95, 025004. http://dx.doi.org/10.1103/RevModPhys.95.025004.

McGee, H., 2004. On Food and Cooking: The Science and Lore of the Kitchen, second ed. Collier Books, Scribner, New York, pp. 147–154.

Moya, J., Lorente-Bailo, S., Salvador, M., Ferrer-Mairal, A., Martínez, M., Calvo, B., Grasa, J., 2021. Development and validation of a computational model for steak double-sided pan cooking. J. Food Eng. 298, 110498. http://dx.doi.org/10.1016/j.jfoodeng.2021.110498.

Myhrvold, N., Young, C., Bilet, M., Smith, R.M., 2011. Modernist Cuisine: The Art and Science of Cooking, first ed. vol. 3, Cooking Lab, Bellevue, WA, pp. 72–79.

Nelson, H., Deyo, S., Granzier-Nakajima, S., Puente, P., Tully, K., Webb, J., 2020. A mathematical model for meat cooking. Eur. Phys. J. Plus 135, http://dx.doi.org/10.1140/epjp/s13360-020-00311-0.

Oroszvári, B.K., Bayod, E., Sjöholm, I., Tornberg, E., 2006. The mechanisms controlling heat and mass transfer on frying of beefburgers. iii. mass transfer evolution during frying. J. Food Eng. 76, 169–178. http://dx.doi.org/10.1016/j.jfoodeng.2005.05.018.

Oroszvári, B.K., Sjöholm, I., Tornberg, E., 2005. The mechanisms controlling heat and mass transfer on frying of beefburgers. i. the influence of the composition and comminution of meat raw material. J. Food Eng. 67, 499–506. http://dx.doi.org/10.1016/j.jfoodeng.2004.05.017.

Ou, D., Mittal, G., 2007. Single-sided pan frying of frozen hamburgers with flippings for microbial safety using modeling and simulation. J. Food Eng. 80, 33–45. http://dx.doi.org/10.1016/j.jfoodeng.2006.03.033.

Pan, Z., Singh, R.P., 2001. Physical and thermal properties of ground beef during cooking. LWT Food Sci. Technol. 34, 437–444. http://dx.doi.org/10.1006/fstl.2001.0762.

Pan, Z., Singh, R., Rumsey, T., 2000. Predictive modeling of contact-heating process for cooking a hamburger patty. J. Food Eng. 46, 9–19. http://dx.doi.org/10.1016/S0260-8774(00)00063-7.

Rocca-Poliméni, R., Vilet, N.Z., Roux, S., Bailleul, J.L., Broyart, B., 2019. Continuous measurement of contact heat flux during minced meat grilling. J. Food Eng. 242, 163–171. http://dx.doi.org/10.1016/j.jfoodeng.2018.08.032.

Thiffeault, J.L., 2022. The mathematics of burger flipping. Physica D 439, 133410. http://dx.doi.org/10.1016/j.physd.2022.133410.

Tornberg, E., 2005. Effects of heat on meat proteins - implications on structure and quality of meat products. Meat Sci. 70, 493–508. http://dx.doi.org/10.1016/j.meatsci.2004.11.021.

Tornberg, E., 2013. Engineering processes in meat products and how they influence their biophysical properties. Meat Sci. 95, 871–878. http://dx.doi.org/10.1016/j.meatsci.2013.04.053.

USDA, 2016. Food safety and inspection service. ground beef and food safety. (Last accessed on July 21 2023).

van der Sman, R., 2007. Moisture transport during cooking of meat: An analysis based on Flory–Rehner theory. Meat Sci. 76, 730–738. http://dx.doi.org/10.1016/j.meatsci.2007.02.014.

Vu, G., Zhou, H., McClements, D.J., 2022. Impact of cooking method on properties of beef and plant-based burgers: Appearance, texture, thermal properties, and shrinkage.. J. Agric. Food Res. 9, 100355. http://dx.doi.org/10.1016/j.jafr.2022.100355.

Warner, R.D., 2017. Chapter 14—The eating quality of meat-iv water-holding capacity and juiciness. In: Toldra', F. (Ed.), Lawrie's Meat Science (Eighth Edition), eighth ed. In: Woodhead Publishing Series in Food Science, Technology and Nutrition, Woodhead Publishing, pp. 419–459. http://dx.doi.org/10.1016/B978-0-08-100694-8.00014-5.

Yan, Z., Sousa-Gallagher, M.J., Oliveira, F.A., 2008. Shrinkage and porosity of banana, pineapple and mango slices during air-drying. J. Food Eng. 84, 430–440. http://dx.doi.org/10.1016/j.jfoodeng.2007.06.004.

Zhang, Y., Brouwer, R., Sala, G., Scholten, E., Stieger, M., 2024. Exploring relationships between juiciness perception, food and bolus properties of plant-based meat analogue and beef patties. Food Hydrocolloids 147, 109443. http://dx.doi.org/10.1016/j.foodhyd.2023.109443.

Zorrilla, S.E., Singh, R., 2003. Heat transfer in double-sided cooking of meat patties considering two-dimensional geometry and radial shrinkage. J. Food Eng. 57, 57–65. http://dx.doi.org/10.1016/S0260-8774(02)00273-X.