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Heat transfer modeling of chicken cooking in hot water

Kritsna Siripon [a], Ampawan Tansakul [a], Gauri S. Mittal [b,*]

[a] Department of Food Engineering, King Mongkut's University of Technology, Thonburi, Pracha-Utit Road, Bangkok 10140, Thailand
[b] School of Engineering, University of Guelph, Guelph, Ontario, Canada N1G 2W1

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Abstract

To calculate the slowest heating point and optimum cooking time of whole chicken cooking in hot water, a 2-dimensional heat transfer model was developed to predict temperature profile and history of the chicken cooked in hot water at 85, 90 and 95 °C. Chickens were divided into 12 sections and the heat transfer model was applied to each cross section. These models were solved with an I-DEAS program. Specific heat and thermal conductivity were measured at temperatures ranging from 25 to 95 °C. The temperature of chicken did not significantly affect the thermal properties. The average values of specific heat of white and dark meats were 3.521 and 3.654 kJ/(kg K), respectively, and the average thermal conductivity values were 0.5093 and 0.4930 W/(m K), respectively. The model was validated against experimental results, and provided an average root mean square error of 2.8 °C. Temperature distributions showed that the slowest heating point was deep in the breast part of the second cross section (3.6 cm far from shoulder) at the symmetric line of the chicken, around 2.1–2.5 cm deep from breast skin. For food safety consideration, the recommended cooking times, for whole chickens in weight range of 2.3–3.2 kg with different initial temperatures (5–30 °C), were around 74–84, 64–74 and 57–67 min for cooking temperatures of 85, 90, and 95 °C, respectively.

Keywords: Chicken cooking; Finite difference analysis; Process modeling; Process simulation; Hot water cooking; Thermal process design; Thermal processing

1. Introduction

Chicken cooked in hot water is frequently used as an ingredient in many Thai food dishes. Due to consumer demand, this product is being prepared on a large industrial scale instead of household scale. As a result of this trend, safety requirements are more critical, particularly with respect to food pathogens. A decrease in a number of pathogens, such as *Salmonella* spp., *Escherichia coli*, *Staphylococcus aureus*, etc. (Hargis, Caldwell, & Byrd, 2001), can be achieved through thermal processing. Temperature at the slowest heating point of the food sample is used to calculate microbial inactivation. This temperature and heating time provide food safety assurance. Recently, bird flu became a huge problem to chicken industry in many countries especially in Southeast Asia where food safety techniques should be emphasized. A slowest heating point is needed to calculate process time. Normally, the cooking process is terminated when the slowest heating point is reached to a desired temperature.

Cooking chicken in hot water involves heat transfer by convection from hot water to chicken surface and by heat conduction inside the chicken. Most research has focused on temperature history. Chang, Carpenter, and Toledo (1998a) presented temperature histories at various locations in a whole turkey during roasting and found that the slowest heating point located at the middle of the breast. Chang, Carpenter, and Toledo (1998b) validated

* Corresponding author. Tel.: +1 519 824 4120x52431; fax: +1 519 836 0227.
E-mail addresses: ksiripon@yahoo.com (K. Siripon), ampawan.tan@kmutt.ac.th (A. Tansakul), gmittal@uoguelph.ca (G.S. Mittal).

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Nomenclature

c_p	specific heat, J/(kg K)
CV	control volume, m^3
D	chicken diameter, m
g	gravity acceleration, m/s^2
Gr	Grashof number
h	heat transfer coefficient, $W/(m^2 K)$
I	electrical current, A
k	thermal conductivity, W/(m K)
L	heater wire length, 0.23 m
n	number of data points
Nu	Nusselt number
Pr	Prandtl number
R	heater wire resistance, 22.1 Ω
RMSE	root mean square error, °C
Slope	slope between sample temperature change and ln (time of heating)
q'	heat input per unit probe length, J/m
t	time, s
T	temperature, °C
V	volume, m^3
x, y, z	space coordinates, m

Greeks

β	thermal expansion coefficient, 1/K
μ	viscosity, Pa s
ρ	density, kg/m^3
ΔT	temperature difference between the chicken surface and hot water, °C
Δt	time interval, s

Subscripts

e	experimental
0	initial
s	simulated
w	water

temperature history for a roasted turkey using a two-dimensional unsteady state heat and mass transfer model.

Huang and Mittal (1995) developed mathematical models for heat and mass transfer to predict temperature and moisture histories of meatballs during cooking by different cooking processes, such as forced convection baking, natural convection baking and boiling. A one-dimensional spherical finite difference model of heat and mass transfer was used to determine central temperature and average mass of the product during cooking. Similar to the method of Huang and Mittal (1995), one-dimensional finite difference based model was used to predict temperature and mass histories of cucumbers during blanching (Fasina & Fleming, 2001). For the sterilization of canned mushrooms, the finite difference method was applied to solve 2-dimensional heat transfer, which included heat convection and conduction (Akterian, 1995). Due to the irregular shape of mushrooms, the average temperature by mushroom volume was considered. In pasteurization of in-shell eggs, Denys, Pieters, and Dewettinck (2003) used CFD, Computational Fluid Dynamics, to investigate heat and fluid movement in the egg. The slowest heating point in the egg shifted from the geometric center since the yolk shifted by the buoyancy force during low temperature treatment.

Since food safety is the main concern, the recommendation of Food Safety and Inspection Service (FSIS, 2004) was referred for final cooking temperature at 72.8 °C. In this study, transient temperature distribution in whole chickens during heating in water was investigated. By these results, the slowest heating point of whole chicken was also located. The cooking times were finally calculated considering temperature at the slowest heating point of the whole chicken.

2. Materials and methods

2.1. Temperature measurement

Fresh whole chickens weighing between 2.3 and 3.2 kg were cooked within the day of purchase and prepared following conventional procedure of Thailand (Fig. 1). The chickens were cleaned and both legs were put inside the abdominal cavity resulting in expansion of the chicken cavity which subsequently allowed hot water to flow through it. A pot (40 cm in diameter and 25 cm in height) was used to cook one chicken at a time without any agitator. Sufficient amount of water for covering the whole body of chicken, approximately, 27–29 kg, was put into the pot. Water was heated by an electrical heater at temperatures of 85, 90, and 95 °C before placing the chicken for cooking. During cooking, the hot water temperature was controlled by a proportional controller. Four T-type needle thermocouple probes (diameter of 0.2 cm and length of 2.0 cm) were inserted in the chicken meat at the breast and thigh parts. Temperature data were recorded on a data acquisition system (Model DR230, Yogogawa, Japan). After cooking, the exact locations of the thermocouple tips were measured with a vernier caliper referring to the y–z axes. Coordinate system (y–z axes) is shown in Fig. 1b, and depth of the thermocouple tips from the chicken surface is in x-axis direction. Correspondingly, the position of thermocouple tips was reported in y, z and depth. Each treatment was replicated four times.

2.2. Thermal properties determination

Chicken meat is conventionally categorized into white and dark meats. The white meat is breast muscle and the dark meat is thigh and drum muscles. Density (ρ) of chicken meat was calculated as a ratio of mass to volume. Chicken meat volume was measured using a water displacement method. Specific heat (c_p) was determined by a differential scanning calorimeter (DSC, Perkin–Elmer, Pyris 1, USA). A constant rate of heat at 5 °C/min was applied for heating meat samples of 10–15 mg from 20 °C to 95 °C. Before measurement, the DSC was calibrated with indium. Density and specific heat of meats from 10 chickens were measured in triplicate and duplicate, respectively.

The line heat source method (Mohsenin, 1980) was used to determine thermal conductivity (k) of white and dark meat samples which was built by Nithatkusol (1998). A meat sample was put into an acrylic cylindrical container (an inside diameter of 43.8 mm and height of 95 mm). A stainless steel needle probe with a nichrome heater wire and an E type thermocouple was inserted at the meat sample center. Samples in the container were immersed in a water bath to maintain a constant temperature. The triplicate measurements of thermal conductivity were conducted at 35, 50, 65, 80 and 95 °C. Electrical power was supplied to the probe heater. Thermal conductivity was calculated by Eq. (1) (Mohsenin, 1980). Before measurement, the line heat source probe was calibrated using 0.5% agar gel solution. The calibration showed good accuracy with only 0.85% error.

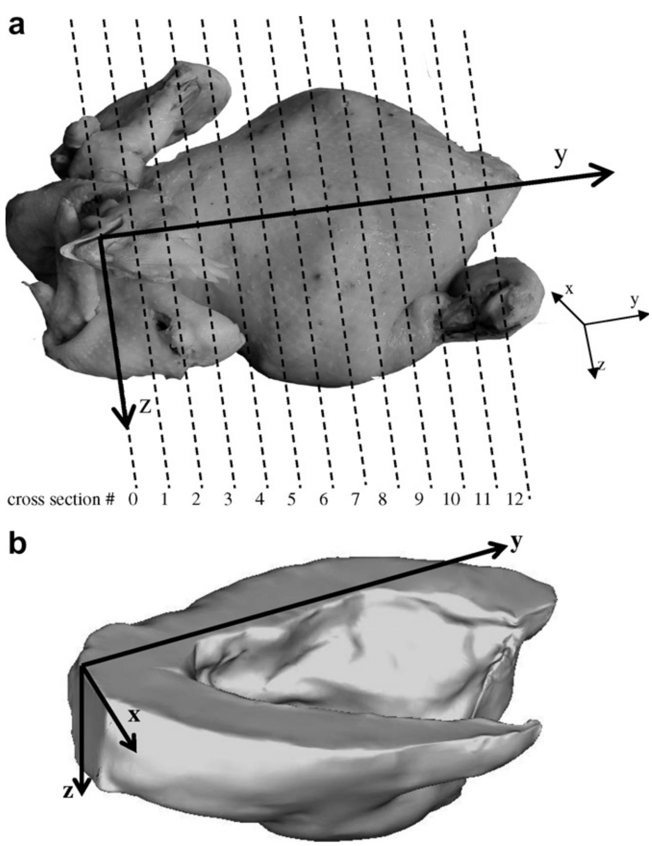

Fig. 1. Cooked chicken, both legs were put into the interval cavity. y-axis was set along keel bone direction, x- and z-axes were perpendicular to keel bone. (a) A whole cooked chicken was sliced into 12 pieces. (b) The model of a half chicken using I-DEAS NX.

$$k = \frac{q'}{4\pi(\text{Slope})} \tag{1}$$

where "Slope" is the slope between sample temperature change and ln(time of heating), and q' is the heat input per unit probe length which is given by

$$q' = \frac{2I^2R}{L} \tag{2}$$

where the heater wire resistance (R) was 22.1 Ω with a length (L) of 0.23 m, and electrical current (I) was in A.

Thermal properties of chicken skin and bone were calculated using their chemical compositions based on Choi and Okos equations (1983). Compositions of bone and skin reported by Ockerman (1979) (Table 1) were used. Table 2 shows calculated thermal conductivity and specific heat of the bone and skin, and density data given by Morley (1972) and Arce, Potluri, Schneider, Sweat, and Dutson (1983).

2.3. Mathematical model

To input the dimensions of a chicken, a half piece of a chicken body (weight of 2.84 kg) was scanned by a 3D-scanner (Optical scanner, Model ATOS, GOM, Germany). Three-dimensional scanned chicken image was imported to I-Deas 11 NX (UGS PLM Solutions Inc., 2004) program, to be used for simulation. Scanned chicken image represented real dimensions of chicken surface. The chicken was sliced equally into 12 sections perpendicular to the keel bone (y-direction) as seen in Fig. 1. The thickness of each slice was 1.83 cm. All cross sections of chicken pieces were uprightly photographed using a digital camera (Model No. DSC-P71, Sony, Japan). In the same way, the scanned chicken was sliced perpendicularly to y-axis into 12 sections. For example, Fig. 2a shows photographs of the cross sections 2, 4, 6, 8, and 10, Fig. 2b shows the same cross sections but from the scanned images. The components, such as bone, breast, thigh, drum and skin, were drawn based on

Table 1
Food compositions (wet basis) of bone and skin of chickens (Ockerman, 1979)

	% Water	% Fat	% Protein	% Ash
Skin	11.80	82.90	5.10	0.20
Rib bone	28.67	18.02	20.63	28.74
Round bone	26.09	29.96	19.63	23.20

Table 2
The bulk thermal conductivity values of chicken meats

Temperature (°C)	Bulk thermal conductivity (W/m K)		
	Breast	Drum	Thigh
35	0.504	0.482	0.484
50	0.513	0.484	0.499
65	0.521	0.498	0.492
80	0.499	0.501	0.504
Average	0.509	0.492	0.495

the photographs of the sections using Drafting Preference (DP from I-Deas). Because each sliced chicken was thin and the contours of both sides of it were not much different, therefore two-dimensional unsteady state heat transfer (Eq. (3)) was applied on each piece. The heat transfer in the third direction (y) will not reach far enough, and not as important as the heat transfer around 12 chicken sections is considered.

The governing heat transfer equation in the Cartesian coordinate system (x–z axes) is (Bird, Stewart, & Lightfoot, 2002):

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c_p}{k}\left(\frac{\partial T}{\partial t}\right) \tag{3}$$

where T is the temperature in the x–z coordinates and t is the time.

An initial temperature (T_0) was measured and used as initial condition (Eq. (4)). During cooking, temperatures of hot water in chicken cavity were also measured. Fig. 3 shows that, during the first 10 min, temperatures of hot water inside cavity of chicken increased rapidly and reached cooking temperature. Therefore, the convective heat transfer coefficients of both outer and inner surfaces of chicken were assumed to be the same (Eq. (5)). Due to the similarity of heat transport phenomena on both left and right sides of the chicken, heat transfer was calculated on one side, and a middle line, keel bone position, was used as an axis-symmetry (Eq. (6)). Therefore, the keel bone line was located along the y-axis as shown in Fig. 1. Initial and boundary conditions are:

$$T_x = T_z = T_0, \quad \text{at } t = 0 \tag{4}$$

$$-k\frac{\partial T}{\partial n} = h(T - T_w), \quad \text{at surface} \tag{5}$$

$$\frac{\partial T}{\partial z} = 0, \quad \text{at } z = 0 \tag{6}$$

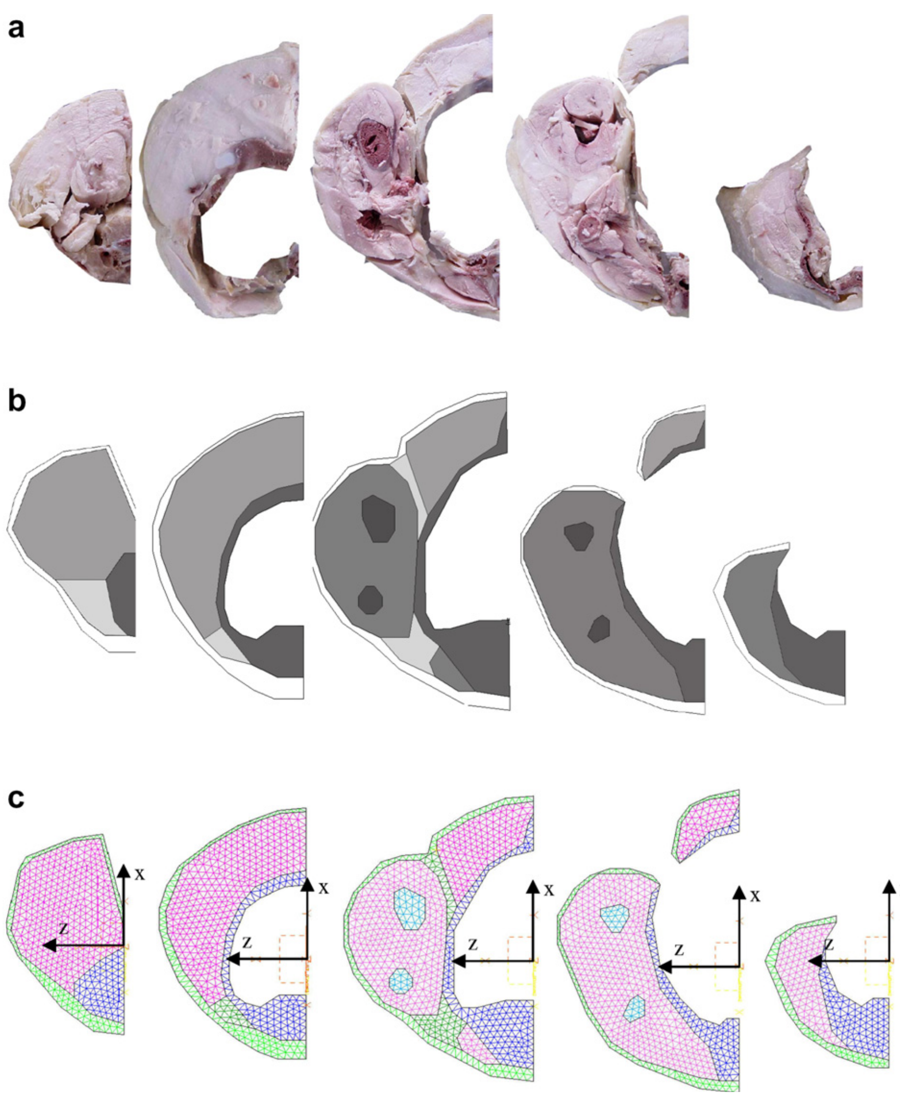

Fig. 2. Photographs and drawing of cross section number 2, 4, 6, 8, 10, respectively (ratio 3:1). (a) Photographs of the section, (b) drawn cross section by I-DEAS program when □ is skin, ▒ is fat, ▒ is white meat, ▒ is dark meat, ■ is rib bone and ■ is round bone, (c) meshed cross section by I-DEAS. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

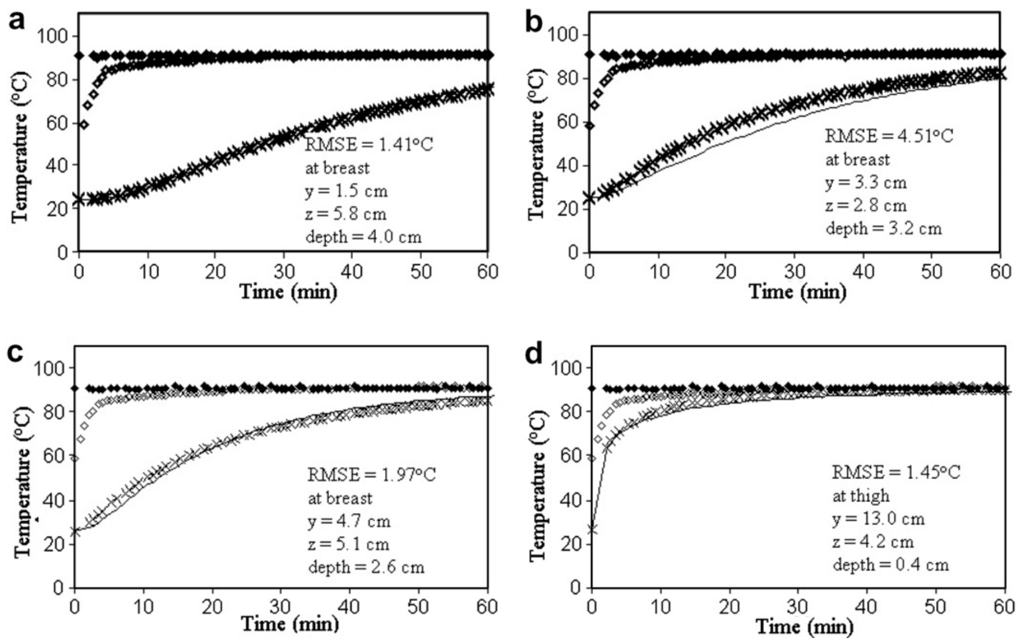

Fig. 3. Comparison of observed and simulated temperatures of chickens of mass 2.92 kg for cooking temperature of 90 °C: (◆) water temperature, (◇) water temperature in chicken cavity, (×) observed temperature, (—) simulated temperature. The observed temperatures at thermocouple a, b, c, and, d were validated with simulated temperatures on cross sections 1, 2, 3, and 7, respectively.

Because the chicken seems to be round along the chicken body, it was assumed to be a sphere for heat transfer coefficient (h) calculation only. The chicken of 2.84 kg was used representing chickens in mass range of 2.3–3.2 kg. Therefore, to calculate the h, the largest diameter (15 cm) and the length along this chicken body (24 cm) were assumed as a diameter and length of the cylinder. These dimensions of chicken were input in the semi empirical equation of Ranz and Marshall (Rahman, 1995) to calculate the h (Eq. (7)). The h values were calculated using the initial temperature of chicken from 5 to 30 °C for hot water at temperatures of 85, 90 and 95 °C, and the results were 162.11–173.53, 164.57–175.36, and 166.04–176.23 W/m^2 °C, respectively

$$Nu = 2 + 0.6(Gr)^{1/4}(Pr)^{1/3} \tag{7}$$

where Nu is the Nusselt number (hD/k_w), Gr is the Grashof number ($g\beta\rho_w^2 D^3 \Delta T/\mu^2$), Pr is the Prandtl number ($c_{p,w}\mu/k_w$), D is the chicken diameter (15 cm), g is the acceleration due to gravity, k_w is the water thermal conductivity, $c_{p,w}$ is the specific heat of water, ρ_w is the density of water, μ is the viscosity of water, β is the thermal expansion coefficient of water, and ΔT is the temperature difference between the chicken surface and hot water.

2.4. Finite difference analysis

Chicken cross section images (Fig. 2b) were meshed using a 3 mm mesh length triangular meshes, and physical properties were assigned to these meshes. The model was solved using TMG (Thermal Model Generator of I-DEAS) which uses advanced finite difference control volume (CV) technology to solve heat transfer problems (UGS PLM Solutions Inc., 2004). Unsteady state heat conduction equation (3) was integrated over CV and over time interval from t to $t + \Delta t$ as

$$\int_t^{t+\Delta t}\int_{CV} \rho c_p \frac{\partial T}{\partial t}\,dV\,dt = \int_t^{t+\Delta t}\int_{CV} \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dV dt + \int_t^{t+\Delta t}\int_{CV} \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)dV dt \tag{8}$$

Chicken surface was surrounded by hot water causing natural heat convection. The model was run at 20 s time interval to calculate nodal temperatures. Simulated data were compared with the experimental data, and root mean squared error (RMSE) was calculated as

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(T_e - T_s)^2}{n}} \tag{9}$$

where T_e is the experimental temperature, T_s is simulated temperature and n is the number of data points.

3. Results and discussion

3.1. Thermal properties

Density (ρ) values of white and dark meats were 1038 and 1026 kg/m^3 with standard deviations of 37.4 and 50.9 kg/m^3, respectively. Ngadi and Ikediala (1998) reported ρ of chicken drum meat as 1192 kg/m^3, and average ρ for chicken meat was reported as 1070 kg/m^3 (ASHRAE, 1982; Rahman, 1995). Different types of chickens among the studies probably provided different ρ values.

The line heat source method was used to evaluate k at 35, 50, 65, 80, and 95 °C. However, k at 95 °C was omitted as the shrinkage of meat sample in the container upon heating was so large that the water filled gaps between the meat sample and cylinder wall. Therefore, k values of the chicken meat at 95 °C were difficult to measure. Thus, k values at 35, 50, 65, and 80 °C were determined. Table 2 shows the determined k. Results showed that temperature did not significantly affect k of both white and dark meats at a 95% confidence. Average k values of white and dark meats were 0.509 and 0.493 W/(m K) with standard deviations of 0.0321 and 0.0376 W/(m K), respectively. Choi and Okos equations (1983) were used to calculate k of white and dark meats using composition of chickens in the study of Siripon, Tansakul, and Mittal (2005). Calculated k of white and dark meats (Table 3) were larger than measured data. Mittal and Blaisdell (1984) reported that k of chicken dark meat was 0.497 W/(m K) whereas Ngadi and Ikediala (1998) found that k values of chicken drum meat was between 0.23 and 0.60 W/(m K). The k values from previous studies of dark meat were similar to the experimental values. The k value of white meat was reported by ASHRAE (1982) as 0.502 W/(m K) which was lower than that in this study.

c_p values of the chicken meats at 20–95 °C with 5 °C intervals were measured, and analyzed using SPSS program (SPSS Inc., 2004). Similar to the results of k, the results showed that c_p of chicken meats did not depend on temperature. Average c_p values of white and dark meats were 3.530 and 3.663 kJ/(kg K) with standard deviations of 0.325 and 0.348 kJ/(kg K), respectively. In comparison to the calculated value using Choi and Okos equations (1983), the c_p of white and dark meat were 3.667 and 3.645 kJ/(kg K), respectively. Experiment values of c_p are in the range of the reported values. Ngadi and Ikediala (1998) found that c_p of drum meat was between 2.67 and 4.08 kJ/(kg K), and c_p of ready to cook poultry meat was 2.94 kJ/(kg K) (ASHRAE, 1982).

3.2. Model validation

Temperatures at different nodes in the chicken were simulated. The closest cross sections to the thermocouple tips were selected for validation. Temperatures at the exact thermocouple positions on those sections were calculated using the temperature data at adjacent nodal positions. A linear shape function (Segerlind, 1984) was used to calculate these simulated temperatures. Predicted results were compared to the experimental temperature data, and both are shown in Fig. 3. At the beginning, the predicted temperature values were lower than the experimental values. However, after 25 min, the predicted temperature history tended to perfectly fit the experimental data. The thermocouple probe was covered by a stainless steel tube of 0.2 cm in diameter and 2.0 cm in length that has much higher thermal conductivity than the meat. Thus, the error could be caused by faster heat conduction through the thermocouple probe than through the meat (Hu & Sun, 2002). This effect is obvious for probes near the chicken surface. Therefore, the temperature history after 1500 s was considered for comparison with simulation data.

As shown in Fig. 3d, the temperatures near the skin surface, at 0.4 cm in depth, rose up very fast due to the effect of heat convection. The predicted temperatures fit the experimental data with a RMSE of 1.5 °C. This small error indicated reliability of calculated h values at the surface. Average RMSE values for cooking temperatures of 85, 90 and 95 °C were 3.4, 2.1 and 2.2 °C, respectively. In some cases, the thermocouple tip was not located at the exact cross section, causing some error in interpolation. For example, for the results in Fig. 3c, the thermocouple tip was located in the breast part. It was at 4.7 cm ($y = 4.7$ cm) from the shoulder. Because cross section 2 was at $y = 3.66$ cm and cross section 3 was at $y = 5.49$ cm, the measured temperature point was between cross sections 2 and 3. To simulate this temperature, cross section 3 was selected because it was nearer to the thermocouple tip than cross section 2 by 2.5 mm. Because of the nature of chicken anatomy, the thickness of the breast decreases in y-direction; therefore the thickness of cross section 2 was greater than the cross section on which the thermocouple was located. Thus, the simulated temperature was probably lower than the experimental temperature as seen in Fig. 3c. Furthermore, some error was from the different mass between the experiment chickens and modeled chicken. For overall data sets, the average RMSE was 2.8 °C.

3.3. Slowest heating point and recommended cooking time

The thickest breast and thigh zones were thought to be the parts having the slowest heating point. The temperature results (Fig. 3) indicated that the slowest heating point was possibly located in the breast part. To evaluate the slowest heating point, temperatures at cross sections 1–9 were simulated. The temperatures at the slowest heating points in all the nine sections were plotted against time (Fig. 4). The results indicated that the slowest heating point for the whole chicken was in cross section 2. The location of this point was around 2.1–2.5 cm deep from the breast skin on the symmetric line. Unfortunately, this point was in the keel bone; the temperature is difficult to measure, so it was simulated and an optimum cooking time was proposed.

Table 3
Thermal properties of chicken

	k (W/(m K))	c_p (kJ/(kg K))	ρ (kg/m^3)
Skin	0.228[a]	2.181[a]	812[b]
Rib bone	0.286[a]	2.167[a]	1040[c]
Round bone	0.265[a]	2.021[a]	1040[c]
Breast	0.549[a]	3.667[a]	1047[a]
Thigh & Drum	0.534[a]	3.645[a]	1032[a]

[a] Calculated from Choi and Okos (1983) relationship.
[b] Morley (1972).
[c] Arce et al. (1983).

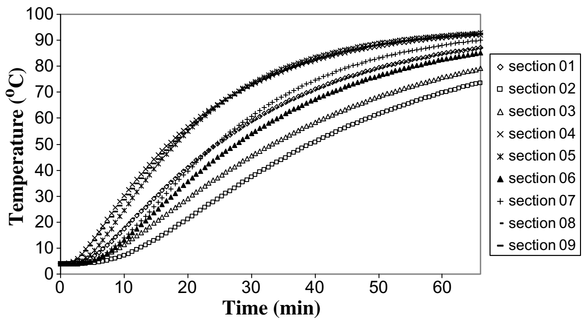

Fig. 4. Simulated temperatures at the slowest heating point of cross sections 1–9 of a chicken weight of 2.84 kg when it was cooked in hot water at 95 °C.

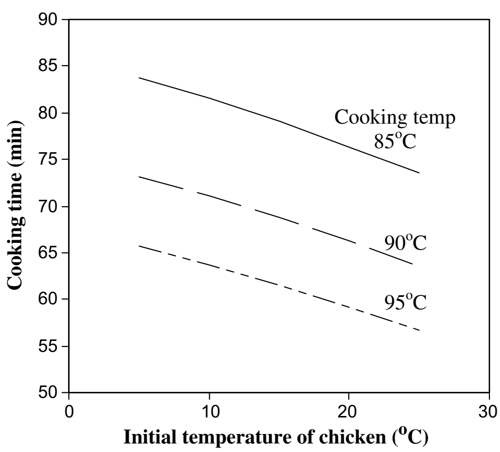

Fig. 5. Estimated cooking times of whole chicken (weight between 2.3 and 2.84 kg) cooking from various initial temperatures (T_0) to FSIS recommendation 72.8 °C, measured at the slowest heating point.

Following the United State Department of Agriculture Food Safety and Inspection (FSIS, 2004) recommendation, the final temperature at the slowest heating point of poultry is 163 °F (72.8 °C) and the holding time is at least 10 s at this temperature. Therefore, the cross section 2 was re-simulated under several cooking conditions. Chicken initial temperature was a variable in the model from 5 to 30 °C (Eq. (4)). Simulations were performed for cooking temperatures of 85, 90, and 95 °C. Final temperature for cross section 2 as shown in Fig. 5 was proposed to be 72.8 °C to prevent food borne illnesses. The calculated cooking times were around 74–84, 64–74, and 57–67 min for cooking temperatures of 85, 90, and 95 °C, respectively. These cooking times were obtained to prevent food borne disease by pathogens. Therefore, weight of chicken model (2.84 kg) should be set as the upper limit of weight range. Thus, the calculated cooking times should be employed for chicken in weight range of 2.3–2.84 kg.

4. Conclusions

Two-dimensional heat transfer model predicted reasonably well the whole chicken temperature profile and history during cooking in hot water using the advanced finite difference control volume method. Average RMSE of 2.8 °C indicated satisfactory prediction accuracy. The model was employed successfully to predict transient temperature of the chicken during cooking. Simulated temperature profiles at 10 sections of whole chicken provided the location of the slowest heating point. This point is located in the chicken breast part. Temperature at the slowest heating point provided optimum cooking time. According to the food safety concern, the calculated cooking times should be used for the chicken weight under 2.84 kg. The recommended cooking times were in the ranges of 74–84, 64–74, and 57–67 min for cooking temperatures of 85, 90, and 95 °C, respectively, for different sizes of chicken.

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