A simplified method for numerical simulation of gas grilling of non-intact beef steaks to eliminate *Escherichia coli* O157:H7

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**Article info**

**Abstract**

The objective of this work was to develop a numerical simulation method to study the heat transfer process and inactivation of *Escherichia coli* O157:H7 during gas grilling of non-intact beef steaks (NIBS). A finite difference and optimization algorithm was developed to determine the effective heat transfer parameters during grilling. After validation, these parameters were used in a finite element method to simulate the temperature profiles at various locations of NIBS (2.54 cm in thickness). The computer simulation results showed that *E. coli* O157:H7 may survive the heating processes if normal grilling conditions for intact beef steaks were used. Computer simulation results also suggested that *E. coli* O157:H7 might be effectively inactivated if NIBS (2.54 cm) were evenly flipped (every 4 min) and cooked for 16 min during cooking. The result of this study may help the food service industry to develop more adequate grilling methods and conditions to cook NIBS.

**1. Introduction**

Beef steaks are popular menu items in many restaurants and usually higher in price. The raw materials for beef steaks are usually premium beef cuts. Beef steaks are often cooked on gas or charcoal grills. Depending on the preference of consumers, many premium beef steaks may require only minimum amount of cooking to ensure that steaks are tender and juicy before consumption. As normal intact beef steaks made from healthy cattle are usually free of foodborne pathogens in the interior, only surface contamination may occur. The surface-contaminated foodborne pathogens can be easily killed during grilling. Therefore, it is possible to safely consume intact beef steaks cooked to “rare” without causing any foodborne bacterial infections.

Non-intact beef steaks (NIBS), on the other hand, are value-added products made from sub-primal beef cuts that are usually “tough” in structure and less desirable for consumption as regular steaks (Sutterfield, 2007). To make sub-primal beef cuts more palatable, mechanical tenderization is usually used to disrupt the structures of beef muscles (Laine et al., 2005; USDA FSIS, 2002, 2005). During mechanical tenderization, an array of mechanical needles or blades is inserted into sub-primal beef cuts, penetrating the beef muscles and making beef cuts more palatable after cooking. Therefore, NIBS are sold at lower prices and are consumed in large quantities in many restaurants.

NIBS, however, can present a serious food safety risk if they are cooked using normal cooking conditions for premium beef steaks (Table 1, [http://www.omahasteaks.com/servlet/OnlineShopping?Dsp=32&FID=recipe_cookchart]). *Escherichia coli* O157:H7, normally found in the intestinal tracts and hides of live animals, may be spread to beef during the slaughtering process (Buchanan and Doyle, 1997). For intact beef cuts, the surface contamination of *E. coli* O157:H7 causes little concern, as the superficial contamination can be easily remedied by heat during cooking. For comminuted products such as ground beef, *E. coli* O157:H7 is a serious public food safety hazard in the United States and around the world. This foodborne pathogen has caused many outbreaks in the United States, and is fatal to some consumers, and particularly those with compromised immune systems. The comminution process causes the originally localized superficial contamination of *E. coli* O157:H7 to spread over the entire production line. Under-cooking of ground beef leads to the survival to *E. coli* O157:H7, upon entering the human digestive tracts, causing bacterial infections.

Similar to ground beef, NIBS can be internally contaminated with *E. coli* O157:H7. During mechanical tenderization, the tenderizing blades can carry the surface-contaminated bacteria along the path of the blades and into the interior of beef cuts, leading to internalization of *E. coli* O157:H7. Huang and Sheen (2010) investigated the process of mechanical tenderization and discovered...
that the internalization of \textit{E. coli} O157:H7 follows a deterministic pattern. Due to internalization of \textit{E. coli} O157:H7, undercooked non-intact mechanically tenderized beef steaks may contain the pathogen surviving through the cooking process, causing foodborne infections. Due to the potential risk of NIBS, the USDA Food Safety and Inspection Service (USDA FSIS) has expanded the \textit{E. coli} O157:H7 adulteration policy to include non-intact beef products (USDA FSIS, 2005).

Computer simulation and numerical analysis have been used recently to study the heat and mass transfer problems during cooking of meat products, particularly frozen ground beef patties. Pan \textit{et al.} (2000) studied the contact-heating process during cooking of frozen hamburgers in a clam-shell style grill, and developed a numerical method to simulate the heat and mass (moisture and fat) transfer based on the enthalpy formulation (Singh and Mannapperuma, 1990). Ou and Mittal (2007) used a finite difference method to simulate the heat and mass transfer that occurred during single-sided pan frying of frozen hamburgers with flippings. This is a very comprehensive study that considered phase transition (melting of ice), mass transfer (migration of moisture and fat), and conductive heating during pan frying of frozen meat. The physical properties of hamburgers and the thermal resistance of bacteria used in both Pan \textit{et al.} (2000) and Ou and Mittal (2007) were not directly measured, but taken from the published literature. More recently, Sargolzaie \textit{et al.} (2011) investigated the unsteady-state heat transfer process during double-sided cooking of frozen hamburgers using one-dimensional finite difference and three dimensional computational fluid dynamic (CFD) models. The effect of cooking temperature and pressure applied to hamburger patties on heat and mass transfer during cooking was evaluated. All these studies were focused on cooking frozen hamburgers, and involved solving both heat and mass transfer problems simultaneously. These numerical models and methods, although available, may not be suitable for analyzing and simulating the steak cooking process, as the steaks are usually cooked after they are thawed. Little information is available concerning heat transfer and computer simulation of open-flame gas grilling of steaks. In addition, these studies considered the effect of moisture and fat changes on heat transfer during hamburger cooking. The inclusion of mass transfer may increase computational difficulties and are more time-consuming during computation.

The objective of this research was to investigate the heat transfer and develop a simplified numerical model to simulate the heating process and estimate the inactivation of \textit{E. coli} O157:H7 during gas grilling of NIBS. This work also aimed to develop a methodology to simulate the temperature profiles in beef steaks and, based on the simulated results, to develop guidelines for safe cooking of NIBS.

2. Materials and methods

2.1. Gas grilling of beef steaks

A commercial gas grill (Model XXE-4, Baker’s Pride, New Rochelle, NY) was used in this study (Luchansky \textit{et al.}, 2009). Upon use, the gas grill was ignited and the oven was turned on for at least 10 min to allow the flame to stabilize. Upon grilling, the beef steaks were placed directly above the gas burner and were flipped from time to time before cooking was completed.

2.2. Beef steaks

Fresh beef meat (bottom round roast) was purchased from a local butcher shop. A custom-designed steak cutter was used to cut the beef meat into slices of 0.02 or 0.03 m (2 or 3 cm) in thickness. Depending on the size of beef cuts, the steaks were approximately 0.1–0.12 m in width and 0.12–0.15 m in length. Each steak was slit open (about 2 cm) in the middle along the plane parallel to the flat surfaces of the steak. The opening in the middle of steaks was prepared for inserting thermocouple probes, which were intended to ensure an accurate measurement of the temperature history at the geometric center during cooking.

2.3. Measurement of surface and center temperatures

Two type-T thermocouple probes (Model TMQSS-032(G)-24, Omega Engineering Inc., Stamford, CT) were inserted into the middle of the steak through the open slit. The diameter of Model TMQSS-032(G)-24 probes was 8 × 10^{-4} m. They were rigid enough to be inserted into the geometric center of beef steaks, yet sufficiently flexible to prevent moving during flipping of steaks. The diameter of these probes was small enough to prevent conductive heating through the metal sheath. Two additional Type T thermocouple probes (Model TMQSS-062(G)-24, Omega Engineering Inc.) were attached to the surface of a steak. Each thermocouple probe was inserted from the opposite surface through the steak to the measuring surface. This procedure was used to prevent direct conductive heating of thermocouples that would lead to erroneous temperature measurements. After the thermocouple probes were attached, the steak was sandwiched between two metal wire meshes. This precautionary measure was taken to prevent the movement of thermocouples during grilling and handling of the steak. The diameter of the metal wires was 1.6 × 10^{-3} m, and the opening of the metal mesh was 2.54 × 10^{-3} m. A thin iron wire (4 × 10^{-4} m in diameter) was used to fix the thermocouple probes in place and closed the middle opening used for inserting probes to measure the geometric center temperature of the steak.

2.4. Temperature measurement and data recording

The thermocouple probes attached to the steak were connected to a data-logger (Personal Daq/3000, IOTech Inc., Cleveland, OH). Two additional thermocouple probes were installed to monitor the boundary temperature conditions. One Type T probe (Model TMQSS-062(G)-24, Omega Engineering Inc.) was installed approximately 0.5 m above the oven to measure the air (ambient) temperature. Another Type J thermocouple probe (MQSS-125(G)-24, Omega Engineering Inc.) was attached 0.01 m directly below the metal frame on which a steak was placed. This probe was used

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## Table 1

Recommended cooking conditions on gas or red hot charcoal grill for beef steaks (http://www.omahasteaks.com/servlet/OnlineShopping?Dsp=32&FID=recipe_cook_chart).
to measure the air temperature directly below the steaks. The temperature data points were collected every 1 s using DasyLab data acquisition software (Version 9.0, DasyTec USA, Inc., Amherst, NH).

2.5. Thermal resistance of E. coli O157:H7 in beef

Thermal resistance of E. coli O157:H7 in beef meat was determined by measuring the survival of the bacteria exposed to constant temperatures maintained at 57, 60, 62.5, and 65 °C. A cocktail of three strains of bacteria, including E. coli O157:H7 strains, 45753-35, 933, and A9218-C1, was used to inoculate beef samples. Each bacterial culture strain, stored in a refrigerator on Sorbitol-MacConkey Agar (SMAC, BD, Sparks, MD) supplemented with Cefoxime and Tellurite (BD), or SMAC-CT agar plates, was transferred to 10 ml Brain Heart Infusion Broth (BHI, BD), incubated at 37 °C overnight, and then harvested by centrifugation, washing, and re-suspension in 5 ml 0.1% peptone water (PW, BD). A cocktail was formed by mixing equal volume of three bacterial strains. The bacterial cocktail was added to 0.5 g beef meat in a filter bag (Whirl-Pak® 7 oz, 95 x 180 x 0.08 mm, NASCO—Fort Atkinson, Fort Atkinson, WI). After inoculation, the filter bag was flattened and vacuum-sealed at ~2715 Pa. The samples were subject to submersion heating in a circulating water bath maintained at 57, 60, 62.5, and 65 °C, respectively. The samples were periodically retrieved to recover the survivors. PW (9.5 ml) was added to each bag and mixed for 3 min at maximum speed in a mechanical stomacher (Model BagMixer® 100 W, Interscience Co., France). The filtrate, after proper dilution, was plated onto Tryptic Soy agar (TSA, BD) plates. The TSA plates were maintained at room temperature for ~2 h to allow the injured cells to resuscitate, and then overlaid with 10 ml SMAT-CT agar plates (Duffy et al., 1999; Riordan et al., 2000). The colonies of E. coli O157:H7 were counted and converted to logarithms (base 10) of colony-forming units per g of beef, or log_{10} cfu/g. The D and z values of E. coli O157:H7 in beef were calculated from the survivor counts. The experiments were duplicated to determine the thermal resistance of the bacteria.

2.6. Heat transfer and numerical analysis

Steak grilling is a complex physical process that involves conduction, convection, and radiation of heat. Fig. 1 is a simplified diagram that illustrates the grilling process. During grilling, a steak was placed on the metal frame. The energy generated by the burning gas, baffled by the metal bars, was transferred to the steak by convection and some radiation. It is necessary to point out that the direct radiation was hampered by the metal bar baffles, and the steak was not directly exposed the gas flame. Within the steak, heat was transferred from the flat surface facing the flame to the interior, and to the air through the other surface by convection. This heat transfer process was a one-dimensional heat conduction problem that can be described using the following equation:

\[
\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} \tag{1}
\]

In Eq. (1), \( \alpha \) is the thermal diffusion coefficient (m/s^2); \( T \) is the temperature (°C) at any time and location within the steak; \( x \) is the vertical distance from the middle plane and; \( t \) is the heating time (s). The origin of the x-axis is located at the geometric center of the steak, and the steak is symmetric with respect to the middle horizontal plane. The thickness of the steak is 2H. At \( t = 0 \), it is assumed that the temperature is uniform across the steak and equal to the internal temperature (\( T_0 \)). To simply the notation, the surface facing the flame (\( x = -H \)) is designated as the flame side, and the other surface (\( x = H \)) as the air side. In all experiments, the steaks were only shrunk by 2.0–3.0% along the x direction after cooking. It is therefore concluded that the change in the dimension of beef steaks was negligible during grilling. Since the steaks were not directly exposed to the gas flames and the air temperature near the flame-side steak surface was very high, it was decided that the heat radiation was negligible and assumed that heat was transferred to steak surfaces by convection.

The boundary condition for the flame side steak surface is:

\[-k \frac{\partial T}{\partial x} \bigg|_{x=-H} = h_f T_f \big|_{x=-H} - T(-H, t) \tag{2}\]

For the air side, the boundary condition is

\[-k \frac{\partial T}{\partial x} \bigg|_{x=H} = h_a T(H, t) - T_a \tag{3}\]

In Eqs. (2) and (3), \( k \) is the effective thermal conductivity (W/m°C); \( h_f \) and \( h_a \) are the flame side and air side effective surface heat transfer coefficients (W/m^2°C), respectively; \( T_f \) and \( T_a \) are the flame side and air side air temperatures (°C); \( T(-H, t) \) and \( T(H, t) \) are the flame side and air side surface temperatures (°C).

To solve Eq. (1), an implicit finite difference method was used (Incropera and Dewitt, 1996; Huang, 2007). The implicit finite difference method was chosen because it was unconditionally stable. In the numerical analysis, the steak was evenly discretized into 50 layers, within and between each layer, the outgoing and inflowing energy was balanced (Fig. 2). Each node in the layers was indexed, starting from the flame side surface.
For the first node on the surface facing the flame, with normal convective conditions, the energy balance becomes

\[(1 + 2F_0) T_{p,1}^{n+1} - 2F_0 T_{p,1}^{n} = 2F_0 T_f + T_0, \tag{4}\]

In Eq. (4), \(p\) is the nodal point of time, which is also discretized; \(F_0\) is the Fourier number, and \(B_i\) is the Biot number on the flame side. The \(F_0\) and \(B_i\) are defined by

\[F_0 = \frac{x \Delta t}{\Delta x^2} \tag{5}\]

\[B_i = \frac{h_i \Delta x}{k} \tag{6}\]

In the above two equations, \(\Delta t\) is the time step between discretized time nodes; \(\Delta x\) is the thickness of each layer. The \(F_0\) number determines the internal heat transfer, and the \(B_i\) number controls the convective surface heat transfer.

Similarly, for any interior node (m) in the discretized domain of a steak, the energy balance equation is expressed as

\[(1 + 2F_0) T_{p,m}^{n+1} - F_0 (T_{p,m-1}^{n+1} + T_{p,m+1}^{n+1}) = T_m^p, \tag{7}\]

The discretization of steak generates a system of finite difference equations that must be solved numerically. The numerical technique used to solve the linear equation systems was called the Gauss–Seidel method (Huang, 2007). To numerically solve the heat transfer equation, a computer program written Matlab® (Release 2009b, The MathWorks, Inc., Natick, MA) was developed and validated for numerical analysis.

2.7. Determination of effective thermal coefficients and properties

To solve the heat transfer equations with complex boundary conditions, the effective values of \(\alpha, k, h_a\), and \(h_f\) were simultaneously determined by solving the discretized heat transfer equations (Eqs. (4) and (7)) in combination with an optimization function, fminsearch, which is an unconstrained nonlinear minimization method in Matlab’s Optimization Toolbox®. To use the optimization tool for solving \(\alpha, k, h_a\), and \(h_f\), an initial guessed value of each parameter was provided to initiate the finite difference method. The objective function of the optimization was

\[\text{min(error)} = \frac{1}{3} \sum [(T_{1,1} - T_{1,m})^2 + (T_{c,1} - T_{c,m})^2 + (T_{a,1} - T_{a,m})^2] \tag{8}\]

The thermocouple positions might be shifted when the steaks were flipped during cooking, leading to inaccurate measurement of temperature histories. In order to accurately estimate the effective values of \(\alpha, k, h_a\), and \(h_f\) during gas grilling, the temperature histories on both surface and geometric center of the steak (thickness = 0.02 m) collected before the steaks were flipped were used for optimization. The period from \(t = 0\) to the point when the steak was first flipped was termed as the first stage of heating in this study.

2.8. Computer simulation of heat transfer

After the effective values of \(\alpha, k, h_a\), and \(h_f\) were determined, a commercial numerical analysis tool (FlexPDE, Version 4.2.16, PDE Solutions, Inc., Spokane, WA) was used to simulate the cooking process. FlexPDE is a general purpose finite element partial differential equation solver. This software was used to verify the accuracy of the effective values of \(\alpha, k, h_a\), and \(h_f\) determined in the previous section by simulating the entire cooking processes for steaks of two different thickness (0.02 and 0.03 m).

After validating the effective heat transfer parameters (\(\alpha, k, h_a\), and \(h_f\), FlexPDE was used to simulate different heating scenarios. The temperature histories at the geometric center of steaks were used to calculate the achieved lethality for \(E. coli\) O157:H7.

2.9. Cumulative lethality of \(E. coli\) O157:H7

The General Method developed by (Biglow et al., 1920) was used to calculate the cumulative lethality (CL) of \(E. coli\) O157:H7 in beef during grilling. The cumulative lethality was calculated by.

\[CL = \frac{1}{D_{ref}} \int_0^t 10^{-\frac{t-\frac{z}{D_{ref}}}{D_{ref}}} dt. \tag{9}\]

3. Results and discussion

3.1. Thermal resistance of \(E. coli\) O157:H7 in NIBS

When \(E. coli\) O157:H7 was exposed to heat, under a constant temperature, the bacteria were inactivated following the first-order kinetics, and the \(\log_{10}\) concentration of bacteria was reduced in a linear manner as heating progressed (Fig. 3A). The \(D\)-values of \(E. coli\) O157:H7, which were the inverse of the slope of each curve in Fig. 3A, were used to calculate the \(z\)-value (Fig. 3B). The \(z\)-value calculated from the inverse of the slope in Fig. 3B was 4.46 °C.

3.2. Determination of effective thermal coefficients and properties

Figs. 4 and 5 show two examples of the temperature histories obtained during grilling steaks of 0.02 m in thickness. The effective

![Fig. 3. The D and z values of E. coli O157:H7 in beef steaks.](image-url)
heat transfer coefficients and thermal properties (thermal diffusivity and thermal conductivity) of steaks were numerically determined using the temperature histories of both surfaces and geometric center of 0.02 m steaks collected during the first stage of heating (Figs. 4 and 5). During this period, the thermocouples were more accurately positioned to the surfaces and geometric center of the steaks. By matching the temperature profiles at the geometric center and on both surfaces of beef steaks (0.02 m thickness) during the first stage of cooking, the effective heat transfer coefficients on both surfaces (facing the flame and air), thermal conductivity and thermal diffusivity of beef steaks were determined. The average effective thermal conductivity of steaks was $1.61 \times 10^{-7} \pm 0.31 \times 10^{-7}$ (m/s$^2$), mean ± standard deviation, $n = 4$; the average effective thermal conductivity was $0.231 \pm 0.03$ (W/m°C); the effective surface heat transfer coefficient on the flame side was $5.73 \pm 1.13$ (W/m$^2$°C), and the effective surface heat transfer coefficient on the open air side was $0.373 \pm 0.239$ (W/m$^2$°C). In a study reported by Sheridan & Shilton (2002), the thermal diffusivity of ground beef exposed to infrared radiation heating was $1.82 \times 10^{-7}$ and $1.62 \times 10^{-7}$, respectively, for patties containing 0% and 10% fat. Fontana et al. (1999) reported that the thermal diffusivity for beef muscles ranged from $1.39–2.15 \times 10^{-7}$ (m$^2$/s). In other publications, the thermal diffusivity of beef ranged from 1.1–1.3 $\times 10^{-7}$ (Huang & Liu, 2009; Rahman, 1996). The effective
thermal diffusivity of steaks obtained by numerical analysis in this study was comparable to the data reported in the literature (Fontan et al., 1999; Rahman, 1996; Sheridan & Shilton, 2002).

The effective thermal conductivity, however, was approximately 50–65% of the thermal conductivity of beef reported in the literature (Fontana et al., 1999; Huang & Liu, 2009; Pan et al., 2000). In general, the thermal diffusivity of beef (muscles and patties) ranges from 0.35 to 0.48 W/m°C). Therefore, the effective thermal conductivity obtained in this study was apparently smaller, and might not be the true physical property of the beef steaks. However, the effective thermal conductivity obtained in this study might have represented the compound effect of both internal and external heat and mass transfer. As moisture evaporated from the surfaces of beef steaks, the internal moisture migrated to the surfaces. Since moisture moved in opposite directions of the internal conductive heat fluxes, the migration of moisture might have caused a cooling effect, reducing the effectiveness of heat conduction. Therefore, the effective thermal conductivity obtained from numerical analysis might be the apparent thermal conductivity, and was smaller than the true thermal conductivity of beef.

3.3. Computer simulation of heat transfer process

When the steaks were flipped to cook the other side, the thermocouples attached onto both surfaces were moved, became loosed from the surfaces of steaks, and got exposed to the air, leading to erroneous temperature measurements on the steak surfaces. Therefore, the surface temperature histories measured after the first stage of heating were not used in the determination of the effective heat transfer coefficients and thermal properties in the previous section. However, since the thermocouples attached to the geometric center of steaks were still firmly attached, these center temperature histories were still accurate throughout the cooking process. If the simulated temperature history obtained by FlexPDE matched the experimentally measured temperature history at the geometric center of a steak, it would be an indication that the estimated effective heat transfer coefficients and thermal properties steaks were accurate.

Fig. 4 also depicts the comparison of the measured and simulated temperature histories on both surfaces and at the geometric center of a steak (Example 1). For the first stage \((t < 200\text{ s})\), before the steak was flipped, the simulated temperature profiles almost completely match the real-time measured temperature histories of the steak. After the steak was flipped, the thermocouples attached to the surfaces of the steaks were moved. Therefore, the measured and simulated temperature histories of the surfaces did not match well after the steak was flipped. However, the simulated and measured temperature histories at the geometric center were almost in complete agreement throughout the cooking process, suggesting that the estimated effective heat transfer parameters were fairly accurate. Fig. 5 shows another example of computer simulation of open-fire grilling of 0.02 m steak (Example 2). Although this steak was turned differently from the previous example, the measured and simulated temperature histories on the both surfaces (first stage only) and at the geometric center of the steak were in a close agreement (Fig. 5). Fig. 6 is another example (Example 3) showing the simulation results of cooking a 0.03 m steak. Again, the simulated and measured temperature histories at the geometric center matched very well. The simulation results shown in Figs. 4–6 for two thicknesses of steaks and different turning patterns clearly suggest that the effective surface heat transfer coefficients, thermal diffusivity, and thermal conductivity of steaks could be used to accurately simulate the geometric temperature of steaks during grilling. The difference between the measured and simulated temperatures at the geometric center of steaks was \(1.29 \pm 2.14\text{ °C} (\text{mean}\pm\text{standard deviation}, n = 583), 0.52 \pm 1.70\text{ °C} (n = 529), \text{and} -0.13 \pm 1.36\text{ °C} (n = 1072)\), respectively, for the temperature history curves shown in Figs. 4–6.
3.4 Lethality analysis of simulated heating scenarios

With the accuracy of computer simulation validated, FlexPDE was used to simulate different cooking scenarios for steak grilling. The objective of computer simulation was to evaluate the effect of different cooking conditions on inactivation of *E. coli* O157:H7.

Table 1 lists an example of recommended grilling instructions that are apparently designed for cooking intact beef steaks. For intact beef steaks, if properly prepared, the interior of the steaks should be almost sterile, and only the surfaces may be contaminated with bacteria. The cooking instructions are designed to suit the preference of consumers, i.e. the degree of doneness, and the definition of doneness may be different for each person. Even if the surfaces are contaminated, normal exposure to heat during grilling should be able to inactivate the contaminating bacteria. Therefore, few *E. coli* O157:H7 outbreaks have caused by intact beef steaks. For NIBS, these cooking instructions may not be adequate. To demonstrate if the commercial cooking instructions are sufficient to kill *E. coli* O157:H7 in NIBS, the finite element method (FlexPDE) was again used to simulate the grilling process. In all computer simulation listed below, the thickness of the streaks was assumed to be 2.54 cm (1 inch) and the initial temperature 5°C.

3.4.1 Scenario 1 – Cooking well-done according to Table 1

Generally, a steak with its internal temperature reaches 71°C or above is considered well-done. For a 2.54 cm steak, the cooking condition listed in Table 1 for a well-done steak calls for an 8 min cooking on the first side and another 6 min on the other side using gas fire or red hot char coal. If this cooking procedure is used to grill a NIBS kept at refrigerated temperatures prior to cooking, undercooking may occur. Fig. 7A illustrates the temperature distribution and histories on both surfaces, at 0.25 and 0.5 thicknesses from each surface, and at the geometric center of the steak. With a starting temperature of 5°C, the temperature at geometric center is only 58.5°C at the end of cooking, and the cumulative lethality is only 0.2 log-cycles for *E. coli* O157:H7 (Fig. 7B). If this process is used to cook a NIBS contaminated with *E. coli* O157:H7, the bacteria will survive and foodborne infection might occur. However, if the starting temperature of the steak was increased to 20°C (room temperature), the internal final temperature indeed could reach 71°C (or 160°F), as shown in Fig. 8. This condition indeed can cook a 2.54 cm steak to a well-done condition. The equivalent cumulative lethality at the geometric center is 230, which will kill all *E. coli* O157:H7 in the beef steak.

For intact beef steaks, most recipes recommend keeping the raw meat at room temperature prior to grilling in order to produce juicy and tender steaks. Raising the initial temperature to room temperature significantly reduces the cook time, which helps improve the quality of the final products. To prevent the bacteria from growing, however, it is necessary to keep raw meats (such as NIBS) refrigerated prior to cooking. This creates a low initial temperature condition, and extra cooking time is needed to increase the internal temperature of steaks to a point lethal to the bacteria. This example clearly demonstrates the need to adjust cooking time according to the initial temperature of NIBS and to check the internal temperature during cooking. To prevent foodborne infections resulting from *E. coli* O157:H7, it is necessary to...
educate consumers to adjust cooking time and use a thermometer to measure the internal temperature prior to consuming a NIBS.

3.4.2. Example 2 – Cooking a steak to 160°F (71.1 °C) at the geometric center, with one flip after the center temperature reaches 80°F (26.7 °C)

In this example, a steak is cooked to a final temperature of 160°F (71.1 °C), a recommended final internal temperature for cooking ground beef. During the cooking process, the steak is turned when the internal temperature at the geometric center reaches 80°F (26.7 °C). Fig. 9A illustrates the temperature histories at different locations of the steak. The temperature at the geometric center reaches 80°F at t = 428 s, or 7.13 min after the heating is started. After the steak is turned to cook from the other side, it takes an additional 564 s, or 9.4 min to allow the temperature at the geometric center to reach the final temperature. Therefore, the total cooking time is 992 s, or 16.53 min. Although the temperature at the geometric center has reached the final temperature, it does not mean that the steak is safe for human consumption. Fig. 9B shows the cumulative lethality values at the geometric center, −0.25H, and −0.5H. The lethality is 79.5 and 7.6 at the geometric center and −0.5H, respectively. The achieved lethality values at these locations are sufficient to inactivate E. coli O157:H7. However, the lethality value is only 3.6 at −0.25H. For low levels of contamination, this amount of lethality is usually sufficient to kill E. coli O157:H7 in NIBS. If the population of bacteria at this location is more than 3.6 logCFU, the inactivation may not be sufficient after cooking.

The temperature at the geometric center of foods with symmetric geometries has always been used to determine the endpoint of cooking processes if the thermal energy is uniformly applied to the surfaces. However, this example shows that the temperature at the geometric center may not be the most suitable location to determine a cooking process if the heat is not uniformly applied. In this example, one side of the steak receives more cooking than the other side. Therefore, even though the temperature at the geometric center has increased to the final temperature, the side that receives less cooking may still be undercooked, leading to survival of E. coli O157:H7.

3.4.3. Computer simulation of an evenly flipped steak during cooking

In the previous sections, it is clearly demonstrated that uneven heating during grilling can lead to inadequate cooking and could not ensure inactivation of the contaminating E. coli O157:H7 in NIBS if the initial temperature is low (5 °C). Therefore, it is necessary to use a process that can achieve more uniform heating. The computer simulation method was used to evaluate a cooking process for a 1-inch (2.54 cm) steak that is flipped once every 4 min with a total cooking time of 16 min. Fig. 10A illustrates the temperature distribution and histories at different locations of the steak during cooking. With this cooking scheme, the geometric center indeed becomes the slowest heating spot in the entire steak. All other points in the steak will cook faster than the geometric center. This location can become the reference point for evaluating the effectiveness of bacterial destruction. Fig. 10B illustrates the cumulative lethality of this process. Using this process, the cumulative lethality would be 2log at 887 s, 3log at 897 s, 4logs at 904 s, and 5logs at 910 s. The corresponding temperature at the geometric center would be 63, 63.7, 64.2, and 64.7 °C, respectively. This process is not too much longer than the time recommended in Table 1 for cooking a well-done 1 inch steak. If heating continues for additional 20s, the cumulative lethality would become almost 11 logs at 66 °C. Complete inactivation can be achieved with this cooking scheme. The cooking conditions shown in Fig. 10 are milder than those shown in Fig. 8, and the steak may be better cooked.

4. Conclusions

This research developed a simplified numerical analysis method to study the effective heat transfer during gas grilling of NIBS. This method was used to determine the effective surface heat transfer coefficients, thermal diffusivity, and conductivity of beef steaks. After the effective heat transfer parameters were validated, a finite element method was used to simulate the temperature distribution and histories during cooking 1-inch (2.54 cm) steaks and evaluate the survival of E. coli O157:H7 in NIBS. The computer simulation results show that some conventional heating times used to cook intact beef steaks may not be adequate to inactivate E. coli O157:H7 in NIBS if the initial temperature is very low (5 °C). The computer simulation results also suggest that NIBS must be cooked with evenly timed, but more frequent turnings during cooking to ensure food safety. The results of this research may be used as a guide for the food service industry to develop and update new cooking times for gas grilling of NIBS.

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