Optimum Cooking Conditions for Shrimp and Atlantic Salmon

Lauren Brookmire, P. Mallikarjunan, M. Jahncke, and R. Grisso

Abstract: The quality and safety of a cooked food product depends on many variables, including the cooking method and time–temperature combinations employed. The overall heating profile of the food can be useful in predicting the quality changes and microbial inactivation occurring during cooking. Mathematical modeling can be used to attain the complex heating profile of a food product during cooking.

Studies were performed to monitor the product heating profile during the baking and boiling of shrimp and the baking and pan-frying of salmon. Product color, texture, moisture content, mass loss, and pressed juice were evaluated during the cooking processes as the products reached the internal temperature recommended by the FDA. Studies were also performed on the inactivation of *Salmonella* cocktails in shrimp and salmon. To effectively predict inactivation during cooking, the Bigelow, Fermi distribution, and Weibull distribution models were applied to the *Salmonella* thermal inactivation data. Minimum cooking temperatures necessary to destroy *Salmonella* in shrimp and salmon were determined. The heating profiles of the 2 products were modeled using the finite difference method. Temperature data directly from the modeled heating profiles were then used in the kinetic modeling of quality change and *Salmonella* inactivation during cooking. The optimum cooking times for a 3-log reduction of *Salmonella* and maintaining 95% of quality attributes are 100, 233, 159, 378, 1132, and 399 s for boiling extra jumbo shrimp, baking extra jumbo shrimp, boiling colossal shrimp, baking colossal shrimp, baking Atlantic salmon, and pan frying Atlantic Salmon, respectively.

Keywords: cooking, doneness, food quality, salmon, shrimp

Introduction

A variety of cooking methods are used in seafood preparation. Methods are chosen based on convenience and consumer preference. These methods include boiling, baking, broiling, frying, and steaming. Different cooking techniques can result in different quality attributes of the final product. The acceptability of the final product is based on both the food's intrinsic properties and the natural preference of the consumer. Taste, color, odor, juiciness, and texture are common sensory attributes used in assessing the quality of foods. While sensory panels are traditionally used in food quality studies, instrumental methods are a beneficial alternative because it eliminates the factor of human judgment and is less time stringent (Rosenthal 1999).

Popular consumer cookbooks define the "doneness" of shrimp by the surface color change and for salmon by the flaking of the product center (Lauer 2004; Rombauer and others 1997). However, the color change on the surface of shrimp and flaking of fish may make the products appear done before fully cooked. Also, fish can easily be overcooked and become dry. Cato (1998) reported that most seafood-related foodborne illnesses were due to consumption of products that did not receive appropriate thermal treatment, were cross-contaminated (with raw or unprocessed meat) after cooking, or were later subjected to time/temperature abuse. The Natl. Advisory Committee on Microbiological Criteria for Foods (NACMCF) reported that it is difficult to visually quantify the doneness of seafood products to ensure a safe product for consumers (NACMCF 2008). In that regard, the FDA Food Code recommends cooking intact fish fillets to an internal temperature of 63 °C or higher for 15 s (FDA 2009).

From 1990 to 1998, the FDA collected and tested 11312 imported and 768 domestic seafood samples for the presence of *Salmonella*, with nearly 10% of imported raw seafood and 1.3% of domestic raw seafood positive for *Salmonella* (Heinitz and others 2000). Three common *Salmonella* serotypes found on imported seafood were *Salmonella* Enteritidis, *Salmonella* Newport, and *Salmonella* Typhimurium; others included *Salmonella* Weltevreden, *Salmonella* Senftenberg, *Salmonella* Lexington, and *Salmonella* Paratyphi-B (Heinitz and others 2000).

Foodborne illness data from the Centers of Disease Control (CDC) of known etiology showed that from 1998 to 2004, finfish accounted for 42.5% of seafood related cases and 30.6% of seafood outbreaks (NACMCF 2008). It is unknown how many of these foodborne outbreaks were associated with improper cooking or from cross contamination (NACMCF 2008).

Mathematical models can be used to predict the heating profile throughout a product as it is being cooked and the temperature data attained from modeled heating profiles can be directly applied to studies addressing temperature-dependent quality change and microbial inactivation. The mathematical modeling of heating profiles during cooking processes have been studied for various cooking methods such as oven baking (Chang and others

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1998; Sablani and others 1998), pan-frying (Zorrilla and Singh 2000; Ou and Mittal 2007), immersion frying (Farkas and others 1996; Southern and others 2000), and microwaving (Chen and others 1993; Mallikarjunan and others 1996; Hu and Mallikarjunan 2002). Simulated heating profiles can be applied to predict quality changes during the cooking process. Several studies have been conducted on the quality change during the thermal processing of various species of mollusks (Chai and others 1991; Casales and others 1988). Limited studies have applied quality kinetic models to the thermal processing of nonmolluscan seafood products (Banga and others 1993; Kong and others 2007; Skipnes and others 2011).

The objectives of this study were to determine the quality attributes of undercooked shrimp and salmon after processing by common cooking methods; determine the effect of internal temperature and cooking method on color, texture, juiciness, and product moisture; develop mathematical models to describe the heating profile in shrimp (*Litopenaeus vannamei* and Atlantic salmon (*Salmo salar*) and to use the heating profiles to investigate the 1st-order quality kinetics and inactivation kinetics during the cooking process; and determine *D* and *Z* values for 6 *Salmonella* strains inoculated into salmon and shrimp.

Materials and Methods

Cooking processes

Common cooking methods used by consumers were selected for this study. For shrimp, boiling and oven baking were analyzed. For salmon fillets (10 cm × 6 cm × 1.5 cm), oven baking and pan frying were analyzed. Oven baking was performed in a home-type electric range (Model: FEF366EC, Frigidaire, Augusta, Ga., U.S.A.) in natural convection mode (no forced air circulation) to simulate general home cooking operation. The cooking process for these methods is outlined below.

1. *Boiled shrimp.* Five shrimps were boiled on an oven stove top in water initially 99 ± 1 °C. A constant 10:1 mass ratio of water to shrimp with an addition of 1 tablespoon of kitchen salt was used in each test.

2. *Oven-baked shrimp*. Identical to constants in the boiling method, tests were run with 5 prawns cooked together. The oven was preheated to 232 °C (450 °F) as instructed on the product's label. A light coating of PAM cooking spray (ConAgra Foods, Omaha, Nebr., U.S.A.) was applied to a metal cooking tray. Extra jumbo shrimp were flipped over after 150 s and colossal shrimp were flipped over at 180 s in order to mimic a consumer's cooking actions.

3. *Oven-baked salmon*. The oven was preheated to 190 °C (375 °F) as recommended on the product's packaging. Five samples were individually wrapped in aluminum foil and placed on a metal cooking tray. Oven baking salmon in aluminum wraps preserves the flavor and is preferred by consumers (Dufour and others 2006). After cooking, the samples were immediately removed from the oven and the foil was removed.

4. *Pan-fried salmon*. A medium-sized frying pan was heated on a kitchen stove to a center temperature of 220 ± 10 °C, representing medium-high heat. One tablespoon of 100% vegetable oil (Food Lion LLC, Salisbury, N.C., U.S.A.) was coated on the pan to prevent undesirable burning. Salmon samples were cooked individually for 7 min and flipped over half way (4 min) through cooking to follow common consumer cooking methods.

Determination of time–temperature profiles

To determine the cooking times necessary for qualitative analysis, initial studies were performed to track the temperature throughout the product during common cooking procedures. The T-type thermocouples with fiber glass insulation were attached to a data logger (21X Micro logger, Campbell Scientific Inc., Logan, Utah., U.S.A.) directly interfaced to a computer. The thermocouples were strategically placed throughout an individual sample. Four thermocouples were inserted into a single shrimp's head, tail, core, and surface regions. Three thermocouples were inserted into a salmon slab's core, surface, and side region. A separate thermocouple was also used to confirm the temperature of the cooking surroundings.

Initial internal temperatures of 5 ± 2 °C for thawed shrimp and 1 ± 1 °C for salmon samples were kept constant. Five replications were performed for each cooking method/product combination. Means were calculated to confirm time points in which each combination reached 45, 50, 55, 60, and 63 plus 15 s. A temperature point of 63 °C plus 15 s was selected for this study since it is the internal cooked temperature recommended in the 2009 Food Code (FDA 2009) for intact seafood products.

Cooking application for qualitative analysis

The procedure used for the initial time–temperature point studies was replicated to obtain cooked samples for qualitative analysis. Initial internal temperatures were also kept constant to ensure an identical temperature rate increase.

Samples were cooked to reach internal temperatures of 45, 50, 55, 60, and 63 °C. All tests were replicated 5 times. After undergoing the cooking process, each sample was immediately placed in a refrigerator (2 ± 2 °C) for 120 s to stop the heating process without affecting the structure of the product. All qualitative analysis followed immediately.

Color analysis

CIE L* a* b* color space readings were made of the products using a Minolta chromameter (Model CR-300, Minolta Camera Ltd., Osaka, Japan). For both salmon and shrimp samples, surface and core readings were made. Surface readings for shrimp samples were taken in the 2nd segment from the head. Surface readings for salmon samples were taken from an area representing the general color of the entire surface. Tests were replicated 5 times for each cooking time using 5 different samples. The samples were sliced in the middle to get a cross sectional sample for core analysis.

Texture analysis

Immediately after cooking, texture was measured. For the shrimp each sample was tested through the 2nd segment. Salmon samples were cut into a cylinder using a 1.5 cm dia corer. The cylinder was cut appropriately so that texture measurement would be made perpendicular to the natural flaking of the fish sample.

The texture was tested using a Warner-Bratzler shear blade attached to a TA.XT Plus texture analyzer (Stable Micro Systems, New York, N.Y., U.S.A.). The texture analyzer was set to a test speed of 5.0 mm/s, posttest speed of 10 mm/s, target distance of 30.0 mm, and an acquisition rate of 200 pps. A macroprogram was created to measure 3 specific parameters: the maximum shear force (N/cm^2), the shear firmness ($N/s\ cm^2$), and the area (s/cm^2) under the curve, which represents the total work performed to cut the sample. Shear force was obtained as the slope of the line connecting the origin of the curve and the maximum shear force.

Tests were replicated 5 times for each cooking time and product type using 5 different samples.

Juiciness

The juiciness of the cooked products was determined by a method developed by Mallikarjunan and Mittal (1994). One gram of core was removed from the cooked sample and placed between 2 pieces of aluminum foil (35 mm × 35 mm). The aluminum foil squares were in turn placed between 2 pieces of preweighed filter paper (Whatman Nr. 5, 110 mm dia). The filter paper was then placed in between 2 Plexi-glass plates wrapped in plastic wrap. The formation was then compressed with 20 kPa for 1 min. The weight difference of the filter papers was recorded as the pressed juice. The test was replicated 5 times with 5 separate samples for each temperature.

Mass loss and moisture content

Before and after the cooking process, each product was lightly wiped with a paper towel and weighed. By lightly wiping the product, moisture exterior of the product was removed without affecting the natural composition of the product. The percent weight change during cooking was calculated as the mass loss.

Moisture content of the cooked shrimp and salmon was determined using the AOAC Official Method 952.08 as outlined by AOAC (2005). Five tests were conducted with 5 separate samples at each temperature.

Heat transfer models

Assumptions. The following assumptions were made when modeling both shrimp and salmon:

(i) The initial temperature of the product was uniform.
(ii) Volume change of the products during cooking was neglected.
(iii) No mass transfer during the heating process was considered.

Separate geometries were used in developing models for shrimp and salmon. A 2-dimensional frustum cone was used for shrimp prawns with a finite difference equation constructed in the r–Z plane. The r-direction was divided evenly into 5 segments and the Z-direction was evenly divided into 10 segments (Figure 1). The basic 2-dimensional heat transfer equation used for shrimp was:

$$\frac{\delta T}{\delta t} = \alpha\left(\frac{1}{r}\frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta r^2} + \frac{\delta^2 T}{\delta z^2}\right). \quad (1)$$

While this is the initially the heat transfer equation for a 2-dimensional cylinder, the coding was altered to create a frustum cone shape. The coding of the model was set up so that the radius at any point along the z-direction was based on the top and bottom radii of the frustum cone. The boundary conditions for heat transfer in the radial and axial directions are:

$$kA\frac{\delta T}{\delta r} = hA\Delta T \text{ and } kA\frac{\delta T}{\delta z} = hA\Delta T. \quad (2)$$

For the modeling of salmon fillets, a 3-dimensional slab was utilized with the finite difference equation constructed for an x–y–z plane. Each direction of the x–y–z was divided into 5 even segments based on the lengths of each direction (Figure 2). The

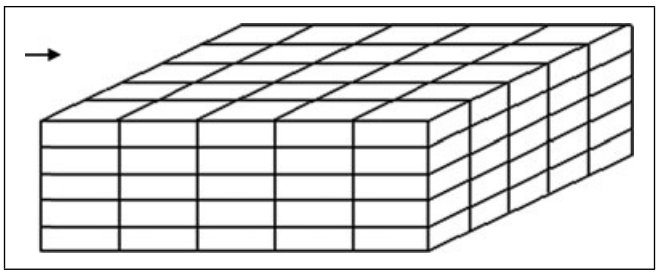

Figure 2–Three-dimensional rectangular slab geometry used in the heat transfer models for cooked Atlantic salmon. The finite difference method was utilized with 5 nodes in each the x, y, and z directions.

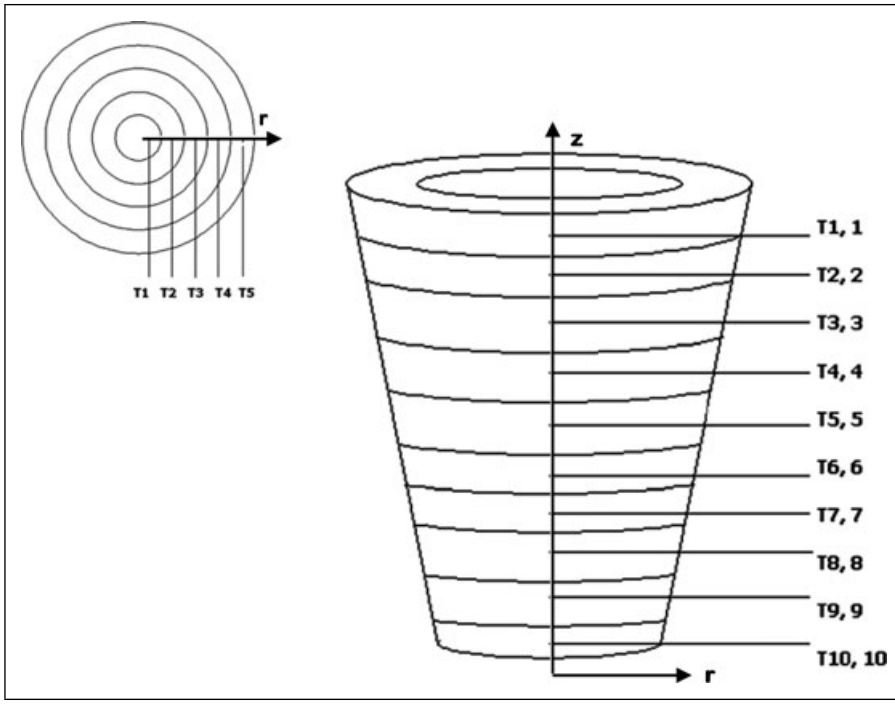

Figure 1–Frustum cone geometry used in the heat transfer models for cooked shrimp. Finite difference method was utilized with 5 nodes in the radial direction and 10 nodes in the vertical direction.

Table 1–Mean color differences (lightness, chroma, and hue angle) during the cooking process as affected by cooking method and product.

			Core			Surface		
Product	**Cooking method**	**Temperature (°C)**	ΔL^*	ΔC^*	Δh_{ab}	ΔL^*	ΔC^*	Δh_{ab}
Extra jumbo shrimp	Boiled	45	16.4	1.37	−29.12	16.64	26.9	−12.48
		50	17.02	1.36	−26.3	23.81	28.64	−15.09
		55	17.18	0.53	−6.47	25.87	30.16	−13.00
		60	24.58	2.13	−45.32	26.85	30.17	−14.24
		63	24.04	1.14	−23.09	19.42	31.09	−14.38
	Baked	45	3.41	1.62	12.92	20.32	1.53	−5.02
		50	1.97	2.73	16.2	23.32	2.37	−13.49
		55	8.62	0.91	−9.77	14.56	20.61	−9.86
		60	12.42	0.85	−13.28	11.48	22.81	−11.90
		63	15.26	1.45	−31.32	14.22	37.50	−12.91
Colossal Shrimp	Boiled	45	4.34	0.60	−7.27	6.41	25.41	−9.05
		50	4.94	0.51	−3.92	5.34	27.09	−7.47
		55	7.72	0.37	−1.97	8.01	28.24	−5.79
		60	15.64	2.23	−33.84	9.26	29.6	−9.09
		63	16.93	2.52	−41.04	10.08	29.24	−10.38
	Baked	45	0.25	3.16	10.28	1.73	5.1	0.89
		50	2.77	2.56	10.8	2.21	16.22	−13.41
		55	7.69	0.76	7.54	4.14	28.74	−9.98
		60	9.60	0.78	1.01	2.97	28.43	−4.28
		63	17.88	1.38	−20.36	8.88	32.70	−4.25
Atlantic Salmon	Baked	45	4.70	9.68	−9.21	7.018	0.77	−1.4
		50	14.68	5.83	1.48	16.22	3.67	3.57
		55	20.78	8.60	−2.14	18.17	3.58	1.02
		60	20.73	4.91	1.47	17.55	2.83	3.05
		63	21.20	2.12	2.66	18.98	4.67	5.34
	Pan-fried	45	8.92	17.79	−2.33	−4.558	15.36	3.78
		50	13.16	16.43	−0.51	−11.23	14.18	−0.46
		55	15.70	14.52	−3.60	−16.20	15.26	−5.19
		60	15.90	16.15	2.94	−13.67	13.50	−0.72
		63	23.82	18.71	5.48	−23.31	8.34	−12.16

basic 3-dimensional heat transfer equation can be written as:

$$\frac{\delta T}{\delta t} = \alpha \left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} \right). \quad (3)$$

The boundary conditions for heat transfer in the x–y–z plane are:

$$kA\frac{\delta T}{\delta x} = hA\Delta T, \quad kA\frac{\delta T}{\delta y} = hA\Delta T, \quad kA\frac{\delta T}{\delta z} = hA\Delta T. \quad (4)$$

The unsteady state heat conduction equation (applicable to a small Biot number) used in this study was:

$$\bar{h} A_s \, (T - T_{\text{inf}}) \, dt = -\rho c V dT, \quad (T = T_i \text{ at } t = 0). \quad (5)$$

The thermal properties used for shrimp ($k = 0.321$ W/(m.K); $C_P = 3480$ J/(kg.K); and $\rho = 1061$ kg/m^3) and Atlantic salmon ($k = 0.429$ W/(m.K); $C_P = 3620$ J/(kg.K); and $\rho = 1125$ kg/m^3) were from research by Chau and Snyder (1988) and Radhakrishnan (1997). Heat transfer coefficients were selected to represent the cooking process and obtained from Ikediala and others (1996) for pan frying and Huang and Mittal (1995) for boiling. For oven baking, the heat transfer coefficient was set at 10 W/m^2.K to represent natural convection in the oven. Separate programs were written for each of the 4 product-cooking method combinations using MATLAB (Mathworks, Natik, Mass., U.S.A.) software.

Quality models

The general change of a quality attribute during thermal processing was represented by

$$\frac{dQ}{dt} = -k(Q)^n, \quad (6)$$

where Q is the quantitative indicator of a quality attribute at time t, k is the rate constant, and n is the order of the reaction (Kong and others 2007). A modified Arrhenius equation was applied in order to take into account any temperature dependence of the reaction:

$$k = A_0 e^{[-\Delta H/(RT)]}, \quad (7)$$

where A_0 is the preexponential constant, ΔH is the enthalpy change, R is the gas constant, T is the absolute temperature, and n is the order of the reaction. The model was constrained to evaluate only zero-, 1st-, and 2nd-order reactions. The temperature data were used from the heat transfer models. A modified 1st-order kinetic model, commonly referred to as a fractional conversion model, was also used in kinetic modeling:

$$\ln\left(\frac{Q_t - Q_{\text{inf}}}{Q_0 - Q_{\text{inf}}}\right) = -kt, \quad (8)$$

where Q_{inf} is the equilibrium quality property after prolonged heating time (Levenspiel 1972). The analysis tool *Solver* in Microsoft Office Excel 2007 was used to determine the ΔH, A_0, and n values for specific quality attributes. The procedure described by Walsh and Diamond (1995) for nonlinear curve fitting using *Solver*

Table 2–Mean texture attributes during the cooking process as affected by cooking method and product.

Product	Cooking method	Temperature (°C)	Shear force (N)	Texture Firmness (N/s)	Total work (N.mm)
Extra jumbo shrimp	Raw	Raw	31.19[a]	1.92[a]	355.78[ab]
	Boiled	45	23.90[ab]	1.46[ab]	297.49[ab]
		50	25.17[ab]	1.46[ab]	298.92[ab]
		55	22.27[b]	1.44[ab]	284.78[a]
		60	24.22[b]	1.51[ab]	310.32[ab]
		63	27.47[a]	1.31[b]	376.82[b]
	Baked	45	27.17[a]	1.73[a]	341.19[a]
		50	26.14[a]	1.61[a]	328.47[a]
		55	25.34[a]	1.67[a]	306.43[a]
		60	26.53[a]	1.70[a]	343.36[a]
		63	31.82[a]	1.93[a]	379.41[a]
Colossal shrimp	Raw	Raw	31.94[a]	1.92[ab]	352.40[a]
	Boiled	45	22.15[a]	1.40[b]	280.03[a]
		50	27.53[a]	1.30[b]	338.81[a]
		55	28.73[a]	1.56[ab]	363.40[a]
		60	27.47[a]	1.31[b]	376.82[a]
		63	26.94[a]	1.42[ab]	363.44[a]
	Baked	45	28.82[a]	1.10[b]	355.65[a]
		50	31.65[a]	1.35[a]	393.77[a]
		55	28.70[a]	1.69[ab]	378.22[a]
		60	32.60[a]	1.83[ab]	376.98[a]
		63	33.17[a]	1.86[ab]	408.93[a]
Atlantic salmon	Raw	Raw	5.28[a]	0.44[a]	70.04[a]
	Baked	45	6.24[a]	0.43[a]	74.85[a]
		50	9.54[a]	0.61[ab]	95.50[a]
		55	15.61[b]	0.93[bc]	146.71[b]
		60	15.40[b]	0.99[bc]	177.57[b]
		63	18.79[b]	1.17[c]	191.9[b]
	Pan-fried	45	24.53[b]	1.12[b]	251.95[b]
		50	23.46[b]	1.11[b]	289.58[b]
		55	26.54[b]	1.32[b]	271.23[b]
		60	28.78[b]	1.18[b]	336.58[b]
		63	25.71[b]	1.35[b]	209.06[b]

[a,b]Means within a column with unlike superscript are significantly different ($P < 0.05$).

Table 3–Mean pressed juice during the cooking process as affected by cooking method and product.

		Mean pressed juice (g/g) Internal temperature (°C)					
Product	Cooking method	Raw	45	50	55	60	63
Extra jumbo shrimp	Boiled	n/a[e]	30.31[a]	29.26[a]	27.20[ab]	24.67[b]	25.15[b]
	Baked		28.64[a]	27.04[a]	25.50[a]	25.58[a]	25.45[a]
Colossal shrimp	Boiled	n/a	30.85[a]	26.84[b]	27.67[ab]	25.76[b]	24.85[b]
	Baked		27.40[a]	25.60[ab]	22.53[bc]	22.80[bc]	21.56[c]
Atlantic salmon	Baked	36.52[a]	35.55[a]	30.99[b]	26.85[c]	26.86[c]	23.20[c]
	Pan-fried		34.20[ab]	32.60[bc]	30.80[c]	25.20[d]	24.20[d]

[abcd]Means within a row with unlike superscript are significantly different ($P < 0.05$).
[e]Raw shrimp unable to press only juice due to physical structure.

Table 4–Mean moisture content during the cooking process as affected by cooking method and product.

		Moisture content (%) Internal temperature (°C)					
Product	Cooking method	RAW	45	50	55	60	63
Extra jumbo shrimp	Boiled	74.31[a]	72.79[ab]	71.98[ab]	70.33[ab]	68.7[ab]	70.62[ab]
	Baked		73.61[a]	72.16[a]	69.8[ab]	65.7[b]	64.92[b]
Colossal shrimp	Boiled	77.01[a]	75.66[a]	76.94[a]	76.26[a]	74.07[a]	73.1[a]
	Baked		73.54[ab]	70.63[bc]	70.25[bc]	67.76[c]	67.66[c]
Atlantic salmon	Pan-fried	65.75[a]	61.9[ab]	56.08[ab]	54.53[b]	55.04[b]	54.18[b]
	Baked		64.81[a]	65.14[a]	65.05[a]	63.58[a]	62.67[a]

[abc]Means within a row with unlike superscript are significantly different ($P < 0.05$).

was followed. The error deviations between the experimental and predicted quality data were calculated as:

$$\sigma = \frac{\sum_{i=1}^{N}(Y_{\text{pred}} - Y_{\text{exp}})^2}{n}. \quad (9)$$

Microbial inactivation kinetics

The temperature distributions obtained from the heat transfer models were also directly applied to calculating the microbial inactivation. A 1st-order kinetic reaction using the Arrhenius equation was assumed

$$-\frac{dN}{dt} = A_0 \times e^{-\frac{E_a}{RT}} \times N,$$

where N is the number of survivors, A is the preexponential factor (frequency factor), E_a is the activation energy, R is the gas constant, and T is the temperature. The results were validated using homogenized salmon and shrimp samples inoculated with a cocktail of *Salmonella*.

Inoculation studies

Three serotypes of *Salmonella* used in Study I were obtained from Remel Microbiology Products (Lanexa, Kans., U.S.A.), and 3 serotypes of *Salmonella* used in Study II were purchased from American Type Culture Collection (ATCC, Manassas, Va., U.S.A.). The serotypes comprising the cocktail in Study I were *Salmonella* Typhimirium (14028), *Salmonella* Newport (6962), and *Salmonella* Enteriditis (13076). The serotypes used in the Study II cocktail were *Salmonella* Heidelberg (8326), *Salmonella* Paratyphi B (8759), and *Salmonella* Typhi (6539). Individual cultures were initially grown overnight at 36 °C in tryptic soy broth (TSB).

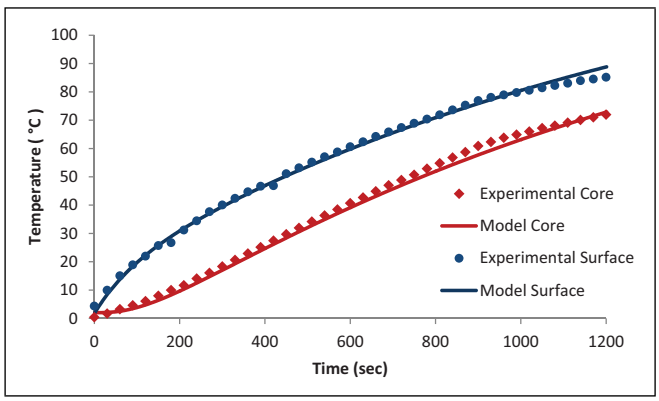

Figure 3–Temperature profile of oven-baked Atlantic salmon fillet.

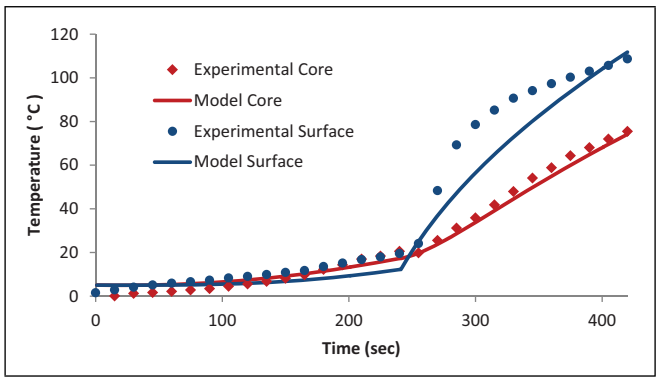

Figure 4–Temperature profile of pan-fried Atlantic salmon fillet.

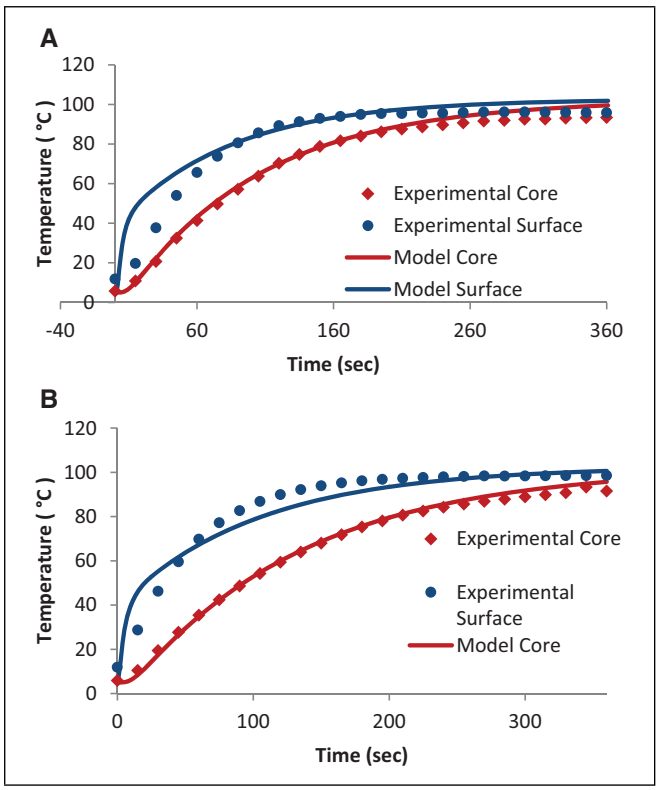

Figure 5–Temperature profiles of (A) extra jumbo size shrimp and (B) colossal size shrimp (boiled).

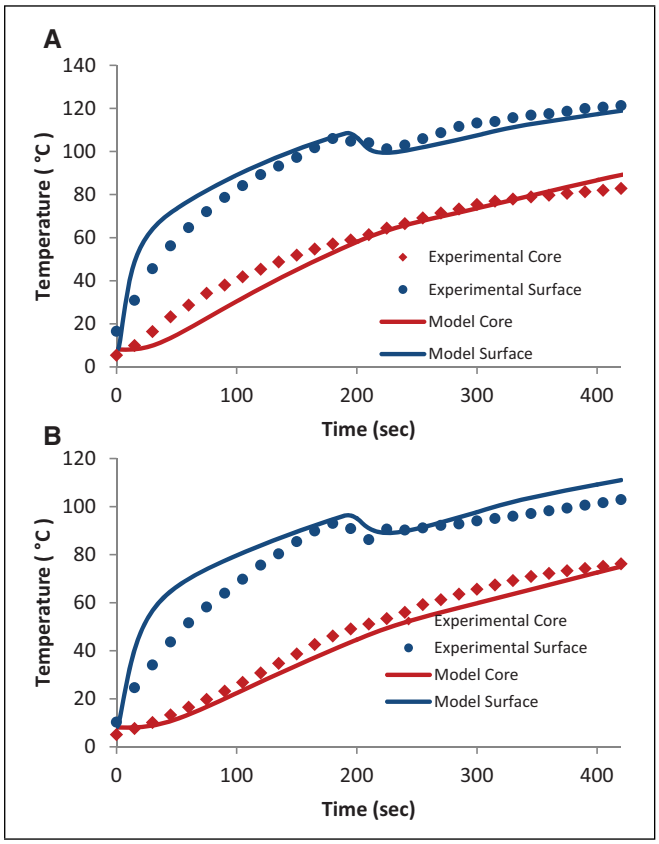

Figure 6–Temperature profiles of (A) extra jumbo size and (B) colossal size shrimp (oven baked).

Table 5– Error deviation between modeled and experimental temperatures for each product-cooking method combination.

Product	Cooking method	Temperature error deviation (°C)	
		Core	Surface
Extra jumbo shrimp	Boiled	0.60	1.64
	Oven-baked	1.99	3.15
Colossal shrimp	Boiled	0.36	1.11
	Oven-baked	1.97	3.37
Atlantic salmon	Oven-baked	0.26	0.20
	Pan-fried	0.54	1.72

Table 6–Calculated *D*-values and *Z*-values for 3-strain *Salmonella* cocktails in homogenized shrimp and salmon.

Product	Cocktail[a]	Temperature (°C)	*D* value (s)	*D* value (r^2)	*Z*-value (°C)	*Z*-value (r^2)
Shrimp	I	60	14.90	0.97	14.75	0.99
		63	10.35	0.98		
		68	4.34	0.99		
	II	60	12.80	0.98	14.56	0.93
		63	5.75	0.98		
		68	3.43	0.96		
Salmon	I	60	37.80	0.98	4.98	0.99
		63	10.95	0.95		
		65	3.67	0.97		
	II	63	7.38	0.92	10.74	0.98
		65	4.11	0.96		
		68	2.48	0.99		

[a]Cocktail I: *Salmonella* Enteriditis, *Salmonella* Newport, *Salmonella* Typhimurium; Cocktail II: *Salmonella* Typhi, *Salmonella* Heidelberg, *Salmonella* Paratyphi B.

Immediately before inoculating samples, 1 mL of each culture was subsequently transferred into a sterile tube and vortexed to create a mixed "poly" culture. This culture was diluted in phosphate buffer solution (PBS) to 10^{-1}, bringing the concentration to about 10^8 CFU/mL.

Sample preparation

Frozen raw shrimp (individually quick frozen, peeled, deveined, Berkley, and Jensen™) and frozen raw fillets of Atlantic salmon (boneless and skinless, Aqua Farms™) were purchased in Hampton, Va., U.S.A. All samples were stored at –80 °C until the day before testing. Samples were then thawed 12 to 16 h in a refrigerator set at 2 ± 2 °C.

One hundred gram samples of salmon and shrimp were homogenized. Using a micropipette, samples were inoculated with the 3 S*almonella* serotype cocktail to produce a 10^7 CFU/g inoculate. A 5 g subsample was removed and placed into a sterile plastic bag (SealPAK Kapak 402, 4'' × 6''). Bags were flattened to express air and sealed with a pouch sealer (Kapak Corp., Minneapolis, Minn., U.S.A.). Each bag was immediately stored at refrigeration temperature until all were prepared for the heating process. Three separate Kapak bags were prepared for each temperature sampling time. Negative controls were also included for each sampling point.

Heat treatment

A circulating water bath (Precision Thermo Scientific, Model 260, Pittsburg, Pa., U.S.A.) containing an extra heater (Fisher Scientific, Isotemp 2150, Pittsburg, Pa., U.S.A.) was used in this study. External-type K thermocouples connected to a thermometer (Fisher Scientific Dual Thermometer, Pittsburg, Pa., U.S.A.) were used to verify a water temperature accuracy of ±0.2 °C. Initial temperature studies were repeated 5 times for both salmon and shrimp using thermocouples to determine the time required for the sample to reach 60, 63, 65, and 68 °C.

The Kapak bags containing the inoculated salmon and shrimp were completely submerged in the water bath at temperatures of 60, 63, 65, and 68 °C for the salmon and 60, 63, and 68 °C for the shrimp samples for a specified period of time based on the preliminary studies. Afterwards, each bag was then cooled in an ice water bath. Samples were then stored in the refrigerator and analyzed within 30 min. A minimum of 3 replicated studies were conducted at each temperature.

Enumeration of surviving bacteria

Each sample (3 bags per sampling time) was placed in a Kapak 402 stomacher bag and sterile PBS (0.85%) was added to each to create a 1:10 dilution. Samples were stomached for 120 s at 230 rpm and plated in tryptic soy agar (TSA). For each sample, both 1 and 0.1 mL were plated in TSA to create concentrations of 10^{-1} and 10^{-2}. Plates were labeled and incubated for 24 h at 36 °C. After incubation, plates were counted for survivors and these data were recorded. For each replicated experiment, the average of 3 platings of each sampling point was used to determine the *D*-values.

Calculation of *D*-values and *Z*-values

D-values (time to inactivate 90% of the population) were calculated from the straight portion of the survival curves by plotting the log survival counts against the corresponding heating times. Survival curves with more than 5 values in the straight portion and a correlation coefficient (r) > 0.90 and descending more than 5 log cycles were used in the calculation. The *Z*-values were estimated by using the linear regression of the mean $\log_{10}$ *D*-values compared with the corresponding heating temperatures.

Optimized cooking conditions

Using the microbial inactivation model results, the cooking time necessary for a 3 log reduction was determined for each cooking method. For each quality that followed an acceptable kinetic model, the cooking time necessary to reach 95% of best quality was determined for each cooking method (Tucker 2003). For data that followed a fractional conversion model, the best quality value was assumed to be the infinite value used for the specific quality. Based on the necessary cooking times both microbial safety and high quality, the optimal cooking time was determined for each cooking method.

Statistical analysis

The JMP8 statistical software package (SAS Inc., Cary, N.C., U.S.A.) was used to evaluate the effect of temperature and cooking method on the quality attributes of the cooked products. To compare the groups of means, Tukey's HSD testing was used following 1-way analysis of variance at a 0.05 level of significance. Multivariate analysis (REML method) was applied to the calculated color differences to test for correlation. Five replicates were analyzed for each product–temperature combination.

Results and Discussion

Effect of internal temperature on color

The change in color and texture in shrimp was a more sudden process during boiling compared with oven baking. External color immediately turned pink during the boiling process, while the change was gradual during oven baking. The external color of shrimp may appear at a point of doneness before the internal

Table 7–First-order kinetic parameters for quality of seafood during cooking.

Color attribute	Product area	Cooking method	Product	$\Delta H \times 10^3$	A_0 (min^{-1}) $\times 10^3$	σ
ΔL (lightness)	Core	Boiling	Extra jumbo	34.722	7.402	0.91
			Colossal	35.691	2.413	1.33
		Baking	Extra jumbo	35.866	3.130	0.88
			Colossal	38.887	4.215	2.09
ΔC (intensity)	Surface	Boiling	Extra jumbo	41.524	50.505	0.13
			Colossal	41.443	40.632	0.17
		Baking	Extra jumbo	57.226	337.041	3.86
			Colossal	47.905	50.071	0.98
ΔL (lightness)	Core	Baking	Salmon	45.771	50228.85	1.32
	Core	Pan frying	Salmon	44.953	39670.7	0.57
	Surface	Baking	Salmon	39.778	3393.23	1.25
	Surface	Pan frying	Salmon	31.588	68.00	1.42
ΔC (intensity)	Surface	Baking	Salmon	30.073	64.59	0.39
Shear force (N)	Core	Baking	Salmon	39.731	3843.25	1.12
		Pan frying	Salmon	39.838	28784.70	1.05
Firmness (N.s)	Core	Baking	Salmon	19.998	3.07	0.10
		Pan frying	Salmon	17.615	4.34	0.08

temperature reached 63 °C. The shrimp become more opaque as the product reached 63 °C.

For salmon, the external color greatly varied based on whether pan frying or oven baking was used. The internal color showed a similar lightening as the internal temperature reached 63 °C. The lightness factor of the core portion best represents the doneness of Atlantic salmon.

Differences in lightness (ΔL), chroma (ΔC), and hue angle (Δh) were calculated from L* a* b* values for both the surface and core regions of the salmon and shrimp throughout the cooking process (Table 1). During the oven baking of salmon, the ΔL rose quickly to 16.22 at 50 °C, and then stayed less than 19.00 through 63 °C. The ΔC and Δh of the surface of salmon slightly increased to 4.76 and 5.34, respectfully, at 63 °C. During pan frying, the surface ΔL decreased to –23.31 by 63 °C, most likely due to the high temperature application and crust formation (Table 1).

Cooked shrimp tend to have a red or pink surface color. This is due to the red carotenoid called astaxanthin, which is released from the carotenoproteins when denaturing (Muriana and others 1993). The ΔC for the surface of boiled shrimp increased to 26.9 and 25.41 at 45 °C for extra jumbo and colossal sizes, respectively (Table 1).

The core ΔL values increased during both boiling and oven baking of shrimp, and lightness values increased more rapidly during the boiling process at 60 °C, (Table 1), which are similar to those reported by Niamnuy and others (2007).

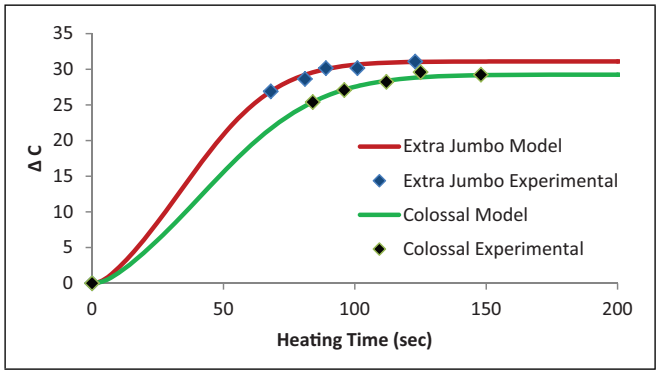

Figure 7–Modeled and experimental surface ΔC (difference in chroma) during the boiling of shrimp.

Effect of internal temperature on texture

The cooking process had a significant effect on the texture attributes of both salmon and shrimp (Table 2). For pan frying of salmon, the shear force significantly increased at 45 °C, and no significant change occurred at higher temperatures. The shear force of salmon did not significantly change during the oven baking process until 55 °C. The oven baked shear force values were not significantly different at internal temperatures of 60 and 63 °C.

The shear force during boiling significantly dropped for extra jumbo shrimp at 45 °C. No significant change in shear force was found during the oven baking (Table 2). The firmness of boiled shrimp decreased with cooking temperature (time) and significant differences were observed from raw sample to fully cooked samples. No significant differences in firmness for baked shrimp. Both cooking operations resulted in an increase in firmness for salmon. Due to the high heat transfer in pan frying, the

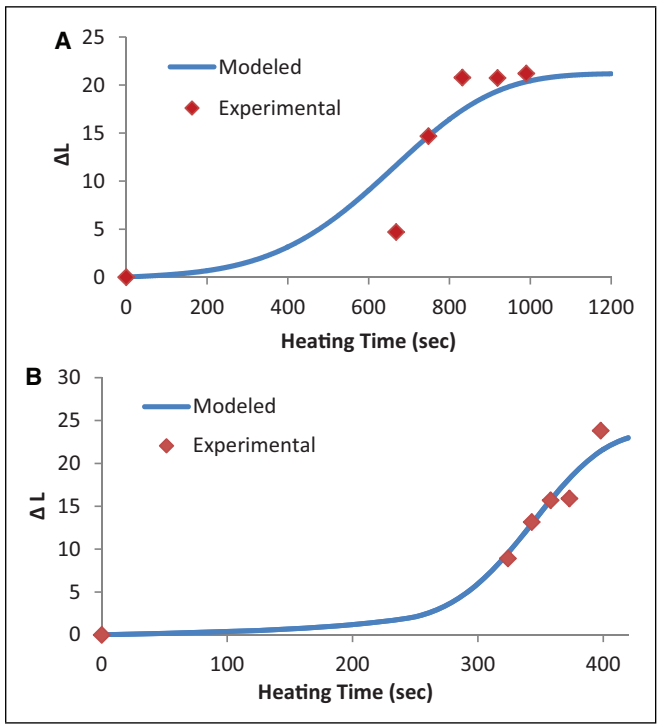

Figure 8–Modeled and experimental internal ΔL (difference in brightness) for (A) oven baked and (B) pan fried Atlantic salmon.

Table 8–Zero-order kinetic parameters for pressed juice of shrimp and Atlantic salmon during cooking.

Product	Cooking method	ΔH	$A_0 \times 10^{-3}$	σ
Extra jumbo shrimp	Boiled	137.12	56.69	0.64
	Oven baked	120.79	21.52	0.32
Colossal shrimp	Boiled	142.08	47.24	0.67
	Oven baked	141.06	25.58	0.70
Salmon	Oven baked	100.02	10.90	1.19
	Pan fried	103.50	16.60	1.44

pan-fried samples are firmer than oven baked samples when samples reached 45 °C, however the final firmness values were comparable and not different from each other at the end of the cooking process. The total work did not vary significantly during the cooking process for shrimp samples. The total work done was significantly higher for cooked salmon when compared to the raw salmon but did not vary significantly during the cooking process. Pan-fried samples had significantly higher total work compared to baked samples and this could be attributed to the type of heat transfer in pan frying (conduction and convection) to oven baking (convection only).

Effect of internal temperature on pressed juice

The pressed juice has shown to be correlated to sensory juiciness (Lee and Patel 1984; Gundavarapu and others 1997). The quantity of thermal treatment had a significant effect on the amount of pressed juice for both salmon and shrimp (Table 3). For oven-baked salmon, the mean pressed juice was reduced to 26.85% at 55 °C, and for pan-fried salmon, mean pressed juice significantly dropped to 25.20% at 60 °C.

The mean pressed juice for the extra jumbo sized shrimp and colossal sized shrimp decreased to 25.15% and 24.85%, respectively, at 63 °C. No significant change in juiciness occurred after 55 °C for boiled extra jumbo shrimp and at 50 °C for boiled colossal shrimp. For the oven baking, there was no significant change in mean pressed juice for the extra jumbo, but colossal size shrimp press juice significantly decreased at 63 °C (Table 3).

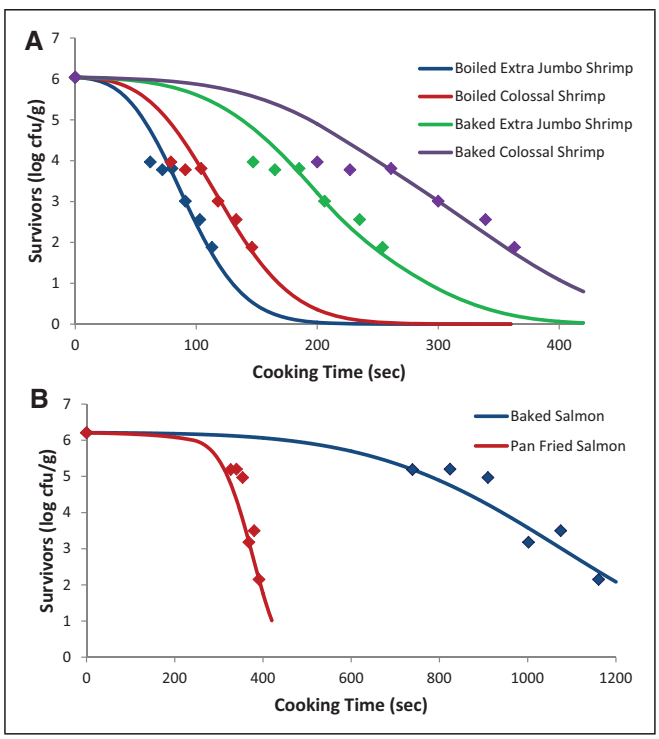

Figure 9–Modeled 1st-order kinetic curves for inactivation of *Salmonella* spp. during the cooking of (A) shrimp and (B) Atlantic salmon.

Effect of internal temperature on moisture content

The moisture content percentages either maintained or dropped during the cooking processes studied for all 3 products (Table 4).

The moisture content did not significantly change in colossal shrimp during boiling. For extra jumbo shrimp, the moisture content significantly changed at 45 °C but did not vary significantly with the cooking process (Table 4). However, the baking process resulted in shrimp samples with significantly low moisture content due to the dehydration during baking. The oven baking process did not significantly affect moisture content in Atlantic salmon. This may be due to the salmon samples being wrapped in aluminum foil. During the pan frying of salmon, the moisture content significantly decreased at 45 °C and resulted in a significantly low moisture product at the end of the cooking process compared to baking (Table 4). The difference in final moisture content of salmon between pan frying and baking is primarily due to the aluminum wrapping for baking process and increase mass transfer during pan-frying operation.

Mathematical models

A comparison of the experimental temperature profile data and model predictions are shown in Figure 3 to 6. All 4 models showed appropriate trends in temperature change based on cooking method. The error deviations between the modeled and experimental temperatures were calculated for each product-cooking method combination (Table 5).

Representing a shrimp as a frustum cone (Figure 1) resulted in agreeable temperature predictions. The external node increased initially at a greater rate in the model compared to the experimental data. This could be due to incorrect thermocouple placement during the experiments. Also, the boiling process creates movement of the shrimp, which may have initially adjusted the positioning of probes further away from the surface, (Stigter and others 2001).

The oven baking of shrimp was accurately modeled for both sizes of shrimp in this study. While the error deviation values were greater for the oven baking process than the boiling process, the oven baking model can still considered agreeable. Similar to the modeled boiling process, the surface temperature initially increased at a more dramatic pace in the model than the experimental data for oven-baked shrimp as well. The reasons for inaccurate surface thermocouple positioning in the boiling process also apply to the baking process.

Using a 3-dimensional rectangular-slab (Figure 2) to represent a salmon fillet showed acceptable results in modeling oven baking and pan frying. The calculated error deviations values were 0.26 and 0.20 °C for the core and surface temperature data, respectively. The pan-frying process involved a single flipping of the salmon. The model simulated this action by reversing all nodes in the γ-direction. The temperature profile of the internal node was accurately modeled before and after the flipping process with model temperatures within ±5 °C of experimental data. While the model processed the dramatic increase in temperature after the flipping of the surface, the modeled temperature increased in a more linear pattern while the experimental data increased in a logarithmic pattern. This may be due to the nodal distance chosen in the model or inconsistent experimental pan temperature. The

Table 9–The timings for the cooking of shrimp and Atlantic salmon to achieve a 3 log reduction in *Salmonella* spp. while maintaining high quality. Times based on predictive models developed for both inactivation kinetics and quality kinetics.

		Cooking time (s)[a]				
Product	Cooking method	3 log	Surface ΔC	Core ΔL	Shear force (N)	Optimal
Extra jumbo shrimp	Boiled	88 (58.1 °C)	83 (55.9 °C)	100 (63.2 °C)	–[2]	100 (63.2 °C)
	Oven baked	206 (59.7 °C)	226 (63.7 °C)	233 (64.8°)	–	233 (64.8 °C)
Colossal shrimp	Boiled	120 (59.9 °C)	103 (54.0 °C)	159 (71.0 °C)	–	159 (71.0 °C)
	Oven baked	299 (59.5 °C)	274 (56.5 °C)	378 (69.7 °C)	–	378 (69.7 °C)
Atlantic salmon	Oven baked	1050 (62.5 °C)	1132 (66.6 °C)	996 (59.7 °C)	892 (54.0 °C)	1132 (66.6 °C)
	Pan fried	368 (60.1 °C)	328 (45.6 °C)	399 (70.6 °C)	323 (43.8 °C)	399 (70.6 °C)

[a]The cooking times for each quality attribute are based on when qualities reach 90% of predicted optimal quality. Qualities used were those that were acceptable fits to kinetic models
[b]Change in shear force (N) followed kinetic modeling for Atlantic salmon but not for shrimp.

error deviation values for the core and surface temperature data were 0.54 and 1.72, respectively.

Thermal inactivation studies

The microbial inactivation data for the 3-strain *Salmonella* cocktails (Studies I and II) in homogenized salmon and shrimp are found in Table 6. The *D*-values were calculated using at least 5 data points along the plotted slope for each temperature–cocktail combination. All *D*-values fit the data points with an R^2 of 0.95 or higher, except for Salmon Cocktail II at 63 °C, where a correlation of 0.93 was the highest achievable. The *D*-values and corresponding *Z*-values are found in Table 6.

The calculated *Z*-values for Salmon Cocktail I, Salmon Cocktail II, Shrimp Cocktail I, and Shrimp Cocktail II were 4.98, 10.74, 14.75, and 14.56 °C, respectively. The shrimp, unlike the salmon, was not able to be homogenized into a smooth paste. There were membrane components and a more lumpy consistency to the solution, which may have provided some thermal protection to the inoculated *Salmonella*. A study by McPhearson and Zywno (1982) also showed higher *Z*-values for inoculated *Salmonella* in shrimp. They calculated a *Z*-value of 11 °C and *D*-values at 60 °C (41 s.); 61.4 °C (37 s); 62.8 °C (23 s) for *S. enterica* serotype Weltevreden inoculated into brown shrimp (*Penaeus aztecus*). *S.* Weltevreden has also been shown to be a more heat resistant *Salmonella* serotype.

Bucher and others (2008) found *Salmonella* Enteriditis to have a lower thermal resistance than *Salmonella* Heidelberg, which correlates with Cocktail I having a lower resistance than Cocktail II. Mazzotta (2000) found a *D*63 of 10.80 s for a *Salmonella* polyculture containing *Salmonella*. Enteriditis and *Salmonella* Typhimurium, which supports the Cocktail I *D*63 values of 10.95 s in salmon and 10.35 s in shrimp.

The *Z*-values for the *Salmonella* cocktails in salmon significantly differed from one another. This could be due to the varying heat resistance of the individual *Salmonella* serotypes in the 2 cocktails. The inactivation rates in cocktails reflect the characteristics of the most heat resistant serotype of the cocktail (Juneja and others 2003). Bucher and others (2008) found *S.* Enteriditis to have a lower thermal resistance than *S.* Heidelberg, which correlates with Cocktail I having a lower resistance than Cocktail II. Mazzotta (2000) found a D_{63} of 10.80 s for a *Salmonella* polyculture containing *S.* Enteriditis and *S.* Typhimurium, which supports the Cocktail I D_{63} values of 10.95 s in salmon and 10.35 s in shrimp.

Quality kinetic models

For the changing color attributes in shrimp, ΔL for the core area and ΔC for the surface area were modeled with 1st-order fractional conversion kinetic model. These color kinetic parameters for both sizes of shrimp undergoing boiling and oven baking are shown in Table 7. The extra jumbo sized prawns had less deviation between experimental and predicted internal ΔL values than the colossal size. The modeling of the ΔC values on the surface of the prawns was accurately modeled during boiling, with error deviation values of 0.13 and 0.17 for extra jumbo and colossal sizes, respectively (Figure 7). The error deviation values for the ΔC models during oven baking were 3.86 for extra jumbo prawns and 0.98 for colossal prawns.

The 1st-order fractional conversion model also appropriately modeled the color change in salmon (Table 7). While adequate correlation was not found in the Δh (difference in hue angle) values over time, ΔL values were modeled with an acceptable representation of both the internal part of the fillet and the surface (Figure 8). The ΔC predictive model effectively described the salmon surface during the oven baking, but pan frying did not efficiently fit the kinetic models tested. For both the internal area of the fillet and the surface, the ΔL 1st-order models had higher Δh values for the oven baking process over pan frying.

The texture data for shear force (N) and firmness (N.s) fit the predictive 1st-order kinetic models for salmon. The kinetic parameters during oven baking and pan frying are shown in Table 7. Similar enthalpy changes were found between the cooking processes. The experimental texture data for shrimp did not acceptably fit the predictive models. This may be due to the high initial raw values for shear force and firmness, which did not represent the general change occurring later in the cooking process. The nature of the veins in the raw shrimp resulted in values unsuitable for modeling. The change in pressed juice during the cooking processes followed a zero-order kinetic model for both shrimp and Atlantic salmon. The parameters and deviations for pressed juice are shown in Table 8.

A 1st-order kinetic model fit the inactivation of *Salmonella* for each cooking method (Figure 9). From the modeled inactivation curves, exact cooking times were determined for various log reductions. The study focused on consumer cooking methods, and the FDA's recommended 3 log reduction for intact seafood products was determined.

There are limited studies on the application of predictive models to the quality and microbial inactivation of shrimp and salmon. Of the studies available, kinetic models are typically fit to experimental data without taking into account the dependency of the rate constant to temperature. A recent study by Kong and others (2007) evaluated the kinetics of reactions leading to changes in salmon quality during thermal processing. Quality changes during the heating of salmon sealed in an aluminum can were studied. Kong and others' study focused more on extending the shelf life in the fish industry, this study focused on optimizing cooking methods practiced by consumers.

Mallikarjunan and others (1995) used temperature distributions obtained from a heat transfer model for microwaved shrimp to develop predictive kinetic models for the inactivation of *Listeria monocytogenes* and the predicted mass loss during microwaving.

Mallikarjunan and others (1996) did not investigate the kinetics of the same quality traits or microorganism as this study. This study supports the effectiveness of applying temperature data from heat transfer models to further predictive models.

Optimized cooking conditions

The cooking times necessary for a 3 log reduction of *Salmonella* during each cooking method was determined based on the inactivation kinetic models. The cooking times needed to achieve 95% of the optimum quality were also determined. The qualities used were those that followed kinetic relationships (ΔC, ΔL, shear force, and juiciness). For the color difference quality attributes, the optimum quality was assumed to be the infinite value used in the fractional conversion models. While juiciness was acceptably modeled by a zero-order model, optimum juiciness cook times were neglected in determining overall optimization cooking conditions. This was due to the constant loss in juiciness over time and the assumption that the minimum cooking time determined was the optimal point for juiciness.

By comparing the various cooking times to achieve microbial safety and to maintain high quality, optimal cooking times were determined for each cooking method (Table 9). These cooking times were based on minimizing the quality loss, yet assuring that a 3 log reduction was achieved.

Conclusions

Using a complex, 3-dimensional slab geometry for salmon and frustum cone geometry for shrimp resulted in agreeable models of the diverse cooking methods studied. All cooking method combinations achieved a 3 log reduction before reaching the FDA's recommended 63 °C for 15 s for intact seafood products. This may be due to the fact that the cooking methods involved a gradual increase in temperature over time, resulting in additional microbial kill during cook time. The temperature data from the heat transfer models were effectively applied to quality kinetic models and *Salmonella* inactivation during the cooking of shrimp and Atlantic salmon and optimum cooking conditions were obtained. The optimum cooking times for 3 log reduction of Salmonella and maintaining 95% of quality attributes are 100, 233, 159, 378, 1132, and 399 s for boiling extra jumbo shrimp, baking extra jumbo shrimp, boiling colossal shrimp, baking colossal shrimp, baking Atlantic salmon, and pan-frying Atlantic Salmon, respectively.

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