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Precooking and Cooling of Skipjack Tuna (*Katsuwonas pelamis*): A Numerical Simulation

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A numerical simulation of the commercial tuna precooking and cooling process was developed as an aid to improving these critical thermal processing steps. Using the finite element method, a two-dimensional model of a tuna consisting of three regions, muscle, backbone, and viscera, was developed. Results from previous research on thermal properties of skipjack tuna were applied in the model. Preprocessor software, GAMBIT 1.1, and commercial finite element software, FIDAP 8.52, were used. The model was tested via comparison with experimental data collected in a commercial processing facility and a pilot plant. Good agreement between the simulation and experimental results was obtained.

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Introduction

The commercial canned tuna industry holds a dominant position in the United States seafood market. In 1999, a total of $1.8 billion dollars worth of human consumable canned fish were produced, with tuna representing 72% of this figure (NMFS, 1999). In the past, albacore tuna was the major species used for canning—its delicate, white meat fetching a high price. However, the decline of albacore tuna production off the Pacific coast of California and the shift to a dolphin safe policy in 1993 have led to yellowfin and skipjack tuna replacing albacore as the main species canned in the United States. It now appears that skipjack has rapidly replaced yellowfin as the largest single contributor of raw material to the tuna canning trade.

Precooking and cooling are two critical thermal processes before retorting. After the thawing and butchering processes, tuna are cooked using atmospheric steam (100–102 °C) in rectangular-shaped steel chambers, a process commonly known as precooking. The precooking process removes muscle water which would otherwise be released during retorting and could lead to rejection of the canned product for high-moisture content and low fill weight (Perez-Martin *et al.*, 1989). In addition, precooking causes partial protein denaturation which improves cleaning speed and yield. Precooking time is governed by fish size, initial temperature, and desired endpoint or target temperature. Further cooking beyond the target temperature greatly reduces yield and alters flavor and color (Bell *et al.*, 2001). The target temperature of the tuna at the thickest point of the fish, as measured along the backbone, ranges from 50 to 70 °C depending on a number of factors including raw material quality and tuna species. The time to reach the target temperature ranges from 1 h for small fish to over 8 h for large fish.

When precooking is complete, the steam is turned off and the fish are removed from the cooker and cooled in ambient temperature air until they reach a core temperature of 32–38 °C. This temperature facilitates the cleaning process. During cooling, tuna undergo some important changes. The weight of the cooked tuna is further reduced through evaporation of moisture from the hot fish. A general drying of the surface of the fish often takes place, leading to case hardening and discoloration at the surface. Oil contained in the tuna, which accumulates on the surface during cooking, may oxidize as a result of the temperatures prevailing during cooling. Finally, there is the risk of microbial and/or enzymatic degradation of the tuna. These factors, and others, increase the importance of minimizing the time

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between precooking and canning, thus reducing the potential for quality and yield losses.

Published research efforts in canned tuna processing to date have focused on degradation of fresh fish (Bateman *et al.*, 1994; Mietz and Karmas, 1977; Ohashi *et al.*, 1991), sensorial quality (Ohashi *et al.*, 1994; Watanabe *et al.*, 1984*a*, *b*, 1987; Karube *et al.*, 1984), and nutritional quality (Callahan and Herz, 1989; Ernster, 1982; Simon and Slater, 1982; Thompson, 1989; Simon *et al.*, 1981). Perez-Martin *et al.* (1989) developed a semi-empirical model to estimate the precooking time of albacore tuna. However, the model was based on albacore, not skipjack, tuna, and thermal property and size/shape differences between these two species limit this model to albacore. Cooling time was not addressed by Perez-Martin *et al.* (1989) or others and no research has been found which addresses the interrelationship between the precooking and cooling processes. Finally, the model proposed by Perez-Martin *et al.* (1989) assumed a cylindrical-bodied fish with a homogeneous composition. This assumption ignores the elliptical shape and composite composition of the fish; including the hollow viscera cavity present after evisceration.

Precooking and cooling are primarily conduction processes which are described by Fourier's law. Analytical solution of the conduction equation is generally restricted to simple geometries and relatively simple initial and boundary conditions. Two techniques for numerical solution are the finite difference method (FDM) and the finite element method (FEM). The FEM is now widely used for a broad range of applications in engineering and mathematical physics (Segerlind, 1984). FEM is readily applied to problems involving nonuniform size, shape, and properties. DeBaerdemaeker and Singh (1977) used FEM for the calculation of heat transfer in foodstuffs, showing how the method could readily accommodate a wide variety of shapes, thermal properties, and boundary conditions within a single simple program. FEM has also been used for the mathematical modeling of beef carcass cooling (Arce *et al.*, 1983). Nicolai and DeBaerdemaeker (1992) discussed the stochastic initial and boundary conditions used for simulating heat transfer in foods by the FEM. However, there has been little research conducted on seafood processing utilizing FEM.

To address these issues, the objectives for this research were (1) to develop a numerical simulation to predict the internal temperature profile of a skipjack tuna during precooking and cooling and (2) to test the simulation with data collected at the pilot and commercial scale.

Materials and Methods

Time and temperature data for the precooking and cooling of skipjack tuna were collected on a pilot scale at NC State University, Department of Food Science and on a commercial scale at a tuna cannery in Mayaguez, Puerto Rico. Additionally, size and shape data needed in the development of the numerical simulation were collected for a range of fish at the NC State University pilot plant.

Pilot plant data

Precooking and cooling. Skipjack tuna of varying size and weight (3.5 – 4.6 kg) were obtained, frozen, from the Star-Kist Seafood plant located in Mayaguez, Puerto Rico. The fish were caught in the Western Tropical Pacific region and brine frozen before arriving at the Star-Kist facility. After shipment to NC State University, the fish were stored at −45 °C. In preparation for precooking, the frozen fish were thawed in ambient temperature, quiescent water to a backbone temperature of 3 °C. Each fish was then placed in a wire mesh basket and individually cooked in a steam retort at atmospheric pressure to a backbone temperature of 60 – 65 °C. After precooking, each fish was removed from the retort and cooled in room temperature air to a backbone temperature of 35 °C. Six type-T thermocouples were used to measure temperatures in each fish. Two thermocouples were used for measuring loin muscle temperature, one for the backbone, one for the viscera, one for the skin, and one for retort temperature (**Fig. 1**). Approximate depth and length inside the loin, viscera, and backbone were measured for each thermocouple. Thermocouples were connected to a Campbell Scientific (Salt Lake City, UT, U.S.A.) data logger and temperature data were collected every 60 s.

Size and shape data. Six different size and weight fish were cut transversely into four cross sections with an

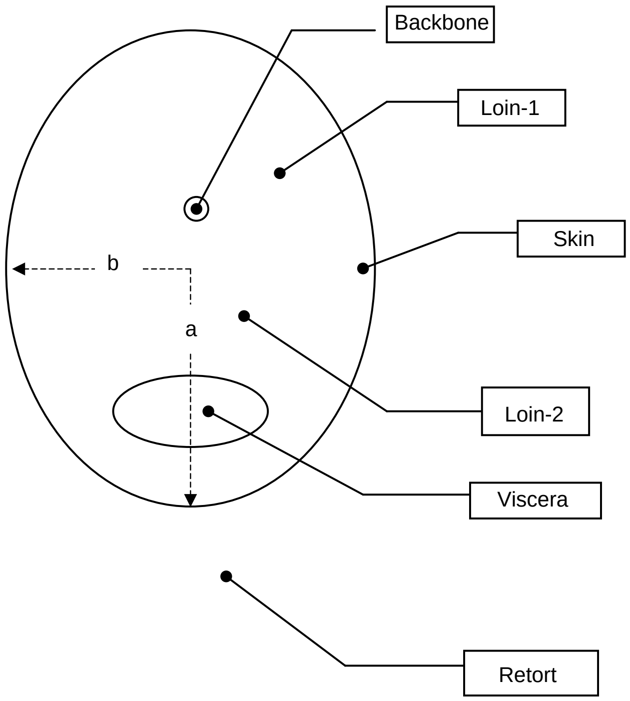

Fig. 1 Relative thermocouple placement for pilot plant experiments and position of major, *a*, and minor, *b*, elliptic radii

Table 1 Input parameters used in the precooking simulation. Size data are given for a single, representative fish

Region	Location	
	Pilot plant	Commercial plant
	Size (m)[a]	
Loin: 2a	0.140	0.150
2b	0.110	0.112
Viscera: 2a	0.056	0.066
2b	0.028	0.044
Backbone: D	0.060	0.060
	Thermal conductivity (W/m K)[b]	
Loin	0.57	0.57
Viscera	0.56	0.03 (air)[c]
Backbone	0.40	0.40
	Specific heat (J/kg K)[b]	
Loin	3536	3536
Viscera	3446	1022 (air)[c]
Backbone	2263	2263
	Density (kg/m^3)[a]	
Loin	1048	1048
Viscera	1048	1.0 (air)[c]
Backbone	1048	1048
	Convective heat transfer coefficient (W/m^{2}K)[a]	
Surface	2000	1400

[a] *Source*: Present work with "a" the major radius and "b" the minor radius of an ellipse (**Fig. 1**)
[b] *Source*: Zhang *et al.* (2001).
[c] All commercial fish were processed with viscera removed.

average thickness of 2 cm each. The cross-section was considered to be an ellipse and the major and minor axes were measured. In addition, the viscera was also considered to be an ellipse and its major and minor axes measured. The backbone was considered as a round body and the diameter was measured. Averages were calculated from these cross section measurements for each fish and used as inputs in the numerical simulation (**Table 1**).

Commercial data
Commercial temperature data were collected using fish of similar size to the pilot-scale testing. Two thermocouples were used, one located at the backbone and a second for cooker temperature. Major and minor axes for loin and viscera were measured as well as the diameter of the backbone. Precooking was carried out according to common commercial practice as described earlier.

Mathematical Model

Model development
A schematic representation of a skipjack tuna was developed (**Fig. 2a**) with an elliptical cross section (**Fig. 2b**) resulting when the fish was cut transversely at the middle.

The tuna body was considered to be nonhomogeneous and anisotropic with a variable geometry.

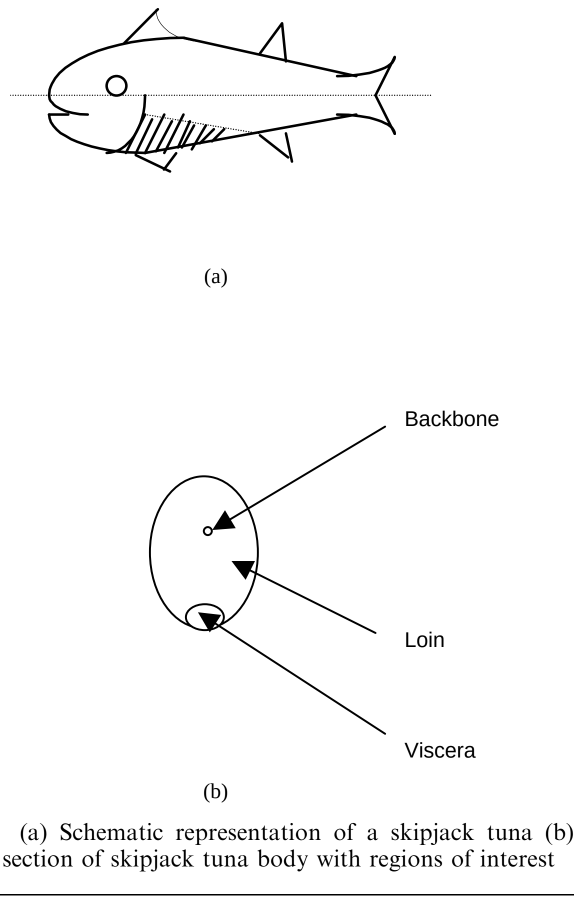

Fig. 2 (a) Schematic representation of a skipjack tuna (b) Cross section of skipjack tuna body with regions of interest

Two-dimensional heat transfer was assumed with axial conduction (head to tail) considered to be negligible. The precooking and cooling processes constitute a heat conduction problem with convection heat transfer at the surface of the fish. The energy equation is given as

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \qquad \text{Eqn [1]}$$

with initial condition

$$T = T_{\mathrm{i}} \qquad \text{Eqn [2]}$$

A convective boundary condition was used at the surface

$$-k\frac{\partial T}{\partial \varphi} = h(T_{\mathrm{a}} - T_{\mathrm{s}}) \qquad \text{Eqn [3]}$$

A symmetry condition at the tuna center was used as the second boundary condition

$$\frac{\partial T}{\partial \varphi} = 0 \qquad \text{Eqn [4]}$$

Software and hardware

There is considerable commercial software available which utilizes the FEM to solve partial differential equations. GAMBIT 1.1 and FIDAP 8.52 were used for this project (Fluent Inc., Lebanon, NH, U.S.A.).

GAMBIT and FIDAP were installed at the North Carolina Super Computing Center (NCSC) on an Origin 2000. The SGI Origin 2000 (Silicon Graphic, Inc.) was equipped with 32 R10000 processors running at 250 MHz, 16 GB of memory, and the IRIX operating system.

The finite element mesh was generated using GAMBIT 1.1, with four-node elements used in the domain. There were 2110 elements and 1962 nodes in the domain for the pilot-scale simulation and 1881 elements and 1732 nodes in the domain for the commercial-scale simulation (**Fig. 3**).

Boundary conditions, initial conditions, and property data

Boundary and initial conditions were determined as previously described for the pilot scale and commercial-scale testing (Table 1). Thermal and physical properties of different regions at the fish (loin, backbone, and viscera) were applied from previous work (Zhang *et al.*, 2001). The thermal conductivities for the loin and the viscera were determined using a line heat source method (Rahman, 1995), while thermal conductivity of the backbone was determined using an empirical model (Singh and Heldman, 1993). Specific heat and protein denaturation temperatures were determined using a differential scanning calorimeter (DSC 7, Perkin Elmer Corp., Norwalk, CT, U.S.A.). Density values for different regions of tuna fish were determined by volume displacement. In the commercial processing facility, fish were eviscerated before the precooking process. To account for this in the simulation, the thermal and physical property data of the viscera region were replaced by those of moist air at 100 °C. A slightly different convective heat transfer coefficient and steam temperature were used to account for the different processing environments within the pilot plant and the commercial facility. The simulation required the main process variables as input: fish physical and thermal properties, and process parameters (**Table 1**) including surrounding (ambient) temperature during precooking and cooling.

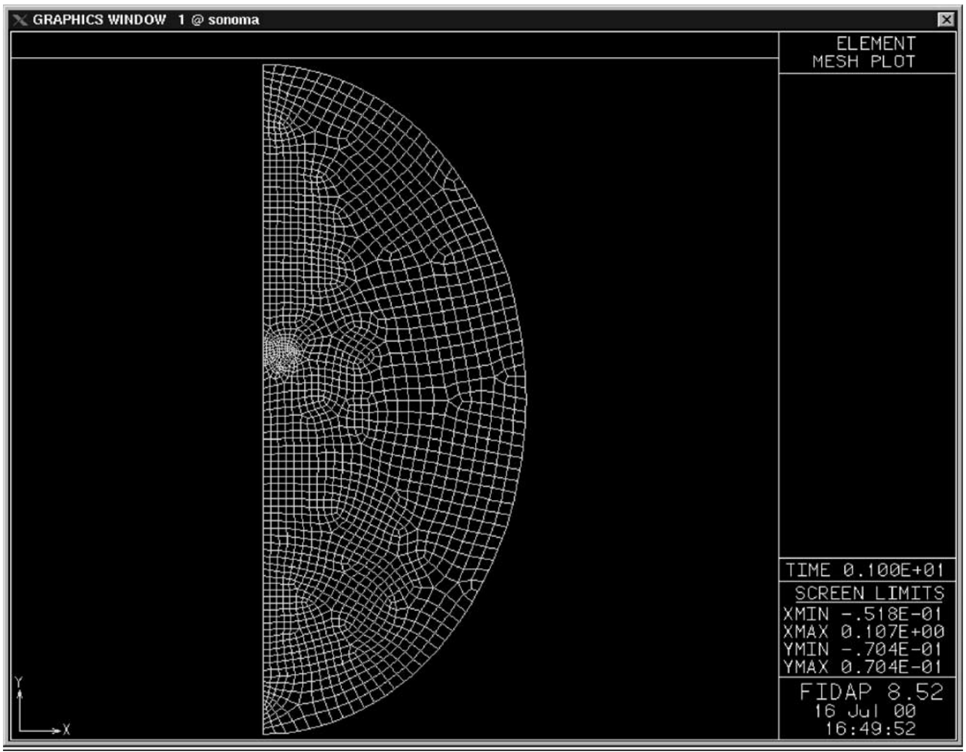

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Fig. 3 Finite element mesh used for commercial skipjack tuna precooking and cooling simulation

Results and Discussion

One of the primary difficulties in comparing numerical and experimental temperature profiles is in the validation of thermocouple placement. As discussed above, the depth and length of thermocouples inside the loin, viscera, and backbone were recorded for pilot plant data. However, it is likely that the location did not match a node point in the model domain. Thus, minor differences were expected between the numerical and experimental data.

Thermal conductivity (k) and specific heat (c_p) for loin, viscera, and backbone were obtained from previous work (Zhang *et al.*, 2001). Each of the methods used to determine these properties contains experimental error. In addition, the measured properties of the raw, biological material varies from fish to fish. The combined effect of experimental error in property determination and variability of the raw material may explain differences between the simulation results and experimental data. The differences were not quantified but Perez-Martin *et al.* (1989) found that small changes ($<10\%$) in thermal diffusivity resulted in simulated temperature values that over or under predicted the experimental data.

Experimental and numerical results

The model was tested by comparing simulation data with the pilot- and commercial-scale temperature profiles from representative fish. All pilot- and commercial-scale runs generated similar time-temperature profiles with variations due to fish size and initial temperature, thermocouple placement, and media heating/cooling rates and temperatures.

Precooking process. Comparison of the mathematical model and pilot-scale data was done by plotting the skipjack tuna backbone, loin, and viscera temperatures for each data set (**Figs 4–6**). The simulation agreed well with the experimental data for each trial, and error was likely due to the initial temperature input from experimental data and differences in property data and thermocouple location. An exception to this lies with the backbone temperature for the first 20 min of precooking (**Fig. 4**). In the simulation, the initial temperature of each region was set using the thermocouple reading from that region in the test fish. While a smooth temperature gradient existed in the test fish (e.g. warmer on the surface to cooler in the core before precooking), this was not done in the simulation, resulting in a step change in temperature between regions. The temperature used in the model for the loin at the backbone was slightly higher than the true temperature. This initial temperature difference between the backbone and loin caused a quick rise in backbone temperature over the first few minutes of the simulation (**Fig. 4**). The loin meat (**Fig. 5**) and viscera (**Fig. 6**) simulation results were in very good agreement with the experimental profiles.

The comparison of the mathematical model and commercial precooking data for skipjack tuna backbone temperature showed excellent agreement (**Fig. 7**). A slight disagreement in the first 10 min remained due to differences in the initial temperatures and spatial temperature gradient. Further refinement of the initial condition to yield a spatially dependent initial temperature would lead to improvements in agreement between

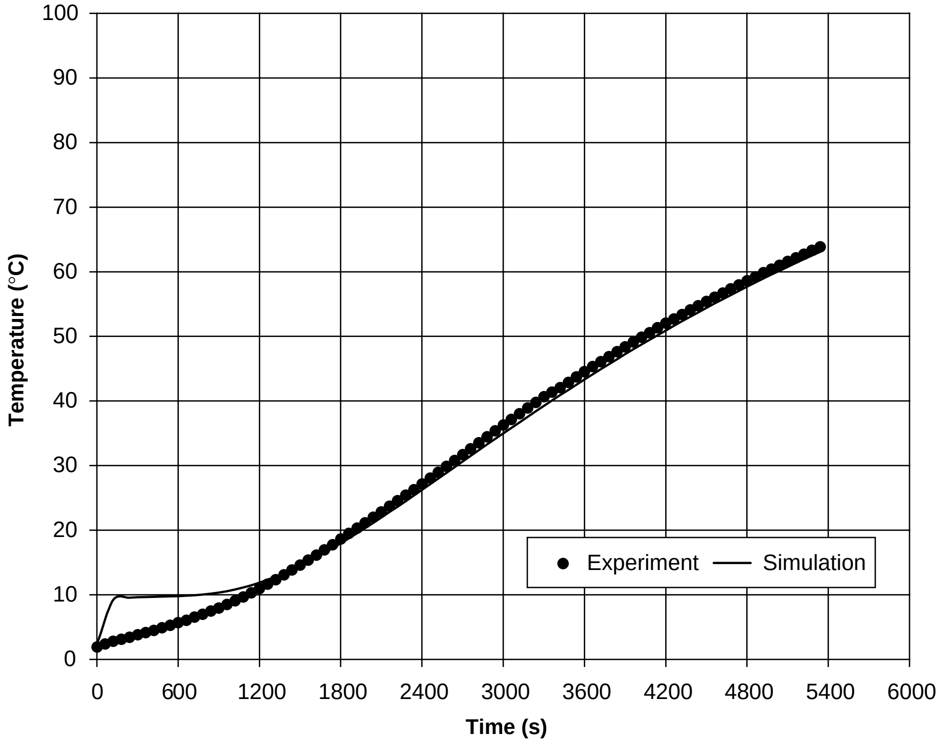

Fig. 4 Model validation: simulation *vs.* experimental backbone temperature profile for pilot-scale skipjack tuna precooking

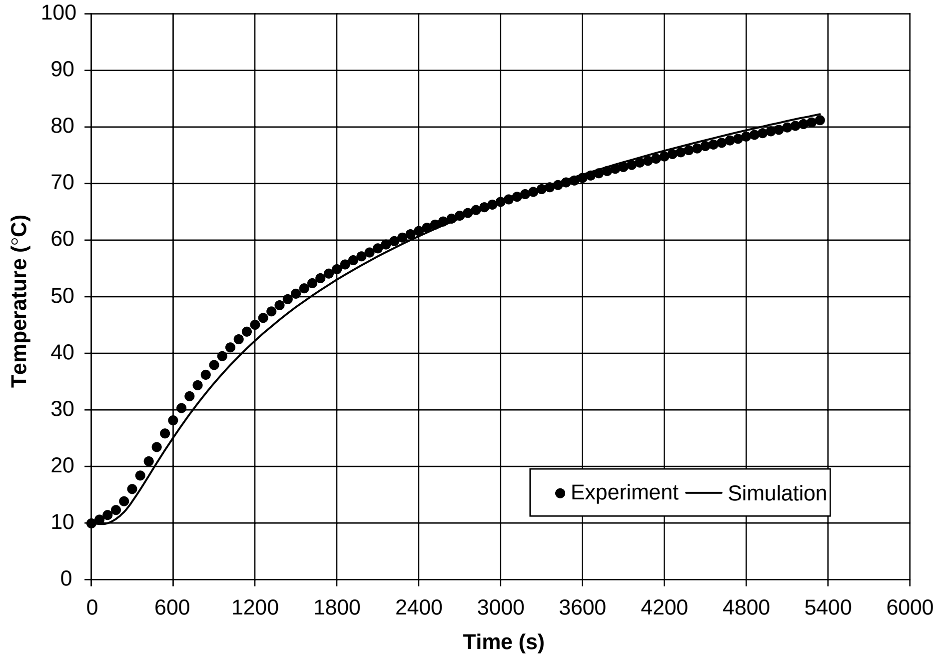

Fig. 5 Model validation: simulation *vs.* experimental loin temperature profile for pilot-scale skipjack tuna precooking

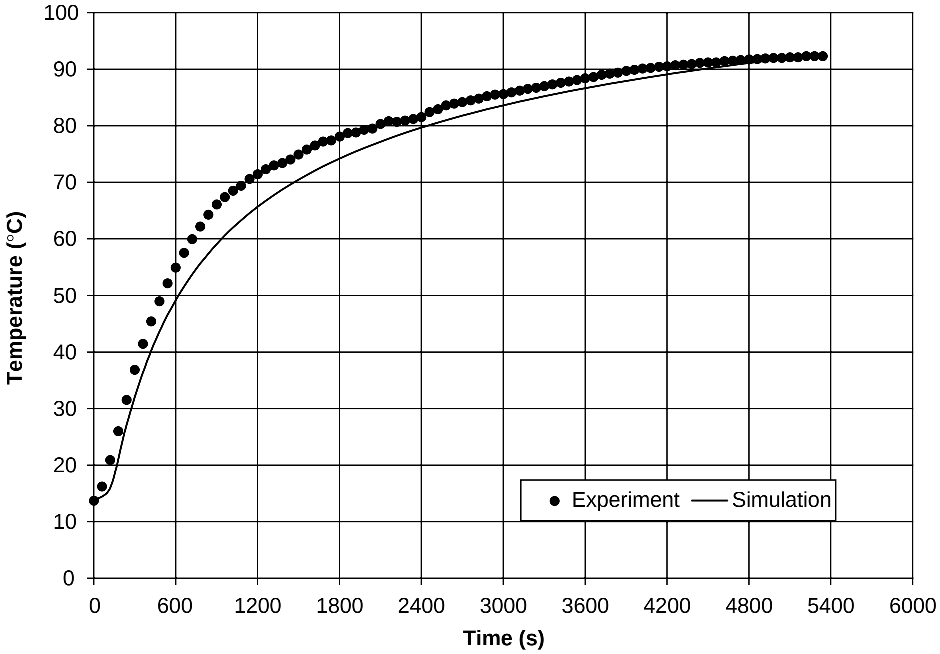

Fig. 6 Model validation: simulation *vs.* experimental viscera temperature profile for pilot-scale skipjack tuna precooking

the model and field data. These improvements would be small relative to the amount of effort required to spatially map the initial temperature variation within the tuna body.

Internal temperature profiles. The temperature profile for four locations in a skipjack tuna during a simulated pilot scale precooking process was plotted to compare the heating rate of each region (**Fig. 8**). The viscera was found to heat faster than loin meat and backbone in the pilot-scale simulation. However, the commercial-scale simulation showed that loin meat had a higher heating rate than the voided viscera region (**Fig. 9**). This was due to the low thermal conductivity of the air occupying the voided viscera region.

While it is mandatory for the tuna industry to eviscerate fish before precooking, there is a question as to how this void region affects the heating rate. This difference in pilot scale (with viscera in, **Fig. 8**) and commercial scale (eviscerated, **Fig. 9**) loin heating rates showed that loin meat of the commercial process heats at a faster rate despite starting at a lower temperature. This greater

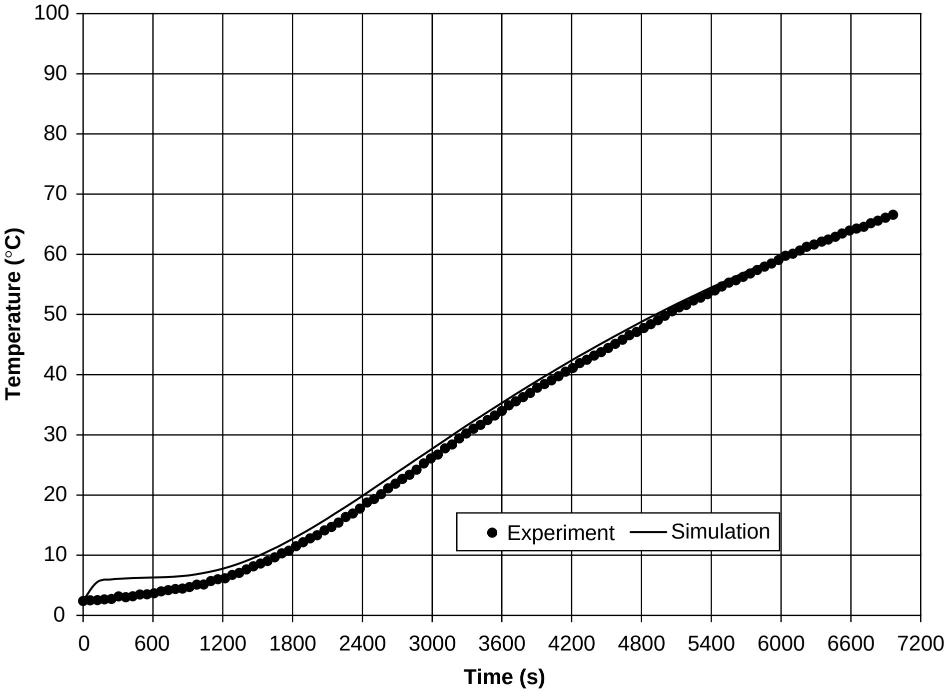

Fig. 7 Model validation: simulation *vs.* experimental backbone temperature profile for commercial skipjack tuna precooking

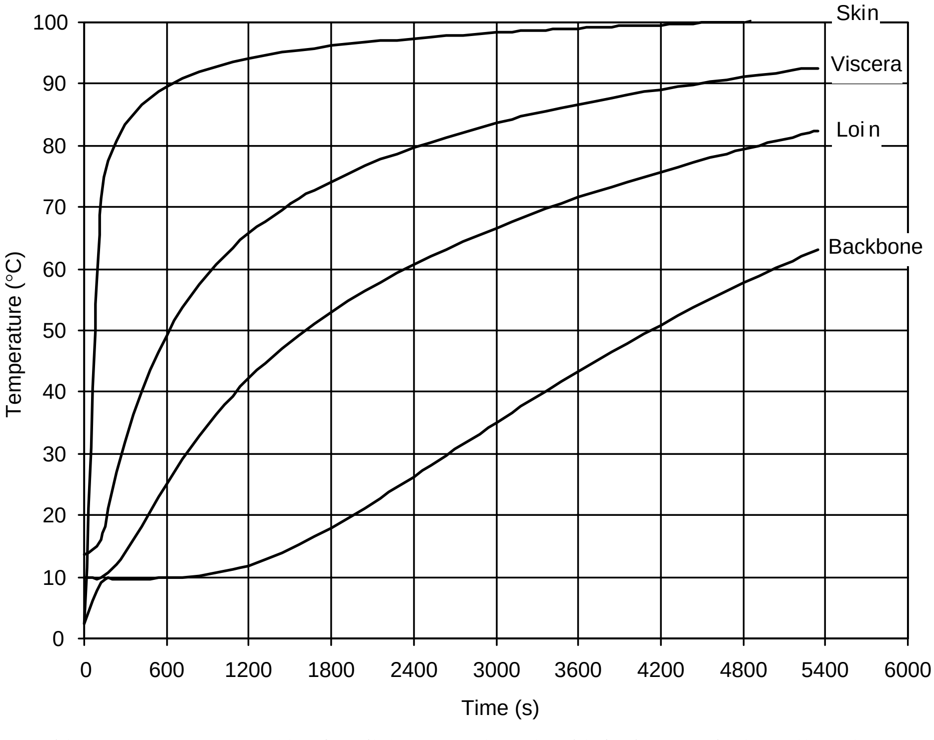

Fig. 8 Simulation cooking temperature profiles for different regions in skipjack tuna during pilot plant processing

heating rate is desirable from the processing standpoint; hence this result will aid in maintaining the evisceration process.

Cooling process. Cooling is achieved, after precooking, via free convection in ambient air. Cooling leads to firming of the precooked muscle and increased yield at the cleaning table. Additionally, cleaning is a manual process and cooling is necessary for ease of handling during cleaning. A comparison of the mathematical model and pilot-scale temperature data for backbone, loin, and viscera showed good agreement (**Figs 10–12**). Agreement between the simulation and commercial data was not as close with the model lagging slightly behind the experimental data (**Fig. 13**). This result is likely due to changes in the fish such as collapse of the viscera

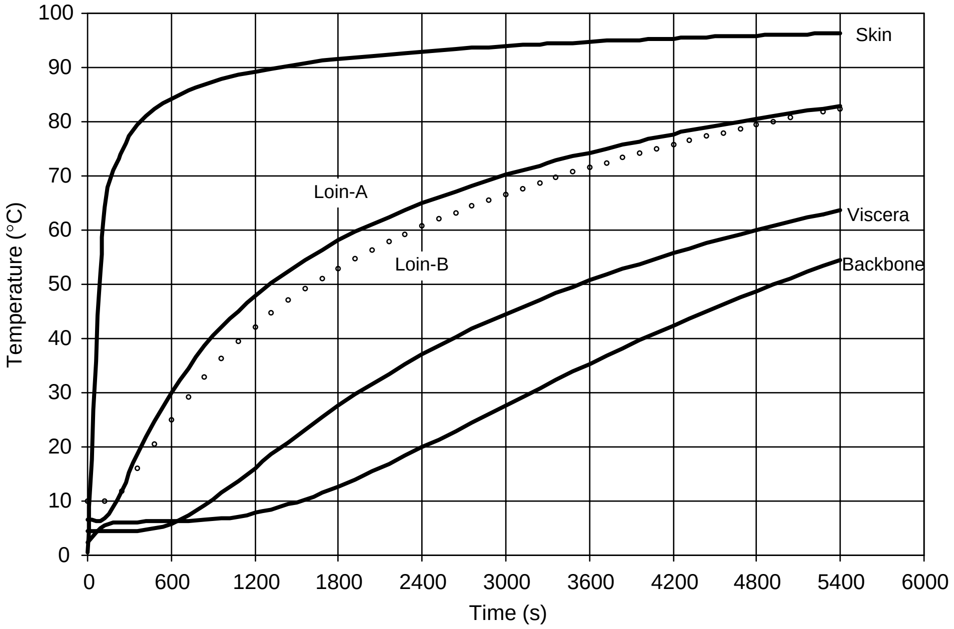

Fig. 9 Simulated cooking temperature profiles for different regions in skipjack tuna during commercial processing. Loin-A refers to the loin temperature for an eviserated fish. Loin-B refers to the loin temperature in a fish with viscera in place

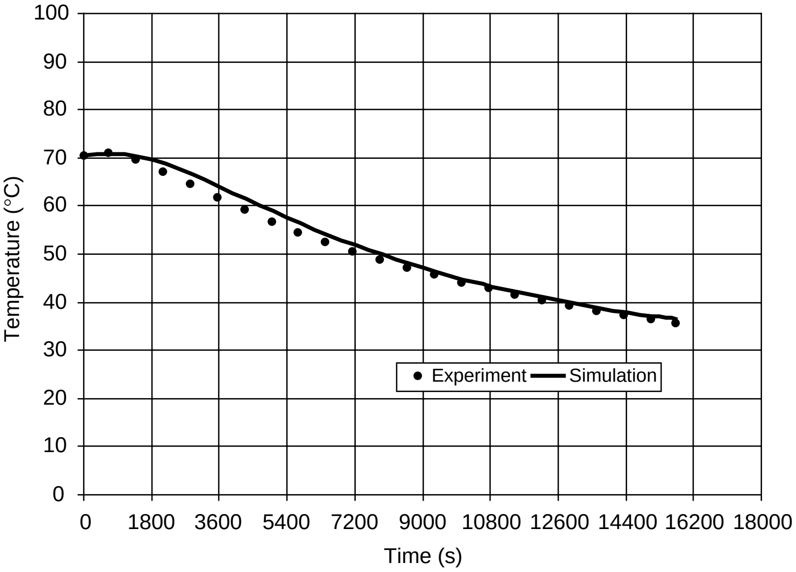

Fig. 10 Model validation: simulation *vs.* experimental backbone temperature profile for pilot-scale skipjack tuna cooling

region and breaking apart of the intact body during precooking. These changes, as well as a loss in moisture, resulted in higher cooling rates in the instrumented fish.

Model limitations. The primary limitation to this simulation of tuna precooking and cooling was the assumption that moisture loss had a negligible effect on heat transfer. In general, there is an 18% moisture loss (unpublished data) in commercial precooking. This could lead to changes in physical and thermal properties and an overall shrinking of the fish body. These are not addressed in the current model's formulation. Regardless, the good agreement between the simulation and experimental data indicates that the assumption was a good one and the model may be used for parametric analysis as an aid in improving the two processes.

Conclusions

A predictive two-dimensional mathematical model for commercial tuna precooking and cooling was developed. Simulated temperature data were compared with experimentally determined data. It was found that the model was in good agreement with temperature profiles generated at the pilot scale and commercial scale. This agreement between the observed data and numerical simulation confirms the validity of the two-dimensional model assumption.

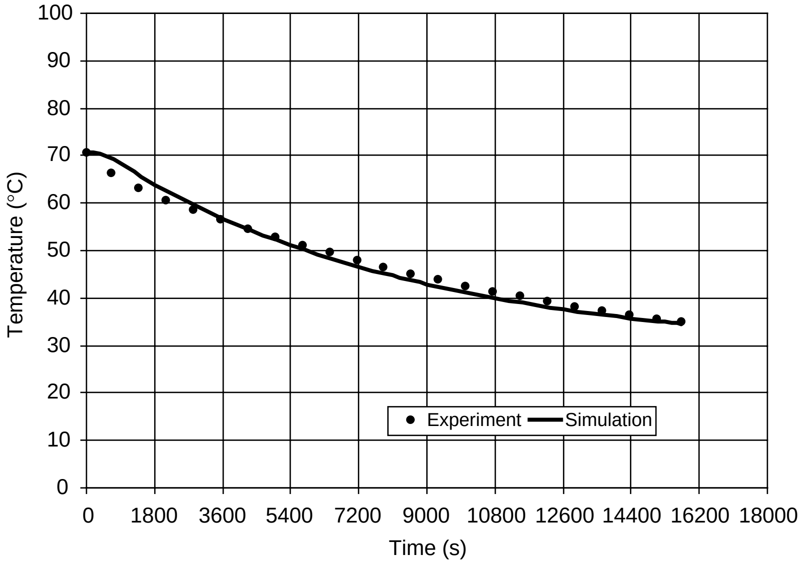

Fig. 11 Model validation: simulation *vs.* experimental loin temperature profile for pilot-scale skipjack tuna cooling

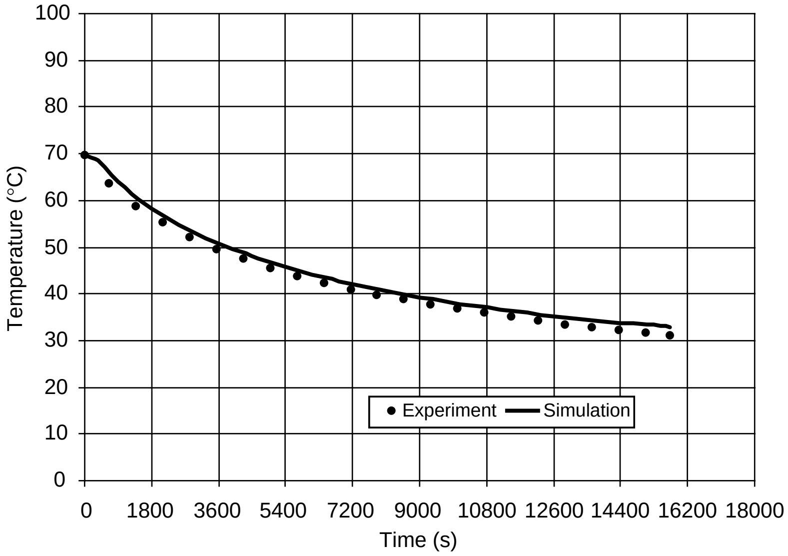

Fig. 12 Model validation: simulation *vs.* experimental viscera temperature profile for pilot-scale skipjack tuna cooling

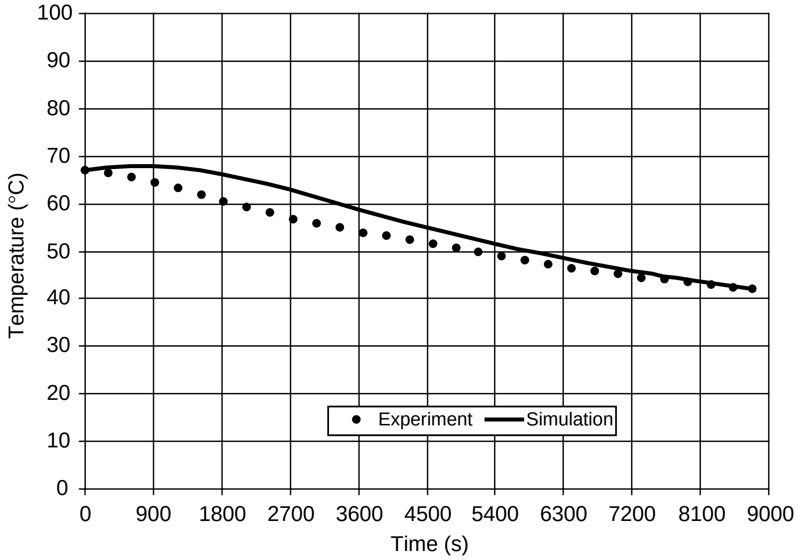

Fig. 13 Model validation: simulation *vs.* experimental backbone temperature profile for commercial skipjack tuna cooling

Heat transfer through tuna during the precooking and cooling process was considered a heat conduction process with convective boundary conditions. While moisture loss represents a significant loss in weight, it was assumed that it would have a negligible impact on heat transfer.

The simulation was confirmed through the comparison with data gathered at the pilot and commercial scales. The simulation may now be used to predict temperature profiles in different regions and for different processing scenarios. Finally, by incorporating physicochemical and biochemical data such as enzyme kinetics, improvements on the current process may be gained.

Nomenclature

c_p	Specific heat capacity (J/kg K)
h	Thermal conductivity (W/m K)
k	Convective heat transfer coefficient ($W/m^2 K$)
t	Time (s)
T	Temperature (°C)

Greek symbols

ρ	Density (kg/m^3)
φ	Dimension of coordinate system (dimensionless)

Subscripts

i	Initial
a	Ambient
s	Surface

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