Finite Element Modeling of Heat Transfer in Meat Patties During Single-sided Pan-frying

J.N. IKEDIALA, L.R. CORREIA, G.A. FENTON, and N. BEN-ABDALLAH

ABSTRACT

Our objectives were to mathematically model heat transfer in meat patties during single-sided pan-frying without and with turn-over, using the finite element method. Moisture loss rate was determined and included in the model to account for evaporation loss. The model was validated by comparing predicted and experimental temperature profiles monitored at three axial positions during pan-frying (one side and turn-over) at 140 and 180°C. Moisture loss rate, cooking time, and crust formation were functions of pan temperature and/or turn-over frequency and time. The least cooked point, predicted at the periphery of the top surface (no turn-over) and midplane (one turn-over), required 20 and 10 min, respectively, to be cooked well-done at 160°C. Turning-over more than once slightly decreased frying time, but may not produce crusted surface.

Key Words: cooking, pan-frying, meat patties, heat transfer, finite element modeling

INTRODUCTION

CONCERNS about the food borne illness ("hamburger disease") associated with *E. coli* O157:H7 have emphasized the need for thorough cooking of meat patties. Adequate heat treatment during cooking destroys pathogenic organisms while maintaining desirable quality characteristics.

Pan-frying is free from inherent concerns of oil uptake and fat thermal degradation compared to deep-fat frying, and gives a unique fried surface crust appearance (Dagerskog and Bengtsson, 1974; Yi and Chen, 1987). Pan-fried meat patties are usually preferred to broiling, baking, or microwaving on the basis of energy consumption and acceptability (Rhee and Drew, 1977), color, appearance and overall sensory quality (Dagerskog and Sörenfors, 1978; Smith and LeBlanc, 1990).

Most published studies of heat transfer in meat patties focussed on experimental aspects and considered only the final temperature attained by the least-cooked point. An internal temperature of 71.1°C is required to be labelled "fully cooked" or "ready-to-eat" according to USDA (1973) and Yi and Chen (1987). Published studies on heat and mass transfer modeling of meat patties has only been reported for convection oven cooking (Holtz and Skjöldebrand, 1986) and double-sided pan-frying (Dagerskog, 1979a,b; Housova and Topinka, 1985) processes. Dagerskog (1979a) reported relationships for density, thermal conductivity and specific heat capacity as functions of meat patty temperature, moisture and fat contents.

Applications of the finite element method (FEM) to model food processes are becoming widely accepted. However, there are limited applications of FEM in cooking, baking, microwave processing, and in quality and texture evaluations. The peculiarities and complexities associated with mathematical modeling in these areas, would make FEM extremely useful (Puri and Anantheswaran, 1993). DeBaerdemaeker et al. (1977) applied the FEM to simulate temperature profiles during pan-frying of beef steak with turning-over, assuming anisotropic and constant material properties. However, their results were not validated with experimental data. No verified model has been reported for single-sided pan-frying of meat patties. The objectives of our research were (1) to mathematically model heat transfer in meat patties during single-sided pan-frying, (2) to experimentally validate the model, and (3) to model the effects of turn-over frequency on temperature distribution, cooking time to desired doneness, and crust formation.

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MATERIALS & METHODS

Theoretical assumptions and heat transfer model development

The following assumptions were made in deriving the governing equation for heat transfer in the meat patty. Heat was transferred inside the patty by conduction, with no heat generation. Although pan temperature was assumed constant, heat transfer between the hot pan (griddle) surface and meat patty underside occurred via a thin film of air/oil/moisture. Due to comminution and mixing, the meat patty was assumed to be homogeneous and isotropic. Since the effect of such changes were reflected in the variable thermophysical properties, the heat of reaction due to denaturation and fat melting was neglected (Hallström, 1980). Meat patty shrinkage/swelling was also neglected.

For a cylindrical meat patty, the following governing equation was used to model 2-dimensional axisymmetric (assuming heat transfer in the circumferential direction was negligible) transient heat conduction, and incorporating the heat removed due to moisture loss:

$$\frac{\partial(\rho C_p T)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + L\rho\frac{d\overline{m}}{dt} \qquad (1)$$

The above equation is subject to the following initial and boundary conditions:

Initial conditions

The entire meat patty sample (Fig. 1a) was assumed to be at the same and known initial temperature and moisture content before frying, given by:

$$T(r,z,t=0) = \overline{T}_o \qquad (2)$$

$$m(r,z,t=0) = \overline{m}_o \qquad (3)$$

Boundary conditions

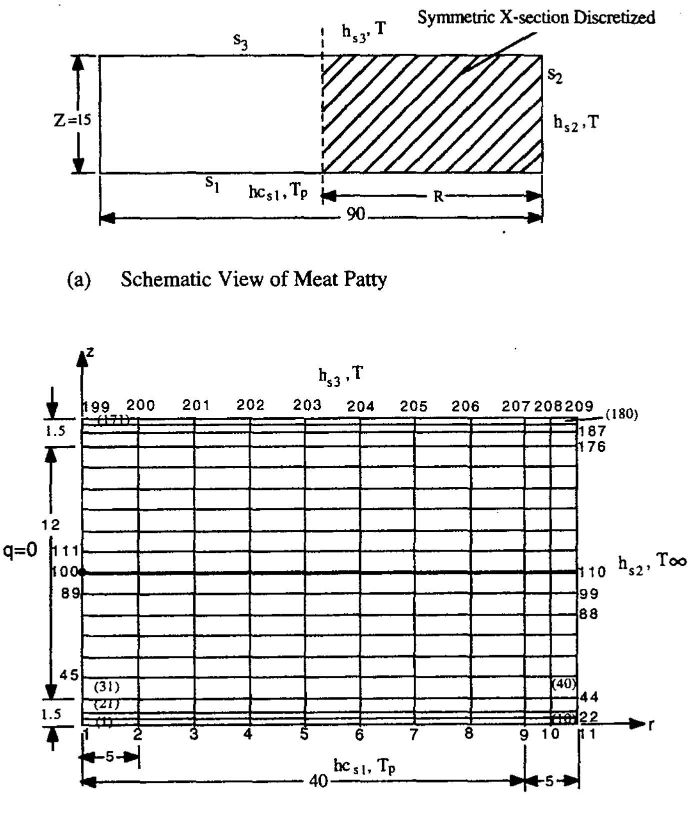
The meat patty underside S_1 was in contact with the hot pan (griddle plate) surface, with heat typically transferred from the griddle plate via a thin film of an oil/air/water interface to the patty. Hence, a contact heat transfer coefficient was employed for S_1 (Housova and Topinka, 1985). The circumferential surface S_2 and the top surface S_3 were exposed to free convection, and radiation was neglected. The boundary surfaces satisfied the following heat transfer conditions:

$$-k_z\frac{\partial T}{\partial z}\Big|_{z=0} = hc_{s1}(T_p - T_{s1}) \qquad (4)$$

on the patty-griddle interface, S_1,

$$k_r\frac{\partial T}{\partial r}\Big|_{r=R} = h_{s2}(T_{s2} - T_\infty) \qquad (5)$$

on the circumferential surface, S_2; and



(a) Schematic View of Meat Patty

(b) Meat Patty Discretization: 209 nodes x (180) elements
● Geometric center

Fig. 1—(a) Cross section of a meat patty with (b) a symmetric half discretized into 180 elements (in parenthesis) and 209 nodes. All dimensions in mm.

$$k_z\frac{\partial T}{\partial z}\Big|_{z=Z} = h_{s3}(T_{s3} - T_\infty) \quad (6)$$

on the top surface, S_3.

For the axisymmetric cylindrical beef patty, due to radial symmetry about the axial (z) direction:

$$\frac{\partial T}{\partial r}\Big|_{r=0} = 0 \quad (7)$$

Moisture loss rate determination

Published values of mass diffusivity and mass transfer coefficient for the meat patty are lacking. Hence, a moisture loss rate term accounting for evaporative moisture loss was experimentally determined. This involved the determination of the average moisture content of the patties as a function of frying time. For a fixed griddle temperature, T_p, the following exponential decay function was used:

$$\overline{m} = \overline{m}_o\exp(-ct) \quad (8)$$

Differentiating Eq. (8) with respect to time yields:

$$\frac{d\overline{m}}{dt} = -\overline{m}_o c\exp(-ct) \quad (9)$$

The exponential constant, c was assumed linearly related to pan temperature as follows:

$$c = a + b\cdot T_p \quad (10)$$

with the constants a and b determined by linear regression.

The governing Eq. (1) in conjunction with Eq. (9) and (10) with accompanying initial and boundary conditions (Eq. 2 to 7), were solved using the FEM.

Finite element transformation

The weighted residual method based on the Galerkin approximation (Zienkiewicz, 1971; Hughes, 1987; Rao, 1982) was used. Solution of the model equations using this method involves four main steps: (1) a statement of the strong form of the boundary value problem, (2) derivation of the weak form, (3) Galerkin approximation, and (4) matrix equation, which is the suitable form for computer implementation. The Galerkin approximation employs linear combinations of interpolating polynomials (basis or shape functions) spanning the entire global domain to approximate the field vector, T. The FEM transformation reduces the set of equations to a matrix form, a system of n equations in n unknowns, suitable for numerical implementation, stated below as:

$$[M]\dot{T} + [K]T - \{F\} = \vec{0} \quad (11)$$

with Eq. (2) and (3) as initial conditions for temperature and moisture, respectively. [M] contains the specific heat capacity and density of the material, whereas [K] contains the thermal conductivity. Following the element-by-element formulation strategy (Winget and Hughes, 1985), at the elemental (local) level the transformation yielded the matrix form expressed as follows:

$$[M^e_{ij}] = 2\pi\int_{v^e} N_i\rho\, C_p N_j r\, dr\, dz \quad (12)$$

$$[K^e_{ij}] = 2\pi\int_{v^e}\left(\frac{\partial N_i}{\partial r}k_r\frac{\partial N_j}{\partial r} + \frac{\partial N_i}{\partial z}k_z\frac{\partial N_j}{\partial z}\right) r\, dr\, dz + 2\pi\left[\int_{s^e_1} hc_{s1}N_iN_j r\, dr + \int_{s^e_2} h_{s2}N_iN_j r\, dz + \int_{s^e_3} h_{s3}N_iN_j r\, dr\right] \quad (13)$$

$$\{F^e_{ij}\} = 2\pi\int_{v^e} L\rho\frac{d\overline{m}}{dt}N_i r\, dr\, dz + 2\pi\int_{s^e_1} hc_{s1}T_pN_i r\, dr + 2\pi\int_{s^e_2} h_{s2}T_\infty N_i r\, dz + 2\pi\int_{s^e_3} h_{s3}T_\infty N_i r\, dr - \int_\Omega [K]\,T d\Omega - \int_\Omega [M]\dot{T} d\Omega \quad (14)$$

These matrices depend on the field vector (temperature), thus making the model and FEM transformation nonlinear. The last two terms were included to maintain the initial condition in the domain, which was assumed to be the same in all the elements. The thermophysical properties (ρ, C_p and k) employed were functions of temperature, moisture and fat contents as expressed by Dagerskog (1979a).

Implementation procedure

The governing equation along with boundary and initial conditions was solved using a generalized successive FEM implementation algorithm with the predictor-corrector iterative scheme (Hughes, 1987). The nonlinear iterative procedure employing the $\dot{T}$-form (temperature rate) during time stepping with the Newton-Raphson scheme was used (Winget and Hughes, 1985; Hughes, 1987). Although the nonlinearity was significant, the discrete number of elements was 180 and the CPU time generally remained less than 1 min.

The finite element computer program

A finite element computer program, MLFEM, containing linear static, linear transient, and nonlinear transient programs was developed. The linear transient fundamental structure was derived from DLEARN (Hughes, 1987), a linear static FEM program as adapted by Fenton (1992). The program MLFEM was capable of utilizing and solving up to a 9-node Lagrangian triangular or quadrilateral elements in Cartesian rectangular or axisymmetric cylindrical domains for linear or nonlinear analyses with mixed boundary conditions. The program was written in FORTRAN for the HP-UNIX® (HP 700 Series) mainframe computer. The symmetrical half portion of the meat patty (Fig. 1a) was discretized into 4-node quadrilaterals of 209 nodes and 180 elements (Fig. 1b). Although, Euler's generalized trapezoidal method was implemented in the program, a Crank-Nicholson scheme (time integration constant = 0.5) was employed in the simulations time stepping. A Gauss quadrature scheme (2×2 Gauss points) was used to perform numerical integration for evaluating element matrices. The solution procedure involved the inversion of the mass matrix, and thus was unconditionally stable for

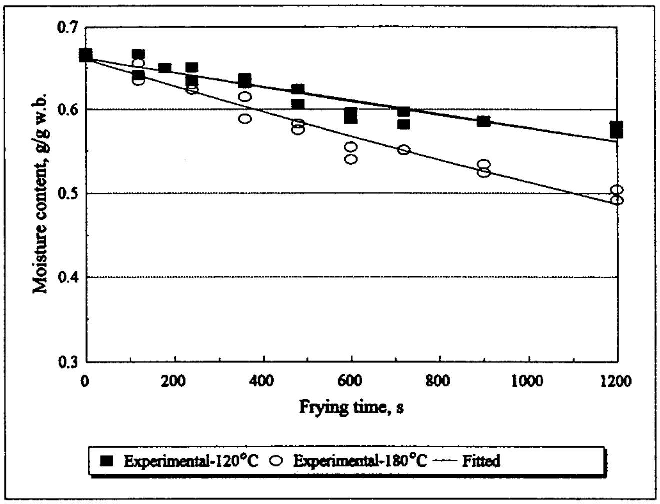


Fig. 2—Experimental and fitted meat patty moisture contents related to frying time at 120 and 180°C pan temperatures.

Table 1—Parameter estimates of predicted moisture content during pan-frying

Pan temp °C	Parameter estimates[a] $\bar{m}_0$ % w.b. Estimate	Std. error	Std. dev.	c s^{-1} Estimate	Std. error	Std. dev.
120	66.19	0.43	0.011	1.38E-04	1.36E-05	3.77E-06
140	66.41	0.35	0.009	1.63E-04	1.06E-05	8.69E-06
150	66.33	0.38	0.008	1.92E-04	1.19E-05	2.35E-06
160	66.78	0.38	0.008	2.24E-04	1.14E-05	9.59E-06
180	66.09	0.50	0.011	2.54E-04	1.58E-05	2.33E-06

[a] of equation 8: $\bar{m} = \bar{m}_0 \exp(-ct)$, (Eq. 8)

numerical integration constant ≥ 0.5 (Hughes, 1987). Furthermore, the program accommodates any number of boundary conditions swaps to simulate the turning-over operation, while maintaining the original discretization node numbering, both at the local and global domain. However, the finite time interval during turn-over of the frying meat patty was assumed negligible.

Sample preparation

Commercial beef patties, manufactured from one batch of lean meat trim, were procured from a local grocery store. The cylindrical patties of thickness 15 mm were separated from one another by nylon paper and immediately frozen. The frozen samples were later individually packed in waterproof sealed plastic bags to prevent moisture loss, and stored in a freezer at a mean temperature of −22 ± 0.13°C for <30 days. The sealed patties were thawed to 7 ± 2°C overnight in a refrigerator before being used in experiments. Since variation in thickness and diameter existed in the batch due to deformations during packing, a sharp cylindrical metal cutter with plunger was used to cut out patties of 90.0 ± 0.5 mm diameter. Thus, patties with mean thickness of 15 mm and diameter of 90 mm were used in the experiments, and these dimensions were also used for finite element discretization (Fig. 1).

Proximate composition of the all-beef low-fat patty was determined according to the following: moisture content by the oven method (ASAE, 1989), fat content by the Bligh and Dyer method (used by Woyewoda et al., 1986) and protein content by the AOAC (1990) procedure. The protein, fat and moisture contents of the meat patties were 20.2 ± 0.4%, 10.4 ± 0.7% and 66.5 ± 1.0% w.b., respectively.

The density of meat patty was determined by a mass-volume determination. The sample mass was measured using a Delta Range® weighing balance (model PM 4600, Metler Instrumente, Greinfersee, Switzerland), and the volume was measured with an air comparison pycnometer (model 930, Beckman Instruments Inc., Fullerton, CA). A line heat source thermal conductivity probe was used to measure thermal conductivity of patty samples. Details of the probe and procedure were reported by Sweat and Haugh (1974) and Ngadi (1995).

Frying equipment

Patties were fried using a Vulcan pan-fryer (electric griddle), model EG 602 (PMI Food Equipment Group, North York, ON, Canada). It consisted of a mild steel griddle plate, 600 × 540 × 15 mm with two temperature control devices, each connected to a pair of heating elements mounted below the plate. Two thermostats on these units controlled the heat such that the surface temperature on each half of the pan could vary from 95–285°C. Due to an uneven griddle surface temperature distribution observed during preliminary testing, an external miniature autotune temperature controller (Omega, model CN9000A, Stamford, CT) and two solid state relays (SSR) were used to obtain plate surface temperature control ±2 °C of set point value.

Frying operation

To find moisture loss rate, the average patty moisture content was determined at 120, 140, 150, 160 and 180°C pan temperatures for frying times up to 20 min. The runs were replicated and the data analyzed using the SAS® nonlinear regression procedure NLIN (SAS Institute, Inc., 1990) on a HP-UNIX® (HP 700 series) mainframe computer.

Three fine type "T" thermocouple wires (TT-T-30, Omega Engineering Inc., Stamford, CT) were enclosed in a sheath. The thermocouple probe section was encased in a 1.0 mm (outside diameter) aluminium tube of length 45 mm, to aid in pushing the sensor into the patty symmetric axis (radius of patty was 45 mm). The thermocouple probes were simultaneously inserted radially (from side S_2) at three positions in the meat patty, one close to the geometric center, and the others were above and below this point. This ensured that the three nodes used for model prediction would have to simultaneously match corresponding experimentally observed temperature positions, thus reducing errors due to uncertainty in both the radial and axial position placement. The geometric center of the meat patty corresponded to node 100 in the FEM mesh. Experimental temperature profiles of meat patties were obtained during frying operations (frying on one side only, or frying with patty overturned once) at 140 and 180 °C pan set point temperatures using an Omegalog data acquisition and control unit (model OM 700, Omega Engineering Inc., Stamford, CT). Patties were fried one at a time, with some manually turned-over after 200 sec of frying. Frying was generally discontinued when the center thermocouple reading was about 71°C which occurred between 8–10 min.

RESULTS & DISCUSSION

FEM model verification for constant material properties

To partially test the FEM computer program, analytical results of temperature profile in an infinite steel plate and cylinder with prescribed temperature and convection boundaries were obtained for arbitrarily chosen heating or cooling processes between 20–300°C and 0–30 min (Schneider, 1955; USDC, 1972). These were compared with the corresponding linear transient (constant thermophysical properties) FEM numerical solution. The maximum percentage difference between analytical and numerical data was 3% (Ikediala, 1994). In general, analytical and numerical solutions were in good agreement, thus validating the FEM model for constant thermophysical properties.

Thermal properties

Some density and thermal conductivity experiments were conducted to ascertain the suitability of using the heat transfer properties reported by Dagerskog (1979a). For patty samples with 66.5 % w.b. moisture content and 10.5 % fat content, the density ranged from 1055-1061 kg/m³ for the temperature range 5–13°C. For similar conditions, Dagerskog (1979a) reported density in the range 1056–1060 kg/m³. Furthermore, Ikediala (1994) determined that thermal conductivity values in their study correlated significantly (corr coeff = 0.974, P>R = 0.0001) with those of Dagerskog (1979a). Hence, empirical relations for thermal properties reported by Dagerskog (1979a), which involved more elaborate experimentation and statistical analysis, were considered acceptable for the mathematical model.

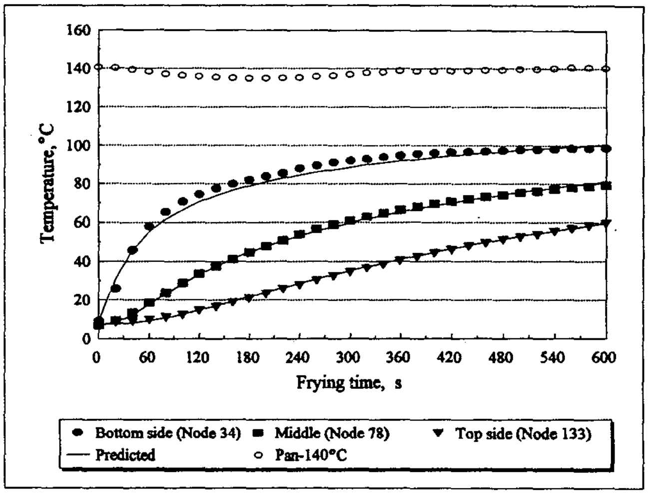


Fig. 3—Relationship between experimental and predicted meat patty temperatures and frying time at 140°C pan temperature. Nodes 34, 78 and 133 were located axially at 1.5 mm above the bottom, 2 mm below the midpoint, and 3 mm above the midpoint, respectively.

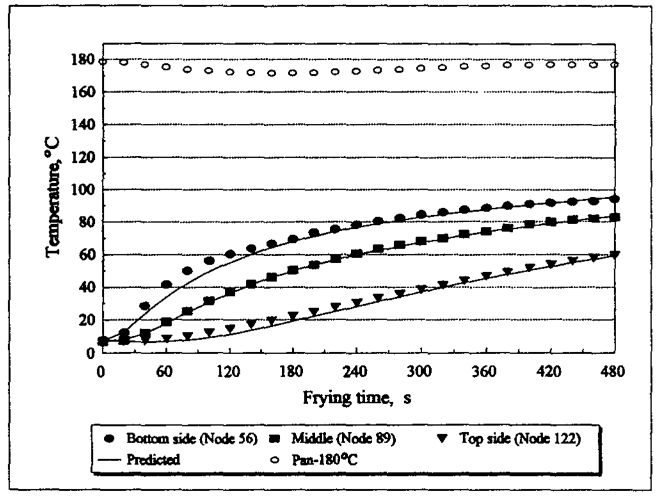


Fig. 4—Relationship between experimental and predicted meat patty temperatures and frying time at 180°C pan temperature. Nodes 56, 89 and 122 were located axially at 3.5 mm above the bottom, 1 mm below and 2 mm above the midpoint, respectively.

Moisture loss rate

Experimental data were fitted to the moisture content model [Eq. (8)]. The parameter estimates corresponding standard errors ($p \leq 0.05$) and standard deviations were compared (Table 1). A typical plot of average moisture content vs time at 120 and 180°C pan temperature (Fig. 2) showed good agreement between observed data and fitted curve. The fitted linear regression model [Eq. (10)] (Pr > the F-value = 0.002, $R^2 = 0.972$) was

$$c = -1.13\ 10^{-4} + 2.04 \times 10^{-6} \cdot T_p$$

where the standard errors of the intercept and the slope were $3.01 \times 10^{-5}\ s^{-1}$ and $2.00 \times 10^{-7}\ s^{-1}{}^{\circ}C^{-1}$, respectively. The standard deviation between observed and predicted values for moisture content, and that for the exponential constant c ranged from 0.011-0.009 kg/kg w.b. and 2.33×10^{-6} to $9.59 \times 10^{-6}\ s^{-1}$, respectively. The assumed model, which also incorporated the influence of pan temperature on moisture loss in the meat patty, sufficiently fitted moisture content with frying time.

Model validation

For the simulations, the assumed contact heat transfer coefficient hc_{s1} was 250 W/(m²°C), whereas the assumed heat transfer coefficients h_{s2} and h_{s3} ranged from 10 to 30 W/(m²°C). These values were similar to those reported and employed by Skjöldebrand (1980), Dagerskog (1979a, b) and Housova and Topinka (1985). The griddle surface temperature dropped when the cold (7 ± 2°C) patty was placed on the pan. This drop was substantial and it's profile was not very consistent but differed for frying replicates, pan set temperatures and frying mode (with or without turning). Housova and Topinka (1985) observed similar pan surface cooling during double-sided contact cooking. However, Dagerskog (1979a, b) did not report such observation. The pan surface "cooling" was particularly higher for frying with turn-over, with as much as 12°C drop observed during some frying operations.

It was difficult to place the thermocouples at exactly the same position during replication. Thus, for experimental and model comparisons, nodal points from the model and thermocouple positions in observed profiles were matched.

Frying without turn-over

Results of experimental and predicted temperature profiles obtained for 140 and 180°C pan temperatures were compared (Fig. 3 and 4). The temperature of the meat patty bottom side rose sharply during early stages of heating, but gradually tended to level off at about 100°C during the 10 min frying operation. The middle section showed a more gradual response, while the top side did not show much response to heating during the first 60 sec. The temperature evolution of nodes at, or close to, the geometric center of the meat patty showed very good agreement (<4% difference and standard deviation from 0.74–0.83°C) with that observed. However, a higher standard deviation (0.59–3.24°C) was observed at nodes farther from the geometric center. The higher standard deviation was obtained for the bottom side when frying at 180°C (Fig. 4).

Model predictions underestimated the profiles for nodes close to the top and bottom surfaces of the patty for the first 180 sec of frying. This corresponded to the period when the pan surface temperature was still decreasing. The discrepancies may also be partly attributed to the assumption of an average moisture content and moisture loss rate for all nodal points in the patty sample. This may be different for the bottom, middle and top sections during this period because of markedly different temperature gradients. Similar results of underprediction were reported for surface nodes with the finite difference method and integral transformation models of Dagerskog (1979a,b) during double-sided pan-frying of meat patties. On the contrary, Holtz and Skjöldebrand (1986) using the FDM, reported better agreement at the surface than at the center during oven roasting of meat balls. However, the model markedly underpredicted the experimental center temperature profile.

Our results appear to be in closer agreement than the aforementioned models, although model prediction adequacy measures were not reported or expressed previously. Dagerskog (1979b) and Holtz and Skjöldebrand (1986) reported maximum discrepancies between observed and predicted temperatures of 15 and 17°C, during double-sided pan-frying and oven roasting of meat patties, respectively. This may be related to the step changes in both pan surface temperature and thermal properties (Dagerskog, 1979b), and surface temperature simplification using linear regression (Holtz and Skjöldebrand, 1986).

Housova and Topinka (1985) also noted that contact heat transfer coefficient value did not remain constant during contact frying, but was influenced by degrees of deformation and shrinkage, degrees of juice release, fat melting and moisture evaporation. Furthermore, local values of heat transfer coefficient may have differed across the product-pan surface. Housova and Topinka (1985) suggested that local nonuniformity of surface temperature of a meat patty during contact heating, imparted characteristic features of lighter and darker spots, typical of and probably peculiar to contact-cooked meat.

Nodes close to the top side were markedly colder than the bottom side during single-sided frying without turn-over. They would require prolonged heating to cook to a well-done state, thus subjecting the underside to overcooking (burning). The profile of nodes farther above the center was apparently not influenced by pan temperature until after about 5 min heating. At pan temperatures of 140 and 180°C, the center temperature attained a well-done cooked state in 10 and 8 min, respectively.

Frying with turn-over

Predicted and experimental meat patty temperatures using 140 and 180°C pan temperatures were also compared (Fig. 5 and 6). Upon turning-over, the new bottom temperatures gradually increased and top temperatures decreased as expected. DeBaerdemaeker et al. (1977) reported a gradual response for the simulated bottom and top surface temperature profiles. However, Dagerskog (1979b) showed a step change ("jump") in temperature at nodes close to the two flat surfaces immediately after each turn-over for single-sided pan-frying. Although, neither of those models were validated with experimental data, our experimental observations confirmed that the change was gradual. Steep temperature gradients typically existed at the top and bottom patty surfaces during the first 100 sec after turn-over. Hence, some discrepancy may be expected between predicted and experimental temperature results. After 200 sec of turn-over, the temperature of the top surface decreased continuously from 80°C or more (attained before turn-over) to <50°C. During the remaining frying (4.5 min), except for nodes very close to the midpoint which showed a moderate increase, the temperature of the top side did not increase. However, the center temperature was apparently unaffected by the turn-over.

The standard deviation ranges of the differences between predicted and observed temperature profiles of the nodes farther inside, near the top, and near the bottom were 1.00–1.72, 2.45–2.53, and 0.79–2.00°C, respectively. The differences between predicted and experimental results were generally <11%. The higher standard deviation was observed for frying at 140°C pan temperature (Fig. 5), probably because the nodes were much closer to the two flat surfaces compared to corresponding nodes at 180°C pan temperature (Fig. 6). Thus, there was better agreement between predicted and observed temperatures farther inside the patty than on top and bottom surfaces.

It was difficult to ascertain the exact location of thermocouples. Some discrepancy may have existed between presumed and actual thermocouple locations, as the discrete nodal points were matched with experimental data. Furthermore, the turned-over patty may have been placed on a fouled pan surface. Sticking of the meat patty underside to griddle surface and fouling occurred because the griddle surface was not stainless steel. The heat transfer coefficient may have been altered and not constant throughout frying (Housova and Topinka, 1985). Dagerskog (1979a, b), Housova and Topinka (1985) and Holtz and Skjöldebrand (1986) did not report this condition since heating was from both sides and they did not turn the patty during frying. In addition, the finite time that elapsed during turning-over was neglected in our model. Nevertheless, predicted and experimental temperature profiles were similar.

Model simulation of pan-frying, crust formation and cooking time

Without turn-over. We also plotted (Fig. 7) the simulated temperature evolutions of i) the bottom patty surface S_1 (nodes 12 and 21) in contact with the hot plate at 160°C, ii) the top surface S_3 (nodes 188 and 197) exposed to the ambient air, and iii) the meat patty horizontal mid-plane (nodes 100, 104 and 109). Along the horizontal mid-plane, temperatures did not differ between axial (node 100) and radial (node 104, midway

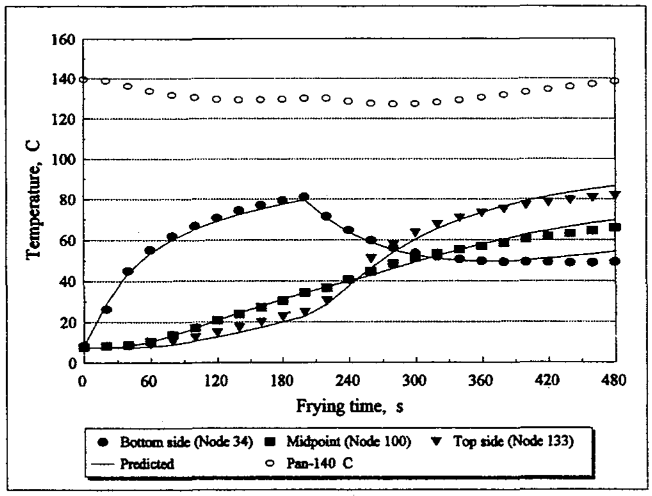


Fig. 5—Relationship between experimental and predicted meat patty temperatures and frying time at 140°C pan temperature (patty overturned once). Nodes 34, 100 and 133 were located axially at 1.5 mm above the bottom, at the midpoint, and 3 mm above the midpoint, respectively.

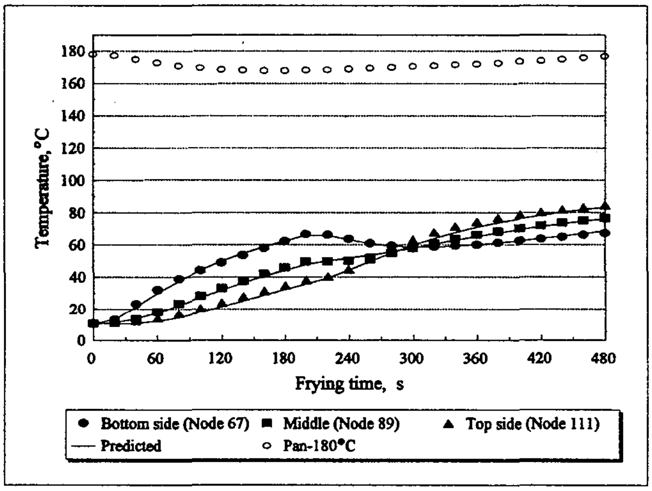


Fig. 6—Relationship between experimental and predicted meat patty temperatures and frying time at 180°C pan temperature (patty overturned once). Nodes 67, 89 and 111 were located axially at 4.5 mm above the bottom, 1 mm below and above the midpoint, respectively.

between axial and circumferential surface) positions in the patty. However, near the circumferential surface (nodes 21, 109 and 197), a difference of up to 8°C was found, suggesting that notable cooling also occurred on the radial (outside) surface of patties. The lowest temperature was at the periphery of the top surface S_3 (node 197). Thus, meat patty cooking time for single-sided pan-frying without turning-over should be based on the temperature at the top peripheral location. The simulated time for node 197 to reach 71°C, a well-done cooked stage, was 1190 sec (≈20 min). At that cooking time, the simulated temperatures at the corresponding locations were mid-plane (node 109) 86°C and the bottom surface (node 21) 129°C. Thus single-sided pan-frying without turning-over required a long time to cook the top surface, while the underside surface may become charred.

The crust is defined as those parts of the product that reached a temperature >100°C (Holtz and Skjöldebrand, 1986). Simulations at 160°C pan temperature showed that after 3 min frying, a crust <0.4 mm was formed. This differed from the report of Dagerskog (1979b), who found crust thickness for the same conditions to be 1.0 mm. However, those findings were valid for double-sided frying in which contact pressure and a covering

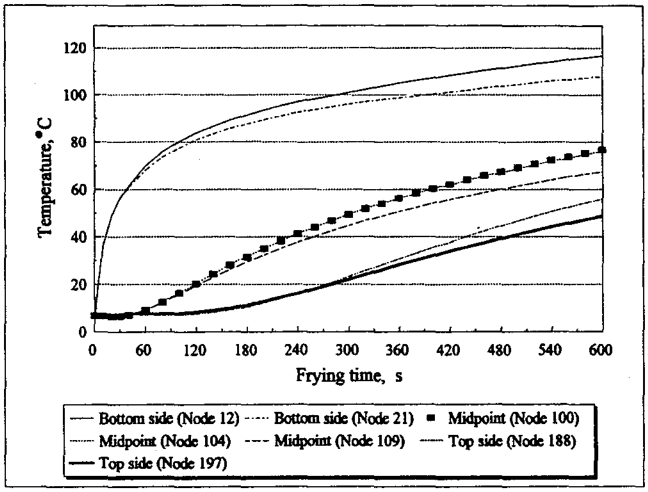


Fig. 7—Simulated meat patty temperature profiles at 160°C pan temperature. Nodes 12, 100 and 188 were located axially at 0.38 mm above the bottom, at the midpoint, and 0.38 mm below the top surface, respectively. Nodes 21, 109 and 197 were located, respectively, at the same elevation as nodes 12, 100 and 188 but were closer to the circumferential surface. Node 104 was halfway between nodes 100 and 109 along the mid-plane.

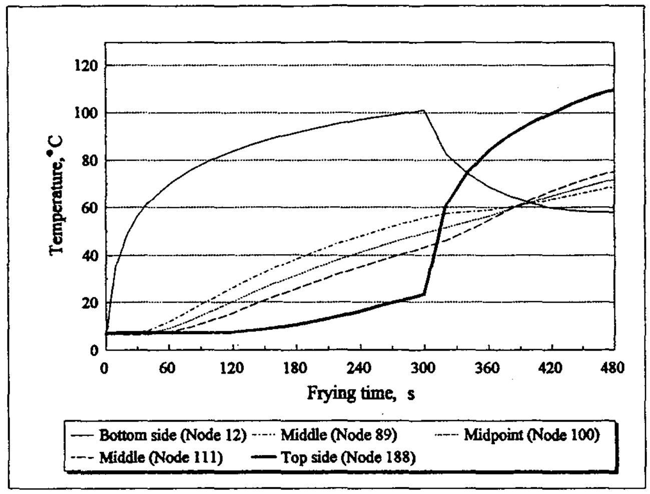


Fig. 9—Simulated meat patty temperature profiles at 160°C pan temperature (overturned once). Nodes 12, 89, 100, 111 and 188 were located axially at 0.38 mm above the bottom, 1 mm below the midpoint, at the midpoint, 1 mm above the midpoint, and 0.38 mm below the top surface, respectively.

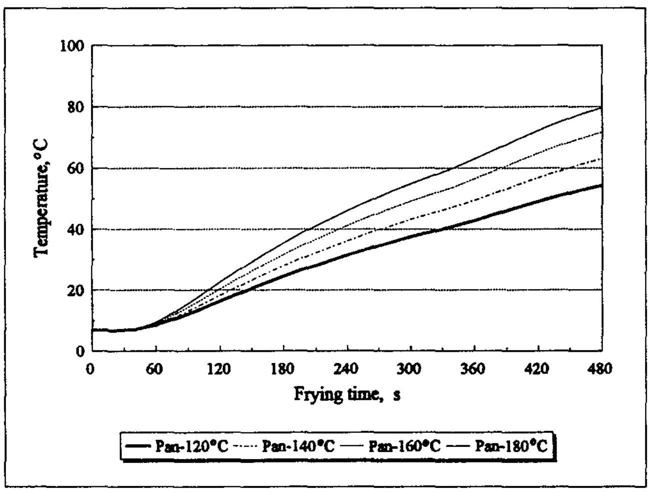


Fig. 8—Comparison of simulated meat patty geometric center (midpoint) temperature profiles during single-sided pan-frying at different pan temperatures (overturned once).

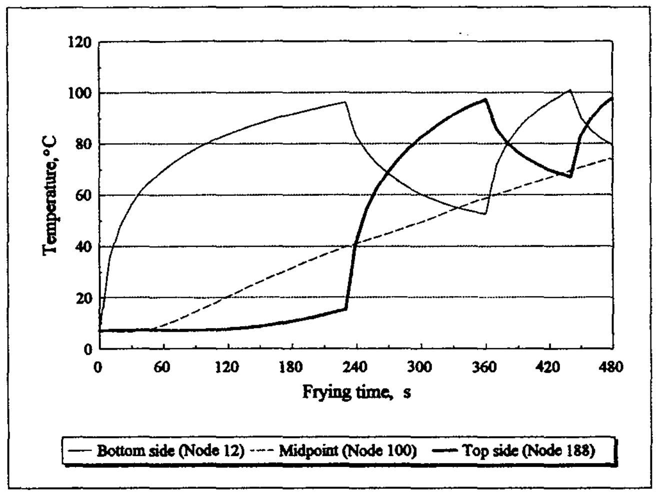


Fig. 10—Simulated meat patty temperature profiles at 160°C pan temperature (overturned three times). Nodes 12, 100 and 188 were located axially at 0.38 mm above the bottom, at the midpoint, and 0.38 mm below the top surface, respectively.

with fat (oil) before frying may have increased patty contact with the hot pan, resulting in higher heat transfer rate. Our results more closely confirmed the results of Ateba and Mittal (1994) during deep-fat frying of meat balls, which showed crust development initiating at 300 sec (6 min) of frying, with only 0.5 mm thickness formed at 370 sec.

With turn-over. A comparison was made of center temperature profiles for the patty sample we used (Fig. 8). The center temperatures were similar for the first 60 sec of frying. However, Dagerskog and Bengtsson (1974) reported that center temperature deviated very little among pan temperatures above 140°C during the first 120 sec in double-sided pan-frying. In our results, with turn-over, the least heated point was along the mid-plane (node 109) and attained well done cooked state in 580 sec (≈10 min). A pan temperature of at least 160°C would be required for a well-cooked patty when frying for less than 10 min with turn-over.

Computer simulated temperature profiles for single-sided pan-frying with turn-over (Fig. 9 and 10) showed that cooking time and formation of crust were functions of pan temperature and turning-over times (period during frying and frequency). Crust formation may not necessarily be obtained (Fig. 9) on one or both flat surfaces of meat patty during frying with turn-over. The timing of the turn-over period and the number of turns are essential in forming the crusted surface(s). At 160°C pan temperature, increasing the number of overturns from one to three reduced cooking time by 30 sec. Dagerskog (1977) also suggested that a higher turn-over frequency may reduce frying time. However, it was evident (Fig. 10) that depending on turning-over intervals and frying time, only one or neither surface would form a minimum (0.38 mm) crust. Thus, to ensure crusted surfaces on both sides, a meat patty should only be turned-over once, when the bottom surface reached 100°C. As a general rule, it has been recommended that turning over be performed at ½ to ⅔ of total frying time (Ikediala, 1994).

The simulated cooking times required for the patty geometric center to reach 71°C with three overturns using single-sided pan-frying and double-sided pan-frying were 470 and 225 s, respectively. Dagerskog and Bengtsson (1974) determined that to achieve the same degree of doneness (center temperature), yield and color, double-sided pan-frying could take less than half the time for single-sided frying. Thus, the FEM program we developed could be used to optimize both single and double-sided pan-frying processes.

CONCLUSIONS

A MATHEMATICAL MODEL of transient heat transfer in meat patties during single-sided pan-frying was developed and solved using FEM. The model was validated experimentally for patties fried with and without turn-over, and good agreement was obtained between model predicted and observed temperature profiles. Standard deviation between predicted and observed profiles at bottom, midpoint and top sides ranged from 0.59–3.24°C. The least cooked point during frying with turn-over was found at the mid-plane circumferential surface, and not the geometric center. Turning-over reduced frying time by half, but at a given pan temperature, the time before turn-over and frequency determined whether a crusted surface(s) would be obtained. Cooking to a microbially safe temperature and to obtain a crust on both surfaces does not require overcooking.

NOMENCLATURE

a, b = constants with dimension s^{-1} and $s^{-1} \cdot {}^\circ C^{-1}$, respectively
c = exponential constant, s^{-1}
C_p = specific heat capacity, J/(kg°C)
e = element
{F} = force vector or forcing function (temperature component of the element force vector)
hc_{s1} = contact heat transfer coefficient on surface S_1, W/(m^2°C)
h_{s2} = convective heat transfer coefficient on surface S_2, W/(m^2°C)
h_{s3} = convective heat transfer coefficient on surface S_3, W/(m^2°C)
k_r = thermal conductivity in radial direction, W/(m°C)
k_z = thermal conductivity in axial direction, W/(m°C)
[K] = conductance or stiffness (heat conductivity) matrix
L = latent heat of vaporization of water, 2257 kJ/kg moisture
$\bar{m}$ = average meat patty moisture content, kg/kg (w.b.)
$\bar{m}_o$ = average meat patty initial moisture content, kg/kg (w.b.)
$d\bar{m}/dt$ = average moisture loss rate, kg moisture/(kg · s)
[M] = mass (heat capacity) matrix
n = number of nodes (in the element)
N_i = shape function associated with node i
N_j = shape function associated with node j
Pr = probability
r, z = radial and axial (vertical) coordinate directions, respectively, m
R = outside radius of meat patty, m
R^2 = coefficient of determination
S_1,S_2,S_3 = meat patty heat transfer surfaces
t = meat patty frying time, sec
T = meat patty temperature, °C
T_p = griddle plate temperature, °C
T_{s1} = meat patty surface, S_1 temperature, °C
T_{s2} = meat patty circumferential surface, S_2 temperature, °C
T_{s3} = meat patty surface S_3 temperature, °C
T_j = discrete nodal temperature associated with node j, °C
$\bar{T}_o$ = average initial meat patty temperature, °C
$\dot{T}_j$ = time differential of field vector, T (temperature rate).
T_∞ = ambient air temperature, °C
v = volume, m^3
Z = height (top) of meat patty, m
ρ = density, kg/m^3

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