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Simultaneous Heat and Mass Transfer Modeling for Frozen Hamburger: Investigation of Cooking Parameters and Microbial Inactivation Kinetics

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Abstract
A model for simultaneous heat and mass transfer during the cooking process of frozen hamburger has been developed, using a modified form of Darcy's law to describe the capillary flow of moisture and Fourier's second law in cylindrical coordinates to describe the heat transfer. The effects of cooking time (0 to 12 minutes), cooking temperature (140 to 160°C), and patty thickness (10 to 14 mm) during the hamburger cooking process on temperature profile, moisture content, and inactivation kinetics of *Salmonella* bacteria were investigated. The results showed that the predicted temperature and moisture values are in good agreement with the measured data. Due to the low convective heat transfer coefficient in the upper part of the sample at the beginning of the cooking process, non-uniformity in temperature was observed, which was resolved by flipping the hamburger and resulted in a reduction in cooking time. In addition, an increase in the heating temperature results in an increase in the rate of evaporation and moisture loss from the hamburger patty. The simulation results showed that at a cooking temperature of 140°C and a patty thickness of 14 mm, all points of the hamburger will not achieve a 12D reduction of *Salmonella* and there is a possibility of salmonellosis under these conditions.

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Cooking
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1. Introduction

The traditional food habits of families, which involved making food at home (MFH), have been altered by the new lifestyle, and now more families are using ready-to-cook food (RTCF). One of these RTCF products is hamburger, which is produced with various plant and animal formulations, colors, shapes, and different quality characteristics. Although the per-capita consumption of processed meat products in Iran is still relatively low compared to developed countries (1.5 kg per person), the younger generation is increasingly inclined towards consuming these products due to their simplicity, speed, and convenience in preparation (Hajimohammadi, et al., 2014). Due to the short shelf life of this product when stored at temperatures between 1 and 4 ºC, it is typically distributed in a frozen state to increase its shelf life. According to the Centers for Disease Control and Prevention

(CDC), foodborne illnesses (especially from cooked meat) result in approximately 48 million cases of illness annually, with many of these illnesses caused by inadequate heating processes to destroy bacteria. In recent years, several cases of food poisoning related to hamburgers have been reported. Studies show that microorganisms such as *E. coli*, *Listeria*, *Salmonella*, and *Staphylococcus* are the main causes of illness in this product (Canning, et al., 2023; Jay, et al., 2005). While it is possible to consume steak partially cooked, this is not true for hamburger because hamburger always contains pathogenic bacteria on its surface that can only be eliminated by cooking (Warmate & Onarinde, 2023).

However, pathogenic bacteria in hamburger can be transferred to the center of the meat through grinding or chopping (Pan, et al., 2000). The primary method for inactivating harmful microorganisms in hamburgers is thermal processing, which involves grilling or frying. To ensure safety, the researchers suggest that hamburgers be heated to a minimum internal temperature of 68°C (154°F) for at least 16 seconds (Zorrilla & Singh, 2003). However, there are several difficulties in following this guideline, such as measuring the temperature in the center of the food product and the heterogeneous composition of the hamburger. As a result, there is often insufficient control over the time-temperature combination, leading to various microbial contaminations, spoilage, and potentially hazardous situations (such as undercooking) for consumers (Barbosa, et al., 2022). Using simulation through mathematical models is a popular method for comprehending the processes of heat and mass transfer that occur during cooking and for producing a safe-to-consume product. The utilization of simulation can lead to an improved understanding of the process, enable predictions, and facilitate optimization as a function of various variables (Plazl, et al., 2006; Sanz-Serrano, et al., 2017).

Modeling the simultaneous heat and mass transfer for frozen hamburger is a complex and challenging process because, firstly, frozen hamburger is a complex system with multiple phases, including ice, water, fat, protein, and air. These phases can melt or even evaporate during the cooking process. Consideration of temperature-dependent of the thermos-physical properties of the product, and simultaneous heat and mass transfer phenomena yields a highly nonlinear coupled system of partial differential equations (Kovácsné Oroszvári, et al., 2006; Pham, 2006). Meanwhile, other physicochemical changes, such as non-enzymatic browning, protein denaturation, and product shrinkage, also occur during cooking, which makes predicting the system behavior during the process challenging (Dong Ou & Mittal, 2006; Pan, et al., 2000).

Studies on heat and mass transfer in the hamburger cooking process have been investigated by various researchers. For example, (Obuz, et al., 2002) simulated the meat grilling process by considering the meat as a non-porous solid and solving the Fourier heat transfer equation. Other studies included the mass transfer (moisture and fat) of the sample during cooking in the model, using either the Fick or Darcy equation (Kondjoyan, et al., 2006; Pan, et al., 2000).

Kovácsné Oroszvári, et al. (2006) developed a simulation for meat cooking by taking into account the pressure-driven flow phenomenon. Dhall, et al. (2012) also developed a multi-phase model that focused on unsaturated flow in a porous medium, taking into account key physical phenomena that occur during cooking, such as heat and mass transfer, evaporation, and pressure-driven flow (van der Sman, 2013).

Despite the importance of simulating the simultaneous heat and mass transfer during hamburger cooking in three dimensions, there has been a very limited number of articles that have investigated this area of research. 3D modeling can provide a more comprehensive and accurate representation of the complex geometries and physical phenomena involved in the transfer process. In contrast, 1D or 2D modeling simplifies the problem by assuming that the transfer occurs only in one or two directions, respectively, which may not be the case in real-world scenarios. Thus, the objective of the current research is to build a three-dimensional mathematical model that can forecast the temperature and moisture variations in frozen hamburger patties during contact heating. The models also take into account the impact of the latent heat of vaporization during the cooking and the flipping process. Additionally, a model for the kinetics of microbial inactivation (*Salmonella*) has been included in the model.

2. Methods and Materials

2.1. Sample preparation and experiments

The hamburger samples were prepared according to Carvalho, et al., 2017 (Table 1) (Carvalho, et al., 2017).

Table 1. Formulation of hamburger

Component	Percentage
Fresh beef	69
Cold water	15
Beef fat	13
Salt	1.2
Monosodium glutamate	0.75
Seasoning	0.65
Sodium tri-polyphosphate	0.4%

In the first step, the chemical composition of the product was determined in triplicate and presented in Table 2 (AOAC, 2005). The cooking process was carried out in a grill (Gastroback, Germany) at three different temperatures (140, 150, and 160°C). During the cooking process, the hamburger was flipped once at a time of 350 seconds. The cooking process continued for 700 seconds. Thermocouples type K were used to measure the temperature changes at the top and bottom points of the sample, and temperature data were recorded every 50 seconds until the end of the heating process.
The moisture content of the specimen was determined through the oven drying technique at 175-second intervals and was then compared to the predicted data (Pero, et al., 2019).

3. Development of mathematical models

3.1. Model assumptions:

1. The hamburger texture is assumed to be homogeneous, and moisture is distributed uniformly across the specimen at the beginning of the cooking.
2. Moisture transfer inside the sample is considered as a capillary flow.
3. The effect of sample shrinkage during heating is ignored in the model. It should be noted that the results of (Zorrilla & Singh, 2003) showed that considering the effect of sample shrinkage in the model has no significant effect on the accuracy of temperature prediction.
4. Heat transfer inside the sample occurs only through conduction.
5. Water can only evaporate from the surface of the specimen.

The model was developed using the COMSOL Multiphysics software (5.5). Table 3 contains a list of the parameters utilized in the model (Dalvi-Isfahan & Daraei Garmakhany, 2021).

3.2. Heat transfer model

In this study, the models were developed based on the assumption that the hamburger patty has a finite cylindrical shape. The governing partial differential equation (PDE) for heat conduction in a three dimensional cylindrical coordinate system, describing the unsteady state situation, is given by equation 1(Dalvi-Isfahan, 2023; D. Ou & Mittal, 2007):

$$\rho\frac{\partial T}{\partial t}=\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{k}{c_p}\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial Z}\left(\frac{k}{c_p}\frac{\partial T}{\partial Z}\right)\right]\;[1]$$

Initial and boundary conditions:

The amount of heat conveyed to the surface through convection is equal to the amount of heat conveyed to the center of the product through conduction, in addition to the heat required for moisture evaporation, also known as the latent heat of vaporization (λ) (Dalvi-Isfahan, 2023). Depending on whether the temperature was higher or lower than the boiling point of water, we applied different conditional boundary conditions on the bottom surface of the hamburger patty.

if T>373 [K],

$$-n.(-k\nabla T) = h_{mb}(T - T_s) - \lambda \frac{\partial m}{\partial t} \quad [2]$$

$$-n.(-k\nabla T) = h_{mu}(T - T_{air}) \quad [3]$$

and

if T>373 [K],

$$-n.(-k\nabla T) = h_{mb}(T - T_s) \quad [4]$$

$$-n.(-k\nabla T) = h_{mu}(T - T_{air}) \quad [5]$$

$$T(r, Z) = T_0 \quad [6]$$

The lower surface of the hamburger is in contact with a heating medium with a convective heat transfer coefficient (h_{mb}), and the upper surface is in contact with the ambient air with a convective heat transfer coefficient (h_{mu}). By over-turning or flipping the hamburger, the position of these two regions will change accordingly (Chen, et al., 1999):

3.3. Mass transfer model

During the process of cooking hamburgers, the transfer of mass, which comprises both moisture and fat, occurs predominantly through capillary flow. The mechanism driven by capillary flow is considered to be more significant than the one based on diffusion. As a result, the current study utilized the modified Darcy model to comprehensively model the transfer of moisture during the cooking process (Ateba & Mittal, 1994; Dalvi-Isfahan, 2023; D. Ou, et al., 2007).

$$\frac{dm}{dt} = -K_W.(m - m_{we}) \quad [7]$$

Where the equilibrium moisture content (m_{we}) depends on the temperature and is obtained by the following equation. In the equation below, T_{wO} is a threshold temperature at which moisture transfer in frozen hamburgers begins and is 30°C according to the sources (Zorrilla, Banga, et al., 2003):

$$m_{we} = m_{w0} e^{(-\delta_{we}(T - T_{wo}))} \quad [8]$$

Initial condition:

$$m_w(r, Z, 0) = m_0 \quad [9]$$

3.4. Microbial death kinetics model

The changes in microbial death over time were analyzed using a first-order model, and Table 3 contains a list of the model's coefficients and constants (Dhall, et al., 2012; Murphy, et al., 2002):

$$\frac{dN}{dt} = -\frac{2.303}{D} N \quad [10]$$

$$D_T = D_r 10^{\left(\frac{T_r - T}{Z_{value}}\right)} \quad [11]$$

3.5. Statistical analysis

A statistical metric, namely the root mean square error (RMSE), was utilized to evaluate the fit between the model and experimental data (Dalvi-Isfahan, 2020).

$$RMSE = \sqrt{\left(\frac{\sum_{i=1}^{N}\left(Y_{exp,i} - Y_{pre,i}\right)^2}{N}\right)} \quad [12]$$

Where, $Y_{pre,i}$ and $Y_{exp,i}$ represent the forecast parameter and experimental parameter, respectively, and N is the number of data points.

Table 2-chemical composition of the product

Parameter	Value (%)
Fat	18.1
Moisture	57.5
Protein	17.2
Carbohydrate	3.6
Ash	3.6

Table 3- Parameters and coefficients used in the model.

Parameter	Symbol (unit)	Value	Reference
Patty diameter	(m)	0.084	Measured
Patty thickness	(m)	0.010-0.012-0.014	Measured
Density below freezing point	ρ (kg/m^3)	1019	Measured
Density above freezing point	ρ (kg/m^3)	1050	Measured
Thermal conductivity below freezing point	k (W/mk)	1.42	Measured
Thermal conductivity above freezing point	k (W/mk)	0.45	Measured
Specific heat below freezing point	Cp (J/kgK)	2200	Measured
Specific heat above freezing point	Cp (J/kgK)	3200	Measured
Initial temperature	T_0 (ºC)	-18	Measured
Ambient temperature	T_{air} (ºC)	30	Measured
Cooking temperature	T_s (ºC)	140,150,160	Measured
Flipping time	(s)	350	Measured
Convective heat transfer coefficient bottom	h_{mb} (W/m^2.K)	250	(Wichchukit, et al., 2001)
Convective heat transfer coefficient at top	h_{mu}(W/m^2.K)	20	(Dong Ou, et al., 2006)
Water conductivity	K_W (1/s)	0.017	(Zorrilla & Singh, 2003)
Water holding capacity coefficient	δ_{we} (1/ ºC)	0.0132	(Zorrilla & Singh, 2003)
Reference decimal reduction time, D	s	545	(Murphy, et al., 2002)
Thermal resistant constant, Z	ºC	9.14	(Murphy, et al., 2002)

4. Results and discussion

4.1. Heat transfer model

The temperature changes during cooking are shown in Fig. 1. As can be seen, the hamburger's flipping occurred at 350 seconds after the beginning of the cooking process. Before this time, the temperature increase only occurred for the lower layers of the hamburger, which are exposed to the heat source, while the upper layers, which are exposed to the surrounding air with a low convection heat transfer coefficient (20 W/m²°C), remained frozen and no phase change was observed. After 350 seconds of the cooking process, the temperature in the upper layer remained about 1.2°C. By flipping the hamburger, the temperature changes are reversed, and we observe a decrease in temperature for the lower layers and an increasing trend for the upper layers.

Fig. 1 also shows the temperature changes at the at the core of the specimen. Three different regions can be observed for this node (N/2). The temperature changes of the hamburger go through three phases, which are the frozen phase (below 0°C), the transitional phase between frozen and unfrozen (around 0°C), and the unfrozen phase (above 0°C) where the temperature reaches to about 85 ºC at the end of the cooking stage (700 seconds).

The figure also shows the good agreement between the experimental and forecast data during the cooking process, with an average root mean square error of about 2.5. Similar results have been reported by (D. Ou, et al., 2007). Figure 2 shows the 3D variations in temperature that occur during the end of the cooking. As expected, the lowest temperature (55.8°C) is observed in the lower part of the sample at a cooking temperature of 140°C, while the maximum temperature of 154°C is observed in the upper part of the hamburger at a cooking temperature of 160°C.

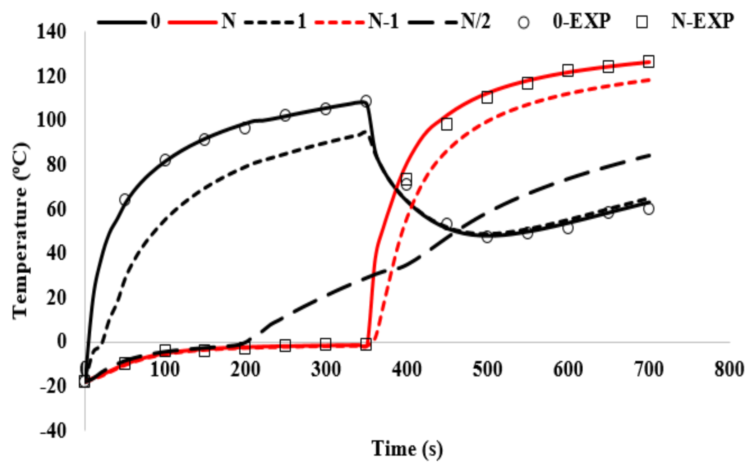

Figure 1- Temperature profile during the cooking process at different nodes
(0= bottom surface, N= top surface (last node), N/2= center point, N-1, the EXP= experimental)

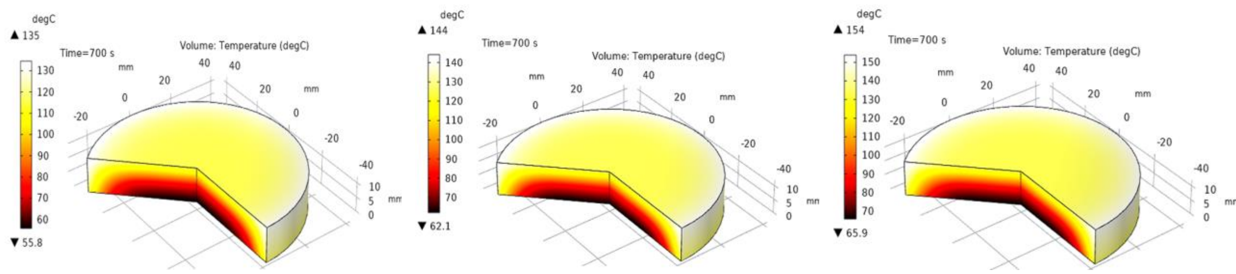

Figure 2- 3D surface plot showing the effect of pressing temperature and (140, 150 and 160 oC)

Regarding this result, it should be noted that after flipping the hamburger at 350 seconds, the upper part of the hamburger is exposed to the cooking temperature while the lower part of the sample is exposed to the ambient air. Therefore, the decrease in temperature in the bottom layer of the hamburger is not surprising, and heat transfer to these areas only occurs due to conduction within the hamburger. As it can be seen, even the upper part of the sample did not reach the cooking temperature after 700 seconds and remained at a maximum temperature of 154°C, which is due to moisture evaporation from the sample. As we know, the process of evaporation is an endothermic process (Ikediala, et al., 1996).

Fig. 3 shows the temperature changes at the centre of the sample at a temperature of 150°C as a function of different hamburger thickness. As can be seen, in the first 250 seconds of the process, the temperature changes for all three thicknesses have a similar trend because the samples are in the transitional phase (ice to water conversion). It should be noted that the latent heat of ice melting is a significant number and is equal to 333 kJ/kg (equivalent to increasing the temperature of 1 kg of water from one degree Celsius to 79 degrees Celsius), and therefore the temperature increase is slow in this period of time. After the sample exits the frozen phase, the rate of temperature changes accelerates, and the effect of differences in sample thickness is evident. At the end of the cooking process, the temperature of the sample with a thickness of 10 mm is about 100°C, while the temperatures for thicknesses of 12 and 14 mm are 84°C and 70°C, respectively.

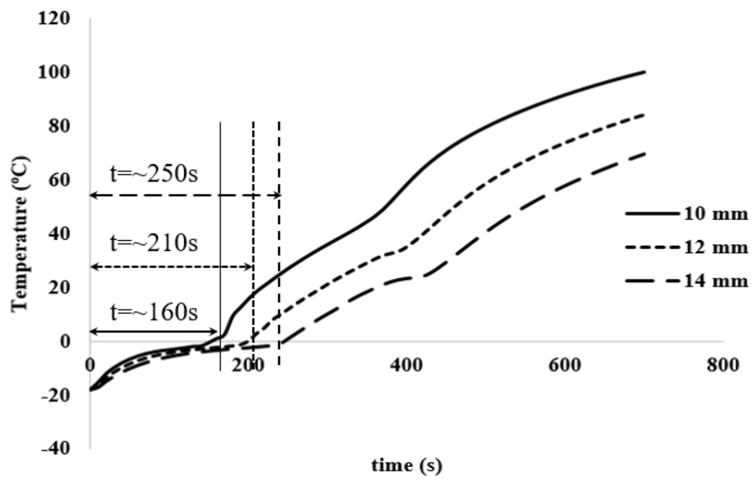

Figure 3- Temperature changes in the center of the sample as a function of patty thicknesses

Fig. 4 presents the changes in the central geometry of the hamburger as a function of cooking temperature. As previously explained, during the first 200 seconds of the process, the sample is in the transitional phase (ice to water conversion) and the temperature changes between the three cooking temperatures are not significant. Between 350 and 400 seconds after cooking, there is a rise in temperature in all three samples, which is linked to the filliping. As expected, by filliping the sample at 350 seconds, heat is distributed more uniformly in all parts, and the variation in temperature between the upper and lower portions of the hamburger reduces. Throughout the remainder of the cooking procedure, the effect of higher cooking temperature becomes more apparent, so that at the end of the process, the temperature at the geometric center of the sample has reached about 73 ºC for a cooking temperature of 160 ºC, but for a cooking temperature of 140 ºC, this temperature is about 61 ºC, indicating a difference of 12 ºC (Kovácsné Oroszvári, et al., 2006).

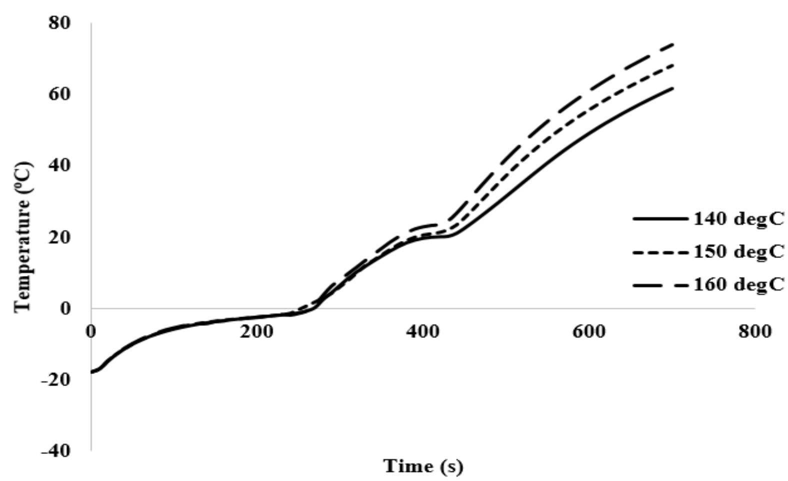

Figure 4 – Temperature changes in the center of the sample as a function of different cooking temperatures

4.2. Mass transfer (Moisture)

Figure 5 presents the changes in moisture content of the sample during the cooking process. As observed, during the first 100 seconds, the changes are very slow and negligible due to the sample being in a frozen state. Once the sample exits the frozen state, the loss of moisture accelerates. The loss of water from the sample is usually attributed to two main mechanisms: evaporation and drip (van Koerten, et al., 2017). If the sample forms a crust during cooking, the moisture loss slows down to some extent (Liu, et al., 2021). Moisture loss from the product is not only economically important but also crucial from a quality perspective, as a high moisture content in the product after cooking affects its taste and consumers prefer juicy products (Lian, et al., 2023). As shown in Fig. 5, the moisture content of the product is highly dependent on the cooking temperature, such that an increase in temperature from 140 to 160 °C shows a significant increase in moisture loss, and at the end of the cooking process, the remaining moisture content shows a 4% difference for the minimum and maximum cooking temperatures. A comparison between the moisture values measured and those observed is also presented in Fig. 5. Although the trend of changes in both is decreasing and acceptable, the measured moisture values at 150 °C are higher than the predicted values. This may be due to assuming a constant value for the water conductivity coefficient (K_W) during the cooking process, while in reality, this coefficient changes during the process (Dong Ou, et al., 2006).

The rate of moisture loss from the hamburger during the cooking is shown in Fig. 6. As seen, during the first 100 seconds of the process, the moisture loss rate is almost slow due to the sample being at a low temperature. As the temperature rises and the sample thaws, the impact of high cooking temperatures on reducing moisture levels becomes more noticeable. However, with continued cooking and a decrease in the moisture gradient in the sample, this trend decreases, and at the end of the 200-second process, it becomes decreasing for higher temperatures but remains almost constant at 140 °C (Santos, et al., 2021).

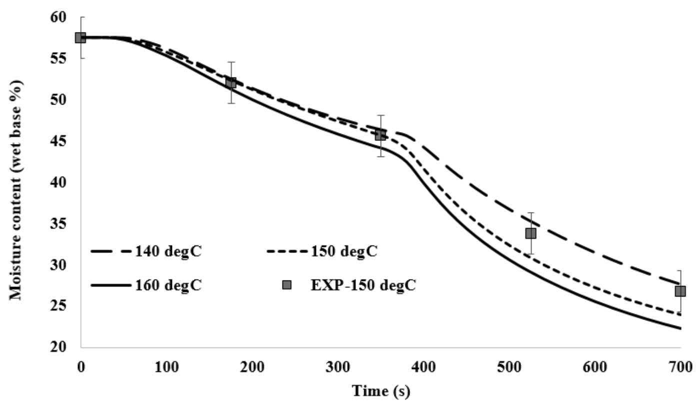

Figure 5- Changes in moisture content within the patty over time, at different processing temperatures.

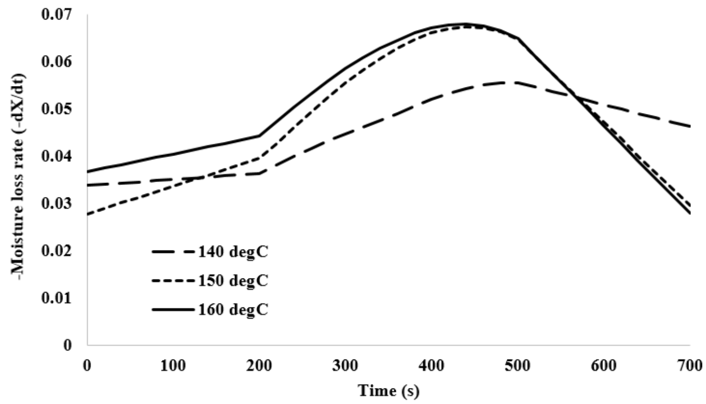

Figure 6-The rate of moisture loss from the patty over time, at various processing temperatures.

4.3. *Salmonella* inactivation model

Due to the importance of producing high-safety products, a kinetic model that demonstrates the inactivation of *salmonella* serotypes over time was incorporated in the model. Fig. 7 shows the predicted inactivation of *salmonella* due to heating at 150 ^{o}C and a thickness of 12 millimeters. Based on this figure, the required time to achieve the standard of a 12D reduction of *salmonella* can be determined in all parts of the hamburger. As expected, in the lower parts of the hamburger that were exposed to high temperatures at the beginning of the process, the rate of microbial destruction is fast. However, in the upper parts, they will only be exposed to the required heat for destruction after being flipped for 350 seconds. For example, the time required to achieve 12D reduction in node 0 and node 7 is 40 and 480 seconds, respectively. Overall, all points of the hamburger at this thickness, after the first 500 seconds of heating, have experienced a 12D reduction. Therefore, it can be expected that there will be no safety issue and foodborne illness related to Salmonellosis in the burger which cooked at 150 ^{o}C (Trifiletti, et al., 2012).

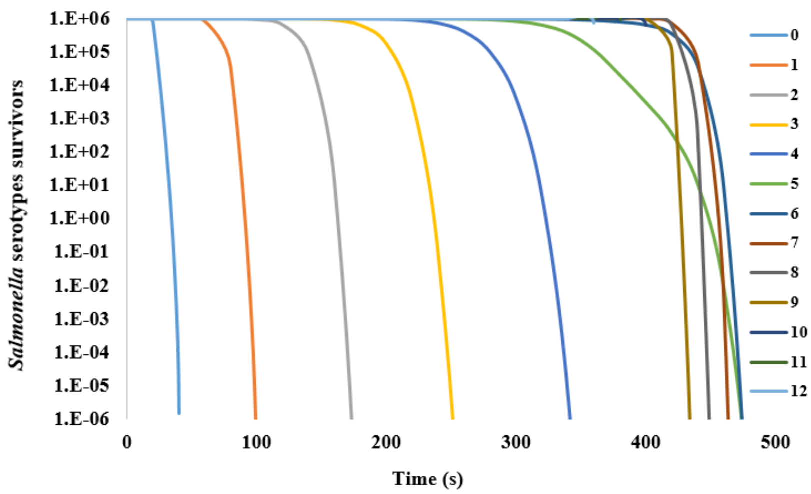

Figure 7- Predicted *salmonella* inactivation at different nodes at a cooking temperature of 150 ^{o}C and a thickness of 12 millimeters.

The same comparison for the harshest and mildest heat treatment conditions in this study is shown in figures 8 and 9, respectively. As can be seen, when the sample thickness is 10 millimeters and the cooking temperature is 160 ^{o}C, all parts of the hamburger have reached a 12D reduction in less than 400 seconds of heating (Fig. 8). This is while, for the mildest heat treatment process and the maximum sample thickness (Fig. 9), nodes 4 and 5 have not yet reached to 12D reductions after 700 seconds of cooking (end of process), and the 4D and 5D reduction has been attained for these two nodes, respectively, indicating the potential risk of salmonellosis. Generally, as the thickness of the product increases, it takes more time to attain a 12-log reduction in the number of bacteria, while an increase in cooking temperature results in a decreasing trend of this required time.

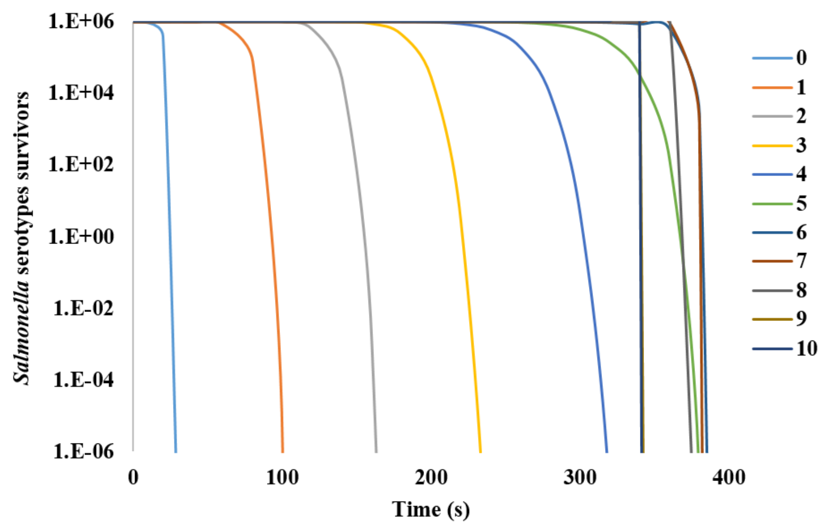

Figure 8 - Predicted *salmonella* inactivation at different nodes at a cooking temperature of 160 ºC and a thickness of 10 millimeters (harshest condition).

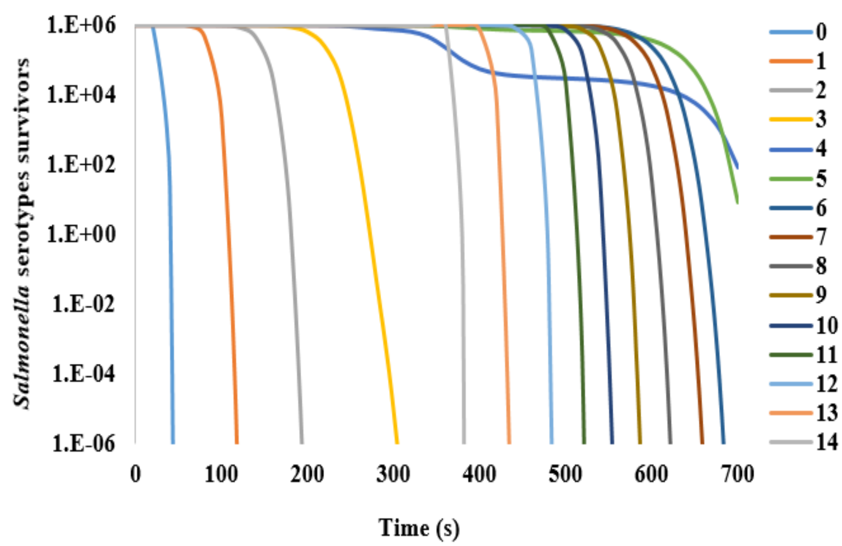

Figure 9 - Predicted *salmonella* inactivation at different nodes at a cooking temperature of 140 ºC and a thickness of 14 millimeters (mildest condition).

Figure 10 shows a 3D representation of the changes in the process time required to accomplish a 12-log decrease in product as a function of the process temperature and hamburger thickness. As observed, the process time is reduced with an increase in process temperature, but it increases with an increase in hamburger thickness. In addition, as previously mentioned, certain points of the 14-millimeter thick hamburger that is subjected to a process temperature of 140 ^{o}C will not achieve a 12-log reduction even after 700 seconds. This is the reason why the figure is not symmetrical.

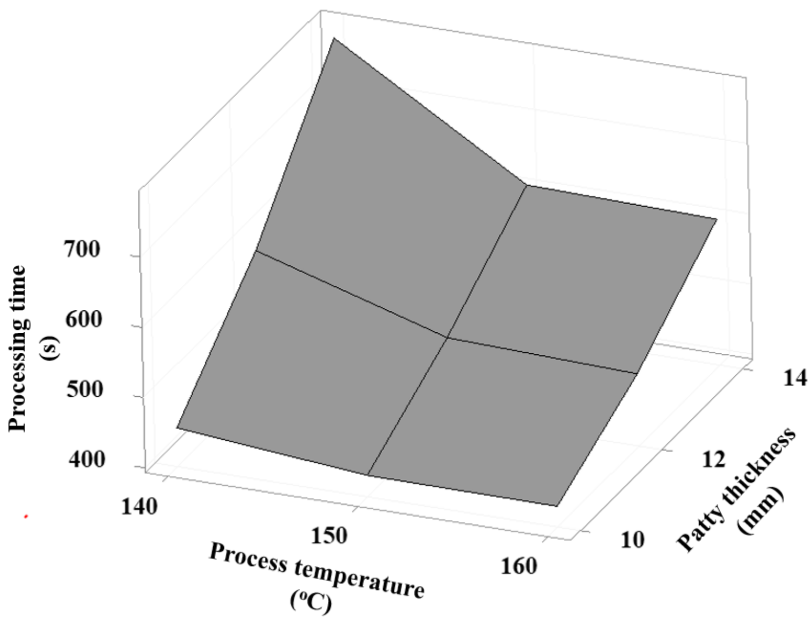

Figure 10- Three-dimensional predictions of process time as a function of different patty thicknesses and processing temperatures

5. Conclusions

A mathematical model was developed to explain the heat and mass transfer that takes place while frozen hamburgers are being cooked via contact heating. The results obtained from the model showed that:

- Cooking time, process temperature and patty thickness have a significant influence on the temperature and moisture distribution within the hamburger patty.
- Moisture content of the hamburger patty decreases rapidly during the initial phase of the cooking process, and then stabilizes at a lower level.
- Flipping or over-turning the hamburger has a significant impact on the uniformity of temperature distribution during cooking.
- Microbial inactivation rate depends strongly on the cooking time, temperature and patty thickness.
- • There is a possibility of survival of pathogenic bacteria and failure to reduce microbial risk to an acceptable level during the cooking process of hamburger patty with high thickness

and low cooking temperature. Therefore, there is a strong need to measure the temperature during the process or to use mathematical models to ensure reaching the safety level.

The developed model can forecast the temperature and moisture in a hamburger patty with different formulations and processing conditions. With slight modifications to the boundary conditions, the model can also be used to predict different cooking processes such as pan-frying. Moreover, the results of this research are anticipated to provide a substantial contribution to future optimization study.

Conflict of interest

The authors do not have any conflict of interest.

NOMENCLATURE

Cp	Specific heat (J/kg K)
h_{mb}	Convective heat transfer coefficient (W/m^{2}K) at bottom
h_{mu}	Convective heat transfer coefficient (W/m^{2}K) at top
hm	Mass transfer coefficient (m/s)
k	Thermal conductivity (W/mK)
K_W	Moisture conductivity (m/s)
m	Moisture
N	Number of data
r	cylindrical coordinates, mm
T	Temperature (ºC)
t	Time (s)
V	Volume (m^3)
Z	cylindrical coordinates, mm
Greek Letters	
ρ	Density (kg/m^3)
δ_{we}	Coefficient of water holding capacity, 1/°C
Subscripts	
i	Initial
e	Equilibrium
W	Water
air	Air (ambient)
exp	experimental
pre	predicted

Highlights

- The study successfully devised a model that predicts cooking a frozen hamburger via contact heating.
- The effects of cooking time, process temperature, and patty thickness during cooking process were investigated.

- Hamburger flipping is crucial to ensure uniform temperature distribution during the cooking process.
- Model demonstrates that the pathogenic bacteria may survive and pose a microbial hazard during hamburger patty cooking.

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