Modeling Heat Transfer During Oven Roasting of Unstuffed Turkeys

H.C. CHANG, J.A. CARPENTER, and R.T. TOLEDO

ABSTRACT

A finite element method was used to solve the unsteady state heat transfer equations for heating of turkeys in a conventional electric oven. Breast, and thigh and wing joint temperature in 5.9, 6.8, 8.6, 9.5, and 10.4 kg turkeys were simulated. A surface heat transfer coefficient of 19.252 W/m²K determined by transient temperature measurements in the same oven, was used. Thermal conductivity measured using a line heat source probe from 0 to 80°C was 0.464 W/mK. Simulated temperatures were within 1.33, 1.47, and 1.22°C of experimental values of temperature in the breast, thigh, and wing joint, respectively. Initial temperature 1 , 2, and 3°C lower than 4°C required additional baking time of 16, 22, and 27 min., respectively for the thigh joint to reach the target endpoint temperature.

Key Words: turkey, heat transfer, mathematical modeling, thermal conductivity, finite element

INTRODUCTION

A CLEAR UNDERSTANDING OF THE DYNAMICS OF CHANGES IN food product properties during processing treatments is required to maintain the desired quality, texture, and sterility. The finite-element method has been successfully applied for understanding, describing, and analyzing food-processing operations. Many works have been reported using mathematical modeling to simulate roasting of meat. Bengtsson et al. (1976) modeled beef roasting and compared the results with experimental measurements. They found that varying partial pressure of water vapor during the roasting process affected rate of moisture loss by evaporation. Similar results were also reported by Godsalve et al. (1977a, b), Hung et al. (1978) and Singh et al. (1983). de Baerdemaeker et al. (1977) showed how heat transfer problems may be solved using the finite element method in roasting beef and chicken.

The unstuffed turkey can be a potential carrier of foodborne illnesses associated with infections by *Salmonella*. The best means of control is ensuring that temperatures attained are adequate to inactivate pathogens. Our objective was to simulate heat transfer of unstuffed turkeys in order to identify sources of variation in cooking times needed to achieve a specified endpoint temperature at critical points in baked whole turkeys.

MATERIALS & METHODS

Heat transfer coefficient estimation

Intact turkey muscles were made into 10.2×7.6×2.54 cm brick-shaped samples. The simple geometry simplified calculations of the surface heat transfer coefficient. The sample was introduced into the oven (Model 130, Daycor, Pasadena, CA) at 162.8°C, with convection fan disabled. The meat temperature was measured with a copper-constantan thermocouple in the center of the sample block. Thermocouple output was acquired and recorded through a Model DAS-TC interface card (Omega, Stamford, CT) and a personal computer. Temperature data were stored at 30 sec intervals for 1.5 h. The experiment was repeated four times. Recorded data were imported into a spreadsheet and analyzed for the slope of the semilogarithmic heating curve, from which, the effective mean surface heat transfer coefficient was calculated (Toledo, 1991).

Thermal conductivity determination

Thermal conductivity was measured using the line heat source method (Gratzek and Toledo, 1991). Thermal conductivity of turkey muscle was measured at 0, 20, 40, 60, and 80°C. Turkey breasts were cored into cylindrical samples 2.54 cm dia. × 15 cm. The thermal conductivity probe was inserted into the center of the sample. When initial temperatures between samples and surrounding environments had equilibrated, the probe was energized for 25 sec while temperature in the probe was continuously monitored using the DAS-TC temperature acquisition card. Data were retrieved and imported into a spreadsheet. The slope of the linear portion of a plot of temperature rise (ΔT) vs ln(t) and the level of energy input were used to calculate thermal conductivity of the samples as follows (Heally, et al., 1976):

$$k = C\,q / 4\pi\ (\text{slope})$$

where q, the rate of energy input, is:

$$q = 2\,I^2\,R$$

We used a current (I) of 0.130 A , and the heater wire resistance (R) was 106.9 Ohms. The instrument was calibrated using glycerin at room temperature (≈23°C) , and the calibration constant, C, was 0.948.

The plots of ΔT vs ln time had high correlation coefficients ($1<r^2<0.99$) for the linear portion which was between 10 and 25 sec after energizing the heater. The same sample was used for measurement at all temperatures. Samples were immersed in a water bath set at the designated temperature. Two water baths were used. After measurement was completed at one temperature, the sample was transferred to the other water bath maintained at the next desired temperature. All measurements were replicated 4 times at each temperature.

Model equations for heat transfer, initial and boundary conditions

The equations were for two-dimensional unsteady state heat transfer with surface conduction and evaporation. To reduce the complexity of the problem, the turkey was assumed to be an infinitely long column with a cross-section (Fig. 1). Breast temperature was calculated in the thickest section in the upper part, wing joint temperature was calculated in the thickest section of the lower left side, and thigh joint temperature was calculated at the bend in the lower middle part of the figure. The assumption of two-dimensional heat transfer was justified by actual temperature vs time curves where temperature recorded in the breast at positions 2.54 cm from each side of a point on a plane perpendicular to the plane (Fig. 1), at the same depth from the surface, were practically the same (Chang, 1997).

The following assumptions were used in formulating the finite-element model for temperature changes at specific points during roasting: (1) Water at the surface behaves like free, or unbound, water as long as sufficient water is available; and (2) There is no internal movement of water by convective flow and diffusion. Only heat transfer was considered within the meat while evaporation was consid-

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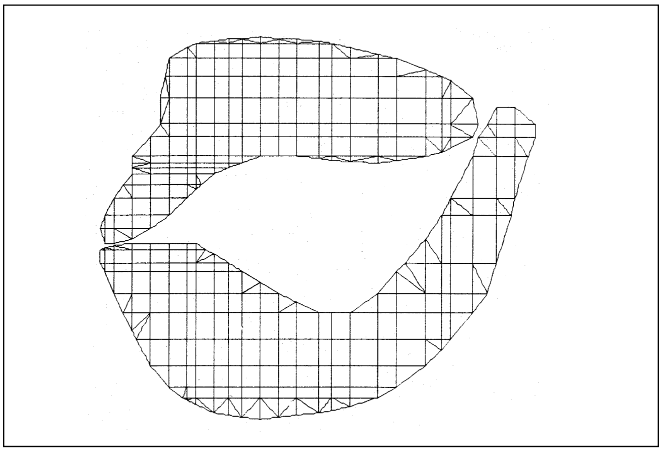

Fig. 1—Finite element mesh layout for the cross-section of the unstuffed turkey.

ered a surface boundary condition. The differential equation for heat transfer in two dimensions is:

$$\frac{\partial T}{\partial t} = a_x \frac{\partial T}{\partial x} + a_y \frac{\partial T}{\partial y} \tag{1}$$

X and Y are the spatial dimensions, t is time, T is temperature, $\alpha = k/\rho C_p$ is the thermal diffusivity of the meat, and the subscripts x and y allow the directional variation of thermal conductivity to be incorporated into the model. k is the thermal conductivity, C_p is specific heat, and ρ is density. Equation (1) is valid as long as there is no internal heat generation (Singh et al., 1983).

The initial condition is $T = T_0$, when the turkeys were introduced into ovens at uniform temperature distribution of T_0°C. The surface boundary condition was that the conductive heat transfer equaled the sum of heat input by convection and heat removed by the latent heat of evaporation at the meat surface. Surface heat transfer to the meat, and convection gain or loss through the surface is given by (De Baerdemaeker et al., 1976):

$$h(T-T_\infty)+q=-(k_x\frac{\partial T}{\partial X}n_x+k_y\frac{\partial T}{\partial Y}) \tag{2}$$

where n_x and n_y are the direction cosines; h is the surface heat-transfer coefficient; T is the fluid (air) temperature surrounding the body; and q is a boundary heat source, which is the latent heat of evaporation. It was assumed that ρ, $C_{p,}$ q and h were rotationally symmetric. The term q in Eq. (2) is

$$q = W\ \rho\ L_v\ (\partial m/\partial t)$$

where the W are weighting functions in the Galerkin finite element formulation, using the shape functions N_i and N_j (Segerlind, 1984); L_v is the latent heat of vaporization, and m is moisture concentration, dry basis. The rate of moisture loss ∂m/∂t was modeled based on an average evaporative moisture loss of 8.6% obtained during cooking of 30 whole unstuffed turkeys. This moisture loss was prorated over the total cooking time by using a mass transfer coefficient and the vapor pressure of water at the surface temperature of the turkey.

The Galerkin Residual Method (Crandal, 1956; Strang and Fix, 1973) was used to transform eqn. 2 into a finite element form. A trial function for T, which satisfied the boundary conditions, was substituted into Eq. (2) and the resulting residual was made orthogonal with respect to a weighting function W.

$$\int_v[\frac{\partial}{\partial X}(k_x\frac{\partial T}{\partial X})+\frac{\partial}{\partial Y}(k_y\frac{\partial T}{\partial Y})-C_p\frac{\partial T}{\partial t}]\ W\ d\ V = 0 \tag{3}$$

Integrating Eq. (3) by parts and applying the divergence theorem yields:

$$\int[k_x\frac{\partial T\partial W}{\partial X\partial X}+k_y\frac{\partial T\partial W}{\partial Y\partial Y}+\rho C_p\frac{\partial T}{\partial t}W]dV+\int[k_x\frac{\partial T}{\partial X}n_x+k_y\frac{\partial T}{\partial Y}n_y]WdS=0 \tag{4}$$

The solution domain was subdivided into smaller elements to which Eq. (4) was applied. The variable temperature T^c in each element was approximated as a function of the temperature values at the nodes (Segerlind, 1984). $T^c = T_1N_1 + T_2N_2 + T_3N_3$, where T_1 , T_2 , T_3 are the nodal temperatures and N_1 , N_2 , N_3 are element shape functions derived from the geometry of the element. The weighting function W was made identical to the interpolating functions N_1 , N_2 , N_3. The equation for T^c in vector form was substituted into Eq. (4) to form a matrix for each element. The differential equation in matrix notation is: $[K]\{T\}+[C]\ \partial\{T\}/\partial t-\{F\}=0$.

The global stiffness matrix [K], and capacitance matrix [C], are square matrices which includes the thermal conductivity, specific heat, and are dependent on the element geometry. The force vector {F} is a column vector of values of the heat input, while {T} is a column vector of the unknown nodal temperatures (Segerlind, 1984). The differential equation was solved using the weighted residual method with linear time elements (Warzee, 1974). The procedure calculated a temperature at the present time $\{T\}_1$, from temperature at a previous time $\{T\}_o$ using a variable time-step size Δt which satisfied the following:

$$(2/3)[K]+(1/\Delta t)[C]\{T\}_1=(1/3)\{F\}_o+(2/3)\{F\}_1-([K]/3-[C]/\Delta t)\{T\}_o$$

where $\{F\}_o$ and $\{F\}_1$ are heat inputs at the beginning and end of the time step.

Generation of experimental time-temperature data

Data were extracted from results of a previous study (Chang et al., 1998) that recorded time-temperature histories at different parts of the turkey on a total of 126 birds baked in a conventional oven at 162.8°C. We used the data on temperature histories of 15 each of fresh or previously frozen/thawed turkeys which were baked unstuffed and unsheilded. The turkeys ranged in weight from 5.8 to 10.4 kg with 3 fresh or previously frozen birds in each of 5 weight categories within this range. The weight categories were designated as a range to guide the suppliers on the weight distribution of the turkeys required. Exact weight of each bird was considered when evaluating temperature histories and moisture loses. Procedures for preparing the turkeys and cooking were described by Chang et al. (1998). Detailed time-temperature histories at 1 min interval throughout the cooking and hold period after cooking, for each bird at 8 positions in the bird, have been reported (Chang, 1997). Temperature data at three thermocouple locations were extracted and used as the experimental data for model verification. These locations were at the breast in the customary insertion point for pop-up timers, 4.13 cm deep from the surface. The thermocouples at the wing and thigh joints were inserted in the bird perpendicular to its outside surface 1.25 cm towards the surface from the bones forming the wing and thigh joints.

Model validation

A computer program written in C was used to solve the two-dimensional field finite element equation with the given appropriate inputs. To account for bird weight in the simulations, size factors were determined using the ratio of average flesh thickness between the 5.9 kg bird and those in the other weight categories. The heat transfer model was validated against the average observed temperature profiles. The root-mean-square of deviations between predicted and observed values was calculated by:

$$\sigma = (\Sigma_{j=1\mapsto N} (T_{p,j} - T_{o,j})^2 /(n - 1)^2)^{½}$$

where Tpj and Toj are predicted and observed temperatures, respectively, at a specific time. A paired-T test was performed to determine the difference between predicted and observed values (SAS Institute, Inc., 1985)

RESULTS & DISCUSSION

Surface heat transfer coefficient and thermal conductivity

The effective surface heat transfer coefficient, under the same conditions used in the cooking of the turkeys, was 19.252 W/m^{2}K. This value is an effective heat transfer coefficient which combines convection and radiation. Thus, the oven temperature, radiant heating element positioning, and temperature cycling in the oven would affect this value. We obtained a higher value than that reported by Huang and Mittal (1993), which could be attributed to differences in the type of oven used. Thermal conductivity was 0.461, 0.464, 0.464, 0.462, and 0.468 at 0, 20, 40, 60 and 80°C, respectively. The effect of temperature was not significant. The average, 0.464 W/m K, was used in the heat transfer simulation.

Heat transfer simulation results

Computer simulated temperature histories in the breast, thigh joint, and wing joint were calculated based on an initial temperature at 4°C. The size factors for the different weight ranges were evaluated using a ratio of average flesh thickness, which included the breast, thigh, and wing joint muscles, in the smallest weight turkey (5.9 kg) to that of larger birds. The turkey shape was obtained using a cross section of the turkey in the customary timer position which was cut parallel from 2.54 cm below the keel bone. This cross-sectional area included the thigh joint and wing joint positions (Fig. 1).

The simulated temperature histories agreed with the experimental data (Fig. 2 to 6). Paired-t test confirmed that there were no significant differences between predicted values and individually observed values (p>0.05). The root mean square deviations between predicted and observed temperatures in the breast, thigh joint and wing joint, respectively, were 1.33, 1.47 and 1.22°C (Table 1).

The breast temperature always reached 82°C in less time than the temperatures at thigh joint and wing joint in an oven at 162.8°C (Fig. 7B). However, temperatures at the thigh joint and wing joint reached 82°C almost at the same time. Thus, if the initial temperatures in the breast, thigh joint and wing joint were at 4°C, when the thigh joint reached 82°C, the wing joint could be > 71°C, the temperature required to kill *Salmonella*.

Additional cooking time for different initial temperatures

The initial turkey body temperature has a strong influence on the total time required to bake turkeys. The initial temperature in the breast, thigh, and wing joint muscles may not be the same because of differences of flesh thickness in these positions. When initial breast temperature was 4°C, the thigh joint and wing joint temperatures were < 4°C. Thus, additional heating time may be needed for the thigh and wing joint to reach the desired endpoint temperature. Heating time needed for the thigh joint and wing joint to reach 4°C from lower initial temperatures in the first 40 min of baking, was simulated. An average 118°C oven temperature was used for simulations because in the initial phase of baking, birds were introduced into a cold oven and timing was started when the oven was energized. The average measured oven temperature from ambient to 40 min after

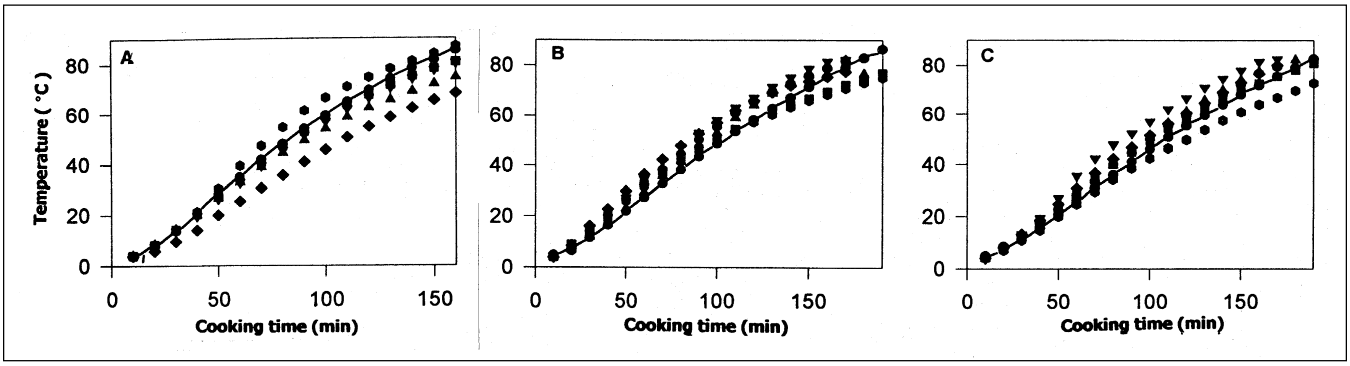

Fig. 2—Comparison of observed and calculated temperature histories at critical points (A–breast ; B–thigh joint; C–wing joint) in baked unstuffed turkeys. ● calculated temperatures for 5.9 kg turkeys. Data points are: ■ 5.6 kg pre-frozen; ▼ 5.5 kg pre-frozen, ● 6.1 kg fresh; ▲ 5.4 kg fresh.

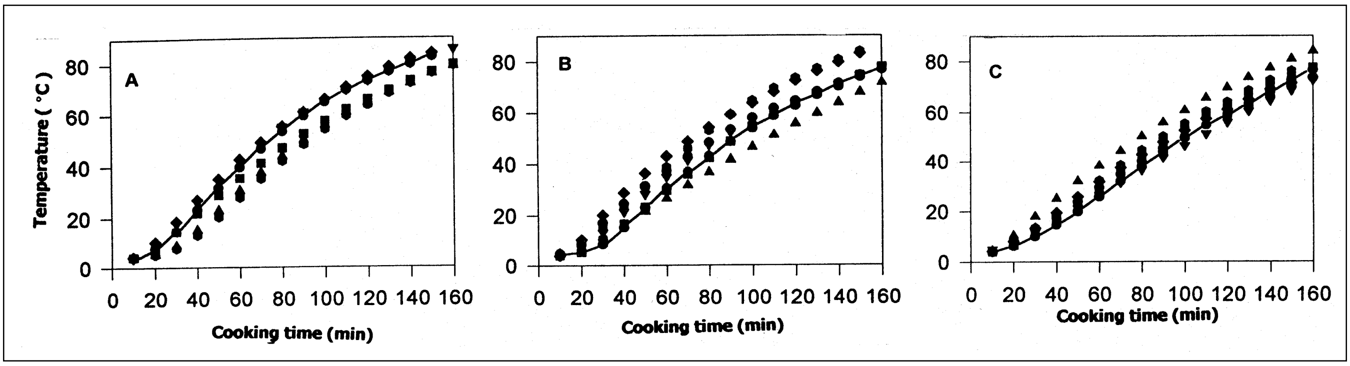

Fig. 3—Comparison of observed and calculated temperature histories at critical points (A–breast ; B–thigh joint; C–wing joint) in baked unstuffed turkeys. ● calculated temperature for 6.8 kg turkeys. Data points are: ▲ 6.8 kg pre-frozen; ◆ 6.6 kg pre-frozen; ■ 6.3 kg fresh; ● 7.1 kg fresh.

Table 1—Root mean square deviations between predicted and observed temperatures at the breast, thigh joint and wing joint positions

Weight (kg)	Temperature °C		
	Breast	Thigh joint	Wing joint
5.9	1.97	2.10	2.18
6.8	1.20	1.21	0.86
8.6	1.51	1.04	0.93
9.5	0.53	1.11	0.44
10.4	1.42	1.87	1.70
Mean	1.33	1.47	1.22

Table 2—Simulated and observed time for temperature to increase from designated initial value to 4°C at the thigh joint

Wt. kg	Heating time (min) to 4°C from:					
	3°C		2°C		1°C	
	Simulated	Observed	Simulated	Observed	Simulated	Observed
5.9	13	10.5±2.5	18	12.0±1.4	21	NA^{a}
6.8	14	12.3±2.5	19	NA	22	24.0±2.8
8.6	14	NA	20	20.0±1.7	24	22^{b}
9.5	16	14.0±2.8	22	28^{b}	26	25^{b}
10.4	16	15.0±2.0	33	22.0±2.7	27	27^{b}

[a] NA = no measurements made.
[b] Only one measurement made.

Table 3—Simulated and observed time for temperature to increase from designated initial value to 4°C at the wing joint

Wt. kg	Heating time (min) to 4°C from:					
	3°C		2°C		1°C	
	Simulated	Observed	Simulated	Observed	Simulated	Observed
5.9	18	16 ± 1.4	22	20 ± 2.6	28	32^{b}
6.8	19	21^{b}	23	29 ± 2.4	28	29.6
8.6	20	21^{b}	25	23^{b}	30	31.0 ± 2.8
9.5	21	NA^{a}	27	27^{b}	32	32.0 ± 1.6
10	22	NA	28	33.5 ± 4.1	34	33.0 ± 2.6

[a] NA = No measurements made.
[b] Only one measurement made.

being energized (set to 162.8°C) was 118°C. The thermal conductivity used in the simulation was 0.461 W/m K, which was measured at 0°C, and close to 1 to 4°C.

Results of the simulation for different initial temperatures in the thigh joint muscle were compared (Table 2). The time needed to increase temperature of the thigh joint was 13 to 16 min from 1 to 4°C, 18 to 22 min from 2 to 4°C and 21 to 27 min from 1 to 4°C. There were no differences between simulated and observed values by paired T-Test (p>0.05). The time for bringing-up bird initial temperature at the wing joint was 18 to 22 min from 3 to 4°C, 22 to 28 min from 2 to 4°C and 28 to 34 min from 1 to 4°C (Table 3). Paired T-Test validated no significant differences between estimated times and observed values (p>0.05).

Cooking times and oven temperatures

A higher oven temperature would shorten processing time (Fig. 7). There was about 50 min difference in total cooking time between the 148.9°C baking temperature and 176.7°C baking temperature. However, a higher oven temperature for roasting turkeys might result in a darker color and a dryer texture in the breast, because the breast could be exposed to the high temperature for at least 25 min longer after the thigh joint temperature reached 82°C at the time of removal from oven (Fig. 7C).

CONCLUSIONS

A TWO DIMENSIONAL FINITE ELEMENT MODEL ADEQUATELY modeled temperature in the breast, thigh joint and wing joint during baking of whole unstuffed turkeys. Surface heat transfer was repre-

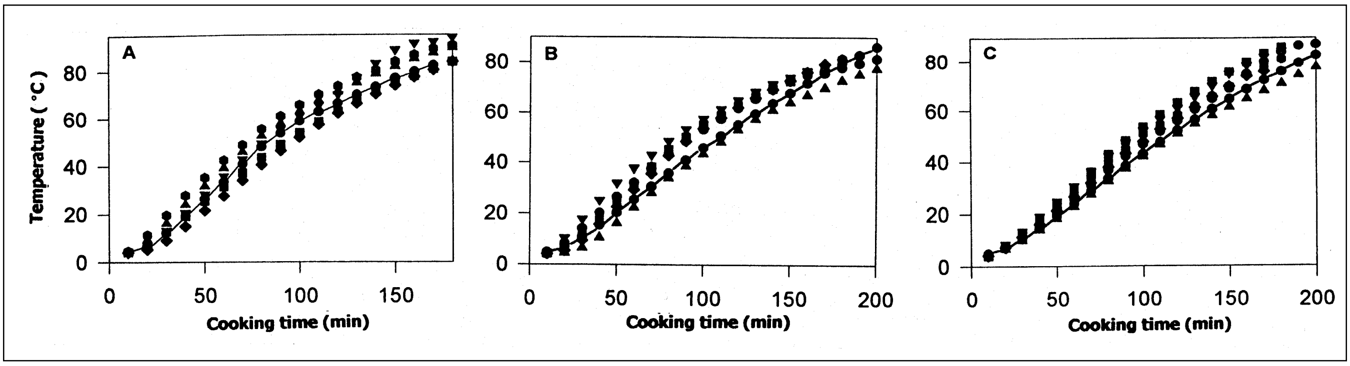

Fig. 4—Comparison of observed and calculated temperature histories at critical points (A–breast ; B–thigh joint; C–wing joint) in baked unstuffed turkeys. ● calculated temperature for 8.6 kg turkeys. Data points are: ● 8.6 kg pre-frozen; ▼ 8.4 kg pre-frozen; ▲ 9.8 kg fresh; ■ 8.9 kg fresh.

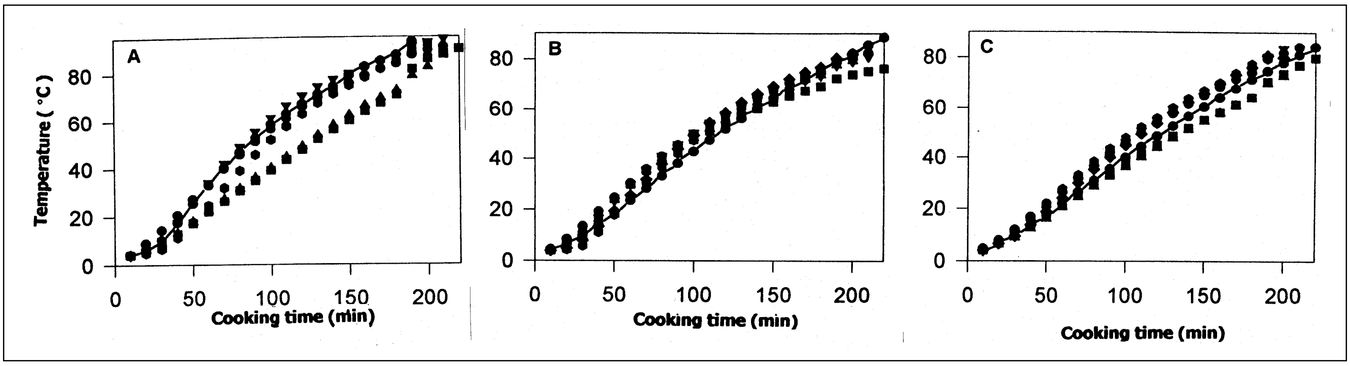

Fig. 5—Comparison of observed and calculated temperature histories at critical points (A–breast ; B–thigh joint; C–wing joint) in baked unstuffed turkeys. ● calculated temperatures for 9.5 kg turkeys. Data points are: ■ 9.8 kg pre-frozen; ▲ 9.9 kg pre-frozen; ▼ 9.6 kg fresh; ● 9.1 kg fresh.

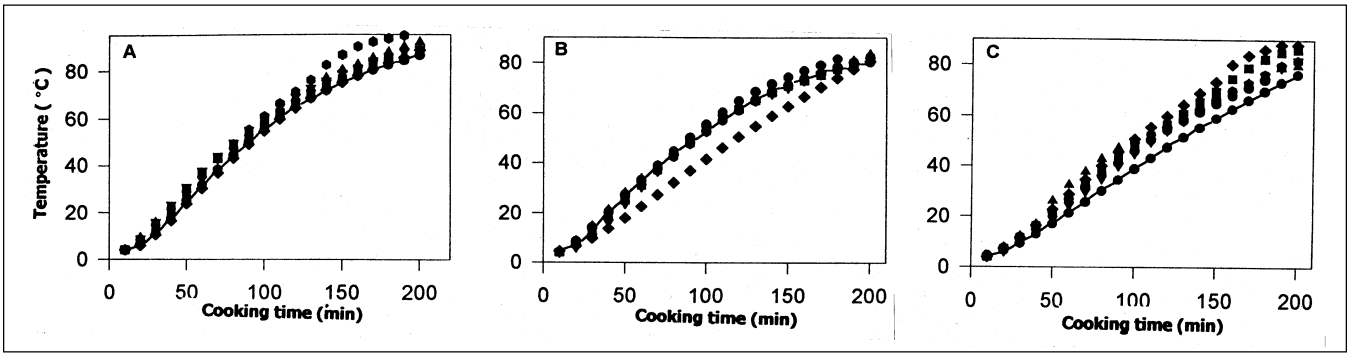

Fig. 6—Comparison of observed and calculated temperature histories at critical points (A–breast ; B–thigh joint; C–wing joint) in baked unstuffed turkeys. ● calculated temperature for 10.4 kg turkeys. Data points are: ◆ 10.8 kg pre-frozen; • 10.6 kg pre-frozen; ■ 10.6 kg fresh; ▲ 10.3 kg fresh.

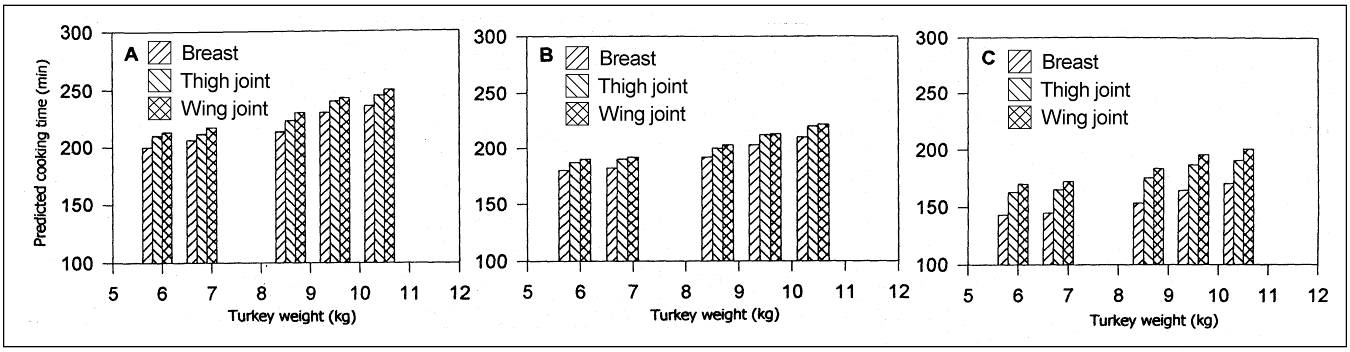

Fig. 7—The calculated cooking times for breast, thigh joint and wing joint muscles to reach 82.2°C for different weights of unstuffed turkeys at 148.9°C (A); 162.7°C (B); and 176.6°C (C).

sented by a measured heat transfer coefficient which combined convection and radiation effects. Surface energy loss from evaporation was quantified from average evaporative loss and prorated over the entire baking time using the vapor pressure of water at the surface temperature of the turkey. Simulation results revealed that increasing oven temperature reduced baking time but resulted in breast temperature reaching the designated endpoint much earlier than what would be required for thigh joint temperature to reach the endpoint. Initial temperature at critical points in the turkey had a strong influence on baking time. Storing turkeys at 4.4°C prior to baking did not ensure initial temperatures of 4°C, and initial temperatures lower than 4°C can increase cooking time to the 82°C endpoint temperature at the critical points by 18 to 34 min.

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