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Heat Transfer in Meat Patties during Double-Sided Cooking

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A simplified mathematical model was developed to predict the temperature profiles during meat patty cooking by double-sided pan-frying. Conduction was considered the main mechanism for heat transfer, and enthalpy formulation was used to avoid the discontinuity problem of the phase change during melting. The energy involved for vaporizing water was considered using appropriate boundary conditions. The model was solved according to a method based on an explicit finite difference approximation and was validated by comparing predicted and experimental temperature profiles obtained at 163°C and 204°C at the bottom platen and 177°C and 221°C at the top platen, respectively. The experimental and predicted data were in good agreement. The model was used to examine the sensitivity of patty cooking to different process conditions.

Keywords: heat transfer, meat patties, double-sided cooking

Ground beef is a popular food in the United States. Patties are typically made from ground beef and are cooked to obtain a microbiologically safe product with desired sensory characteristics. Undercooked ground beef patties have been implicated as a vehicle for *Escherichia coli* O157 : H7 (Hague *et al.*, 1994). For this reason, United States Department Agriculture has recommended that patties be cooked to 71°C for home preparation, and U.S. Food and Drug Administration has stated that patties should be cooked to 68°C for at least 15 s in commercial operations (Hague *et al.*, 1994).

The effects of meat cooking have been summarized as a softening of the connective tissue by conversion of the collagen to gelatin, accompanied by a toughening of the meat fibers due to heat coagulation of the myofibrillar proteins (Harris & Shorthose, 1988). Textural changes and shrinkage of the material can be observed during meat cooking. A consequence of denaturation of muscle proteins is a decrease in water-binding capacity. Furthermore, fat is melted during heating. These phenomena lead to mass transfer of fat and water from the material. These changes occurring during the relatively short cooking time emphasize the complexity of the process.

Different industrial methods of frying meat patties, such as deep fat frying, contact, infrared radiation, and convection heating have been discussed (Dagerskog & Sörenfors, 1978a, b). For double-sided contact frying of meat patties, Dagerskog and Bengtsson (1974) studied how surface crust appearance and yield depend on recipe, frying temperature, and time. They observed a continuous increase in surface color change with frying time. Color changes also depended on the frying temperature and on the different recipes studied. They concluded from the experimental data that the center temperature differs very little when different pan temperatures are applied above 140°C during the first two min, possibly due to the fact that the evaporating zone just below the surface crust is essentially a wet surface. However, they also observed that the plate temperature is important when the evaporation zone recedes inwards. They determined that a higher contact pressure resulted in shorter cooking times. However, depending on improved heat transfer and reduced swelling of the patties, the total weight loss was minimal. The explanation was that poor contact with low compression results in prolonged frying times and thus increasing weight loss, whereas in the case of high pressure the weight loss increases were due to higher compression.

Mathematical models are useful for better understanding of processes and for having a greater control of the cooking system. For this reason, some researchers have developed different models for studying the cooking process during pan-frying (Dagerskog, 1979a, b; Ikediala *et al.*, 1996; Pan, 1998). Dagerskog (1979a) proposed a model of heat and mass transfer during double-sided contact frying. For the calculation of temperature distribution, the heat conduction equation was solved. At the surface, the position of the evaporation zone and the surface temperature were calculated by simplified heat balance equations. However, the assumptions were not explained, making it difficult to follow the model development. The internal mass transfer was based on an empirical relation between water-retaining capacity and temperature. Using a heat transfer coefficient of 260 W/m^2 °C, the investigators found that when the mass transfer was considered, an increase in center temperature was observed. Dagerskog (1979b) modified his original model for use with the frozen state, but the model was not well explained. Experimental and theoretical values did not agree very well. In both cases, the models were solved by finite difference methods.

Ikediala *et al.* (1996) mathematically modeled the heat transfer in meat patties during single-sided pan-frying with and without turn-over and experimentally validated the model. They assumed that the heat was transferred inside the patty by conduction with no heat generation, negligible radiation and heat for fat melting, cylindrical geometry, homogeneous and isotropic meat, negligible meat patty shrinkage or swelling, and unfrozen initial state. They incorporated the heat removed due to moisture loss,

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which was experimentally determined. The model was solved by a finite element method. They used a heat transfer coefficient of 250 W/m^2 °C. The mechanism to explain the movement of water during pan-frying is not well understood but is thought to be due to a gradient of pressure or concentration, or to tissue shrinkage and accompanying water loss. Because not all the water loss is due to vaporization it would be incorrect to take into account the heat necessary to vaporize the water using the total water loss.

Pan (1998) developed a model for cooking a frozen hamburger patty based on the enthalpy formulation, considering the effect of mass transfer, variable heating temperature and heat transfer coefficient. Water and fat losses were obtained experimentally and affected the thermal properties. The prediction taking into account mass transfer did not significantly improve the results. The heat transfer coefficient was as high as 800 W/m^2 °C.

The aforementioned models considered the mass transfer, but because of the complex mechanisms involved, empirical equations were used. Empirical equations were also used to describe the heat removed by water evaporation. It would be useful to have a simplified model that takes into account the heat involved during water evaporation but avoids the empirical relations. In this work, a thorough analysis of the different assumptions and methodologies applied for developing a simplified model is considered. The theoretical values are validated with experimental ones.

Theory

When a frozen hamburger patty is placed on a grill (at $T >$ 160°C), the heat is transferred from the grill surface into the patty. The cooking process starts and, as far as heat penetrates the patty, fat and ice melt. Near the patty surface, the temperature exceeds 100°C, water evaporates, and by a combination of dehydration and browning reactions, the formation of a crust takes place. Water and fat are released from the patty, affecting mainly the heat transfer resistance between the hamburger and the hot plate. A solid-liquid interface (during melting) and a liquid-vapor interface (during evaporation) can be assumed when a frozen hamburger is cooked by contact. Thus, the problem can be studied as a multiphase, moving-boundary one.

The transient heat-transfer problems involving melting or solidification are generally referred to as "phase-change" or "moving-boundary" problems. Sometimes, they are referred to as "Stefan" problems, which refer to the pioneering work of Stefan around 1890 in connection with the melting of the polar ice cap (Ozisik, 1994). The mathematical formulation of phase-change problems is governed by the partial differential equation of the parabolic type; but as the location of the moving solid-liquid interface is not known a priori, it has to be determined as a part of the solution. As a result, the phase-change boundary problems are nonlinear, and their analytical solution is very difficult. The numerical methods of solving phase-change problems may be categorized as fixed-grid, variable-grid, front-fixing, adaptive-grid generation, and enthalpy methods (Ozisik, 1994). In food processing, some examples of this type of problem are air-drying, freezing-thawing, freeze-drying, or frying.

On one hand, heat transfer during contact cooking of a frozen patty can be modeled as a thawing process. Generally, foodstuffs have more than one phase, and each one has more than one component, resulting in a very complex system. However, for the thawing process, a food can be treated as consisting of just two components: an aqueous solution of various water-soluble compounds in water and the water-insoluble solids. The actual phase change takes place over a wide range of temperatures in which food properties change considerably. The thawing process inside the food material can be treated as heat conduction with phase change. Mannapperuma and Singh (1988) proposed a method that uses the approach of enthalpy formulation to solve this heat conduction problem involving gradual phase change under convective and fixed-temperature boundary conditions for simple geometrical shapes.

On the other hand, when the vaporization temperature is reached, a moving interface appears. Farkas *et al.* (1996a) proposed that the interface separates two regions—a core region and a crust region—and that the temperature at the interface is the boiling temperature of water. Vijayan and Singh (1997) studied the heat transfer during immersion frying of frozen foods and developed a model to connect the enthalpy formulation with the heat transfer in the crust.

Assuming the hamburger patty as an infinite slab of constant thickness L (Fig. 1); one-dimensional heat transfer; negligible heat transfer by radiation, chemical reactions and convection; and thermal properties changing with temperature, the governing equation for the core region can be written as (Mannapperuma & Singh, 1988):

$$\frac{\partial H(x,t)}{\partial t}=\frac{\partial}{\partial x}\left(k(H)\frac{\partial T(H)}{\partial x}\right) \quad S_1(t)<x<S_2(t);\ t>0, \qquad (1)$$

where H is the enthalpy, k is the thermal conductivity of the core, T is the temperature, t is the time, and x is the space coordinate perpendicular to the patty plane surface. $S_1(t)$ and $S_2(t)$ are the positions of moving boundaries associated with the evaporation interface and separate the crust region from the core. Two different moving boundaries are considered to take into account different plate temperatures. This equation is considered valid over the domain where only the thawing process takes place and the solution of the phase change problem is reduced to the solution of a single problem in terms of enthalpy.

The boundary conditions to solve Eq. (1) are:

$$T=T_b \qquad x=S_1(t),\ S_2(t);\ t>0, \qquad (2)$$

where T_b is the boiling temperature. A uniform temperature is assumed as the initial condition

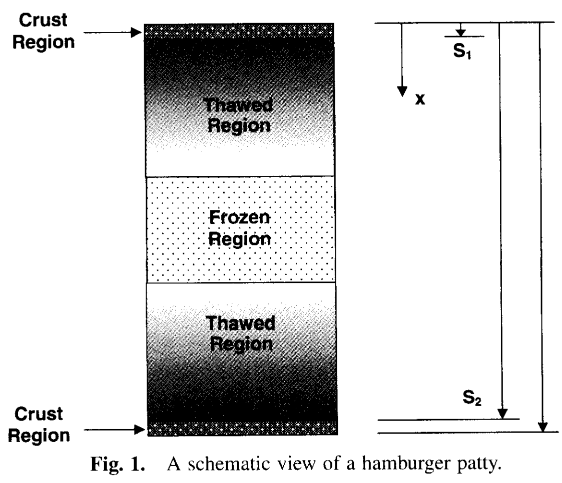

Fig. 1. A schematic view of a hamburger patty.

$$T=T_0 \qquad t=0;\ S_1(t)<x<S_2(t). \qquad (3)$$

Initially $S_1(t)=0$ and $S_2(t)=L$. Two further conditions are needed on the moving interfaces to determine their positions (Vijayan & Singh, 1997):

$$-k_{crust}\frac{\partial T}{\partial x}+k\frac{\partial T}{\partial x}=\lambda_v \rho m\frac{dS_i(t)}{dt} \quad x=S_i(t);\ t>0;\ i=1, 2, \quad (4)$$

where k_{crust} is the thermal conductivity of the crust, λ_v is the latent heat of water vaporization, ρ is the hamburger density, and m is the decimal moisture content.

The surface temperature can be calculated equating the heat flux from the plates and the conductive heat flux toward the crust:

$$-k_{crust}\frac{\partial T}{\partial x}=h(T_{p1}(t)-T) \quad x=0;\ t>0, \qquad (5)$$

$$-k_{crust}\frac{\partial T}{\partial x}=h(T-T_{p2}(t)) \quad x=L;\ t>0, \qquad (6)$$

where h is the contact heat transfer coefficient (Housova & Topinka, 1985), while $T_{p1}(t)$ and $T_{p2}(t)$ are the plate temperatures that can vary with time. Because the crust thickness is small compared with slab thickness for the usual cooking times, a linear temperature change in the crust can be assumed. Thus, the heat transfer in the crust region can be approximated by the relationship (Vijayan & Singh, 1997):

$$\frac{\partial T}{\partial x}=\frac{T_b-T}{S_1(t)} \quad x=0;\ t>0, \qquad (7)$$

$$\frac{\partial T}{\partial x}=\frac{T_b-T}{L-S_2(t)} \quad x=L;\ t>0. \qquad (8)$$

The solution of the system comprised of Eq. (1)–(8) was obtained numerically using a finite difference method. The patty thickness is divided into p segments of Δx thickness, and (p+1) nodes are considered. Mannapperuma (1988) demonstrated that Eq. (1) in finite difference form for each node i between time levels j to j+1 can be written as:

$$H_i^{j+1}=H_i^j+\frac{\Delta t}{\Delta x^2}\left[k^i_{i-\frac{1}{2}}(T^j_{i-1}-T^j_i)-k^i_{i+\frac{1}{2}}(T^j_i-T^j_{i+1})\right], \qquad (9)$$

where $k_{i\pm\frac{1}{2}}=\frac{k_{i\pm1}+k_i}{2}$. The enthalpy at the core node nearest to the interface can be calculated following the methodology proposed by Vijayan and Singh (1997). Considering m as the node nearest to the interface, the enthalpy at this node can be calculated as:

$$H_m^{j+1}=H_m^j+\frac{\Delta t}{\Delta x}\left[k_n^j\frac{(T_b-T^j_m)}{\Delta x_n}-k^j_{m+\frac{1}{2}}\frac{(T^j_m-T^j_{m+1})}{\Delta x}\right]$$

$$\Delta x_n\geq\frac{\Delta x}{2}, \qquad (10)$$

or

$$H_m^{j+1}=H_m^j+\frac{\Delta t}{\left(\Delta x_n+\frac{\Delta x}{2}\right)}\left[k_n^j\frac{(T_b-T^j_m)}{\Delta x_n}-k^j_{m+\frac{1}{2}}\frac{(T^j_m-T^j_{m+1})}{\Delta x}\right]$$

$$\Delta x_n<\frac{\Delta x}{2}, \qquad (11)$$

where Δx_n is the distance between the interface and the node next to the interface, and k_n is the average of thermal conductivities at the interface and at the node m. Once the nodal enthalpies are known using Eq. (9)–(10), temperatures at the nodes are calculated using a relationship between H and T which can be obtained from experimental data or interpolation tables. In this case, interpolation tables generated using the procedure developed by Mannapperuma (1988) were used.

Using the Euler's method, Eq. (4) can be written as,

$$S_1^{j+1}=S_1^j+k_{crust}\left[\frac{(T^j_{s1}-T_b)}{S^j_1}-\left(\frac{k_b+k_m}{2}\right)\frac{(T_b-T^j_m)}{\Delta x^j_n}\right]\frac{\Delta t}{\lambda_v\rho m}, \qquad (12)$$

where k_b is the thermal conductivity at the interface, k_m is the thermal conductivity at node m, and T_{s1} is the temperature at the patty surface ($x = 0$). An analogous equation can be obtained for the other interface position in terms of S_2 and T_{s2} (patty surface temperature at $x = L$). For this method, it is necessary to use initial values of $S_1(t)$ and $S_2(t)$. Farkas (1994) and Farkas *et al.* (1996b) proposed that the initial guess was at least one order of magnitude smaller than the distance traveled by the crust-core interface in one time step Δt used in the numerical solution and can be estimated by:

$$h(S_1(0))^2+k_{crust}S_1(0)=\frac{k_{crust}h\Delta t}{\rho\lambda_v}(T_{p1}(0)-T_b), \qquad (13)$$

$$h(L-S_2(0))^2+k_{crust}(L-S_2(0))=\frac{k_{crust}h\Delta t}{\rho\lambda_v}(T_{p2}(0)-T_b). \qquad (14)$$

The stability criterion used was (Mannapperuma & Singh, 1988):

$$\frac{k_i\Delta t}{\Delta x^2 C_i^j}\leq\frac{1}{2}, \qquad (15)$$

where C_i^j is the apparent specific heat at node i and level time j.

Materials and Methods

Simulation A computer program was written in Digital Visual Fortran Version 5.0. The input data are gap thickness between plates, product composition, unfreezable water content, initial freezing point, initial temperature of the product, plate temperature history, contact heat transfer coefficient, and total cooking time. The gap thickness between plates is smaller than the patty thickness to ensure that hamburger patty remains in contact with both plates during entire cooking time. Therefore, the "patty thickness L" in this study will be the set gap thickness between plates for calculation purposes.

Thermal properties varying with temperature were calculated using the procedure developed by Mannapperuma (1988) based on composition, unfreezable water content, and initial freezing point. The properties for the unfrozen state were estimated using the correlations (Valentas *et al.*, 1997) based on the composition (24% fat content, 60% w.b. moisture, 16% protein content; Pan, 1998) and the following values were obtained: density, 1056.7 kg/m^3; apparent specific heat, 3268 J/kg °C; thermal conductivity, 0.416 W/m °C; unfreezable water, 4% and initial freezing point, −1°C.

The contact heat transfer coefficient takes into account the resistance of a thin layer of fat/air/moisture. Generally, a constant value of this coefficient is assumed (Dagerskog, 1979a; Ikediala *et al.*, 1996). Housova and Topinka (1985) have shown experimentally that the contact heat transfer coefficient depends on product type, contact plate temperature, contact pressure, and stage in the heat treatment. The heat transfer coefficients measured were in the range of 200 to 1200 W/m^2 °C. Pan (1998) determined experimentally some values of this coefficient by measuring the heat flux involved and the temperatures of the heating surface and the patty surface. The contact heat transfer coefficients obtained were in the range of 200 to 1200 W/m^2 °C. Because this coefficient may vary with pressure, heating temperature, or layer composition, further investigation is necessary. In the present study, an average contact heat transfer coefficient of 900 W/m^2 °C was assumed.

Experimental procedure At a hamburger patty manufacturing plant, steel needles (diameter 1 mm) were inserted into the patties immediately after the patties were formed. Care was taken to ensure that in each case the needle tip was at the geometric center of a patty. Patties were frozen and sent to the laboratory. The average patty thickness was 0.0122 m. Prior to cooking, the patties were kept frozen in a walk-in freezer at −30°C.

A commercial, double-sided, clam-shell grill (Taylor, Rockton, IL) was used. The grill has two separated top heating plates covered with Teflon release sheets and one common bottom heating plate. Type "K" thermocouples were inserted by the grill manufacturer at 14 different positions in the top and bottom plates. The top and bottom plates were heated to specified temperatures. Temperatures were monitored using a data acquisition system consisting of a PC computer, 21X Micrologger (Campbell Scientific, Edmonton, Canada), and LABTECH Notebook software (Laboratory Technologies Corporation, Wilmington, MA).

Six patties were used for each trial, but the temperatures of only two were monitored. After the needle was extracted from a frozen patty, a type "T" thermocouple (Omega Engineering, Stamford, CT) enclosed in a Teflon™ sheath was inserted in the place of the needle. The two patties with thermocouples and four additional patties without thermocouples were placed on the grill, and the cooking cycle was carried out. Each experimental trial was repeated three times.

Results and Discussion

Figures 2 and 3 show the experimental and theoretical temperatures at the patty center and the plate temperatures for each case. The plate temperatures were set at 163°C and 177°C in the first case and at 204°C and 221°C in the second. A drop in the plate temperatures can be observed when the patties are placed on the grill. Some difference between the experimental and theoretical data can be related to the thermocouple positions in the hamburger. As can be seen, a small change in the position (0.0005 m) is associated with a significant change in the temperature profile, mainly at the end of the melting process. However, good agreement was obtained for both cases studied. The required center temperature of 71°C was reached only in the second case (Fig. 3).

Temperature profiles as a function of axial position for selected times are shown in Fig. 4. As shown, the liquid-solid interface during the melting process moves inward faster than the crust-core interface. Taking into account the boiling point temperature at the crust-core interface as well as the latent heat of

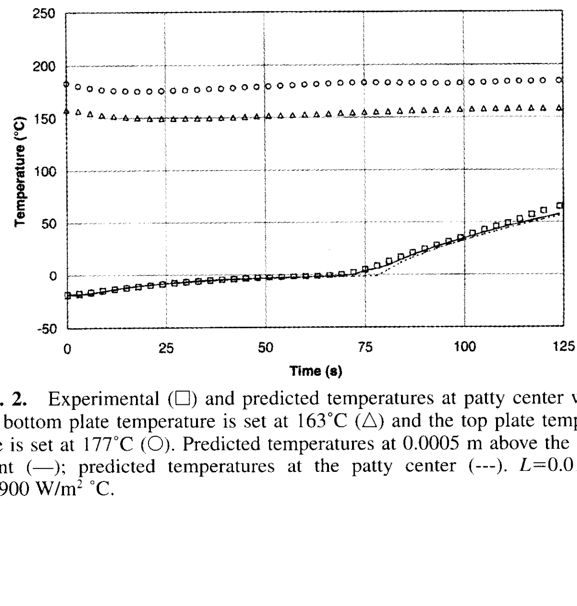

Fig. 2. Experimental (□) and predicted temperatures at patty center when the bottom plate temperature is set at 163°C (△) and the top plate temperature is set at 177°C (○). Predicted temperatures at 0.0005 m above the midpoint (—); predicted temperatures at the patty center (---). L=0.011m, h=900 W/m^2 °C.

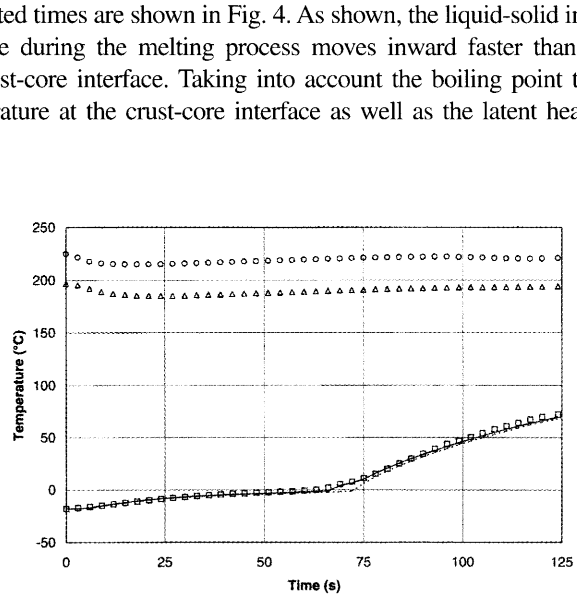

Fig. 3. Experimental (□) and predicted temperatures at patty center when the bottom plate temperature is set at 204°C (△) and the top plate temperature is set at 221°C (○). Predicted temperatures at 0.0005 m above the midpoint (—); predicted temperatures at the patty center (---). L=0.011m, h=900 W/m^2 °C.

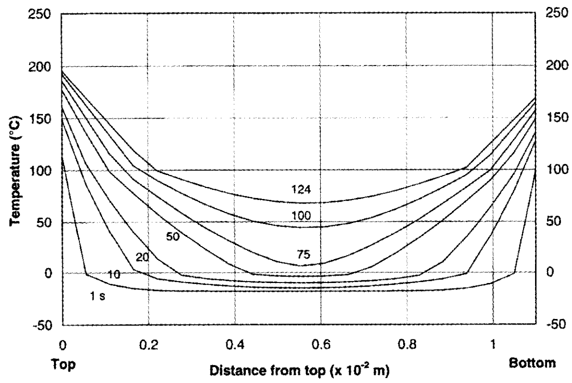

Fig. 4. Simulated temperature profiles when the bottom plate temperature is set at 204°C and the top plate temperature is set at 221°C at selected cooking times. L=0.011m, h=900 W/m^2 °C.

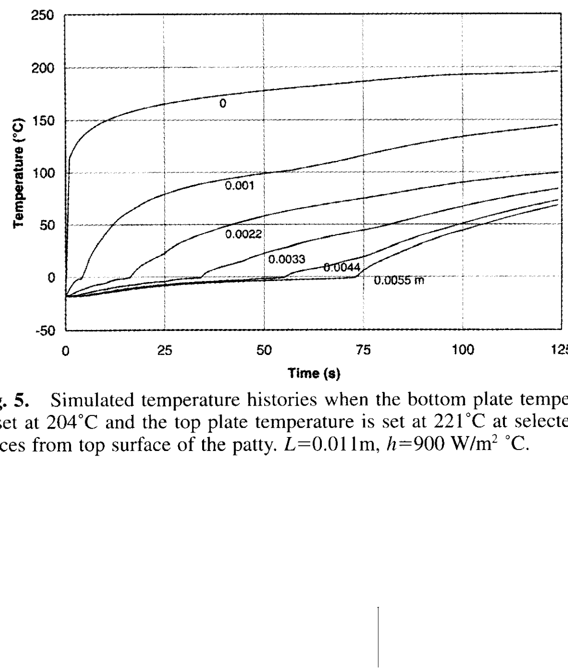

Fig. 5. Simulated temperature histories when the bottom plate temperature is set at 204°C and the top plate temperature is set at 221°C at selected distances from top surface of the patty. L=0.011m, h=900 W/m^2 °C.

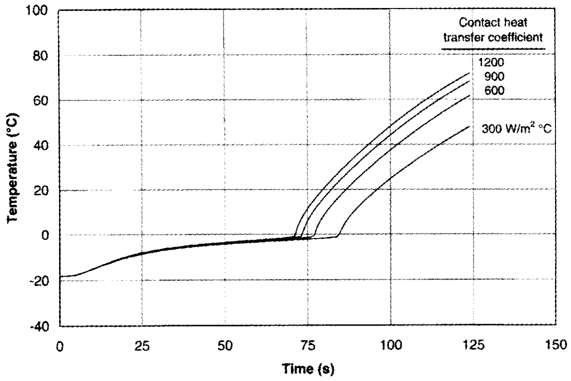

Fig. 6. Simulated temperature histories at patty center when the bottom plate temperature is set at 204°C and the top plate temperature is set at 221°C considering different heat transfer coefficients. L=0.011m.

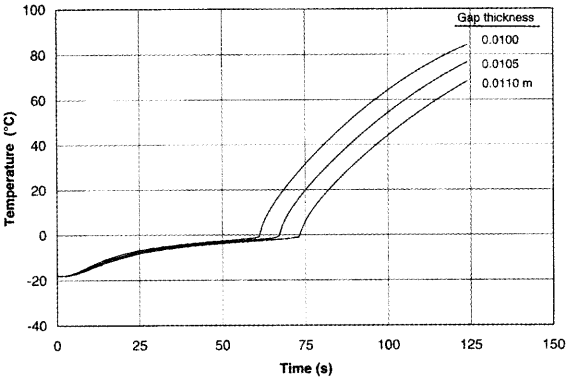

Fig. 7. Simulated temperature histories at patty center when the bottom plate temperature is set at 204°C and the top plate temperature is set at 221°C considering different gap thicknesses between plates. h=900 W/m^2 °C.

water vaporization, the center temperature will not increase as fast as when these conditions are not considered.

The temperature histories for selected positions are shown in Fig. 5. When the melting process has finished, the temperature increases more rapidly. Simulated temperature histories at patty center when bottom plate temperature is set to 204°C and the top plate temperature is set to 221°C are shown in Fig. 6 for different heat transfer coefficients. The influence of this coefficient on heat transfer is important. But in most of the previous studies a constant value has been assumed because of difficulty in obtaining experimental values of this coefficient. Further studies are needed to obtain reliable values of this coefficient for the entire cooking cycle.

Simulated center temperature histories when the bottom plate temperature is set to 204°C and the top plate temperature is set to 221°C considering different gap thicknesses between plates are shown in Fig. 7. The gap thickness between plates has a dramatic effect on the center temperature profile. A small change in the gap thickness, e.g. 1 mm, may result in more than 20°C difference in the end point temperature at the center of a patty. In this case, the same heat transfer coefficient of 900 W/m^2 °C is assumed, although there may be a relationship between gap thickness and heat transfer coefficient. When the patty is pressed more, the contact surface increases, which may increase the heat transfer. However, the fat and water releases also increase, and the composition of the layer between the hamburger and the plate may possibly change and affect the heat transfer. These variables should be investigated in future studies.

Although new information related to the heat transfer coefficient must be obtained, this simplified model provides sufficiently reliable results for the center temperature. This model is useful for predicting the heat transfer during contact heating and could be used to optimize the cooking process.

Conclusions

A simple mathematical model for predicting the heat transfer in meat patties during two-sided pan-frying was developed and solved by a numerical method. The model was validated experimentally by cooking hamburgers at different plate temperatures. Although the mass transfer was not considered, a good agreement between the experimental and theoretical values was obtained. An increase in the plate temperature reduced the time for reaching 71°C at the midpoint. The required center temperature was reached in 124 s when 204°C bottom and 221°C top set plate temperatures and a set gap thickness of 0.011 m were used.

Nomenclature

C Apparent specific heat, J/kg °C
h Contact heat transfer coefficient, W/m^2 °C
H Enthalpy, J/m^3
k Thermal conductivity in the core, W/m °C
k_b Thermal conductivity at the crust-core interface, W/m °C
k_{crust} Crust thermal conductivity, W/m °C
k_n Average of thermal conductivities at the crust-core interface and at the node m, W/m °C
m Moisture content, decimal
L Gap thickness, m
S_1, S_2 Positions of moving boundary that separates the crust region from the core one, m
t Time, s
T Temperature, °C
T_b Boiling temperature, °C
T_{p1}, T_{p2} Plate temperatures, °C
T_{s1}, T_{s2} Patty surface temperatures, °C
T_0 Initial temperature, °C
x Space coordinate perpendicular to the patty plate surface, m
Δt Time step, s
Δx Position step, m
Δx_n Distance between the interface and the node next to the interface, m
λ_v Latent heat of water vaporization, J/kg
ρ Hamburger density, kg/m^3
[subscripts]
i Node
j Time level
m The nearest node to the interface

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