Optimization of the Quality and Safety of Cooked Seafood Products

Lauren Marie Brookmire

Thesis submitted to the Faculty of Virginia Polytechnic Institute and State
University in partial fulfillment of the requirement for the degree of

Master of Science

in

Biological Systems Engineering

Parameswar Kumar Mallikarjunan, Chair

Michael L. Jahncke, Co-Chair

Robert D. Grisso

September 10, 2010

Blacksburg, Virginia

Keywords: seafood, shrimp, salmon, quality, cooking, microbial inactivation, optimization, modeling

Optimization of the Quality and Safety of Cooked Seafood Products

By

Lauren Marie Brookmire

P. Kumar Mallikarjunan, Chair

Michael Jahncke, Co-chair

Biological Systems Engineering

ABSTRACT

Seafood products are a common consumer choice and a variety of cooking methods are used in seafood preparation. Although often cooked, products such as shrimp and salmon remain some of the most common carriers of foodborne disease. Cooking these products at elevated temperatures efficiently reduces foodborne disease causing pathogens to a safe level, but applying too much heat to seafood products can produce an overcooked, low quality food. It is necessary to investigate the cooking processes used in seafood preparation and establish appropriate consumer cooking parameters that optimize both the quality and microbial safety of the products. To achieve these goals, this study develops mathematical models for the inactivation of *Salmonella* sp., change in quality attributes, and the product heating profiles during the cooking process for shrimp and Atlantic salmon.

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 homogenized and non-homogenized

shrimp and salmon. To effectively predict inactivation during cooking, the Bigelow, Fermi distribution, and Weibull distribution models were applied to the homogenized data. Minimum cooking temperatures necessary to destroy *Salmonella* sp. in shrimp and salmon were also determined. The heating profiles of the two products were modeled using the finite difference method. Temperature data directly from the modeled heating profiles was then used in the kinetic modeling of quality change and *Salmonella* inactivation during cooking.

It was concluded that consumers need to judge the doneness of both shrimp and Atlantic salmon by the lightness factor (CIE L*) of the core region of both products. The core region's lightness factor, which a consumer may consider as opaqueness, more accurately represented the thermal doneness than the external qualities. The FDA's current recommendations for a 3 log reduction for intact seafood products and homogenized seafood products were each analyzed. Results were in agreement with the recommended 68°C plus 15 seconds for homogenized products. For intact products, shrimp inactivation results were in agreement with the recommended 63°C plus 15 seconds, but intact salmon achieved only a 2 log reduction by the temperature-time combination.

It was also found that predictive models can effectively describe the survival data for two *Salmonella* cocktails. The Weibull distribution model, which takes into account any tailing effect in survival data, fit the survival data of *Salmonella* in shrimp acceptably. The Fermi distribution model, which incorporates any shouldering effect in data, was an acceptable fit for the inactivation data for salmon.

Using three-dimensional slab geometry for salmon fillets and two-dimensional frustum cone geometry for shrimp resulted in acceptable model predictions of thermal distributions for the cooking methods studied. The temperature data attained directly from the modeled heating

profiles was effectively used in the predictive quality and inactivation models. Agreeable first-order kinetic models were formulated for ΔL and ΔC color parameters in shrimp and salmon. Other kinetic models formulated were for texture change in salmon and pressed juice in both salmon and shrimp. Using a fixed inactivation level of 3 logs and a fixed quality of 95% best quality, optimal cooking conditions were determined that both provide a high quality product and assure microbial safety. Based on the specific cooking methods in this study, the optimal boiling times for extra jumbo and colossal sized shrimp were 100 seconds and 159 seconds, respectfully. The optimal oven baking times were 233 seconds for extra jumbo shrimp and 378 seconds for colossal shrimp. For Atlantic salmon, the optimal oven baking time was 1132 seconds and the optimal pan frying time was 399 seconds.

ACKNOWLEDGEMENTS

I would first like to that my advisor Dr. Kumar Mallikarjunan for all of his guidance and support throughout my studies. I am not only grateful for mentorship, but also for his passion for the field of food process engineering. His knowledge and enthusiasm are what led me to realizing my interest and enjoyment for this field of study.

I also extend my heartfelt gratitude to Dr. Jahncke for serving as the co-chair for my project and assisting with my research. Thank you for supplying me with my seafood samples and letting me work at the Virginia Seafood Agricultural Research and Extension Center. I would also like to express my thanks and appreciation to Helen Crocker for her assistance and patience during my studies in Hampton.

My special thanks go to Dr. Grisso for sharing his insights and serving as my committee member. I am also very grateful to BSE staff member Laura Teany for her assistance in the Food Engineering lab.

I want to express my sincere thanks to the Virginia Sea Grant and National Fisheries Institute Fisheries Scholarship Fund for the funding that supported my research. Much appreciation is also extended to the Biological Systems Engineering department and the Food Science and Technology department for allowing me to use their facilities to conduct my research.

Lastly, I would like to say thank you to my parents for all of their love and encouragement. They have always been there for me, supporting every step of my journey. Thanks for everything!

ATTRIBUTION

The chapters of this thesis were created by the author with assistance from several colleagues and coworkers. A brief description of the outside contributions are included here.

Dr. P. Kumar Mallikarjunan – Ph.D. (Biological Engineering, University of Guelph, Canada) was the primary Advisor and Committee Chair. Dr. Mallikarjunan provided his knowledge and expertise pertaining to food process engineering, quality analysis, and mathematical modeling. More specifically, he assisted in the heat transfer and predictive quality kinetic modeling.

Dr. Michael Jahncke – Ph.D. (Food Science, Cornell University) is both a professor in the Food Science and Technology Department at Virginia Tech and the director of the Virginia Seafood Agricultural Research and Extension Center. Dr. Jahncke served as co-chair for the research project. He provided his support and extensive knowledge on present quality and microbiological studies as pertaining to seafood products.

Dr.Robert Grisso – Ph.D. (Agricultural Engineering, Auburn University) is a professor in the Biological Systems Engineering department at Virginia Tech. Dr. Grisso provided assistance in overall compilation of the research project. In addition, he assisted with the subjects and grammatical aspects of the thesis.

Helen Crocker – Microbiologist (Virginia Tech) assisted in the training necessary for the microbiology experiments with *Salmonella* sp. Furthermore, she provided raw data necessary for comparing inactivation kinetic models.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

Seafood products are part of a flourishing industry and product demand is continually growing. Seafood is the most highly traded food commodity internationally (FAO, 2009). In 2006, world exports of fish and fish products reached $85.9 billion, which is an increase of 32.1 percent since 2000 (FAO, 2009). In addition to seafood's taste appeal, it is also a desirable food option nutritionally. The essential minerals and high-quality digestible protein found in seafood products make them a popular diet choice. Docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) are also abundant in some seafood types, and studies indicate they may reduce cardiovascular disease and promote infant neurological development (Burdge, 2004).

Seafood preparation is usually performed by a variety of cooking methods, and the resulting qualities vary greatly based on the procedure used. Varying parameters such as cooking time and applied temperature can significantly affect the resulting product. Undercooking or overcooking the product can diminish the quality, making the seafood undesirable. A high quality seafood product is often described by consumers as fresh-like, and minimally processed (Ngadi and Bazhal, 2004). When judging the quality of fish products, the most important quality attributes to a consumer are the sensory attributes such as color, odor, texture, and flavor (Boggio et al., 1985).

Many seafood cooking methods have a vague explanation for determining "doneness". These doneness specifications are usually defined by the product's sensory attributes. For example, shrimp are commonly considered fully cooked as soon as their surface turns pink. In popular cook books, shrimp have also been described as cooked completely when the inside is

fully opaque (Rombauer et al., 1997). The doneness of fish fillets is also challenging to quantify. While it is common to cook meat products for extended periods of time, fish may only take a few minutes to fully cook. Fish are qualitatively rendered done cooking when the center of the fish flakes or turns opaque (Miller, 2006). The risk of overcooking fish results in an unappealing, dry, tasteless product.

Along with creating a desirable tasting product, cooking processes are also used to ensure the microbial safety of seafood. In 2004, the United States Government Accountability Office (GAO) reported that seafood products represented about 15% of foodborne illness outbreaks, which is a level higher than that associated with poultry or meat products. Most seafood illnesses from pathogens are associated with the consumption of products that are under-cooked, affected by time/temperature abuse, or cross-contaminated (Cato, 1998).   Reaching the necessary internal temperature for the specific product ensures that any contamination has been reduced to a safe level. The Food Safety and Inspection Service (FSIS) under the United States Department of Agriculture (USDA) recommends that seafood products reach a minimum internal temperature of 145°F (63°C) prior to consumption (2007).

Mathematical relations can be used to predict and optimize reactions in foods. Kinetic models translate knowledge on reactions such as chemical, enzymatic, physical, or microbial into mathematic equations describing such changes (van Boekel, 2009). Concerning the microbiological safety of food, the quantitative mathematical modeling approach is a more appealing alternative than the costly, inefficient quality control method based on inspection (Baranyi and Pin, 2001). Other useful modeling techniques applicable to food processing involve continuum models, which primarily deal with transport phenomena, i.e., heat transfer, mass transfer, and fluid flow (Datta and Sablani, 2007).

Hypothesis

The hypothesis of this research is that scientific based time/temperature cooking parameters for consumers can be established to safely reduce *Salmonella* sp. in Atlantic salmon and shrimp and still maintain a high quality product. In addition, prediction mathematical models can be used to optimize the quality and microbial safety during common cooking processes of Atlantic salmon and shrimp.

Objectives

The goal of this research was to investigate the effect of thermal treatment on the quality and microbial safety of Atlantic salmon and shrimp. The specific objectives were as follows:

1. Evaluate the quality of Atlantic salmon and shrimp products undergoing heat treatment by common consumer cooking methods. Determine when different quality attributes reach "doneness" in the product.

2. Evaluate the destruction of *Salmonella* sp. in Atlantic salmon and shrimp during thermal treatment and determine necessary internal temperatures to ensure product safety.

3. Develop and apply mathematical models including the Bigelow model, Weibull distribution function, and Fermi equation to *Salmonella* sp. survival data and compare performances of the different kinetic models.

4. Develop heat transfer models using the finite difference method to accurately describe the heating profile of Atlantic salmon and shrimp during common cooking procedures. Apply kinetic models to relate the thermal processing of the products to

quality attributes and *Salmonella* survival data as to obtain optimum cooking

parameters for product quality.

Rationale and Significance

Seafood products are common carriers of pathogens that cause foodborne disease.

Salmonella sp. is one of the most prevailing pathogens detected in seafood. *Salmonella* sp. can

be reduced to a safe level by simply cooking the product to the appropriate destructive

temperatures. However, it is difficult to conclude when seafood products such a salmon and

shrimp have reached safe internal temperatures during conventional cooking methods. Due to

the ease of overcooking and diminishing the quality, consumers may undercook these seafood

products and increase risk of foodborne disease. Cooking parameters that both optimize the

quality of the product and ensure the destruction of pathogens would benefit both the seafood

industry and consumers. It is necessary to investigate the thermal inactivation of *Salmonella* sp.

in seafood products and establish appropriate consumer based cooking parameters that ensure

product safety. With shrimp and salmon being two of the most frequently consumed seafood

products, it is beneficial to focus studies on these products. This research was conducted to

investigate cooking parameters as to optimize the quality and microbial safety of Atlantic salmon

and shrimp.

References

Baranyi, J., Pin, C. 2001. Modelling microbiological safety. In: Tijskens, L. M. M., Hertog, M. L. A. T. M., Nicolai, B. M., editors. *Food process modelling*. England: Woodhead Publishing. 383-401 p.

Boggio, S. M., Hardy, R. W., Babbitt, J. K., Brannon, E. L. 1985. The influence of dietary lipid source and alpha-tocopheryl acetate level on product quality of rainbow trout. *Aquaculuture*. 51: 3-24.

Burdge, G. 2004. Alpha-Linolenic acid metabolism in men and women: nutritional and biological implications. *Current Opinion in Clinical Nutrition & Metabolic Care*. 7:137-144.

Cato, J. C. 1998. Economic values associated with seafood safety and implementation of seafood Hazard Analysis Critical Control Point (HACCP) programmes. *FAO Fisheries Technical Paper.* Rome: FAO. No 381. 70 p.

Datta, A. K., Shyam, S. S. 2007. Mathematical modeling techniques in food and bioprocesses: an overview. In: Sablani, S. S., Datta, A. K., Rahman, M. S., Mujunmdar, A. S., editors. *Handbook of food and bioprocess modeling techniques*. Boca Raton, FL: Taylor & Francis. 1-12 p.

Food and Agricultural Organization of the United Nations (FAO). 2009. The State of the World Fisheries and Aquaculture 2008. Rome: FAO. Available at: ftp://ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf. Accessed July 7, 2010.

GAO. 2004. Food Safety. FDA's imported seafood safety program shows some progress, but further improvements are needed. United States General Accounting Office. GAO-04-246.

Lauer, T. 2004. *The Saltwater Cookbook. Fish and seafood: from ocean to table*. Chanhassen, MN: Creative Publishing. 18-23 p.

Miller, J. 2006. *Better Homes and Gardens New Cook Book*. Des Moines, IA: Meredith. 319-360 p.

Ngadi, M., Bazhal, M. 2004. Emerging food processing technologies: food safety and quality. In: Shahidi, F., Simpson, B., editors. Sea*food Quality and Safety: Advances in the New Millennium*. NL, Canada: ScienceTech. 7-30 p.

Rombauer, I. S., Becker, M. R., Becker, E. 1997. *Joy of Cooking*. New York, NY: Simon & Schuster. 488-526 p.

U. S. Department of Agriculture, Food Safety and Inspection Service. 2007. Keep Food Safe! Food Safety Basics. Available at:

http://www.fsis.usda.gov/factsheets/Keep_Food_Safe_Food_Safety_Basics/index.asp. Accessed July 7, 2010.

van Boekel, M. A. S. 2009. *Kinetic modeling of reactions in foods*. Boca Raton, FL: Taylor & Francis. 1-8 p.

CHAPTER 2

LITERATURE REVIEW

A variety of cooking methods are practiced by consumers in order to prepare cooked foods. Pan frying, oven baking, and boiling are all common methods used to cook a raw product to a point of doneness. This level of "doneness" is a consumer's perception as to when the food item is ready to be consumed. However, this quality measurement may not satisfy the appropriate confirmation of microbial inactivation in the product. This false perception is a current issue for the cooking process of seafood products. It is important to understand how the cooking process affects both the quality aspects and microbial survival trends for the product in order to optimize the quality and safety of the product. This review provides information on the basics of thermal food processing, the properties affected, safety concerns with seafood products, and the current research on optimizing food quality and safety.

Introduction to Thermal Food Processing

Thermal processing can be defined as the controlled use of heat to alter the rate of reactions in foods (Earle, 1983). Several methods are used in applying heat to a food product. Methods from simply applying steam to using an advanced ohmic heater can be used to successfully thermally process a food, depending on the desired effect. In large scale production, a food material may go through thermal processing at various stages during preparation towards a final product. Heat application is frequently used in secondary processing stages such as radiation, pasteurization, drying, and packaging.   Packaging processes such as bottling and canning use heat to stabilize the food and to provide sterilization (Holdsworth and Simpson, 2007).

Along with the uses of thermal processing during the commercial production of a food product, heat application is also used by the actual consumer. A variety of cooking methods are used by consumers to create the final product they desire. While it is not possible to enforce specific cooking methods on consumers, suggested guidelines are provided by various organizations. The National Sanitation Foundation provides various tips, like how to properly cook using a microwave and how to monitor the temperature of a cooked product (NSF International, 2004). Together, the Food and Drug Administration (FDA), the Centers for Disease Control and Prevention (CDC), and the Food Safety and Inspection Service (FSIS) provide updated editions of the Food Code. The Food Code is a reference document for foodservice operations, retail food stores, and interested consumers. It establishes science-based guidelines and enforceable provisions for risk processes related to foodborne illness (FDA, 2009). Information is provided on a variety of practices, from maintaining hygiene to reaching specific internal temperatures for specific food products.

Food Properties Affected During the Cooking Process

When studying the processing of a material, it is necessary to understand its natural properties. Several engineering properties distinguish a food product and make it unique. They are generally any attribute affecting the handling or processing of a food and the majority can be classified as thermal, electrical, optical, and mechanical. These parameters can significantly change when the food is structurally altered. There are intrinsic properties as well, which are primarily controlled by the material itself (Barbosa-Canovas et al., 2004).

Mathematical modeling can be used to investigate factors affected during the cooking of foods. Prediction models for quality change can be created by applying kinetic models to experimental data. Connecting quality parameters to cooking methods allows for the

optimization of the cooking process as a whole. For example, Haiqing et al. (1999) created a

model that successfully predicted transient temperature and moisture distributions during

convection cooking of chicken patties. From these prediction models, conclusions can be made

on the optimal time-temperature combination for this specific food product. To effectively

model the cooking of a food, it is necessary to first understand the basic properties of the food

material being studied.

Mechanical Properties

In order to appropriately characterize a food material, the structural properties and

strength properties must be evaluated. Density, porosity, and shrinkage are common structural

properties that are studied. Texture is an important strength attribute on a food material and

affects consumer perception of quality. Instrumental measuring devices have been developed

that correlate to the quality of sensory measurements. One current test of food texture is *Texture*

Profile Analysis (TPA), which was created by General Foods in the 1960's (Rosenthal, 1999).

Through the use of a texture analyzer, parameters ranging from hardness to elasticity to

chewiness can be equated. Modeling an accurate relationship between sensory and instrumental

measurements can aid in predicting which sensory attributes affect a food material's quality,

such as moisture, deformability modulus, and slope in puncture (Benedito, 2000).

Electrical Properties

Electrical conductivity and electrical permittivity are useful properties to understand in

the electrical electromagnetic processing and resulting quality of foods.   By correlating these

properties with other characteristics of the food, the effects of electroprocessing can be better

understood. Measuring conductivity is particularly useful during ohmic and conventional

heating methods (Barbosa-Canovas, 2004). The bulk dielectric properties (dielectric constant,

dielectric loss factor) are principally studied to aid in predicting heating rates of materials

subjected to microwave electric fields or high frequency. Models for a wide range of frequencies

have been created comparing dielectric properties and their effects in food processing

(Vankatesh, 2005). Dielectric properties of food products assist in optimizing packaging

materials and the design of radio frequency and microwave heating equipment. Dielectric

properties data have also been investigated to optimize uniform microwave heating (Chatterjee,

2007).

Optical Properties

      Optical properties of a food product are based on consumer judgment on its visual

appearance. These properties govern how a material responds to the absorption of visible color,

light, and the refraction and reflection of visible light (Figura, 2007). In the study of quality

control during food processing, one of the most common optical properties studied is color.

Through use of a colorimeter, results can be analyzed that correlate with human visual

measurements. While there are different scales used in quantifying color readings (CIE system,

Munsell system, Hunter system, etc), they are numerically related (Barbosa-Canovas, 2004).

With the need to optimize safe cooking processes, applications are continuously being looked

into that increase the microbial safety of a product and still maintain desirable optical properties.

Aside from quality control, optical properties are also essential in optimizing machine vision

systems that are used on food processing lines (Saravacos, 1996).

Thermal Properties

      With thermal properties being involved in most food processing operations, the heat

transfer and water transfer that occur are studied for many food products. The main thermal

properties are thermal conductivity (k W m^{-1} C^{-1}), thermal diffusivity (D – mm^2 s^{-1}), and specific

heat (Cp – J cm^{-3} C^{-1}) (Fontana, 1999). This knowledge of a product is necessary for calculating

energy demand during the processing of a food product and therefore the optimization of the

design of processing equipment. The safety and quality of a food product depend critically on

the temperature history of the product and the distribution and state of water in the product

(Nesvadba et al., 2004). Thermal properties are dependent on other properties of the food,

including structure, composition, and interaction with surrounding variables.

Heat and Mass Transfer in Food Products

Heat transfer occurs in the processing of foods as energy transfers through conduction,

convection or radiation. Radiation uses electromagnetic waves to raise a product's energy level,

while conduction and convection involve energy transfer between molecules. Different cooking

methods differ in their predominant heat transfer mechanism. For foods with high moisture

contents, water itself is used as processing medium. As water experiences a phase change, the

heat transfer experienced is what creates the cooking of the food product. When boiling a

submerged product, a phase change occurs between liquid water and vapor. The heat flux

dramatically changes between the product surface and the boiling liquid dependently based on

the temperature difference (Wang, 2006). The greater the temperature difference, the faster the

rate of heat flow. The general mathematical heat transfer equations for convection, conduction,

and radiation are:

$$q = h\,A\,(T_m - T_s) \qquad \text{(convection)} \qquad 2.1$$

$$q = \frac{k\,A}{L\,(T_m - T_s)} \qquad \text{(conduction)} \qquad 2.2$$

$$q = \sigma\,\varepsilon\,A\,(T_m - T_s) \qquad \text{(radiation)} \qquad 2.3$$

where q is the heat flow, h is the heat transfer coefficient, k is the thermal conductivity, L

is the length the heat travels, A is the cross-sectional area of the heat being transferred, ε is the

emissivity, σ is the Stefan-Boltzman constant, T_m is the temperature of the environment, and T_s is

the temperature of the object's surface (Jamnia, 2009). The combination of conduction and convection is commonly encountered as heat transfers convectively between a gas or fluid on one surface, conductively through a solid, and sometimes convective heat transfer again on an opposing surface (Toledo, 2007). This combination occurs in oven baking, where heat is transferred by convection from air to the product surface and then by conduction from the surface toward the product center. In this atmospheric air-drying, the capacity of water removal from the material's surface depends on drying air characteristics, such as humidity, air temperature, and air velocity (Lazarides, 2003).

Simultaneously to heat transfer, mass transfer occurs during the thermal processing of foods as materials move in fluid systems. Often this material is moisture that is evaporating from the product into the surrounding system. There is little information on the mass transfer of food components aside from water, such as salt, sugar, and flavor compounds.

Cooking and the Quality of Food

A food product's acceptability can be defined by both its intrinsic properties and the natural preference of the consumer. While little can be done to alter the consumer, the properties of the food manipulated to optimize its acceptability. Researching the subjective perception of consumers towards quality attributes of specific food products can optimize the acceptability of the product.

Assessing Food Quality

Methods for judging the quality of a product are usually through sensory evaluation techniques. These can be classified into three categories: (1) discrimination tests, (2) descriptive analysis techniques, and (3) acceptability measured by degrees of liking (Bourn and Prescott, 2002). Common sensory attributes studied when assessing the quality of foods are taste, color,

odor, texture, juiciness, and moisture. Recent developments in instrumentation technologies have provided opportunities to quantitatively describe sensory quality attributes. Instrumental technology is more beneficial than the use of sensory panels because it is both less time stringent and eliminates the factor of human error. The complex correlation between sensory measurements and instrumental measurements is also beneficial towards quality assurance applications (Rosenthal, 1999). In addition to sensory properties, the nutritive values, mechanical properties, and chemical constituents define the quality of a product.

Effects of the Cooking Process

A lot of desirable sensory attributes are found in the raw food material. The taste, flavor, and texture of fresh fruits, vegetables, nuts, etc. all depend on the presence of natural compounds (Sikorski, 2007). While many of these properties are carried through the processing of products, some of these properties diminish. The cooking of vegetables causes a flavor loss into the cooking liquid or by evaporation, which can be a desirable effect for strong-flavored products such as onions and brussel sprouts. Nutritional aspects can also decrease after exposure to the cooking process. The USDA National Nutrient Database for Standard Reference provides nutritional information for more than 130 nutrients in over 7,000 foods (USDA-ARS, 2009). Vitamins in a raw food can be destroyed by heat, light, pH, and oxidizing agents. Minerals can be removed from foods during processing by both leaching out into the cooking water and by physical separations (Reddy et al., 1999).

Thermal processing can also improve the quality of certain food products. Some foods such as meats and eggs are not even considered edible in raw form. The quality of a cooked final product can be controlled through parameters such as the cooking method used, temperature applied, cooking time, and flavor addition such as spices. Altering a parameter such as temperature or cooking time to a point outside of an acceptable range can create a qualitatively

13

unappealing final product. Boiling noodles for more than an acceptable cook time will cause a loss of solids in the water and result in a sticky, soggy, low quality product. Beef products such as steak can be found qualitatively acceptable at various points through thermal processing. Several studies have been performed on optimizing all degrees of doneness that a consumer may prefer in dark meats. For example, Neely et. al (1999) studied various cooking methods and the degree of doneness for top round steak on the satisfaction of customers in various nationwide locations. The varying parameters that come with various consumer preferences make the analysis of quality parameters a complex process.

Optimizing Quality

With new products and cooking equipment constantly being introduced, continuous studies are performed to find the cooking parameters that create an optimal quality product. The effects of the recently introduced steam-convection oven were compared with the traditional methods of cooking such as roasting, boiling, and frying (Danowska-Oziewicz, 2007). The steam-convection oven cooking method resulted in higher retention of vitamin C in vegetables and higher protein content. While nutritionally appealing, research focusing on the sensory attributes of this new cooking alternative is necessary to prove the acceptability of products this new appliance provides.

Cooking and the Microbiological Safety of Food

In order for a food to be considered safe, it must not contain harmful organisms or chemical compounds above specific levels. The sources of harmful organisms range from being an inherent constituent of the food to being introduced to the food product during food production, processing, or preparation (Snowdon, 1990). Foodborne disease can also be transmitted through contact with infected farm animals and through water. Once introduced, the

14

growth of the microorganisms is then dependent on both the intrinsic and extrinsic parameters of the food product. Intrinsic parameters of greatest importance include moisture content, pH, nutrient content, antimicrobial constituents, and the biological structure. Extrinsic parameters include storage temperature, presence of other microorganisms, relative humidity of the environment, and the presence of gases (Jay et al., 2005).

Microbial Inactivation

While the thermal processing of foods is used to produce desirable quality changes, its primary benefit is to deactivate harmful microorganisms to an acceptably low level. Different parameters can affect the efficiency of heat treatment in pathogen inactivation, such as pH, salt, temperature, oxygen level, etc (Rosnes, 2004). Through multiple experiments, thermal death models and inactivation kinetics are developed for specific pathogens and food materials. Target pathogen survivals can then be predicted to better optimize the safety of the food product.

Bigelow and Esty (1920) first used the concept of a thermal death point, which is defined as the length of time to completely destroy a specific concentration of microorganisms at different temperatures. The thermal death time depends on the growth medium, the nature of the organisms, and the number of cells. When a pathogen is exposed to a lethal temperature, the viable count of that pathogen decreases logarithmically with time. In modeling the thermal destruction of microorganisms, the thermal resistance of a specific microorganism in a specific food product is represented as a "z-value". A basic way of calculating this value is finding the slope of the thermal death time curve through one log on semi-log paper. Another term used in thermal inactivation is the F-value, which is the time in minutes that is required to destroy an organism at a specific temperature (Townsend et. al, 1938). The most common method of measuring microbial destruction is by decimal reduction time (D-value). The D-value is defined as the time in minutes to achieve a 90% reduction (1-log) in a specific microorganism at a

specific temperature in a specific growth medium (Lund, 2000). Since it is nearly impossible to destroy all microbial cells, a pre-determined amount of surviving organisms is deemed acceptable to reduce to for specific products. For example, processed foods must ensure at least a 12D reduction for *Clostridium botulinum* in low acid foods (Dalgaard, 2006).

Pathogen Survival during Cooking

Thermal processing reduces pathogens in foods, yet there are still approximately 79 million foodborne illnesses and 5,000 deaths in the United States each year (Mead et al., 1999). This may be due to inaccurate thermal treatment and product abuse. The thermotolerance of pathogens has been widely studied for food products, and specific time-temperature combinations have been determined that inactivate pathogens for most food products. The continuing high foodborne illness rate is most likely due to consumers not meeting this time-temperature cooking guideline. The illnesses can also be attributed to outside contamination, including feces, human handling, transport containers, rinse water, and processing equipment (Burnett and Beuchat, 2001).

Surveillance of Foodborne Disease

The CDC (Centers for Disease Control and Prevention) works in conjunction with state health departments to monitor surveillance systems in the US in order to collect foodborne disease data. Medical case histories, risk models, and other scientific reports also contribute to pathogenic prevalence sources of data. However, accurate reporting for foodborne disease is uncommon. An individual must report their illness, correct diagnosis must be made, correct identification of the foodborne disease agent must be made, and the results need to be reported to the proper agency that maintains records on foodborne disease (Snowdon, 1990). Since this entire chain of events does not always happen, the true incidence of foodborne disease can only

be estimated. Correction factors are developed through both research and surveys and are

applied to actual numbers of cases identified by laboratories.

Foodborne Disease Related to Seafood Products

Seafood products are of high interest for both pathogenic safety and quality

improvement. Many factors influence seafood safety, including microorganism composition,

environment type, water pollution, and overall product handling (Galaviz-Siyla et al., 2009). A

large percentage of seafood products originate in developing countries and the importing process

is associated with the risk of foodborne illness. Seafood is not only a high internationally traded

food commodity, but an important component in diets worldwide. It is estimated that over one

billion people around the world rely on fish as their main source of animal protein (FAO, 2000).

Shrimp consumption per capita has increased over the years from an average of 1.0 kg in 1989 a

record high of 1.8 in 2005 (NMFS, 2007). Shrimp continues to be the top consumed seafood

product in the United States. With the growing interest in healthier food products, seafood has

proven to be a healthier alternative to other animal protein. A study by Mahaffey et al. (2008)

found salmon and shrimp to be principle seafood sources of omega-3 fatty acids containing the

least amount of the undesired methyl mercury. Consumer interest in seafood products creates

the need for ongoing research on safety in this food area.

Salmonella as a Leading Cause

Foodborne pathogen statistics show declines in incidences from 1998 to 2005 from some

pathogens but an increase for others. Specific strands of *Salmonella* are included in the statistics

of increased incidences, including *Salmonella* Enteritidis and *S.* Heidelberg increasing each by

25%, and *S. javiana* by 82% (Bhunia, 2008). For the year 2007, the FoodNet Surveillance

Report by the Centers for Disease Control and Prevention (CDC) revealed Salmonella to have

the highest incidence of laboratory-confirmed infections caused by specific pathogens (14.86/100,000 population), followed by *Campylobacter* (12.78) and *Shigella* (6.24) (CDC, 2009). The report also found the greatest number of deaths from foodborne illness occurred in persons with *Salmonella* infections.

In a study from 1990-1998, the FDA found an overall Salmonella incidence of 7.2% in imported and 1.3% in domestic seafood (Heinitz et al., 2000). The infectious dose of Salmonella is about 10^6 cells, and a much lower cell count (10-100) can be infectious if protected against stomach acid (Dalgaard, 2006). Microorganisms are found on all the outer surfaces and the intestines of fresh fish (Huss, 1988). Salmonella contamination on food products is usually due to contamination of the product through fecal waste or water contact.

Thermal death times for Salmonella and specific seafood products can be established through statistical data analysis and then applied to safe cooking standards. Plaza and Gabriel (2008) researched the thermal death time of *S.* Typhimurium in oyster meat at 60°C. A cooking process was created capable of significantly reducing with microbial load without significantly altering the quality of a popular heat-treated oyster recipe. Another study found the thermal inactivation rates of *S.* Typhimurium in a food product containing snail meat (Gabriel and Ubana, 2006). Minimal research can be found on thermal inactivation of Salmonella in types of seafood aside from shellfish (Chintagari, 2009; Haines and Comar, 1984).

Mathematical Modeling

Mathematical modeling is a useful tool simplifying complex real world situations. This applies to the effect of processing conditions on food quality attributes. Foods are complex systems and using mathematical models help to describe a chemical reaction and its reaction rate. There have been recent advances in the area of microbial modeling in food microbiology.

Intrinsic factors such as water activity, pH, and temperature and their effects on pathogen growth are continuously being modeled (McClure et al., 1994). Mathematical models are also useful in modeling the relationship between the number of surviving microorganisms and the treatment time at a given temperature. Collected data is summarized in as an equation, and by interpolation, predictions can be made about data that was not specifically tested. It was traditionally assumed that all microorganisms had the same survival curves during thermal processing (van Boekel, 2002). With the realization that different microorganisms have different thermal resistance curves, inactivation of specific pathogens in specific foods has been studied. Common log-linear models, such as the Bigelow model, consider microbial inactivation a process that follows first-order kinetics (Alzamora et al., 2010). While several linear models have been used to describe this relationship, more complex models have been introduced that factor in the presence of shoulders or tails (Peleg, 2000). This includes the Weibull distribution model, which follows a basic power equation, and the Fermi distribution model, which has a sinusoidal shape. By using more complex models, the underlying frequency distribution of sensitivities and statistical properties of the frequency distribution can be determined directly from the survival data.

In order to model the quality change of a food, it is necessary to connect various models to each other with a proper use of mass and energy balances (van Boekel, 2009). Kinetic models are using in food processing to quantify the chemical and physical changes taking place in a product. When first-order reaction kinetics are applied to quality parameters, the quality can be expressed as

$$\ln{(C/C_0)} = k_c(t_2 - t_1) \qquad\qquad 2.4$$

where C is the quality attribute, C_0 is the initial quality attribute, and k_c is the rate constant. Due to the natural complexity of foods and the difficulty of using temperature profile models, steady-state methods are used in most studies to estimate kinetic parameters (Ahmed and Shivhare, 2006).

Bigelow model

The Bigelow model incorporates the use of the decimal reduction value (D-value) as an additional parameter and serves as a thermal death time model. This model, also referred to as the TDT curve (thermal death time curve), is applied to survival data as

$$\log \frac{N_t}{N_0} = -t/D \qquad\qquad 2.5$$

where N_t is the number of survivors at time t, N_0 is the initial number of survivors, and D is the decimal reduction value. The *z* parameter can then be calculated as the slope of the plot of temperature verses log(D). The z-value indicates the temperature increase needed to increase the lethal rate 1 log (Denyer and Hodges, 2004). This model is commonly used for the validating and monitoring of a sterilization process. Many studies extend this linear model, adding beneficial parameters such as pH and water activity (Leguerinel, 2005). Regulatory agents often use such model parameters when studying thermal treatments for food safety.

Arrhenius equation

The Arrhenius equation is commonly used for the temperature dependence of a chemical reaction. It can also be applied to describe microbiological growth and quality deterioration. Arhenius' law states that

$$k = A * e^{-Ea/RT} \qquad\qquad 2.6$$

where A is the pre-exponential factor (frequency factor), Ea is the activation energy

(cal/mol or joule/mol), R is the gas constant, and T is the absolute temperature. In most

reactions, A is dependent over an extended temperature range. The reactants must pass through

a highly activated complex stage before they are converted to products (Law, 2006). The

activation energy is this quantified energy barrier that molecules need to reach to be able to react.

The higher the temperature, the more molecules with enough energy will be able to make it over

the barrier. Arrhenius' equation is often used to find the activation energy from the temperature

dependence of the pre-exponential factor rate (Sturge, 2003).

Ocio et. Al (1994) conducted a study comparing the Bigelow and Arrhenius models for

inactivation predictions of *Bacillus stearothermophilus* in a mushroom-alginate substrate. In

comparing actual safe processing rates, it was found that the Arrhenius model was a better

predictor of the inactivation rate constants at the study's temperatures.

Fermi distribution function

The Fermi distribution can also be applied to survival data in the following form:

$$\ln S(t) = -\ln\left(1 + e^{k*(t-t_c)}\right) \qquad\qquad 2.7$$

where k is the rate contant (min^{-1}) and t_{cm} is the critical time at which half of the

survivors exists. This logistic function takes into account the initial "shoulder" of the survival

curve, which is the period of time where no measureable inactivation takes place (Peleg, 2000).

The Fermi distribution has a characteristic sigmoid shape with identical mode and mean. It

assumes that inactivation follows first-order kinetics at the end of the lag time, rather that immediately at time zero like the Bigelow model and Arrhenius model do. Peleg shows that this distribution represents survival curves as a dose-response correlation when proper distribution parameters are used. Studies such as that of Zhong et al. (2005) apply the model to the microbial inactivation kinetics by the use of pulsed electric field. Fermi's equation has also been applied to other areas of interest in order to test other mechanisms and kinetics. Giner et. al (2000) applied a modified version of the equation to the rate of enzymatic inhibition of tomato pectin methylesterase activity by high intensity electric field pulses.

Weibull frequency distributions

While the Weibull frequency distribution can be arranged in several ways, the standard formula for the survival function is

$$S(t) = e^{-\left(\frac{t}{b}\right)^{a}} \hspace{4cm} 2.8$$

where t is the treatment time, S(t) is the fraction of survival microorganisms, and a and b are the scale and shape factors, respectively. Once a and b are calculated, they can be used to plot the sensitivities frequency curve and other statistics. Patel et. al (1976) supply equations that use the b and a values to equate statistics such as mode, mean, variance, and coefficient of skewness. The Weibull frequency distribution is useful in survivorship studies because the shape and scale parameters define the shape of the survivorship curve (Pinder et al., 1978). That survivorship curve can be tested for similarity in shape to survivorship estimates of different populations through their Weibull distribution shape parameters.

Accuracy of Predictive Models

These models, along with many other predictive models, need to demonstrate that they are valid models for accurately predicting the behavior of micro-organisms in foods. It needs to

be determined that the model is statistically acceptable relative to the data that has been logged in earlier microbiology literature (Ross, 1996). One method for determining the accuracy of a predictive model compares the model on the basis of the sum of squares of the differences of the natural logarithm of observed and predicted values. This model, introduced by McClure et al. (1993), then ranks the model with a measure of precision called the "accuracy factor".

$$accuracy\ factor = 10^{\Sigma\frac{|\log(GT_{predicted}/GT_{observed})|}{n}} \qquad 2.9$$

where $GT_{predicted}$ is the predicted generation time, $GT_{observed}$ is the observed generation time, and n is the number of observations.

Conclusions

If consumers reach a food material's microbial inactivating temperature and maintain the necessary hold time, foodborne illness traced back to cooked foods will be significantly reduced. Seafood products are at high risk for foodborne illness, and minimal studies have been done on thermal death times for seafood. Therefore, food safety strategies and guidelines are needed specifically for safe seafood practices. In 2007, the National Advisory Committee for Microbiological Criteria for Foods expressed the need for extensive cooking parameters for fish and shellfish (NACMCF, 2007). Combining quality optimization with these seafood cooking parameters will assist consumers in cooking a safe, desirable product.

References

Ahmed, J., Shivhare, U.S. 2006. Thermal processing of vegetables. In: Sun, D., editor. *Thermal food processing: new technologies and quality issues*. Boca Raton, FL: Taylor & Francis. 387-424 p.

Alzamora, S. M., Guerrero, S. N., Lopez-Malo, A., Palou, E., Char, C. D., Raffellini, S. 2010. Models for microorganism inactivation: application in food preservation design. In: Ortega-Rivas, E., editor. *Processing Effects on Safety and Quality of Foods*. Taylor & Francis: Boca Raton, FL. 87-116 p.

Barbosa-Canovas G. V., Juliano, P., Peleg, M. 2005. Food Engineering. In: Barbosa-Canovas G. V., editor. *Encyclopedia of Life Support Systems (EOLSS)*. Paris: UNESCO.

Benedito, J., Gonzalez, C., Rossello, C., Mulet, A. 2000. Instrumental and Expert Assessment of Mahon Cheese Texture. *J. Food Sci.* 65: 1170-1174.

Bhunia, A. K. 2008. *Foodborne Microbial Pathogens: mechanisms and pathogenesis*. New York, NY: Springer Science + Business Media. 1-19 p.

Bigelow, W. D., Esty, J. R. 1920. Thermal death point in relation to time of typical thermophilic organisms. *J. Infect. Dis.* 27: 602-617.

Bourn, D., Prescott, J. 2002. A comparison of the nutritional value, sensory qualities, and food safety of organically and conventionally produced foods. *Crit. Rev. Food Sci. Nutrition.* 42: 19-22.

Burnett, S. L., Beuchat, L. R. 2001. Human pathogens associated with raw produce and unpasteurized juices, and difficulties in contamination. *J. Indust. Microbiol. Biotechnol.* 27: 104-110.

Centers for Disease Control and Prevention. 2009. FoodNet 2007 Surveillance Report. Atlanta, GA: U. S. Department of Health and Human Services.

Chatterjee, S., Basak, T., Das, S. 2007. Microwave driven convection in a rotating cylindrical cavity: a numerical study. *J. Food Eng.* 79: 1269-1279.

Chintagari, S. 2009. Determination of minimum safe cooking temperatures for shrimp to destroy foodborne pathogens. MS Thesis. Louisiana State University. Baton Rouge, LA.

Dalgaard, P. 2006. Microbiology of marine muscle foods. In: Hui, Y. H., editor. *Handbook of Food Science, Technology, and Engineering*. Boca Raton, FL: Taylor & Francis Group. (53) 1-20 p.

Danowska-Oziewicz, M., Karpinska-Tymoszczyk, M., Borowski, J. 2007. The effect of cooking in a steam-convection oven on the quality of selected dishes. *J Foodservice*. 18: 187-197.

Denyer, S., Hodges, N. 2004. Sterilization procedures and sterility assurance. In: Denyer, S., Hodges, N., Gorman, S., editors. *Pharmaceutical Microbiology*. 7th edition. Malden, MA: Blackwell Science. 346-349 p.

Earle, R. L. 1983. *Unit Operations in Food Processing*. New York, NY: Pergamon Press.

Figura, L., Teixeira, A. 2007. *Food Physics: measurement and applications*. Germany: Springer-Verlag Berlin Heidelberg. 391-416 p.

FAO (Food and Agriculture Organization of the United Nations). 2000. The state of the world fisheries and aquaculture. Available at: ftp://ftp.fao.org/docrep/fao/003/x8002e/X8002E00.pdf. Accessed: July 20, 2010.

Fontana, A. J., Varith, J., Ikediala, J. Reyes, J., Wacker, B. 1999. Thermal properties of selected food using a dual needle heat-pulse sensor. In: *International Annual Meeting of the American Society of Agricultural Engineers*; 1999. Toronto, Canada.

Gabriel, A. A., Aranza, M. 2006. Decimal reduction times of Salmonella Typhimurium in guinataang kuhol: An indigenous Filipino dish. *LWT – Food Science and Technology*. 40:1108-1111.

Galaviz-Silva, L., Gomez-Anduro, G., Molina-Garza, Z., Ascencio-Valle, F. 2009. Food safety issues and the microbiology of fish and shellfish. In: Heredia, N., Wesley, I., Garcia, S., editors. *Microbiologically Safe Foods*. Hoboken, NJ: John Wiley & Sons Inc. 227-253 p.

Giner, J., Gimeno, V., Espachs, A., Elez, P., Barbosa-Canovas, G., Martin, O. 2000. Inhibition of tomato (Licopersicon esculentum Mill.) pectin methylesterase by pulsed electric fields. *Innov. Food Sci. Emerg. Tech.* 1: 57-67.

Gram, L., Huss, H. 2000. Fresh and Processed Fish and Shellfish. In: Lund, B., Baird-Parker, T., editors. *The Microbiological Safety and Quality of Food*. Gaithersburg, Maryland: Aspen Publishers. 472-506 p.

Haiqing, C., Marks, B., Murphy, R. 1999. Modeling coupled heat and mass transfer for convection cooking of chicken patties. *J. Food Eng.* 42: 139-146.

Haines, G. J., Comar, P. 1984. Survival of Salmonella in experimentally contaminated breaded shrimp during deep fat frying. In: *Proceedings of the Ninth Annual Tropical and Subtropical Fisheries Conference.* Texas A&M University. 9:45-51.

Holdsworth, S., Simpson, R. 2007. *Thermal processing of foods*. New York, NY: Springer Science + Business Media. 1-13 p.

Heinitz, M. L., Ruble, R. D., Wagner, D. E., Tatini, S. R. 2000. Incidence of Salmonella in fish and seafood. *J Food Prot.* 63: 579-595.

Huss, H. H. 1988. Fresh fish: quality and quality changes. *FAO Fisheries Series No 29.* Rome: FAO. 43 p.

Jamnia, A. 2009. *Practical guide to the packaging of electronics: thermal and mechanical design and analysis*. 2nd edition. Boca Raton, FL: Taylor & Francis Group. 5-8 p.

Jay, J. M., Loessner, M. J., Golden, D. A. 2005. *Modern Food Micriobiology*. 7th edition. New York, NY: Springer Science + Business Media. 39-60 p.

Law, C. K. 2006. *Combustion Physics*. New York, NY: Cambridge. 51-83 p.

Lazarides, H. L. 2003. Dehydration System Design. In: Heldan, D. R., editor. *Encyclopedia of Agricultural, Food, and Biological Engineering*. New York, NY: Marcel Dekker. 180-185 p.

Leguerinel, I., Spegagne, I., Courvert, O., Gaillard, S., Mafart, P. 2005. Validation of an overall model describing the effect of three environmental factors on the apparent D-value of Bacillus cerus spores. *Int. J. Food Microbiol*. 100: 223-229.

Lund, B. M., Peck, M. W. 2000. Clostridium botulinum. In: Lund, B. M., Baird-Parker, T. C., Gould, G. W., editors. *Microbiological Safety and Quality of Food*. Gaithersburg, MD: Aspen Publishers. 1057-1109 p.

Mahaffey, K. R., Clickner, R. P., Jeffries, R. A. 2008. Methylmercury and omega-3 fatty acids: Co-occurrence of dietary sources with emphasis on fish and shellfish. *Environmental Research.* 107:20-29.

Marriott, N. G. 1999. *Principles of Food Sanitation*. 4th edition. Gaithersburg, MD: Aspen Publishers. 11-52 p.

McClure, P. , Baranyi, J., Boogard, E., Kelly, T., Roberts, T. 1993. A predictive model for the combined effect of pH, sodium chloride, and storage temperature on the growth of Brocothrix thermosphacta. *Int. J. Food Micro.* 19: 161-178.

McClure, P. J., Blackburn, C. W., Cole, M. B., Curtis, P. S., Jones, J. E., Legan, J. D., Ogden, I. D., Peck, M. W., Roberts, T. A., Sutherland, J. P., Walker, S. J. 1994. Modeling the growth, survival, and death of microorganisms in foods: the U.K. food micromodel approach. *Int. J. Food Microbiol.* 23: 265-275.

Mead, P. S., Slutsker, L., Dietz, V., McCraig, L. F., Bresee, J., Shapiro, C., Griffen, P., Tauxe, R. 1999. Food-related illness and death in the United States. *Emerg. Infect. Dis.* Atlanta, GA: Centers for Disease Control and Prevention. (5) 5.

National Advisory Committee on Microbiological Criteria for Foods (NACMCF). 2007. Response to the questions posed by the Food and Drug Administration and the National Marine Fisheries Service regarding determination of cooking parameters for safe seafood for consumers. NACMCF, Washington, DC. U.S. Department of Health and Human Services, Public Health Service, Food and Drug Administration. *Food Code 2005*. College Park, MD.

National Marine Fisheries Service. 2007. Seafood consumption declines slightly in 2005. News from the National Oceanic & Atmospheric Administration (NOAA). US Department of Commerce. Available at: http://www.nmfs.noaa.gov/mediacenter/docs/05_seafood_consumption_FINAL.pdf . Accessed July 8 2010.

National Science Foundation International. 2004. Guidelines for Proper Cooking. Available at: http://www.nsf.org/consumer/food_safety/fsafety_cooking.asp?program=FoodSaf . Accessed July 8 2010.

Neely, T. R., Lorenzen, C. L., Miller, R. K., Tatum, J. D., Wise, J. W., Taylor, J. F., Buyck, M. J., Reagan, J. O., Savell, J. W. 1999. Beef customer satisfaction: cooking method and degree of doneness effects on the top round steak. *J. Animal Sci.* 77: 653-660.

Nesvadba, P., Hou, M., Wolf, W., Gekas, V., Jarvis, D., Sadd, P., Johns, A. 2004. Database of physical properties of agro-food materials. *J. Food Eng.* 61: 497-503.

Ocio, M. J., Fernandez, P. S., Alvarruiz, A., Martinez, A. 2008. Comparison of TDT and Arrhenius models for rate constant inactivation predictions of Bacillus stearothermophilus heated in mushroom-alginate substrate. *Letters in Applied Microbiology*. 19: 114-117.

Patel, J. K. Kapadie, D. H., Owen, D. B. 1976. *Handbook of Statistical Distributions*. New York, NY: Marcel Dekker. 126-140 p.

Peleg, M. 2000. Microbial survival curves – the reality of flat "shoulders" and absolute thermal death times. *Food Research International*. 33: 531-538.

Peleg, M., Cole, M. 1998. Reinterpretation of Microbial Survival Curves. *Critical Reviews in Food Science*. 38(5): 353-380.

Pinder, J. E., Wiener, J. G., Smith, M. H. 1978. The Weibull Distribution: A New Method of Summarizing Survivorship Data. *Ecology*. 59: 175-179.

Plaza, I. B., Gabriel, A. A., 2008. Thermal death time of Salmonella Typhimurium in oyster meat: establishment and application in a heat-treated ceviche recipe. *J. Foodservice*. 19, 277-285.

Reddy, M. B. Love, M. 1999. The impact of food processing on the nutritional quality of vitamins and minerals. *Adv. Exp. Med. Biol.* 459: 99-106.

Rosenthal, A. 1999. Food *Texture: Measurement and Perception*. Gaithersburg, MD: Aspen Publishers. 1-17 p.

Rosnes, J. T. 2004. Identifying and dealing with heat resistant bacteria. In: Richardson, P., editor. *Improving the thermal processing of foods*. Cambridge, England: Woodhead Publishing Limited. 456-470 p.

Ross, T. 1996. Indices for performance evaluations of predictive models in microbiology. *J Applied Bacteriology*. 81: 501-508.

Saravacos, G., Kostaropoulos, A. 1996. Engineering properties in food processing simulation. *Computers and ChemEng*. 20: S461-S466.

Sikorski, Z., Piotrowska, B. 2007. Food components and quality. In: Sikorski, Z., editor. *Chemical and functional properties of food components*. Boca Raton, FL: Taylor and Francis Group LLC. 1-17 p.

Snowdon, J. A., Buzby, J. C., Roberts, T. 1990. Epidemiology, cost, and risk of foodborne disease. In: Cliver, D. O., editor. *Foodborne Diseases*. San Diego, CA: Academic Press. 31-52 p.

Sturge, M. 2003. *Statistical and thermal physics: fundamentals and applications*. Natick, MA: A K Peters Ltd. 96-106 p.

Toledo, R. T. 2007. *Fundamentals of Food Process Engineering*. 3rd edition. New York, NY: Springer Science + Business Media LLC. 223-284 p.

Townsend, C. T., Esty, J. R., Bselt, F. C. 1938. Heat resistance studies on spores of putrefactive anaerobes in relation to determination of related processes for canned foods. *Food Res.* 3: 323-346.

U. S. Department of Agriculture, Agriculture Research Service. 2009. USDA National Nutrient Database for Standard Reference, Release 22. Available at http://www.ars.usda.gov/ba/bhnrc/ndl. Accessed March 1, 2010.

U. S. Food and Drug Administration. 2009. Food Code: 2009 Recommendations of the United States Public Health Service Food and Drug Administration. Available at: http://www.fda.gov/downloads/Food/FoodSafety/RetailFoodProtection/FoodCode/FoodCode2009/UCM189448.pdf. Accessed July 8, 2010.

van Boekell, M. 2002. On the use of Weibull model to describe thermal inactivation of microbial vegetative cells. *Int. J Food Microbiology*. 74:139-159.

van Boekell, M. 2009. *Kinetic Modeling of Reactions in Foods*. Boca Raton, FL: Taylor & Francis Group. 2:1-12 p.

Venkatesh, M., Raghavan, G. 2005. An overview of dielectrical properties measuring techniques. *Canadian Biosystems Eng.* 47: 7.15-7.30.

Wang, L., Sun, D-W. 2006. Heat and Mass Transfer in Thermal Food Processing. In: Sun, D-W., editor. *Thermal Food Processing: new technologies and quality issues*. Boca Raton, FL: Taylor & Francis Group. 35-72 p.

Zhong, K., Chen, F., Wu, J., Zhengfu, W., Liao, X., Hu, X., Zhang, Z. 2005. Kinetics of inactivation of Escherichia coli in carrot juice by pulsed electric field. *J. Food Process Eng.* 28: 595-609.

CHAPTER 3

The Effect of Consumer Cooking Methods on the Quality of Atlantic Salmon and Shrimp

Lauren Brookmire[1], P. Mallikarjunan[1], M. Jahncke[2], and R. Grisso[1]

[1]Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

[2]Department of Food Science and Technology, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

ABSTRACT

Studies have shown that seafood products are a common carrier of pathogens causing foodborne disease. Foodborne disease is usually caused by the consumption of products not cooked appropriately for microbial destruction. Due to the ease of overcooking and diminishing the quality of seafood, consumers tend to undercook products such as fish and shrimp. The qualities which consumers are judging during cooking may not accurately represent the thermal doneness of seafood products. It is necessary to understand the quality changes in seafood products during preparation by consumers.

The main objective of this study was to determine the effects of consumer cooking methods (boiling, baking, and pan frying) on the quality of Atlantic salmon and shrimp. Color, texture, pressed juice, mass loss, and moisture content were measured during each cooking process as the product's internal temperature reached 45°C, 50°C, 55°C, 60°C, and 63°C +15 seconds. These temperature points were studied as a means of investigating the quality attributes experienced by consumers undercooking their products. The final temperature point of 15 seconds after 63°C was chosen based on the cooking recommendation by the FDA for raw seafood products.

The rise of internal temperature had a significant effect ($p < 0.05$) on the mass loss, juiciness, color, and texture. Internal temperature also had a significant effect on the moisture contents of oven baked shrimp and pan fried salmon, but not oven baked salmon and boiled shrimp. For most attributes, the boiling of shrimp and the pan frying of salmon had a more drastic effect on quality than the oven baking of either product. The results of this study suggest that the lightness of the core portion of the product may be the best indicator of thermal doneness of both shrimp and salmon.

INTRODUCTION

Seafood is a popular food selection both in the United States and worldwide. In 2007, the yearly consumption of seafood in the United States reached 16.3 pounds per person (NOAA, 2007). It is appealing in taste and also nutritious. Seafood products provide protein, are low in saturated fat, and are a source of omega-3 fatty acids. The nutrients in some seafood types may even reduce cardiovascular disease and promote infant neurological development (Burdge, 2004).

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 error and is less time stringent. Also, using instrumental measurements is beneficial in quality assurance research and practice (Rosenthal, 1999).

It is difficult to quantify the doneness of seafood products. Popular consumer cookbooks define the doneness of shrimp by the surface color change and the doneness of salmon by the flaking of the product center (Lauer, 2004; Rombauer, 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 overcook and become dry, resulting in possible undercooking of fillets. The FDA recommends cooking intact fish fillets to an internal temperature of 63 or higher for 15 seconds (FDA, 2009). This temperature is recommended as to provide a microbiologically safe

food. With seafood products being a leading cause of foodborne illness, it is necessary to

understand the quality changes of the products during the cooking process. Most seafood

illnesses are related to the consumption of products that did not receive the appropriate thermal

treatment, were cross contaminated after cooking, or were later subjected to time/temperature

abuse (Cato, 1998).

The primary focus of this study was to observe the quality attributes of undercooked

shrimp and salmon after processing by common cooking methods. The effect of internal

temperature and cooking method on color, texture, juiciness, and product moisture were

analyzed. The main objective of this study was to determine which attributes from cooking may

cause people to unintentionally undercook seafood products.

MATERIALS AND METHODS

3.1 Sample Preparation

Frozen raw fillets of Atlantic salmon (boneless and skinless, AQUA FARMS) and two

sizes of frozen raw shrimp prawns (individually quick frozen, peeled, deveined,

BERKLEY&JENSEN) were obtained from BJ's Wholesale Club (Hampton, VA). The products

were placed in an ultra low freezer (-80°C) until further use.

Samples were thawed 12-16 hours in a refrigerator set at 2±°2C prior to use. Salmon

samples were cut into uniform 90cm x 55cm x 20cm slabs weighing 68±2 grams. This fillet

structure was chosen based on the initial structure of the purchased fillets and the necessity of

using a thickness that could be kept constant for all cut samples. This sample structure also

represents an individual fish serving in the form that a consumer would use. For the preparation

of the shrimp samples, tail shelling was removed from shrimp to aid in accurate thermocouple

placement. Sample sizes were kept constant at a single prawn mass of 14±1.5 grams for extra jumbo size and 20±1.5 grams for the colossal size.

3.2 Cooking Processes

Common cooking methods used by consumers were selected for this study. For shrimp prawns, boiling and oven baking were analyzed. For salmon fillets, oven baking and pan frying were analyzed. Each specific cooking procedure was followed identically during both the initial determination of time-temperature profiles and the cooking of the samples for qualitative analysis.

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

2. *Oven baked shrimp.* Identical to constants in the boiling method, tests were run with five prawns cooked at a time. The oven was preheated to 450°F (232°C) as instructed on the product's label. A light coating of PAM cooking spray (ConAgra Foods, Omaha NE) was applied to a metal cooking tray. Extra jumbo shrimp were flipped over after 2.5 minutes and colossal shrimp were flipped over at 3 minutes in order to impersonate a consumer's cooking actions.

3. *Oven baked salmon.* The oven was preheated to 375°F (190°C) as recommended on the product's packaging. Five samples were individually wrapped in aluminum foil and placed on a metal cooking tray. 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.) was coated on the pan to prevent undesirable burning. Salmon samples were cooked individually and flipped over half way through cooking to follow common consumer cooking methods.

3.2.2. Determination of Time-Temperature Profiles

In order to determine the cooking times necessary for qualitative analysis, initial studies were performed to track the temperature change throughout the product during common cooking procedures. Five cords of Type T thermocouple wire with fiber glass insulation were cut, stripped, and soldered. Fiber glass insulation was chosen for its high temperature tolerance (482 °C). The thermocouples were attached to a data logger (21X Micro logger, Campbell Scientific Inc., USA) directly interfaced to a computer running LoggerNet, a datalogger support software by Campbell Scientific Inc. 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. Figures 1 and 2 show a visual representation of the thermocouple placement in the samples. A separate thermocouple was also used to confirm the temperature of the product's 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°C, 50°C, 55°C, 60°C, and 63°C plus 15 seconds. A temperature point of 63°C plus 15 seconds was selected for this study since it is the internal cooked temperature recommended in the 2009 Food Code (USDA, 2009) for solid seafood products.

3.2.3. 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.

For oven baking salmon, samples were cooked to the necessary times to reach the internal temperatures of 45°C, 50°C, 55°C, 60°C, and 63°C. This was repeated for pan frying salmon, oven baking both sizes of shrimp, and boiling both sizes of shrimp. All tests were replicated five times. After undergoing the cooking process, each sample was immediately placed in a refrigerator (2±2°C) for two minutes to stop the heating process without affecting the structure of the product. All qualitative analysis immediately followed.

3.3 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, both surface and core readings were made. Surface readings for shrimp samples were taken in the second 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 five times for each cooking time using five different samples.

Digital photographs of the samples were also taken on a gridded transparency sheet. The purpose of the photographs was to aid in comparing the visual outcome of the different cooking methods and to aid in consumer judgment of doneness.

3.4 Texture Analysis

Immediately after each product was cooked, texture readings were made. For the shrimp prawns, each sample was tested through the second segment of the whole prawn. Salmon samples were cut into a core cylinder with a 1.5 cm diameter. The cylinder was cut appropriately so that texture measurement would be made perpendicular to the natural flaking of the fish sample.

The texture of the cooked products was tested using a Warner-Bratzler shear blade attached to a TA.XT Plus texture analyzer (Stable Micro Systems, New York). The texture analyzer was set to a test speed of 5.0 mm/sec, post-test speed of 10 mm/sec, target distance of 30.0 mm, and an acquisition rate of 200 pps. A macro program was created to measure three 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 five times for each cooking time and product type using five different samples.

3.5 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 two pieces of aluminum foil (35 mm x 35 mm). The aluminum foil squares were in turn placed between two pieces of pre-weighed filter paper (Whatman No.5, 110 mm diameter). The filter paper was then placed in between two Plexi-glass plates wrapped in plastic wrap. The formation was then compressed with 20 kPa of pressure for one minute. The weight

37

difference of the filter papers was recorded as the pressed juice. The test was replicated five

times with five separate samples for each temperature.

3.6 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 run with five separate

samples for each temperature.

3.7 Statistical Analysis

The JMP8 statistical software package (Statistical Analysis System, North Carolina,

USA) 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 one-way analysis of variance (ANOVA) ate 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

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 products throughout the cooking process (Table 3.1).

During the oven baking of salmon, the ΔL rose quickly to 16.22 at 50°C, and then stayed lower than 19.00 through 63°C. The ΔC and Δh of the surface of salmon slightly increased to 4.76 and 5.34, respectfully, by 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. The surface ΔC and Δh did not consistently change as the product reached 63°C. The ΔL of the core of the salmon increased to 21.20 and 23.82 by 63°C for oven baking and pan frying, respectively. The ΔC and Δh values during oven baking varied over time, but always stayed with ±10 of the raw values. The ΔC of the core of salmon during pan frying stayed between 14.52 and 18.71. The core Δh did not vary greater than 5.48, which occurred at 63°C.

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 et a, 1993). The ΔC for the surface of boiled shrimp rose greatly to 26.9 and 25.41 at 45°C for extra jumbo and colossal sizes, respectively. These ΔC values minimally rose over time as internal temperature reached 63°C. For the oven baking of shrimp, the surface ΔC values rose as internal temperature rose, but not as rapidly as for boiled shrimp. At 63°C, extra jumbo shrimp had a surface ΔC value of 37.50, and colossal shrimp had a value of 32.70. The surface ΔL and Δh values varied inconsistently as internal temperature rose during the cooking of both shrimp sizes.

39

The core ΔL values increased during both the boiling and oven baking of shrimp. The lightness values increased more rapidly during the boiling process, reaching ΔL values of 24.58 and 15.64 for extra jumbo and colossal sizes, respectfully, by 60°C. These ΔL values are similar to those found by Niamnuy et al. (2007) for boiled shrimp. Oven baked resulted in ΔL values of 12.42 and 9.60 by 60°C. Minimal change was seen in the ΔC values of the core portion of cooking shrimp. The Δh values of shrimp core portion varied greatly over time, yet inconsistently. This was due to the frequent use of small a* and b* values between -1 and 1 in the hue angle calculation. The means of the a* and b* values did not greatly vary from zero (data not shown). For ΔL, ΔC, and Δh calculations, ΔL values appear most valuable for the core portion of shrimp and ΔC for the surface of shrimp.

While studies have been conducted on color attributes of smoked salmon (Bugueno et al., 2003; Bencze Rora et al., 1998), minimal research can be found on color differences during pan frying and oven baking of salmon. Bugueno et al. (2003) found CIE color values of 41.0, 9.5, and 8.4 for L*, a*, and b* values, respectively, for smoked salmon. The majority of research on the color of salmon and other fin fish is in the aquaculture field, where color composition of fillets is measured instrumentally in order to optimize aqua farming techniques.

Effect of Internal Temperature on Texture

The cooking process had a significant effect on the texture attributes of both salmon and shrimp (Table 3.2). For raw salmon, the mean values for shear force, firmness, and total work were 5.28 N, 6.24 N/s, and 9.54, respectively. For pan frying, the shear force significantly increased at 45°C, and no significant change occurred at further temperature points. 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 found significantly different at internal temperatures of

40

60°C and 63°C. Identical significance trends were found for mean firmness and mean total work values for the cooking of salmon. Pan frying significantly affected the firmness and total work immediately at the 45°C reading, while the two textural attributes did not significantly change during oven baking until an internal temperature of 55°C.

The mean shear force, firmness, and total work values for raw extra jumbo shrimp were 31.19 N, 1.92 N/s, and 255.78 N.mm, respectively. For the colossal shrimp, the raw product values were 31.94 N, 1.92 N/s, and 352.40 N.mm. When introduced to boiling, the shear force significantly dropped for extra jumbo shrimp at 45°C. The force did not significantly change as internal temperature increased until 63°C, where it increased to 27.47 N. While boiled colossal shrimp similarly dropped in shear force value at an internal temperature of 45°C before a gradual increase, the change in means were not found significant. No significant change in shear force was found during the oven baking of both sizes of shrimp. At 45C, the mean firmness significantly dropped from the raw product value for both sizes of shimp and both cooking methods. No apparent correlation was observed between the increase in temperature and the firmness of shrimp for both cooking methods. There was no significant change in the total work during oven baking for both shrimp sizes. For the boiling of both shrimp sizes, the total work initially dropped from the raw product mean. There was no significant correlation between the boiling process of shrimp and total work.

Effect of Internal Temperature on Pressed Juice

The amount of thermal treatment had a significant effect on the amount of pressed juice produced for both salmon and shrimp (Table 3.3). The mean amount of pressed juice for raw salmon was 36.52%. A measurement on raw shrimp was not able to be made due to the physical structure of the core material. When pressure was applied to the juicing mechanism, liquid did

not separate from solid material, resulting in a gelatin-like product on the filter paper. This data was not included in statistical analysis. However, all cooking time/temperature combinations for shrimp resulted in a product capable of being pressed for juice.

For oven baked salmon, the mean pressed juice reduced to 26.85% by 55°C and did not show significantly different results for 60°C and 63°C. The maintained amount of juiciness may be attributed to the fillets being wrapped in aluminum foil during the baking process. For pan fried salmon, the mean pressed juice significantly dropped to 25.20% as the internal temperature rose to 60°C, with no significant change at 63°C.

The mean pressed juice for the extra jumbo sized shrimp and colossal sized shrimp decreased to 25.15% and 24.85%, respectively when boiled to an internal temperature of 63C. No significant change in juiciness was seen after 55°C for boiled extra jumbo shrimp and 50°C for boiled colossal shrimp. For the oven baking of shrimp, there was no significant change in mean pressed juice for the extra jumbo size. The colossal size, however, continuously significantly decreased to a mean pressed juice of 21.56% at 63°C. This significance could be due to the fact that the colossal size takes a longer amount of cooking time than the extra jumbo size to raise the internal temperature. A similar pressed juice method was used by Gundavarapu et al. (1995) in studying the quality of microwaved shrimp. The pressed juice (%) decreased during the microwave process to 16±2%. The results show that the boiling and oven baking processes followed in this study produce a juicier final product than by microwave treatment. Gundavarapu et al. also found the pressed juice of a boiled shrimp to be 24.07%, which supports the data found in this study.

Effect of Internal Temperature on Moisture Content

The mean moisture contents for raw extra jumbo shrimp, colossal shrimp, and Atlantic salmon were 74.31%, 77.01%, and 65.75%. These values are similar to those found in other studies (Karunakar et al., 1998; Gundavarapu et al., 1998; Lee et al., 2000). The moisture content percentages either maintained or dropped during the cooking processes studied for all three products (Table 3.4).

The oven baking process had no significant change in moisture content in the Atlantic salmon. This may be due to the salmon samples being wrapped in aluminum foil. This supports the consumer methodology of wrapping fish fillets to preserve moisture and any added marinade during oven baking. During the pan frying of salmon, the moisture content significantly decreased from a raw product value of 65.75% to 61.90% at an internal temperature of 45°C. No significant change in moisture content occurred at any further time/temperature points.

The moisture content did not significantly change in colossal shrimp during the boiling process. For extra jumbo shrimp, the moisture content significant dropped from a raw product value of 74.31% to 72.39% at 45°C. There was no significant change in moisture content during the boiling process of the extra jumbo shrimp past 45°C. Moisture content was significantly affected as the shrimp internal temperature increased during oven baking. For extra jumbo shrimp, the mean moisture content decreased to 69.80% at 55°C and did not significantly change at the further internal temperatures of 60°C and 63°C. For colossal shrimp, the moisture content significantly dropped to 67.76% at 60°C with no further significant change at 63°C.

Comparison of Cooking Methods and Quality

The cooking method used affected the quality changes occurring for both salmon and shrimp products. The oven baking of a salmon fillet wrapped in aluminum foil had a lower rate

of quality change than for the pan frying process. The oven baking method was a longer heating process with gradual increasing heat on the surface of the salmon. The pan frying method presented a high temperature conduction process on one surface of the fillet, creating a crust material on the food product. The pan frying process resulted in lower product moisture content and mean pressed juice than the oven baking process. The frying process also resulted in higher shear force, firmness and total work textural attributes. The differences in the qualities of the final cooked salmon fillets do not necessarily conclude one cooking method as an optimal choice over the other. The optimal cooking method for a consumer to select is based on the desired quality attributes of the final product.

For shrimp, the boiling cooking process resulted in higher moisture content and pressed juice values than for oven baking. The shear force, firmness, and total work values were higher for oven baking than for boiling. This suggests that the drier the sample, the tougher it is. The toughness of shrimp is affected by heat application, and the filaments of myofibrillar proteins begin to overlap and therefore decrease in length of muscle. The shortened muscle then requires higher shear force necessary for cutting (Harwalker, and Ma, 1990; Bayliss, 1995). Since the texture values were higher for oven baking, the study suggests that oven baking creates a higher degree of shortened muscle and therefore more overlapping of the myofibrillar proteins.

CONCLUSIONS

The application of thermal processing had a significant effect on various quality attributes of shrimp prawns and Atlantic salmon fillets. The quality changes varied based on the cooking method used. For shrimp prawns, the change in color and texture was a more sudden process during boiling than in oven baking. External color immediately turned pink during the boiling

process, while the change was gradual during oven baking. Figure 3.2 shows a visual

representation of the change in appearance of shrimp during both the boiling and oven baking

processes. It can be concluded that the external color of shrimp may appear at a point of

doneness before the internal temperature reached 63°C. The internal lightness factor, which a

consumer may consider the opaqueness of the product, more accurately represented the doneness

of the prawns than the external pinkness. The shrimp become more opaque as the product

reached 63°C.

For Atlantic salmon, texture significantly increased during the pan frying process. The

texture attributes during the oven baking process greatly varied from the pan frying process. The

oven baking process involved a fillet wrapped in aluminum foil – a common method used to

preserve moisture and any additional marinade. The external color greatly varied based on the

method used. The internal color, however, showed a similar lightening as the internal

temperature reached 63°C. Figure 3.3 shows the visual change in salmon during both the pan

frying and oven baking cooking processes. Due to the variation in external appearance based on

cooking method used, the lightness factor of the core portion best represents the doneness of

Atlantic salmon.

References

AOAC. 2005. Official Methods of Analysis of AOAC International, 16th ed. Washington, DC (2005).

Bayliss, P. 1995. Chemistry in the kitchen: the chemistry of flesh foods II. *Nutrition Food Sci.* 95:21-6.

Bencze Rora, A. M., Kvale, A., Morkore, T., Rorvik, K., Hallbjorn, S., Magny, S., Thomassen, S. 1998. Process yield, colour and sensory quality of smoked Atlantic salmon (Salmo sala) in relation to raw material characteristics. *Food Research International*. 31:601-609.

Bugueno, G., Escriche, I., Martinez-Navarrete, N. M., Camacho, M. del M., Chiralt, A. 2003. Influence of storage conditions on some physical and chemical properties of smoked salmon (Salmo salar) processed by vacuum impregnation techniques. *Food Chemistry*. 81:85-90.

Burdge, G. 2004. Alpha-Linolenic acid metabolism in men and women: nutritional and biological applications. *Current Opinion in Clinical Nutrition & Metabolic Care*. 7:137-144.

Cato, J. C. 1998. Economic values associated with seafood safety and implementation of seafood Hazard Analysis Critical Control Point (HACCP) programmes. *FAO Fisheries Technical Paper.* Rome: FAO. No 381. 70 p.

Gundavarapu, S., Hung, Y. C., Reynold, A. E. 1998. Consumer acceptance and quality of microwave-cooked shrimp. *J. Food Quality*. 21: 71-84.

Harwalker, V. R., Ma, C. Y., 1990. *Thermal analysis of foods*. 2nd ed. London: Elsevier.

Karunakar, B., Mishra, S. K., Bandyopadhyay, S. 1998. Specific heat and thermal conductivity of shrimp meat. *J. Food Eng*. 37:345-351.

Lauer, T. 2004. *The Saltwater Cookbook. Fish and seafood: from ocean to table*. Chanhassen, MN: Creative Publishing. 18-23 p.

Lee, S. M., Hwang, U. G., Cho, S. H. 2000. Effects of feeding frequency and dietary moisture content on growth, body composition and gastric evacuation of juvenile Korean rockfish (Sebastes schlegeli). *Aquaculuture*. 187:399-409.

Mallikarjunan P., Mittal, G.S. 1994. Meat quality kinetics during beef carcass chilling. *J. Food Sci.* 59:291-   294,302.

Muriana, F. J. G., Ruiz-Gutierrez, V., Gallardo-Guerrero, M., Minguez-Mosquera, M. I. 1993. Study of the lipids and carotenoproteins in the prawn. *J. Biochem.* 114:223-229.

National Oceanic and Atmospheric Administration (NOAA). 2007. Seafood consumption increases in 2006. Vol 2008. Available at: http://www.publicaffairs.noaa.gov/releases2007/jul07/noaa07-r123.html. Accessed May 5, 2010.

Niamnuy, C., Devahastin, S., Soponronnarit, S. 2007. Quality changes of shrimp during boiling in salt solution. *J. Food Sci.* 72:S289:S297.

Rombauer, I. S., Becker, M. R., Becker, E. 1997. *Joy of Cooking.* New York, NY: Siman & Schuster. 488-526 p.

Rosenthal, A. 1999. Food Texture: Measurement and Perception. Gaithersburg, MD: Aspen Publishers. 1-17 p.

U.S. Department of Agriculture. 2009. Food Code. *US Public Health Service*. Food and Drug Administration. US Department of Health and Human Services. College Park, MD.

U. S. Food and Drug Administration. 2009. Food Code: 2009. Recommendations of the United States Public Health Service Food and Drug Administration. Available at: http://www.fda.gov/downloads/Food/FoodSafety/RetailFoodProtection/FoodCode/FoodCode2009/UCM189448.pdf. Accessed July 12, 2010.

TABLE 3.1 Mean color differences (lightness, chroma, and hue angle) during the cooking process as affected by cooking method and product.

Product	Cooking Method	Temp °C	Core			Surface		
			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
	Oven 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
	Oven 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	**Oven 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

TABLE 3.2. Mean texture attributes during the cooking process as affected by cooking method and product.

Product	Cooking Method	Temp °C	Texture		
			Force (N)	Firmness (N/s)	Total Work (N.mm)
EXTRA JUMBO SHRIMP	**Boiled**	Raw	31.19[a]	1.92[a]	355.78[ab]
		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]
	Oven 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	**Boiled**	Raw	31.94[a]	1.92[ab]	352.40[a]
		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]
	Oven 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	**Oven Baked**	RAW	5.28[a]	0.44[a]	70.04[a]
		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]

[ab]Means within a column with unlike superscript are significantly different ($p<0.05$).

TABLE 3.3. Mean pressed juice during the cooking process as affected by cooking method and product.

Product	Cooking Method	Internal Temperature (°C)					
		Raw	45	50	55	60	63
Extra Jumbo Shrimp	Boiled	n/a[1]	30.31^a	29.26^a	27.20^{ab}	24.67^b	25.15^b
	Oven 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
	Oven Baked		27.40^a	25.60^{ab}	22.53^{bc}	22.80^{bc}	21.56^c
Atlantic Salmon	Oven 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 ($p<0.05$).
[1]Raw shrimp unable to press only juice due to physical structure

TABLE 3.4. Mean moisture content during the cooking process as affected by cooking method and product.

Product	Cooking Method	Internal Temperature (°C)					
		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}
	Oven 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
	Oven 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
	Oven-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).
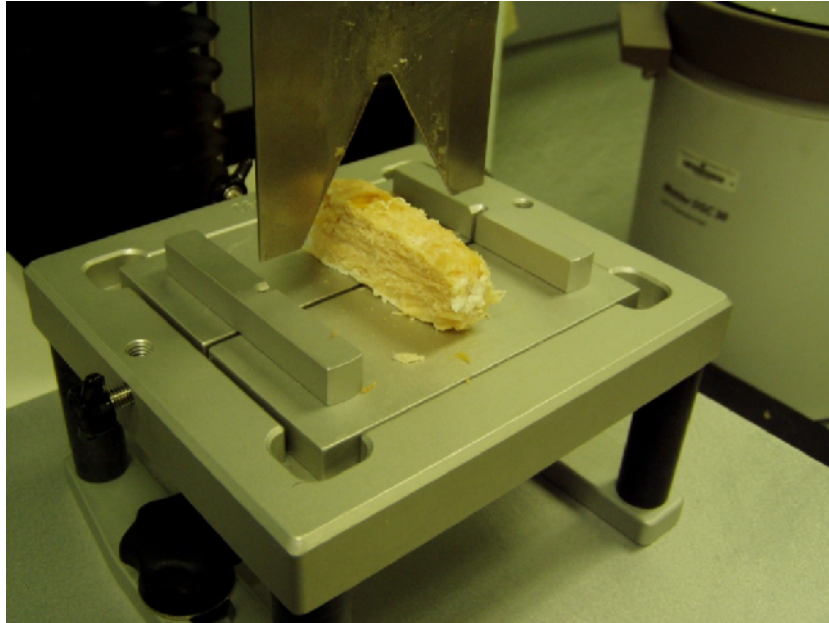
FIGURE 3.1. TA.XT Plus texture analyzer with Warner Bratzler blade setup for salmon analysis

FIGURE 3.2 Change in appearance of shrimp during boiling and oven baking processes. Pictures of both whole product and core region are shown as internal temperature increases and the product reaches being fully cooked.
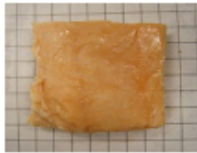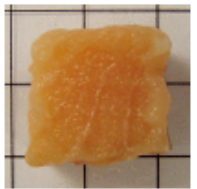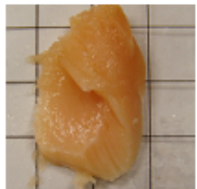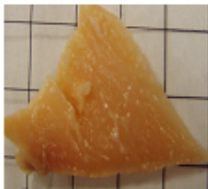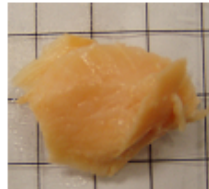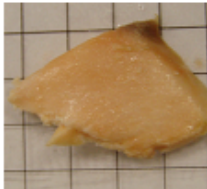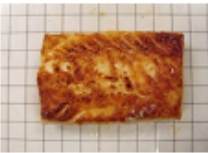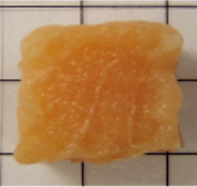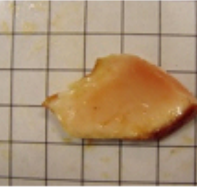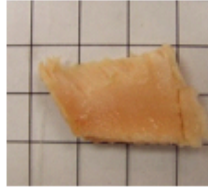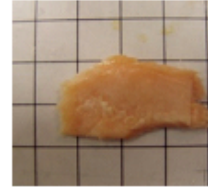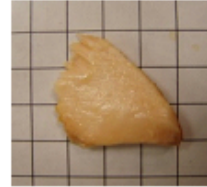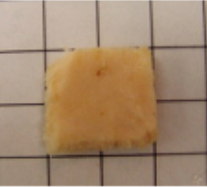
	Internal Temperature (°C)					
	Raw	45	50	55	60	63+15sec
			Oven Baked			
Surface						
Core						
			Pan Fried			
Surface						
Core						

FIGURE 3.3 Change in appearance of Atlantic salmon during oven baking and pan frying processes. Pictures of both whole product and core region are shown as internal temperature increases and the product reaches being fully cooked.
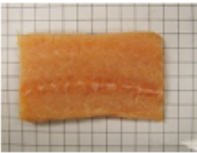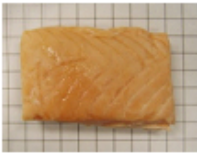
CHAPTER 4

Thermal Inactivation of *Salmonella* sp. in Shrimp and Atlantic Salmon with a Comparison of Kinetic Models

Lauren Brookmire[1], P. Mallikarjunan[1], M. Jahncke[2], and R. Grisso[1]

[1]Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

[2]Department of Food Science and Technology, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

ABSTRACT

Studies were conducted on the thermal inactivation of *Salmonella* sp. in shrimp and Atlantic salmon. Separate methodology was followed to determine minimum cooking temperatures to eliminate *Salmonella* sp. and to attain survival data for mathematical modeling. To determine minimum cooking temperatures, non-homogenized products were inoculated with a six-strain *Salmonella* culture and subjected to a water bath set at 80°C. Shrimp samples were inoculated on the surface and salmon samples were inoculated on either the surface or internally to replicate likely contamination areas. The microbial counts were observed at various internal temperatures based on pre-determined time-temperature profiles. In order to achieve a 3 log reduction, the current cooking recommendation by the FDA for intact seafood products is 63°C plus 15 seconds. It was found that inoculated shrimp achieved a 3 log reduction by this temperature-time combination, but inoculated salmon achieved only a 2 log reduction by this temperature-time combination.

For the comparison of kinetic models, homogenized salmon and shrimp were inoculated with one of two 3-strain *Salmonella* cocktails. Cocktail I consisted of *S.* Enteriditis, *S.* Newport, and *S.* Typhimurium, and cocktail II consisted of *S.* Typhi, *S.* Heidelberg, *S.* Paratyphi B. Samples were held at temperatures ranging from 60°C to 68°C for predetermined periods of time. The D and z-values were calculated for each of the cocktail-product combinations. The D-values found supported the current FDA recommendation of 68°C plus 15 seconds for a 3 log reduction in homogenized seafood products.

Three mathematical models based on the Bigelow model, Weibull distribution model, and Fermi distribution model were applied to the *Salmonella* sp. survival data. Cocktails I and II showed similar thermal resistance in shrimp products, but cocktail II showed significantly higher

thermal resistance than cocktail I in salmon. The Weibull distribution model predicted the inactivation for both *Salmonella* cocktails in shrimp with the most accuracy. Both the Weibull distribution model and Fermi distribution model predicted the inactivation in salmon with high accuracy.

Keywords: *Salmonella* sp., shrimp, salmon, inactivation kinetics models, seafood

INTRODUCTION

With seafood products being a popular food choice for consumers worldwide, it is necessary to optimize the microbial safety of seafood. Microbial contamination in foods can result in foodborne illness in humans. One of the main sources of foodborne illness is the pathogen *Salmonella*. The 2007 FoodNet Surveillance report by the CDC showed *Salmonella* to be the pathogen of top incidence for laboratory-confirmed infections and the pathogen with the highest number of deaths from foodborne illness (CDC, 2009). From 1990-1998, the microbiological testing of imported and domestic seafood samples found nearly 10 percent of imported and 1.3 percent of domestic raw seafood positive for *Salmonella* (Heinitz et. al, 2000). According to the National Advisory Committee on Microbiological Criteria for Foods (NACMF), from 1998 to 2004, outbreaks of foodborne illness associated specifically with seafood found *Salmonella* to be the leading cause in non-molluscan seafood (NACMF, 2007).

Microorganisms can contaminate seafood products prior to catch based on the quality conditions of the environment and the natural bacteria flora in the water. The handling of seafood from the point of harvesting to the point of consumption also creates the potential of microbial contamination (Lyhs, 2009). Being a high internationally traded food commodity also increases the risk of contamination.

Heat treatment is an effective method for reducing the microbial count in food products. Different time and temperature combinations must be met during heat treatment for different food products and microorganisms. In a report by the NACMF (2007), it was found that the most recommended consumer cooking methods for seafood products are based on quality aspects and not on scientific information that ensures the destruction of pathogens. The report also states that there are limited studies on the thermal inactivation of pathogens in seafood products.

Studies focusing on thermal inactivation during the cooking process would help ensure the safety of cooked seafood products.

The inactivation of microorganisms in specific food products can be expressed as a measured 'D-value' (decimal reduction time) and a corresponding thermal resistance parameter, 'z' (Ball, 1943). These values are calculated based on the assumption that there is a linear relationship between the treatment time at a given temperature and the number of surviving organisms. However, many studies show tailing and shouldering effects for the inactivation rate over treatment time (Anderson et al., 1996; Fernandez et al., 1999; Juneja et al., 2010). Nonlinear models that take into account a degree of variability provide a more accurate representation of the thermal resistance characteristics in food products.

The focus of this study was to determine the effect of thermal processing on the reduction of *Salmonella* species in shrimp and salmon. The first objective of this study was to determine internal cooking temperatures necessary to reduce the *Salmonella* to a safe level. Contamination on the product surface was tested for both product types, and internal contamination was additionally tested for salmon. The second objective was to apply various mathematical models (Bigelow model, Fermi equation, and Weibull frequency distribution) to microbial survival data and compare performances of the different kinetic models. The current FDA cooking recommendations for a 3 log reduction in the intact and homogenized products were also evaluated.

METHODS AND MATERIALS

Thermal Inactivation Study I: High Heat Application

Inoculum Preparation

  All six strains of *Salmonella* used in this study were obtained from the American Type Culture Collection (ATCC, Manassas Virginia). The strains used were *Salmonella* Typhimirium (14028), *Salmonella* Heidelberg (8326), *Salmonella* Newport (6962), *Salmonella* Paratyphi B (8759), *Salmonella* Typhi (6539), and *Salmonella* Enterica (13076). All cultures were initially grown overnight at 36°C in Tryptic Soy Broth (TSB). Immediately before inoculating samples, one 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 prawns (individually quick frozen, peeled, deveined, BERKLEY&JENSEN) and frozen raw fillets of Atlantic salmon (boneless and skinless, AQUA FARMS) were purchased from BJ's Wholesale Club (Hampton, VA). All samples were stored at -80°C until the day before testing. Samples were then thawed 12-16 hours in a refrigerator set at 2±2°C. The shrimp samples' tails were removed and only prawns weighing 12±1.5 grams were used. Salmon fillets were cut into 25±1 gram samples of equal length and width. A thickness of 2 cm was kept constant for all salmon samples. After preparation of each sample, it was placed in a sterile plastic bag (SealPAK Kapak 400, 4x6") and labeled. Samples were stored at 2±2°C until completion of all sample preparation.

Using a micro pipette, samples were inoculated with 10ul of *Salmonella* culture per gram of sample to produce a 10^6 cfu/g inoculate. While shrimp samples were only inoculated on the surface, salmon were divided into two separate tests: surface inoculation and internal inoculation. For the internally inoculated samples, the same amount of culture was injected into the most core region. Bags were flattened to express air and sealed with a pouch sealer (Kapak Corporation). Each bag was immediately stored at refrigeration temperature until all were prepared for the heating process. Each temperature treatment was prepared for 5 replicates.

Heat Treatment

A circulating water bath (Precision Thermo Scientific, Model 260) containing an extra heater (Fisher Scientific, Isotemp 2150) was set to 80°C. External type K thermocouples connected to a thermometer (Fisher Scientific Dual Thermometer) were used to verify a water temperature accuracy of ±0.2°C. Using the thermocouples, initial studies were performed to find the time required for the sample's center to reach 45°C, 50°C, 55°C, 60°C, 63°C, 68°C, 71°C, and 74°C. An additional thermocouple was used to track the surface temperature as well. Initial internal temperatures of 7±2°C for shrimp and 3±2°C for salmon samples were held constant throughout the study. These temperatures, which are slightly higher than the internal temperature immediately out of the refrigerator, were chosen to take into account the slight temperature increase occurring in the inoculated samples during inoculation preparation. The initial temperature studies were repeated five times for both salmon and shrimp.

Each bagged sample was fully immersed in the water bath for the specified time found in the initial studies. Each bag was then cooled in an ice water bath for one minute to immediately stop the heating process. Samples were placed back in the refrigerator until all heating treatment was complete.

Enumeration of Bacteria

Each sample was placed in a Kapak 402 stomacher bag and sterile PBS (0.85%) was added to each to create a 10:1 dilution. Samples were stomached for 2 minutes at 230 RPM () and plated in Tryptic Soy Agar (TSA). For each sample, both 1 ml and 0.1 ml were plated in Tryptic Soy Agar (TSA) to create concentrations of 10^{-1} and 10^{-2}. Plates were labeled and incubated for 24 hours at 36°C. After incubation, plates were counted for survivors and the data was recorded.

Verification Studies

Both inoculated and non-inoculated raw samples were of identical shape and size were stomached with sterile PBS and plated. The purpose of testing the non-inoculated samples was to verify that the samples were not originally contaminated. Raw inoculated samples were tested to verify the initial concentration of the bacteria.

Thermal Inactivation Study II: Survival Data for Kinetic Models

A separate experiment was performed by a microbiologist staff member in order to attain the appropriate data to determine D-values. The six strains of *Salmonella* were used to create two 3-strain cocktails. 'Cocktail I' consisted of *S.* Enteriditis, *S.* Newport, and *S.* Typhimurium. 'Cocktail II' consisted of *S.* Typhi, *S.* Heidelberg, and *S.* Paratyphi B. Samples were prepared in an identical procedure as that for the high heat inactivation study, except homogenized 5 gram samples were used. The same inoculation procedure was followed for each of the two cocktails.

Identical materials and equipment used in the high heat inactivation study were used in this study. The KAPAK bags containing the inoculated products were completely submerged in the water bath set at various temperatures from 60°C to 68°C. Samples were heated for varying times at each temperature, based on time-temperature combinations found in initial water bath

studies. Time zero was defined as the time when the sample reached the target temperature. Three replicate samples were heated at each temperature.

Procedure identical to that in Thermal Inactivation Study I was followed for the enumeration of the bacteria and the verification studies.

Calculation of D-values and z-values

Data obtained during the thermal death time study was used to evaluate the D-values for each cocktail in both homogenized shrimp and salmon. When the log of the survivors was plotted against the heating time, the reciprocal of the reaction rate (the inverse slope of the data) was calculated as the D-value for each temperature. The z-value was then determined as the reciprocal of slope of the log D values (minutes) plotted versus temperature.

Mathematical modeling

The survival fraction rate in the homogenized products of the study was plotted over time. The following mathematical models were fit and compared with the experimental data:

Bigelow Model:

$$\log \frac{N_t}{N_0} = -t/D \qquad\qquad 4.1$$

where N_t is the number of survivors after an exposure time t and N_0 is the number of survivors initially (Bigelow, 1921).

Fermi equation:

$$\frac{N_t}{N_0} = 1/\{1 + e^{\frac{t-t_{cm}}{a}}\} \qquad\qquad 4.2$$

where t is the time, t_c is the critical time where the survivor fraction is 0.5, and a is the inverse of the reaction rate (1/k) (Peleg, 1996).

Weibull distribution function:

$$\ln \frac{N_t}{N_0} = -(t/a)^n$$
4.3

where t is the treatment time and a and n are scale and shape factors (Peleg & Cole, 1998).

The precision of the developed predictive models was evaluated by its accuracy factor, as proposed by Ross (1996) and expressed as:

$$\log A_f = \frac{\log \left(\frac{predicted}{observed}\right)}{n}$$
4.4

where A_f is the accuracy factor, and n is the number of observations used in the calculation.

4.3.7 Statistical Analysis

The effect of internal product temperature on the inactivation of *Salmonella* in shrimp and salmon was analyzed for significance using JMP8 statistical software (Statistical Analysis System, North Carolina, USA). The Student's t test was used in analyzing the different internal temperature treatments following one-way analysis of variance (ANOVA) at $p < 0.05$. Five replicates were analyzed for each temperature treatment.

RESULTS AND DISCUSSION

High Temperature Treatment

When introduced to a constant heat treatment of 80°C, both inoculated shrimp samples and inoculated salmon samples achieved a 5-log reduction over time. All samples began with an initial count of the *Salmonella* poly-culture of about 6.00 log CFU/g. At an internal temperature of 71°C, the internally inoculated salmon, surface inoculated salmon, and the surface inoculated shrimp all reduced to a count of less than 1.00 log CFU/g.

Thermal inactivation in shrimp was only tested on surface-contaminated products, because internal contamination of non-homogenized shrimp prawns is physically unlikely. At an internal temperature of 45°C, the microbial count reduced to 3.97 log CFU/g. The count did not statistically decrease again until an internal temperature of 60°C. A gradual decrease then occurred until minimal *Salmonella* sp. was detectable at 71°C. The microbial count at 74°C increased slightly to 1.16 log CFU/g. This thermal resistance could be due to the physical properties of the shrimp. Another possible cause of the bacterial heat resistance is the synthesis of Heat Shock Proteins (HSP) in bacteria (Alvarez-Ordonez et al., 2008).

Due to the flaking structure of a raw salmon fillet, the thermal resistance of *Salmonella* sp. was studied for both internally contaminated samples and surface contaminated samples. The surface inoculated salmon decreased to 3.74 log CFU/g at 45°C, but did not decrease to a lower microbial count until 68°C. The internally inoculated salmon remained above 5 log CFU/g until 60°C, where it decreased to 3.18 log CFU/g. The microbial count steadily decreased as the internal temperature continued to rise, and reached a negligible count of 0.86 log CFU/g at 71°C. While the surface temperature of the samples increased faster than the internal temperature, both inoculation methods resulted in similar inactivation curves. This could be due to migration of

65

the bacteria from the surface into the product. Other studies have shown *Salmonella* penetrating depths greater than 1 cm in whole, intact products such as beef muscle and turkey breasts (Warsow et al., 2003) (Gill and Penney, 1977).

While the heat resistance curves varied between shrimp and salmon samples, both achieved 5 log reductions by 71°C. Similar results were found in a study by Bucher et al. (2008), which found that 71°C reduced *Salmonella* sp. to non-detectable levels in frozen chicken strips. Chintagari (2009) found that 70°C was necessary to reduce a *Salmonella* cocktail to non-detectable levels in shrimp.

While it is common for inactivation studies to use a high microbial count (10^6 cfu/g), it is unlikely that a consumer product would have a microbial load count high enough to require a 5 log reduction. Using a high microbial count helps in verifying where smaller log reductions occur. It may be difficult to observe small log reductions when beginning with a small microbial count due to any tailing in the data at low counts. It is necessary to understand that contamination levels in seafood may be much lower than 10^6 cfu/g in consumer products, and these log reduction rates may not be present with low microbial loads due to the tailing effect.

The recommended cooking temperatures by the FDA are based on a 3 log reduction for seafood products. This is a recommendation for retail and consumers based on the assumption that there is a minimal count of *Samonella* sp. in the products. For intact seafood products, the specific internal temperature-time combination recommended is 63°C plus 15 seconds. For surface inoculated shrimp, the log reduction at this time-temperature combination was 3.48. For salmon, the corresponding log reductions for internal inoculation and surface inoculation were 2.71 and 2.25, respectfully. The shrimp inactivation results are agreeable with the FDA's suggestion for a 3 log reduction, but the salmon results suggest only a 2 log reduction at 63°C

plus 15 seconds. While this reduction in salmon is most likely a safe suggestion since microbial

count on consumer products is minimal, it is necessary to look further into what time-

temperature combination ensures a 3 log reduction. This keeps the log reduction consistent

throughout various product cooking recommendations.

D-value and z-value studies

The microbial inactivation data for the two 3-strain *Salmonella* cocktails in homogenized

shrimp and salmon can be found in Appendix A.1. 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 0.92 was the highest achievable. As temperature increased, the D-values

decreased for all product-cocktail combinations. All D-values and corresponding z-values can

be seen in Table 4.1.

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 *Salmonella*

cocktails show similar high-temperature sensitivity in shrimp products. This could be due to the

difficulty in creating a perfectly homogenized shrimp mixture, increasing the hold of the

pathogen onto the product. 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 two cocktails. The inactivation rates in cocktails reflect the

characteristics of the most heat resistant serotype of the cocktail (Juneja et al., 2003). Bucher et.

al (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 seconds for a *Salmonella* polyculture containing *S. Enteriditis* and *S. Typhimurium*, which supports the cocktail I D_{63} values of 10.95 seconds in salmon and 10.35 seconds in shrimp.

The FDA recommends a cooking time-temperature combination of 68°C and 15 seconds for homogenized seafood products. This recommendation addresses a 3 log reduction in *Salmonella* sp., specifically for retail and consumers. The possible microbial count is expected to be minimal in consumer seafood products, and a 3 log reduction is expected to be a safe assurance of minimal remaining microorganisms. The D-values found in this study for a 1 log reduction at 68°C were between 2 seconds and 5 seconds. These results are in agreement with the recommended holding time of 15 seconds for a 3 log reduction at this temperature. The findings on the necessary holding times for 1, 3, and 5 log reductions at 68°C for both homogenized products can be seen in TABLE 4.2. The holding times were based on the higher value when comparing cocktail I and cocktail II.

Inactivation models

The Bigelow, Weibull distribution, and Fermi distribution models were fit to the inactivation data for each of the two *Salmonella* cocktails in homogenized shrimp and salmon. The resulting model parameters, correlation coefficients, and accuracy factors can be seen in TABLE 4.3 – TABLE 4.6.

The Bigelow model created a log-linear representation of the inactivation rate over time. The accuracy factors for the Bigelow models were all under 3.00 except for cocktail II in shrimp at 68°C, which had an A_f of 3.33. This specific set of data had a high A_f of 3.04 for the Fermi distribution model but a low A_f of 1.31 for the Weibull distribution model.

The Weibull model treats the survival data as an empirical power law model, rather than a log-linear regression. This model fit the *Salmonella* inactivation data for both cocktails the best in shrimp. The A_f values for shrimp were all under 1.50, except for cocktail II at 63°C, which had an A_f of 1.66. The parameter b, which is considered the shape factor, was less than 1.00 for all shrimp data, showing a consistent tailing effect during inactivation. The Weibull model also accurate modeled the survival data for the salmon samples, with all R^2 values greater than 0.94. All A_f values for the Weibull modeling of salmon were less that 2.00, except for cocktail I at 65°C, which had an A_f of 2.29.

In the Fermi distribution model, the parameter t_c represents the initial lag time that creates the "shouldering" effect when there is minimal inactivation at the beginning of heat application. The t_c values for salmon models were 1.89, 9.13, and 3.78 seconds for cocktail I, and 6.43, 2.65, and 1.02 seconds for cocktail II. The Fermi models for shrimp had t_c values of 0 seconds for all cocktail temperatures except cocktail II at 63°C, which had a value of 0.23 seconds. This shows that there is minimal delay in response of *Salmonella* sp. in shrimp, but notable delay in salmon. This is consistent with the Weibull modeling, where shrimp data all had b values <1 and salmon data primarily having b values >1.

The Fermi equation considers microbial response to have a gradual transition from marginal effects at relatively low intensities to sudden inhibitory effects at high intensities of the lethal agent (Alzamora et al., 2009). The equation is typically used to describe microbial exposure to high pressure treatment, pulsed electric fields, radiation, etc. Minimal research can be found on the lethal agent being high temperature. The fact that the Fermi equation accurately described the thermal inactivation of *Salmonella* in salmon suggests that this equation is applicable to high temperature studies.

Comparative studies on the effectiveness of mathematical models including the Bigelow, Fermi, and Weibull distribution functions can be found pertaining to the inactivation of *Salmonella* sp. in a variety of food products (Mattick et al., 2001; Bialka et al., 2008; Chen, 2007; Shachar and Yaron, 2006). Higher accuracy has typically been found by non-log linear models such as the Fermi equation and the Weibull distribution function. van Boekel (2002) compared the Weibull model to the Bigelow model for the microbial inactivation data for fifty-five case studies in literature. The results of the study found that the Weibull model performed more accurately that the Bigelow in the modeling of thermal inactivation. This supports the results in this study suggesting that the Fermi and Weibull models are more applicable to the inactivation of *Salmonella* sp. in shrimp and salmon.

CONCLUSIONS

Introducing salmon and shrimp products inoculated with a *Salmonella* culture to a water bath at 80°C represented the cooking of a contaminated product. This part of the study showed the thermal resistance of *Salmonella* and determined minimum internal temperatures necessary to safely reduce any contamination that may have been in the raw product. The results of this study show that a 3 log reductions occurs by the FDA Food Code's recommended 63C plus 15 seconds for intact shrimp products. However, this recommended time-temperature combination ensures only a 2 log reduction for both surface inoculated and internally inoculated salmon samples. While a 2 log reduction should be acceptable for the minimal amount of *Salmonella* in consumer seafood products, it is necessary to further look into the appropriate time-temperature combination for a 3 log reduction in order to keep consistency in Food Code recommendations.

The D and z-values were calculated for the inactivation of two *Salmonella* cocktails in homogenized shrimp and salmon. The D-values for each cocktail-product combination at 68°C ranged between 2 seconds and 5 seconds. This data is in agreement with the Food Code's cooking recommendation of 68°C plus 15 seconds for homogenized seafood products.

Prediction models can effectively be applied to survival data for *Salmonella* cocktails in both shrimp and Atlantic salmon. Of the three models compared in the study, the Weibull distribution model fit the survival data of *Salmonella* in shrimp with the best accuracy. This was due to a notable tailing effect which the other two models do not take account for. The Fermi distribution model fit the inactivation data for salmon most accurately. All Fermi distribution models for salmon data had t_c values >1, showing a shouldering effect which this specific model takes account of.

References

Alvarez-Ordonez, A., Fernandez, A., Lopez, M., Arenas, R., Bernardo, A. 2008. Modifications in membrane fatty acid composition of *Salmonella Typhimurium* in response to growth conditions and their effect on heat resistance. *Int. J. Food Micro.* 123: 212-210.

Alzamora, S. M., Guerrero, S. N., Lopez-Malo, A., Palou, E., Char, C. D., Raffelini, S. 2009. Models for Microorganism Inactivation: application in food preservation design. In: Ortega-Rivas, E., editor. *Processing Effects on Safety and Quality of Foods*. Boca Raton, FL: Taylor & Francis. 87-116p.

Anderson, W. A., McClure, P. J., Baird-Parker, A. C. Cole, M. B. 1996. The Application of a Log-Logistic Model to Describe the Thermal Inactivation of *Clostridium botulinum* 213B at Temperatures below 121.1C. *J. Appl. Bacteriol.* 80. 283-290.

Ball, C. O. 1943. Short-time pasteurization of milk. *Ind. Eng. Chem.* 35: 71-84.

Bialka, K. L., Demirci, A., Puri, V. M. 2009. Modeling the inactivation of Escherichia coli O157:H7 and Salmonella enteric on raspberries and strawberries resulting from exposure to ozone or pulsed UV-light. *J. Food Eng.* 85:444-449.

Bigelow, W. D. 1921. The logarithmic nature of thermal death time curves. *J. Infect. Dis.* 29: 528-536.

Bucher, O., D'Aoust, J.Y., Holley, R. A. 2008. Thermal resistance of Salmonella serovars isolated from raw, frozen chicken nuggests/strips, nugget meat, and pelleted broiled feed. *Int. J. Food Microbiol.* 124:195-198.

Center for Disease Control and Prevention. FoodNet 2007 Surveillance Report. Atlanta: U.S. Department of Health and Human Services. 2009.

Chen, H. 2007. Use of linear, Weibull, and log-logistic functions to model pressure inactivation of seven foodborne pathogens in milk. *Food Micro.* 24:197-204.

Chintagari, S. 2009. Determination of minimum safe cooking temperatures for shrimp to destroy foodborne pathogens. MS Thesis. Louisiana State University. Baton Rouge, LA.

Fernandez, A., Salmeron, C., Fernandez, P., Martinez, A. 1999. Application of a frequency distribution model to describe the thermal inactivation of two strains of *Bacillus cereus*. *Trends Food Sci. & Tech.* 10. 158-162.

Gill, C. O., Penney, N. 1977. Penetration of bacteria into meat. *Appl. Environ Microbiol.* 33:1284-1286.

Heinitz, M. L., Ruble, R. D., Wagner, D. E., Tatini, S. R. 2000. Incidence of *Salmonella* in fish and seafood. *Journal of Food Protection* 63. 579-592.

Juneja, V. K., Marks, H. M., Huang, L. 2003. Growth and heat resistance kinetic variation among various isolates of Salmonella and its application to risk assessment. *Risk Analysis.* 23:199-213.

Juneja, V. K., Porto-Fett, A. C., Call, J. E., Marks, H. B., Tamplin, M. L., Luchansky, J. B. 2010. Thermal inactivation of *Bacillus anthracis* Sterne in irradiated ground beef heated in a water bath or cooked on commercial grills. *Innovative Food Science and Emerging Technologies*. 11. 123-129.

Lyhs, U. 2009. Microbial methods. In: Rehbein, H., Oehlenschlager, J., editors. *Fishery Products: Quality, safety and authenticity*. West Sussex, United Kingdom. 318-348p.

Mattick, K. L., Legan, J. D., Humphrey, T. J., Peleg, M. 2001. Calculating Salmonella inactivation in non-isothermal heat treatments from isothermal non-linear survival curves. *J. Food Protection.* 64:606-613.

Mazzotta, A. S. 2000. D- and z- values of Salmonella in ground chicken breast meat. *J Food Safety*. 20:217-223.

National Advisory Committee on Microbiological Criteria for Foods (NACMCF). 2007. Response to the questions posed by the Food and Drug Administration and the National Marine Fisheries Service regarding determination of cooking parameters for safe seafood for consumers. NACMCF, Washington, DC. U.S. Department of Health and Human Services, Public Health Service, Food and Drug Administration. *Food Code. 2005.* College Park, MD.

Peleg, M. 1996. Evaluation of the Fermi equation as a model of doze response curves. *Applied Microbiology Biotechnology*. 46: 303-306.

Peleg, M. Cole, M. 1998. Reinterpretation of microbial survival curves. *Critical Reviews in Food Science*. 38: 353-380.

Ross, T. 1996. Indices for performance evaluations of predictive models in microbiology. *J. Applied Bacteriology*. 81: 501-508.

Shachar, D., Yaron, S. 2006. Heat tolerance of Salmonella enteric serovars Agona, enteritidis, and Typhimurium in peanut butter. *J. Food Protection.* 69:2687-2691.

van Boekel, M. A. J. 2002. On the use of the Weibull model to describe thermal inactivation of microbial vegetative cells. *Int. J. Food Micro.* 74:139-159.

Warsow, C. R. 2003. Penetration of Salmonella sp. into whole muscle turkey breasts during vacuum tumbling marination. MS Thesis. Michigan State Univ, East Lansing, MI.

Yayanos, A. A., Dietz, A. S. 1982. Thermal inactivation of a deep-sea barophilic bacterium, isolate CNPT-3. *Appl. Environ. Microbiol.* 43:1481-1489.

TABLE 4.1. Calculated D-values and z-values for 3-strain *Salmonella* cocktails in homogenized shrimp and salmon.

Product	Cocktail[1]	Temp °C	D value (sec)	D value r^2	z-value °C	z-value r^2
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		
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		

[1]Cocktail I: *S.* Enteriditis, *S.* Newport, *S.* Typhimurium;
Cocktail II: *S.* typhi, *S.* Heidelberg, *S.* Paratyphi B.

TABLE 4.2 Temperature and holding time combinations necessary to achieve *Salmonella* reduction in homogenized Atlantic salmon and shrimp

Product	Temperature + Holding Time		
	1 log	3 log	5 log
Atlantic Salmon	68°C + 3 sec	68°C + 9 sec	68°C + 15 sec
Shrimp	68°C + 5 sec	68°C + 15 sec	68°C + 25 sec

TABLE 4.3 Comparison of kinetic parameters for *Salmonella* cocktail I (*S.* Enteriditis, *S.* Newport, *S.* Typhimurium) in homogenized salmon.

Temperature (°C)	Bigelow			Weibull				Fermi			
	D	R^2	A_f	a	b	R^2	A_f	k	t_c	R^2	A_f
60	37.80	0.98	1.60	10.12	0.82	0.98	1.89	0.06	1.89	0.98	1.76
63	10.95	0.96	1.81	8.91	1.46	0.99	1.33	0.29	9.13	0.99	1.46
65	3.67	0.97	2.91	2.23	1.08	0.96	2.29	0.71	3.78	0.99	1.63

[a] D: D-value in seconds
[b] A_f: Accuracy factor
[c] a and b: scale and shape factors of Weibull distribution
[d] k is the rate contant (min^{-1}) and t_c is the shoulder length of Fermi distribution

TABLE 4.4 Comparison of kinetic parameters for *Salmonella* cocktail II (*S.* Typhi, *S.* Heidelberg, *S.* Paratyphi B.) in homogenized salmon.

Temperature (°C)	Bigelow			Weibull				Fermi			
	D	R^2	A_f	a	b	R^2	A_f	k	tc	R^2	A_f
63	7.38	0.92	2.03	6.90	1.49	0.95	1.84	0.38	6.43	0.94	2.04
65	4.11	0.95	2.79	2.98	1.21	0.98	1.99	0.59	2.65	0.97	2.16
68	2.48	0.99	1.47	1.49	1.14	0.99	1.39	0.99	1.02	0.99	1.59

[a] D: D-value in seconds
[b] A_f: Accuracy factor
[c] a and b: scale and shape factors of Weibull distribution
[d] k is the rate contant (min^{-1}) and t_c is the shoulder length of Fermi distribution

TABLE 4.5 Comparison of kinetic parameters for *Salmonella* cocktail I (*S.* Enteriditis, *S.* Newport, *S.* Typhimurium) in homogenized shrimp.

Temperature (°C)	Bigelow			Weibull				Fermi			
	D	R^2	A_f	a	b	R^2	A_f	k	tc	R^2	A_f
60	14.90	0.96	1.35	3.38	0.81	0.96	1.36	0.19	0	0.95	1.73
63	10.35	0.96	1.69	2.18	0.76	0.99	1.17	0.24	0	0.96	1.78
68	4.34	0.99	1.62	1.15	0.83	0.99	1.39	0.53	0	0.98	1.81

[a] D: D-value in seconds
[b] A_f: Accuracy factor
[c] a and b: scale and shape factors of Weibull distribution
[d] k is the rate contant (min^{-1}) and t_c is the shoulder length of Fermi distribution

TABLE 4.6 Comparison of kinetic parameters for *Salmonella* cocktail II (*S.* Typhi, *S.* Heidelberg, *S.* Paratyphi B.) in homogenized shrimp.

Temperature (°C)	Bigelow			Weibull				Fermi			
	D	R^2	A_f	a	b	R^2	A_f	k	tc	R^2	A_f
60	12.8	0.94	1.76	0.71	0.54	0.99	1.29	0.23	0	0.83	2.80
63	5.70	0.98	1.82	2.16	1.00	0.98	1.66	0.46	0.22	0.98	1.83
68	3.43	0.94	3.33	0.34	0.61	0.99	1.31	0.65	0	0.91	3.04

[a] D: D-value in seconds
[b] A_f: Accuracy factor
[c] a and b: scale and shape factors of Weibull distribution
[d] k is the rate contant (min^{-1}) and t_c is the shoulder length of Fermi distribution
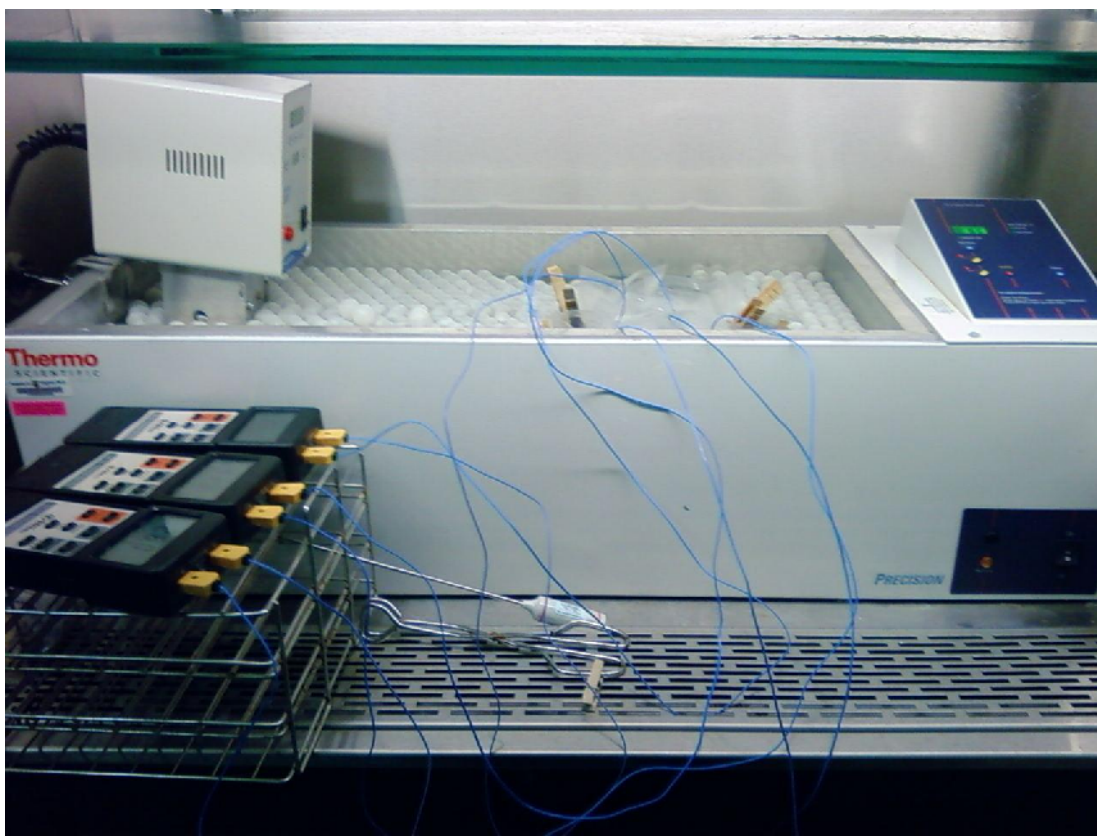
Figure 4.1 Water bath setup during initial time-temperature studies.

Figure 4.2. Plating of samples onto Tryptic Soy Agar.
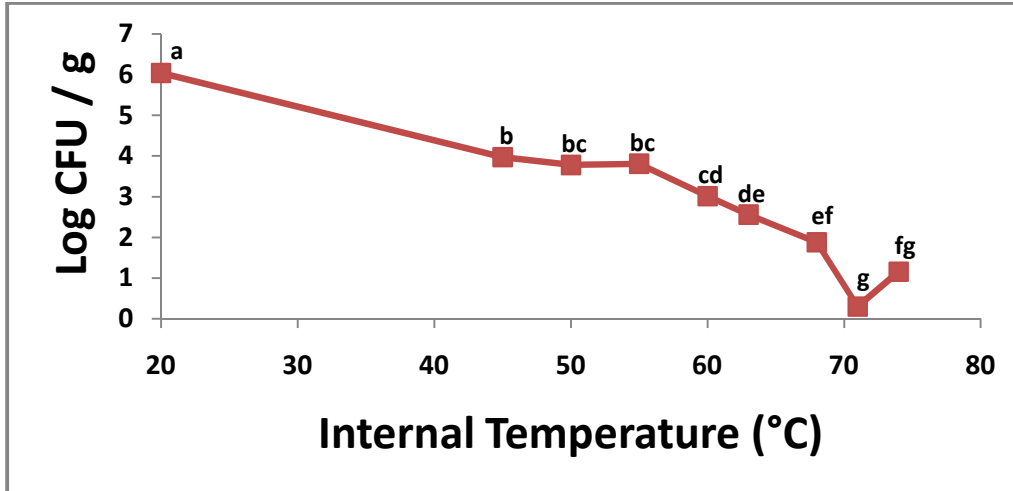
Figure 4.3. Thermal resistance of *Salmonella* 6-strain cocktail in shrimp at different internal temperatures when subjected to a water bath set at 80°C. Non-homogenized shrimp prawns subjected to surface inoculation. Data with the same letters are not significantly different from each other (p<0.05).
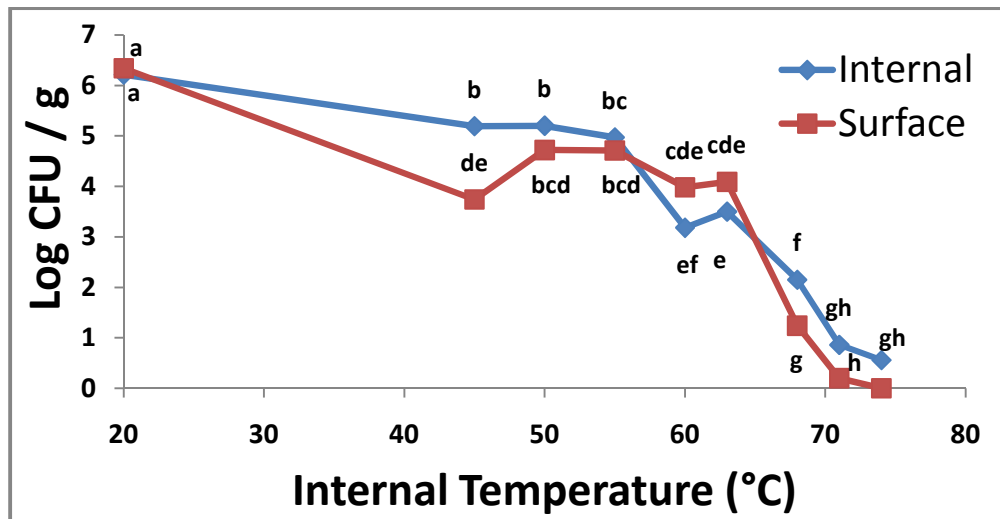
Figure 4.4. Thermal resistance of *Salmonella* 6-strain cocktail in Atlantic salmon at different internal temperatures when subjected to a water bath set at 80°C. Separate studies on non-homogenized samples subjected to internal and surface inoculation. Data with the same letters are not significantly different from each other ($p < 0.05$).

CHAPTER 5

Mathematical Modeling of Heat Transfer and Quality Change during the Cooking of Shrimp and Atlantic Salmon

Lauren Brookmire[1], P. Mallikarjunan[1], M. Jahncke[2], and R. Grisso[1]

[1]Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

[2]Department of Food Science and Technology, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

ABSTRACT

The quality of a cooked food product is dependent on many variables, including the cooking method used and heating temperature applied. The overall heating profile of the food can be useful in predicting the quality changes and microbial inactivation occurring during cooking. However, attaining an accurate heating profile is difficult since the temperature change is non-uniform over time. Mathematical modeling can be used to attain the complex heating profile of a food product during cooking. The purpose of this study was to investigate the heating profile and predicted optimal cooking conditions for shrimp and Atlantic salmon through the application of predictive mathematical models.

The finite difference method was used to model the heating profiles during the boiling and oven baking of shrimp and the oven baking and pan frying of salmon. A two dimensional frustum cone geometry was used for shrimp and a three-dimensional slab geometry was used for salmon fillets. The models accurately predicted the heating profiles for the various methods of heat application. The shrimp models were effective for both product sizes studied.

The temperature data attained from the heating profile models were then directly used in the application of predictive quality and microbial kinetic models. The model predictions on color difference, texture, and pressed juice were in good agreement with the observed data. A modified first order model accurately modeled the ΔL change internally for shrimp and the ΔC change for the surface of shrimp. Similar modeling was performed on the ΔL and ΔC change during the cooking of salmon as well. First order models also predicted shear force (N) and firmness (N.s) change in salmon with little deviation from experimental data. A zero-order kinetic model was used for predicting the change in pressed juice (%) during the cooking of both

shrimp and salmon. Using a fixed inactivation level of 3 logs and a fixed quality of 95% best

quality, optimal cooking times were determined that both provide a high quality product and

assure microbial safety. In general, the heat transfer, quality change, and microbial inactivation

were accurately modeled for the specific experimental methods used this study. Optimized

cooking conditions can be established for specific products and cooking methods by combining

these modeling techniques.

INTRODUCTION

Thermal processing is commonly used during food preparation. Different cooking processes use different methods of heat transfer which can result in varying final products. Common processes used by both companies and consumers include boiling, baking, microwaving, steaming, broiling, pan-frying, and deep fat frying.

Seafood products are a familiar food choice worldwide, popular both for taste and nutritional value. Products such as fin fish and shrimp are cooked by various methods during preparation. While a popular food commodity, seafood is also one of the highest sources of foodborne disease. Disease-causing pathogens can be minimized in food products by thoroughly cooking products to the appropriate inactivation temperatures necessary. A report released by the NACMF in 2007 specifies that further studies are needed on the thermal inactivation of pathogens in seafood products.

In order to improve the safety of a food, it is necessary to understand the temperature change in the product during cooking processes. Mathematical models can be used to predict the heating profile throughout a product as it is being cooked. Modeling is beneficial because it can take into account the non-uniform temperature change occurring throughout a food. The temperature data attained from modeled heating profiles can be directly applied to studies on 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 (Sablani et al., 1998; Chang et al., 1998), pan-frying (Ou and Mittal, 2007; Zorrilla and Singh, 2000), immersion frying (Farkas et al., 1996; Southern et al., 2000), and microwaving (Mallikarjunan et al., 1996; Hu and Mallikarjunan, 2002; Chen et al., 1993). 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 et al., 1991; Casales et al., 1988). Limited studies have applied quality kinetic models to the thermal processing of non-molluscan seafood products (Kong et al., 2007; Banga et al., 1993).

The objectives of this study were to develop predictive mathematical models to describe the heating profile in shrimp and Atlantic salmon and to use the heating profiles to investigate the first order quality kinetics and inactivation kinetics during the cooking process. The cooking methods optimized were boiling and oven baking for shrimp and oven baking and pan frying for salmon.

MATERIALS AND METHODS

Experimental procedure

Experimental data was used from previous studies on the heating distribution and quality change during the cooking of shrimp and Atlantic salmon (see Chapter 3). Specific methodology was followed for the boiling of shrimp, oven baking of shrimp, oven baking of salmon, and pan frying of salmon. Two sizes of shrimp were studied experimentally. The qualities studied were color, texture, pressed juice, and moisture content as the product reached specific internal temperatures. All studies were replicated five times for both time-temperature evaluations and quality attributes for both shrimp and salmon.

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.

Heat Transfer Models

Separate geometries were used in developing models for shrimp and salmon. A two-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 five segments and the Z-direction was evenly divided into ten segments (FIGURE 5.1). The basic 2-D heat transfer equation used for shrimp was:

$$\frac{\delta T}{\delta t} = \alpha \left(\frac{1}{r}\frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta r^2} + \frac{\delta^2 T}{\delta z^2} \right) \qquad\qquad 5.1$$

While this is the initially the heat transfer equation for a two-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:

$$kA\frac{\delta T}{\delta r} = hA\Delta T \qquad \text{and} \qquad kA\frac{\delta T}{\delta z} = hA\Delta T. \qquad\qquad 5.2,\ 5.3$$

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 five even segments based on the lengths of each direction (FIGURE 5.2). The basic 3-D heat transfer equation can be written as:

$$\frac{\delta T}{\delta t} = \alpha \left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2} + \frac{\delta^2 T}{\delta z^2} \right) \qquad\qquad 5.4$$

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

$$kA\frac{\delta T}{\delta x} = hA\Delta T\,, \qquad kA\frac{\delta T}{\delta y} = hA\Delta T, \qquad kA\frac{\delta T}{\delta z} = hA\Delta T. \qquad\qquad 5.5,\ 5.6,\ 5.7$$

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

this study was:

$$\bar{h}A_s\left(T - T_{inf}\right)dt = -\rho cVdT, \qquad (T=T_i\ \text{at}\ t=0). \qquad\qquad 5.8$$

The thermal properties used for shrimp and Atlantic salmon were attained from research

by Chau and Snyder (1988) and Radhakrishnan (1997). Separate programs were written for each

of the four product-cooking method combinations using MATLAB2009b software (Appendix

B).

Quality Models

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

$$\frac{dQ}{dt} = -k(Q)^n \qquad\qquad 5.9$$

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 et al., 2007). A modified Arrhenius equation was

applied in order to take into account any temperature dependence of the reaction:

$$k = A_0\, e^{[-\Delta H/(RT)]} \qquad\qquad 5.10$$

where A_0 is the pre-exponential 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, first, and second order reactions. The temperature data was

used from the heat transfer models. A modified first-order kinetic model, commonly referred to

as a fractional conversion model, was also used in kinetic modeling:

$$\ln\left(\frac{Q_t - Q_{inf}}{Q_0 - Q_{inf}}\right) = -kt \qquad\qquad 5.11$$

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 non-linear curve fitting using *Solver* was followed. The deviations between the experimental and predicted quality data were calculated as:

$$\sigma = \frac{\sum_{i=1}^{N}(Y_{pred} - Y_{exp})^2}{n} \qquad\qquad 5.12$$

Microbial Inactivation Kinetics

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

$$-\frac{dN}{dt} = A_0 \; e^{-\frac{E_a}{RT}} \; N \qquad\qquad 5.13$$

where N is the number of survivors, A_0 is the pre-exponential factor (frequency factor), E_a is the activation energy, R is the gas constant, and T is the temperature.

The results were validated using a 6 strain mixture of *Salmonella* (Chapter 4). Non-homogenized shrimp and salmon samples were inoculated internally with approximately 10^6 cfu/g. Samples were introduced to a water bath at 80°C and the microbial count was analyzed at specific time-temperature points. All procedures were replicated five times.

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. 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.

RESULTS AND DISCUSSION

Mathematical Models

A comparison of the experimental temperature profile data and model predictions can be seen TABLE 5.2-TABLE 5.5. All four models showed appropriate trends in temperature change based on cooking method. The deviations between the modeled and experimental temperatures were calculated for each product-cooking method combination (TABLE 5.1).

Using a three dimensional rectangular slab to represent a salmon fillet showed accurate results in modeling oven baking and pan frying. The calculated equation for non-steady conduction proved an accurate method for modeling the temperature increase of aluminum foil on the surfaces of the fillet. Both the internal node and surface node were accurately modeled for oven baking, with temperatures all ±4°C of experimental temperatures. The calculated σ values were 0.26 and 0.20 for the core and surface temperature data, respectively.

The pan frying process involved a single flipping of the salmon fillet at 3 minutes. The model simulated this action by reversing all nodes in the y-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 node onto the pan, 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 σ values for the core and surface temperature data were 0.54and 1.72, respectively.

Representing a shrimp prawn as a frustum cone proved an accurate method in predicting the temperature profiles during cooking. The specified internal and surface nodes modeled accurately increased during boiling for both the extra jumbo and colossal sized shrimp. Identical models were used for both sizes with different initial radiuses. There was little variation within the experimental and modeled internal nodes. The external node, however, increased initially at a greater pace in the model than the experimental data. This may be due to the thermocouple not being in the correct position during the experimental procedure. There may have been human error in placing and maintaining the thermocouple position perfectly. Also, the boiling process creates movement of the shrimp, which may have initially adjusted the positioning of probes further away from the surface.

The oven baking of shrimp was accurately modeled for both sizes of shrimp in this study. The modeling of the internal and surface nodes followed an accurate pattern before and after the opening of the oven. While the σ values were greater for the oven baking process than the boiling process, the oven baking model was still considered effective. 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.

Quality and Inactivation Kinetic Models

The experimental quality data was fit to the kinetic models in order to see which quality

changes can accurately be modeled with predicted temperature data. For the changing color

attributes in shrimp, ΔL for the core area and ΔC for the surface area were accurately modeled

with first order fractional conversion kinetic model. These color kinetic parameters for both

sizes of shrimp undergoing boiling and oven baking can be seen TABLE 5.2. 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 σ values of 0.13 and 0.17 for extra jumbo and colossal sizes,

respectively (FIGURE 5.5). The σ values for the ΔC models during oven baking were 3.86 for

extra jumbo prawns and 0.98 for colossal prawns.

The first order fractional conversion model also appropriately modeled the change color

during the cooking of salmon (TABLE 5.3). While adequate correlation was not found in the Δh

(difference in hue angle) values over time experimentally, ΔL values were modeled with an

acceptable representation of both the internal part of the fillet and the surface (FIGURE 5.6).

The ΔC predictive model affectively modeled the salmon surface during the oven baking of

salmon, but pan frying did not efficiently fit the kinetic models tested. For both the internal area

of the fillet and the surface, the ΔL first-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) were effectively fit to predictive

first-order kinetic models for salmon. The kinetic parameters during oven baking and pan frying

can be seen in TABLE 5.4. 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. It would be beneficial to conduct

studies at more time-temperature points further in the cooking process to in order to accurately

model the texture change in shrimp.

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 can

be seen in TABLE 5.5. The shrimp data had slightly higher ΔH values for the boiling process

over the baking process. The deviation values for the shrimp models were efficiently $\leq 0.70\%$.

The σ values for salmon were 1.19 for oven baking and 1.44 for pan frying.

A first order kinetic model acceptably fit the inactivation of *Salmonella* sp. for each

cooking method studied (FIGURE 5.9). While the experimental data used was based on an

inactivation study performed in a water bath at 80°C, assumptions were made that similar

survivals would be seen at identical temperature points during the cooking methods. From the

modeled inactivation curves, exact cooking times can be determined for various log reductions.

With the study focusing on consumer cooking methods, the FDA's recommended 3 log reduction

for intact seafood products cooked by consumers was determined (TABLE 5.6).

Limited studies can be found 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 et al. (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 et al.'s study focused more on extending the shelf life in the fish industry, this study focused on optimizing cooking methods practiced by consumers.

Mallikarjunan et al. (1995) used temperature distributions obtained from a heat transfer model for microwaved shrimp in the formulation of further kinetic models. The predictive kinetic models obtained were for the inactivation of *Listeria monocytogenes* and for the predicted mass loss during microwaving. While Mallikarjunan et al. (1996) did not investigate the kinetics of the same quality traits or microorganism as this study, the 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 in order to achieve 95% of the optimum quality were also determined. The qualities used were those that were determined to follow 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 of 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 5.6). These

cooking times were based on minimizing the quality loss, yet assuring that a 3 log reduction was achieved. All six product–cooking method combinations achieved a 3 log reduction before reaching the FDA's recommended 63°C plus 15 seconds 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. It is also important to note the size of the products studied. Using smaller sized products may cause the internal temperature to rise at a faster rate, and reaching 63°C plus 15 seconds may be necessary. It would be beneficial to further look into the size of products and the cooking times necessary.

As expected, the optimal cooking times for colossal shrimp were greater than the times for extra jumbo shrimp. It was also found that the pan frying of salmon is optimal at 399 seconds and the oven baking of salmon is optimal at 1132 seconds. This emphasizes the fact that food samples can have significantly different cooking recommendations based on cooking method chosen. It is necessary to note that the optimum cooking conditions found are specific to the products studied and the methodology followed. Slight alterations in procedure may significantly affect the results. Also, it must be emphasized that quality attributes were measured up to the FDA's recommended temperature of 63°C plus 15 seconds. To gain a better representation of optimal quality cooking times, it is recommended to investigate the attributes at longer processing times.

CONCLUSIONS

Using a complex, three dimensional slab geometry for salmon and frustum cone geometry for shrimp resulted in agreeable models of the diverse cooking methods studied. There were slight variations in the temperature profiles, but the general methods of heat application

were well represented. It would be beneficial to expand on the models created by additional research on variations in product size and temperature application.

The temperature data from the heat transfer models was effectively applied to kinetic modeling of quality change and *Salmonella* inactivation during the cooking of shrimp and Atlantic salmon. Acceptable first-order models were formulated for ΔL and ΔC color parameters in both products. The texture change in salmon also followed a first-order kinetic model. Pressed juice for both products was accurately modeled as a zero-order kinetic model. A first order kinetic model was an acceptable fit for the inactivation of *Salmonella* sp. in both products. The best cooking times for each quality and microbial safety were used to determine optimum cooking conditions for each cooking method. It can be concluded that the cooking of shrimp and Atlantic salmon can be optimized through the use of heat transfer modeling, quality kinetic modeling, and microbial inactivation modeling. It is recommended that this technique be used on other products as well in order to verify its acceptability to seafood product optimization in general. Concerning this specific study, it is recommended that the quality attributes and microbial counts at additional time-temperature points are experimentally studied to perfect the modeling of quality change and microbial inactivation in shrimp and Atlantic salmon.

References

Banga, J. R., Alonso, A. A., Gallardo, J. M., Perez-Martin, R. I. 1993. Kinetics of thermal degradation of thiamine and surface colour in canned tuna. *Lebensm.-Wiss. U-Technol.* 197:127-131.

Casales, M. R., Del Valle, C. E., Soule, C. L. 1988. Changes in composition of mussels due to thermal processing. *J. Food Sci.* 53:282-283.

Chai, T., Liang, K. T., Pace, J., Schlimme, D. V. 1991. Effect of heat processing on quality of pasteurized oysters. *J.Food Sci.* 56:1292-1294.

Chang, H. C., Carpenter, J. A., Toledo, R. T. 1998. Modeling heat transfer during oven roasting of unstuffed turkeys. *J. Food Sci*. 63:257-261.

Chau, K. V., Snyder, G.V. 1988. Mathematical model for temperature distribution of thermally processed shrimp. Trans. ASAE 31:608-612.

Chen, D. D., Singh, R. K., Haghighi, K., Nelson, P. E. 1993. Finite element analysis of temperature distribution in microwaved cylindrical potato tissue. *J. Food Eng.* 18: 351-368.

Farkas, B. E., Singh, R. P., Rumsey, T. R. 1996. Modeling heat and mass transfer in immersion frying. I, model development. *J. Food Eng.* 29:211-226.

Hu, X., Mallikarjunan, P. 2002. Mathematical modeling of heat transfer of microwave heated fish gel. 2002 ASAE Annual International Meeting. Paper No. 026043. Chicago, IL.

Kong, F., Tang, J., Rasco, B., Crapo, C. 2007. Kinetics of salmon quality changes during thermal processing. *J. Food Eng.* 83:510-520.

Levenspiel, O. 1972. Interpretation of batch reactor data. In: *Chemical Reaction Engineering*. 2nd edition. New York, NY: Wiley. 41-47p.

Mallikarjunan, P., Hung, Y. C., Gundavarapu, S. 1996. Modeling microwave cooking of cocktail shrimp. *J. Food Process Eng.* 19:97-111.

National Advisory Committee on Microbiological Criteria for Foods (NACMCF). 2007. Response to the questions posed by the Food and Drug Administration and the National Marine Fisheries Service regarding determination of cooking parameters for safe seafood for consumers. NACMCF, Washington, DC. U.S. Department of Health and Human Services, Public Health Service, Food and Drug Administration. *Food Code*. *2005*. College Park, MD.

Ou, D., Mittal, G. S. 2007. Single-sided pan frying of frozen hamburgers with flippings for microbial safety using modeling and simulation. *J. Food Eng.* 80:33-45.

Radhakrishnan, S. 1997. Measurement of thermal properties of seafood. M.S. Thesis. Virginia Tech. Blacksburg, VA. 43-76 p.

Sablani, S. S., Marcotte, M., Baik, O. D., Castaigne, F. 1998. Modeling of simulatenous heat and water transport in the baking process. *Lebensm.-Wiss. U.-Technol.* 31:201-209.

Southern, C. R., Farid, M. M., Chen, X. D., Howard, B., Eyres, L. 2000. Thermal validation of a simple moving boundary model to determine the frying time of a thin potato crisp. *Heat and Mass Transfer*. 36:407-412.

Walsh, S., Diamond, D. 1995. Non-linear curve fitting using Microsoft Excel Solver. *Talanta*. 42:561-572.

Zorrilla, S. E., Singh, R. P. 2000. Heat transfer in meat patties during double-sided cooking. *Food Sci. Technol. Res.* 6:130-135.

TABLE 5.1 Deviation between modeled and experimental temperatures for each product-cooking method combination.

Product	Cooking Method	Temperature °C Deviation (σ)	
		Core	Surface
Atlantic Salmon	Oven-Baked	0.26	0.20
	Pan-Fried	0.54	1.72
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

TABLE 5.2 First-order kinetic parameters for color differences of shrimp during cooking.

Color Attribute	Product Area	Cooking Method	Prawn Size	$\Delta H *10^3$	$A_0 (min^{-1})$ $*10^3$	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

TABLE 5.3 First-order kinetic parameters for color differences of Atlantic salmon during cooking.

Color Attribute	Product Area	Cooking Method	$\Delta H *10^3$	A_0	σ
ΔL (lightness)	core	oven baking	45.771	50228.85	1.32
		pan frying	44.953	39670.7	0.57
	surface	oven baking	39.778	3393.23	1.25
		pan frying	31.588	68.00	1.42
ΔC (intensity)	surface	oven baking	30.073	64.59	0.39

TABLE 5.4 First-order kinetic parameters for texture attributes of Atlantic salmon during cooking.

Texture Attribute	Cooking Method	$\Delta H *10^3$	A_0	σ
Shear Force (N)	Oven Baking	39.731	3843.25	1.12
	Pan Frying	39.838	28784.70	1.05
Firmness (N.s)	Oven Baking	19.998	3.07	0.10
	Pan Frying	17.615	4.34	0.08

TABLE 5.5 Zero-order kinetic parameters for pressed juice of shrimp and Atlantic salmon during cooking.

Product	Cooking Method	ΔH	$A_0 * 10^{-3}$	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

TABLE 5.6 The timings for the cooking of shrimp and Atlantic salmon to achieve a 3 log reduction in *Salmonella* sp. while maintaining high quality. Times and corresponding temperatures are based on predictive models developed for both inactivation kinetics and quality kinetics.

Product[1]	Cooking Method	Cooking Decription[2]	Cooking Time (sec)[3]				
			3 log	Surface ΔC	Core ΔL	Shear force (N)	Optimal
Extra Jumbo Shrimp	Boiled	10:1 mass ratio water to shrimp; water initially 99±1°C; 1 tsp. salt	88 (58.1°C)	83 (55.9°C)	100 (63.2°C)	-[4]	100 (63.2°C)
	Oven Baked	Oven at 450°F, flipped once	206 (59.7°C)	226 (63.7°C)	233 (64.8°)	-	233 (64.8°C)
Colossal Shrimp	Boiled	10:1 mass ratio water to shrimp; water initially 99±1°C; 1 tsp. salt	120 (59.9°C)	103 (54.0°C)	159 (71.0°C)	-	159 (71.0°C)
	Oven Baked	Oven at 450°F, flipped once	299 (59.5°C)	274 (56.5°C)	378 (69.7°C)	-	378 (69.7°C)
Atlantic Salmon	Oven Baked	Wrapped in aluminum foil, oven at 375°F	1050 (62.5°C)	1132 (66.6°C)	996 (59.7°C)	892 (54.0°C)	1132 (66.6°C)
	Pan Fried	Medium-high pan temperature, 1 tbsp. veg. oil, flipped once	368 (60.1°C)	328 (45.6°C)	399 (70.6°C)	323 (43.8°C)	399 (70.6°C)

[1]Extra jumbo shrimp: 13±2g, colossal shrimp: 19±2g, Atlantic salmon: 55x90x20cm; all products initially thawed overnight.
[2]Results are based on specific cooking methods followed. Altering cooking parameters may alter recommended cooking times.
[3]The cooking times for each quality attribute are based on when qualities reach 90% of predicted optimal quality. Qualities used were those which were acceptable fits to kinetic models
[4]Change in shear force (N) followed kinetic modeling for Atlantic salmon but not for shrimp.
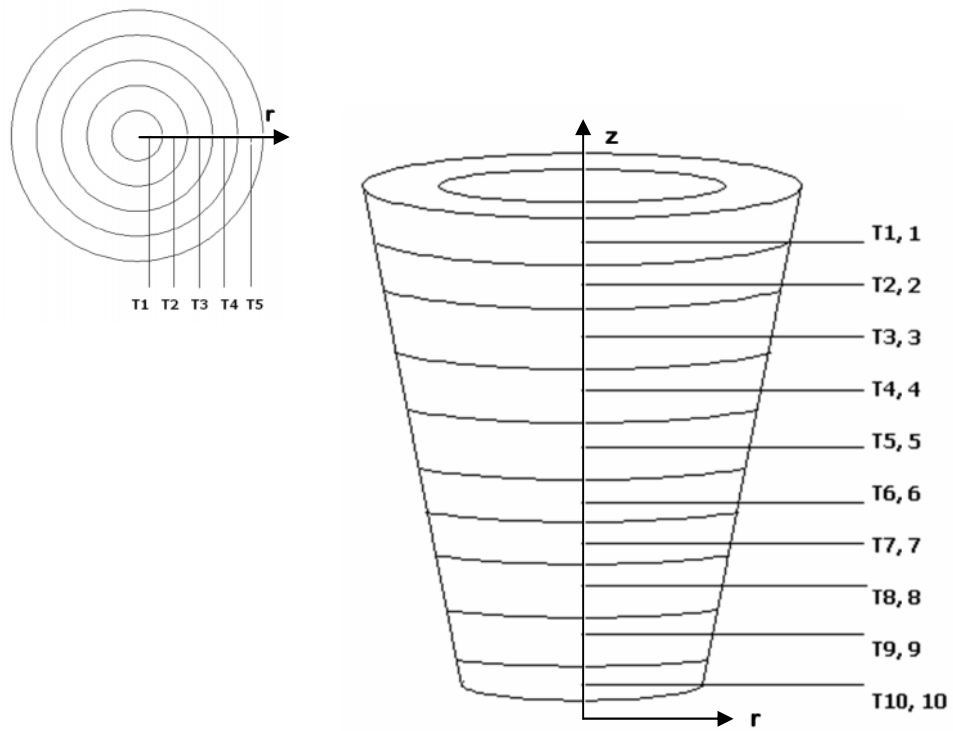
FIGURE 5.1. Frustum cone geometry used in the heat transfer models for cooked shrimp. Finite difference method was utilized with 5 nodes in the r-direction and 10 nodes in the z-direction.
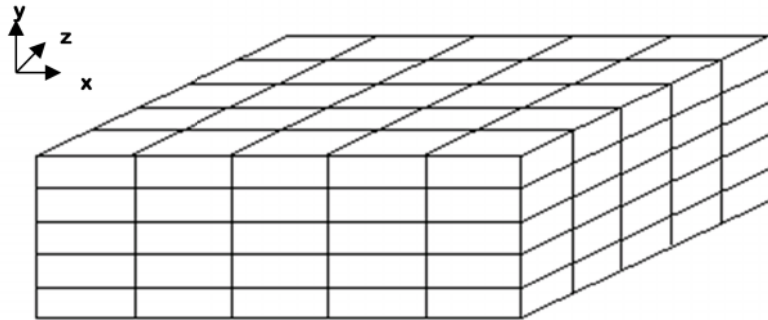
FIGURE 5.2. Three dimensional rectangular slab geometry used in the heat transfer models for cooked Atlantic salmon. The finite difference method was utilized with five nodes in each the x, y, and z directions.
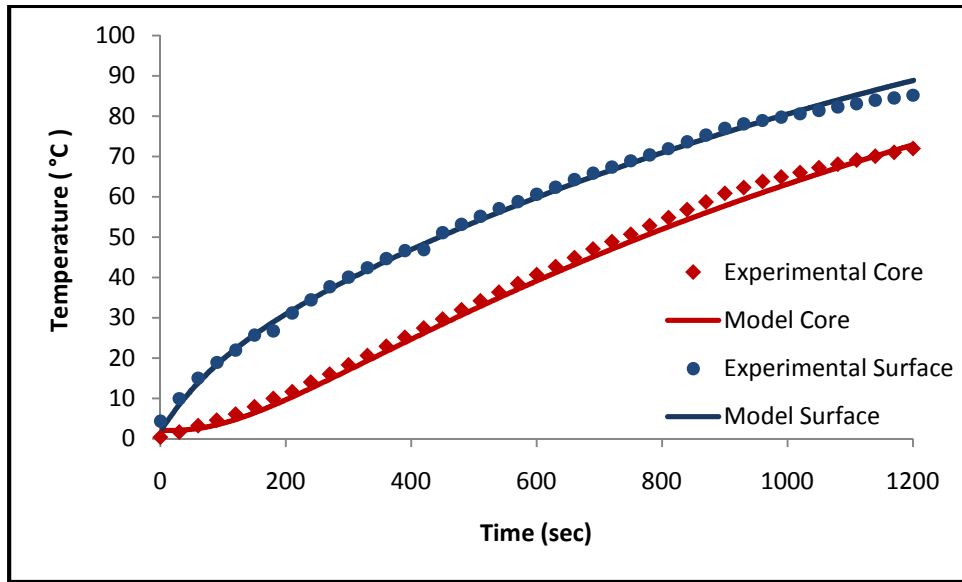
FIGURE 5.3 Temperature profile of oven-baked Atlantic salmon fillet wrapped in aluminum foil at oven temperature of 350°F.
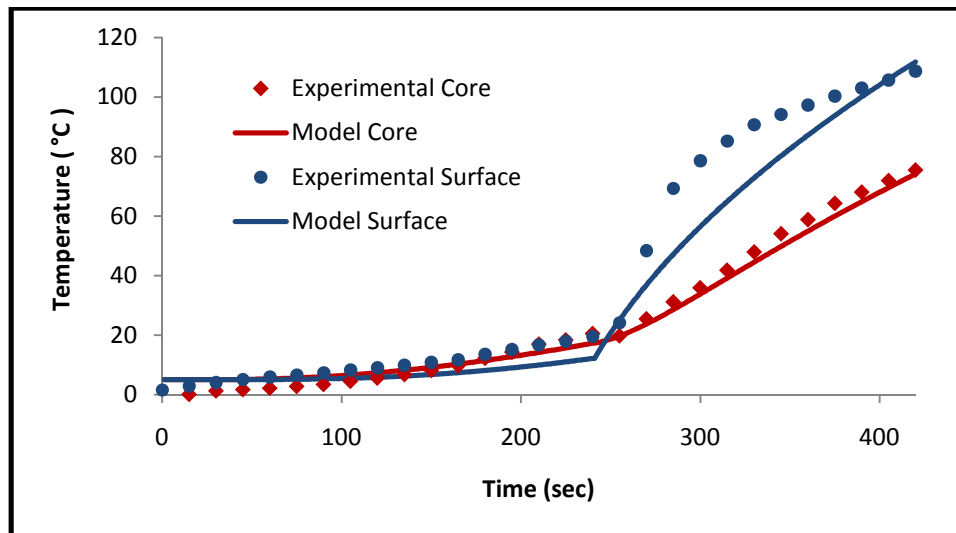
FIGURE 5.4 Temperature profile of pan-fried Atlantic salmon fillet with average pan temperature of 220°C. Fillet was flipped at 240 seconds. Surface data shown is for surface originally on opposite side of pan.
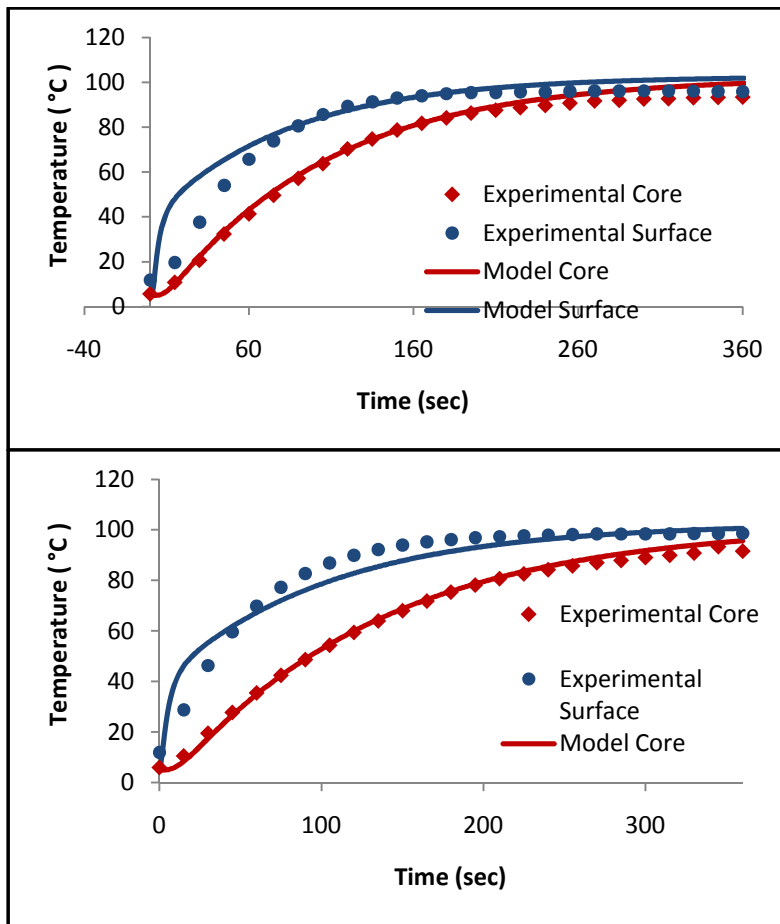
FIGURE 5.5 Temperature profile of (a) extra jumbo size shrimp and (b) colossal size shrimp during boiling process. Extra jumbo shrimp correspond to 13±2g and colossal shrimp correspond to 19±2g.
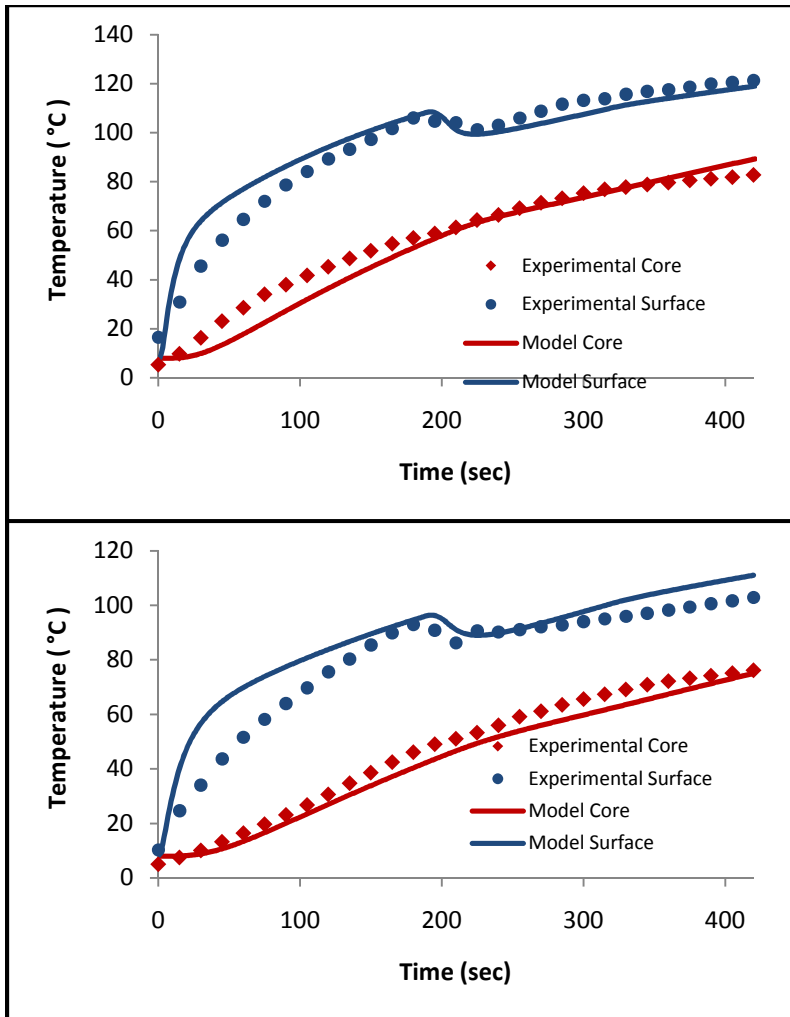
FIGURE 5.6 Temperature profile of (a) extra jumbo size shrimp and (b) colossal size shrimp during oven baking process. Oven was opened and shrimp were shifted at 180 sec. Extra jumbo shrimp correspond to 13±2g and colossal shrimp correspond to 19±2g.
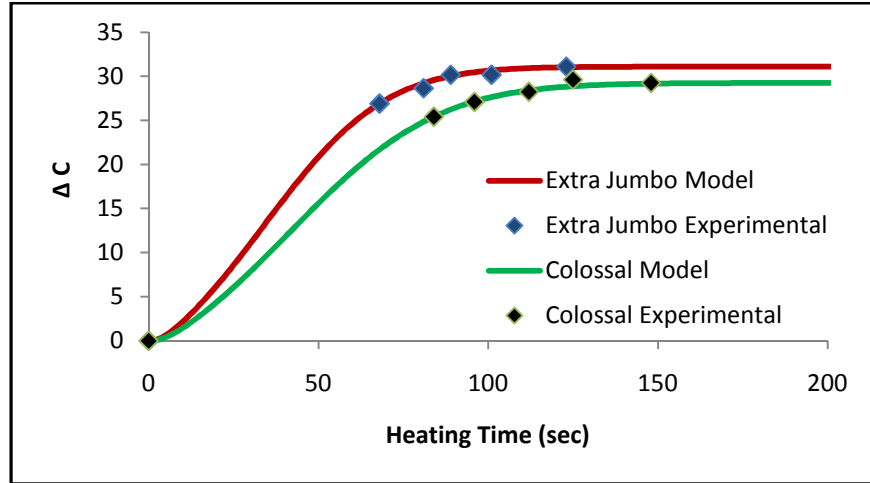
FIGURE 5.7. Modeled and experimental surface ΔC (difference in chroma) during the boiling of shrimp. Extra jumbo represents prawns 13±2g and colossal represents prawns 19±2g.
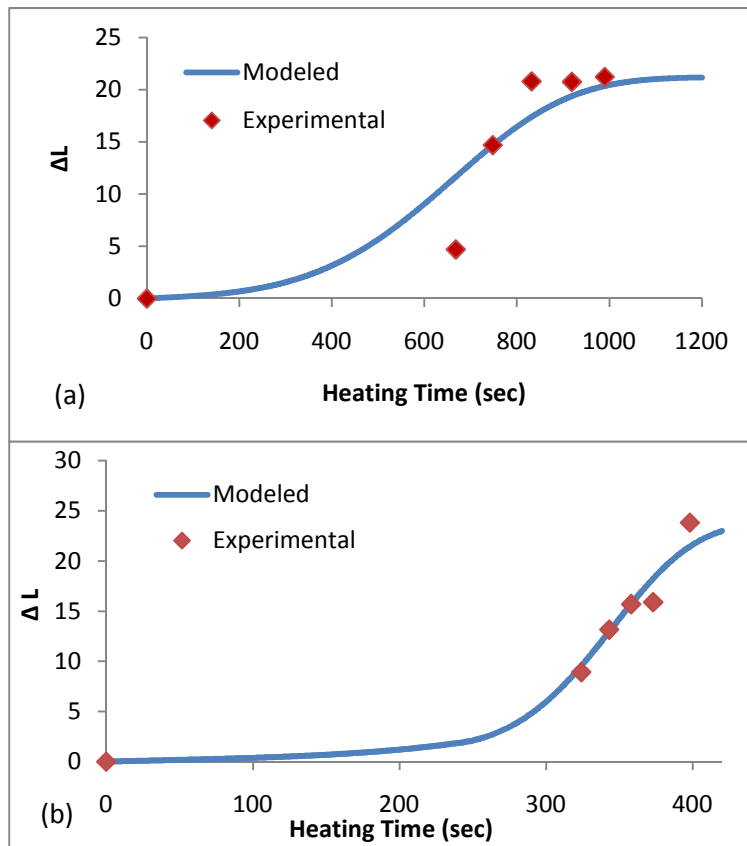
FIGURE 5.8 Modeled and experimental internal ΔL (difference in brightness) during the (a) oven baking and (b) pan frying of Atlantic salmon.
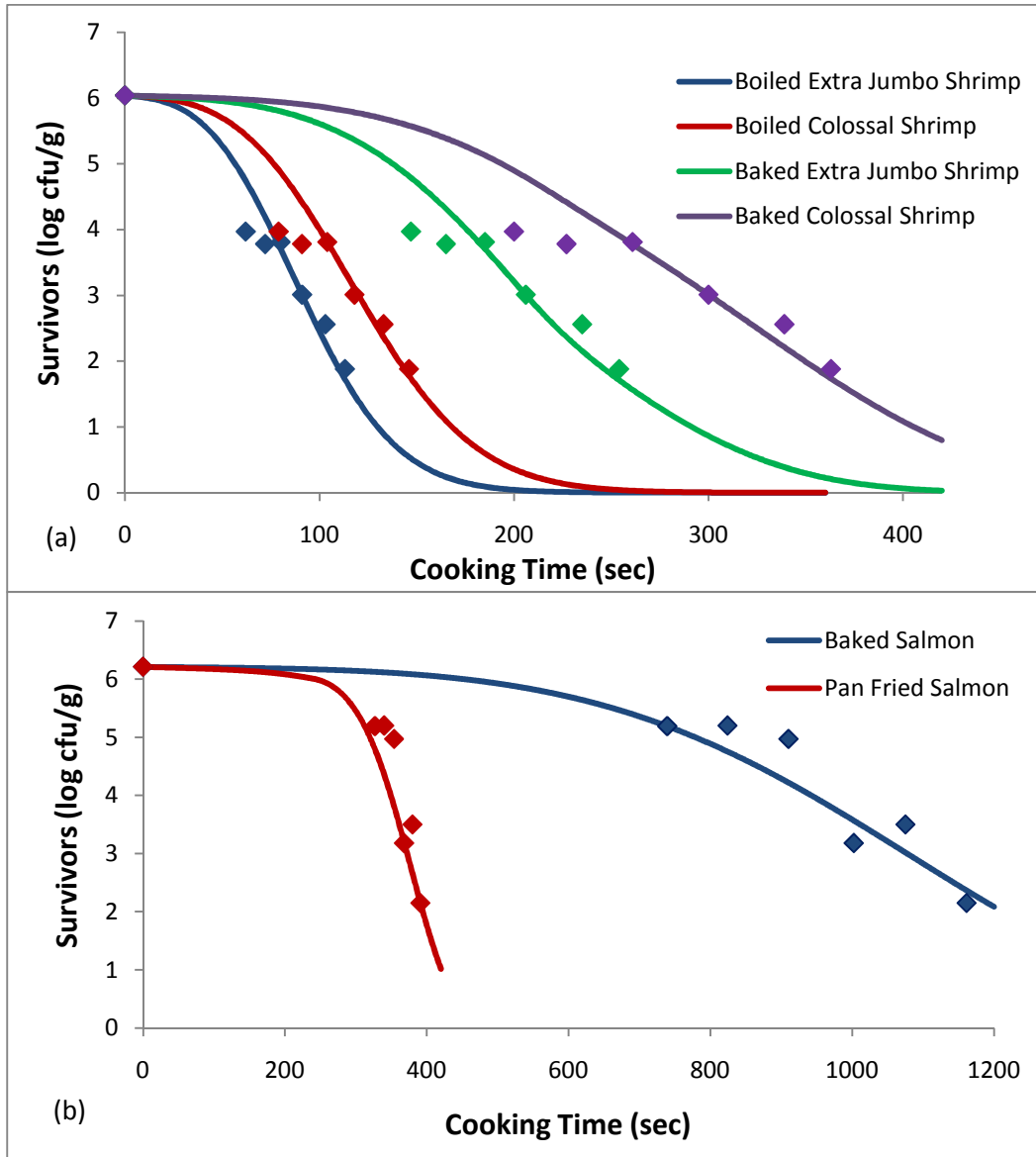
FIGURE 5.9 Modeled first order kinetic curves for inactivation of *Salmonella* sp. during the cooking of (a) shrimp and (b) Atlantic salmon. Solid lines represent the modeled data and the individual points represent the experimental data. The results are based on specific procedures for each cooking method.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This research project investigated the effect of thermal treatment on the quality and microbial safety of Atlantic salmon and shrimp. Various quality attributes were evaluated during common consumer cooking processes. Temperature change throughout the product was also determined during cooking. Heat transfer models using the finite difference method were created to describe the heating profile of Atlantic salmon and shrimp during the cooking methods. Quality kinetic models and inactivation models were then applied to the modeled heat transfer in correlation to the experimental data gathered. Optimal cooking conditions were determined that both provide a high quality product and assure microbial safety.

This study also evaluated the destruction of *Salmonella* sp. in Atlantic salmon and shrimp during thermal treatment. The Bigelow model, Weibull distribution function, and Fermi equation were applied to the survival data and the performances of the different mathematical models were compared.

In the first of the three studies, the effect of thermal processing on various quality attributes of Atlantic salmon fillets and shrimp prawns was studied. The cooking methods used were boiling and oven baking for shrimp and oven baking and pan frying for salmon. Color, texture, pressed juice, and moisture content were analyzed as the products reached 15 seconds after an internal temperature of 63°C, which was considered the point of being fully cooked. Conclusions were made on the data as to how consumers can accurately understand the doneness of both shrimp and Atlantic salmon. For shrimp, it was concluded that the external color of

shrimp may appear at a point of doneness before the internal temperature of 63°C plus 15 seconds. The internal lightness factor (CIE L*), which a consumer may consider the opaqueness of the product, more accurately represented the doneness of shrimp prawns than the external pinkness. For Atlantic salmon, the texture and external color greatly varies based on the cooking method used. The internal color, however, showed a similar lightening as the internal temperature reached 63°C plus 15 seconds. It was concluded that the lightness factor of the core portion best represents the doneness of Atlantic salmon.

In the second study, the thermal inactivation of *Salmonella* sp. in Atlantic salmon and shrimp was studied. The results of this study show that a 3 log reduction occurs by the FDA Food Code's recommended 63C plus 15 seconds for intact shrimp products. However, this recommended time-temperature combination ensures only a 2 log reduction for both surface inoculated and internally inoculated salmon samples. This study also found that predictive models can effectively describe the survival data for two *Salmonella* cocktails in both homogenized Atlantic salmon and shrimp. The D and z-values were calculated for each of the cocktail-product combinations. The D-values found supported the current FDA recommendation of 68°C plus 15 seconds for a 3 log reduction in homogenized seafood products. The Weibull distribution model, which takes into account any tailing effect in survival data, fit the survival data of *Salmonella* in shrimp with the best accuracy. The Fermi distribution model, which incorporates any shouldering effect in data, fit the inactivation data for salmon most accurately.

The third study served as a follow up study to the first study which investigated the change in temperature and quality during the cooking of shrimp and Atlantic salmon. The finite difference method was used to model the heating profiles during each cooking method. Using three-dimensional slab geometry for salmon and frustum cone geometry for shrimp resulted in

accurate models of the cooking methods studied. The temperature data attained from the heating profile models were then directly used in the application of predictive quality kinetic models. Accurate first-order kinetic models were formulated for ΔL and ΔC color parameters in shrimp and salmon. The other kinetic models accurately attained were for texture change in salmon and pressed juice in both salmon and shrimp. Using a fixed inactivation level of 3 logs and a fixed quality of 95% best quality, optimal cooking conditions were determined that both provide a high quality product and assure microbial safety.

It is recommended that further studies are conducted based on the results of this project. Conclusive results were found on the quality changes and inactivation of *Salmonella* sp. during the cooking of shrimp and Atlantic salmon. Mathematical models were created that accurately predict the heating profiles and quality change of the products. However, it is necessary to understand that these results are for the specific seafood products studied. Several variables could create significantly different results than found in this study. For example, product size, product brand, cooking method, and temperature application could greatly affect the final product's quality and microbiological safety. It is recommended that these variables are looked into and that conclusions be made on how cooking guidelines vary based on the variables.

The quality change studies in this project focused on fully cooked products and undercooked products. It is recommended that further studies are conducted that look into the overcooking of the products. Further studies on the microbial inactivation in shrimp and Atlantic salmon should also be looked into. It would be beneficial to investigate individual *Salmonella* serotypes used in this study and understand the differing heat resistances of each. Another interesting subject that should be addressed is the fact that the surface and internally inoculated salmon samples had similar inactivation patterns, even though the product's surface temperature

increased at a more rapid pace than the internal temperature. Specific structural attributes may

be significantly affecting the thermal inactivation of surface-contaminated products.

APPENDICES

APPENDIX A

Table A.1 Thermal processing of *Salmonella* cocktail I (*S.* enteridits, *S.* newport, and *S.* typhimurium) in homogenized shrimp.

Temperature (°C)						60					
Heating time (sec)	0	5	10	15	20	25	30	35	40	45	50
Log cfu/g	7.03	6.09	5.86	5.56	5.25	4.86	4.52	4.40	4.10	3.63	2.61

Temperature (°C)					63						
Heating time (sec)	0	10	20	30	40						
Log cfu/g	7.19	5.92	4.8	3.94	3.35						

Temperature (°C)					68						
Heating time (sec)	0	5	10	15	20	25					
Log cfu/g	6.95	5.30	4.47	3.54	2.07	1.46					

Table A.2 Thermal processing of *Salmonella* cocktail II (*S.* Typhi, *S.* Heidelberg, and *S.* Paratyphi B) in homogenized shrimp.

Temperature (°C)	60										
Heating time (sec)	0	5	10	15	20	25	30	35	40	45	50
Log cfu/g	7.14	5.62	5.31	5.03	4.61	4.02	4.00	3.72	3.23	3.04	2.64

Temperature (°C)	63						
Heating time (sec)	0	5	10	15	20	25	30
Log cfu/g	6.95	5.70	4.73	4.30	3.30	1.60	1.00

Temperature (°C)	68				
Heating time (sec)	0	5	10	15	20
Log cfu/g	6.93	4.92	3.36	2.59	1.95

Table A.3 Thermal processing of *Salmonella* cocktail I (*S.* enteridits, *S.* newport, and *S.* typhimurium) in homogenized Atlantic salmon.

Temperature (°C)						60					
Heating time (sec)	0	30	60	90	120	150	180	210	240	270	300
Log cfu/g	7.30	6.56	5.35	5.05	3.81	3.73	2.74	1.38	0.97	1.07	0.97
Temperature (°C)						63					
Heating time (sec)	0	5	10	15	20	25	30	35	40	45	50
Log cfu/g	7.26	6.9	6.73	6.41	6.11	5.11	4.43	4.29	3.42	2.57	1.88
Temperature (°C)						65					
Heating time (sec)	0	5	10	15	20	25					
Log cfu/g	7.71	6.91	6.17	3.92	2.86	1.04					

Table A.4 Thermal processing of *Salmonella* cocktail II (*S.* Typhi, *S.* Heidelberg, and *S.* Paratyphi B) in homogenized Atlantic salmon.

Temperature (°C)	63							
Heating time (sec)	0	5	10	15	20	25	30	35
Log cfu/g	7.11	6.25	6.20	5.99	5.52	3.65	3.28	2.26
Temperature (°C)	65							
Heating time (sec)	0	5	10	15	20	25	30	
Log cfu/g	7.48	6.31	5.94	4.52	3.31	1.05	0.74	
Temperature (°C)	68							
Heating time (sec)	0	5	10	15				
Log cfu/g	7.26	5.32	3.7	1.09				

APPENDIX B

B.1 MATLAB PROGRAM

Computation of the Heating Profile in Boiled Shrimp (2-D frustum cone)

```
%% 2-D Frustum Cone Heat Transfer Model - Boiled Shrimp
%A two-dimensional frustum cone geometry was used to develop the modeling
%of heat transfer during the boiling of shrimp.  The finite difference
%method was constructed in an r-Z plane.

%The changing radius is set up to change in the loops as 'j' changes, which
%defines the position / height in the Z-direction.

clear all

%% Thermal Properties and Initial Constants

h = 10; % heat transfer coeff (W/m^2*K)
k = .3211; % thermal conductivity of block (W/m*K)
Cp = 3480; % Specific Heat capacity J/kg*K
rho = 1061; % Density kg/m^3

Tinf=100; % heat temperature (C)
Lrtop=5.5; % radius of top of frustum cone in r direction (mm) (larger r)
Lrbot=2; % radius of bottom of frustum cone in r direction (mm) (smaller r)
Lz = 60; % height of block in z direction (mm)
Totaltime=360; %total heating time in (sec)
T0=5; % initial temperature throughout block;

%% Determine spatial grid for the geometry
Nr = 5;  % number of nodes in the x-direction
Nz = 10; % number of nodes in the y-direction
dz = Lz/Nz;

%establishing changing radius for frustum cone
frust=linspace(1,Lz,Nz);
frustR=Lrbot+((Lrtop-Lrbot).*frust)./Lz;
dfrustR=frustR./Nr;

alpha=k/rho/Cp*10^6; % thermal diffusivity (m^2/sec * 10^6)
a2=alpha/(dz*dz); % simplified constants for finite difference equation
a1=alpha./(dfrustR.^2);

BiR=h.*(dfrustR)/k; %Biot numbers for r and Z directions
BiZ=h*(dz)/k;

%% Allocate storage space
N = Nr*Nz;
A = zeros(N,N);
B = zeros(N,1);
```

```
%% Central Nodes

for j = 2:Nz-1
    for i = 2:Nr-1
        n = i+(j-1)*Nr;  %used to define positioning in matrix A
        A(n,n-1) = a1(j)*(1+(1/(i*2-1)));
        A(n,n+1) = a1(j)*(1-(1/(i*2-1))); % left and right neighbors
        A(n,n) = -2*(a1(j) + a2); % self coupling
        A(n,n-Nr) = a2;
        A(n,n+Nr) = a2; % bottom and top neighbors
    end
end

%% Outer Boundaries (Excluding Corners)
% Left Boundary
i = 1;
for j = 2:Nz-1
    n = i+(j-1)*Nr;
    A(n,n+1) = (4/3)*a1(j); % right neighbor
    A(n,n) = (-4/3)*a1(j)+(-2*a2); % self coupling
    A(n,n-Nr) = a2;
    A(n,n+Nr) = a2; % bottom and top neighbors
    B(n)=0;
end

% Bottom Boundary
j = 1;
for i = 2:Nr-1
    n = i+(j-1)*Nr;
    A(n,n-1) = a1(j)*(1+(1/(i*2-1)));
    A(n,n+1) = a1(j)*(1-(1/(i*2-1))); % left and right neighbors
    A(n,n) = (-4*a2)+(-2*a1(j))+((8/3)*a2)/(1+BiZ); % self coupling
    A(n,n+Nr) = (4/3)*a2; % top neighbor
    B(n) = (8/3)*a2*((BiZ)/(1+BiZ));
end

% Right Boundary
i = Nr;
for j = 2:Nz-1
    n = i+(j-1)*Nr;
    A(n,n-1) = ((4/3)+(4/27))*a1(j);
    A(n,n) = (-2*a2)+(-4*a1(j))+((8/3)*a1(j))/(1+BiR(j))-
(4/27)*a1(j)*((1/(1+BiR(j)))); % self coupling
    A(n,n-Nr) = a2;
    A(n,n+Nr) = a2; % bottom and top neighbors
    B(n) = ((8/3)*a1(j)*1.025*((BiR(j))/(1+BiR(j)))-
(4/27)*a1(j)*((BiR(j))/(1+BiR(j)))); % left and right neighbors
end


% Top Boundary
j = Nz;
for i = 2:Nr-1
    n = i+(j-1)*Nr;
    A(n,n-1) = a1(j)*(1+(1/(i*2-1)));
    A(n,n+1) = a1(j)*(1-(1/(i*2-1))); % left and right neighbors
```

```
        A(n,n) = (-2*a1(j))+(-4*a2)+((8/3)*a2)/(1+BiZ); % self coupling
        A(n,n-Nr) = (4/3)*a2;
        B(n) = (8/3)*a2*((BiZ)/(1+BiZ)); % bottom and top neighbors
end

%% Four Corner Nodes
% Lower Left
i = 1; j = 1;
n = i+(j-1)*Nr;
A(n,n+1) = (4/3)*a1(j); % right neighbor
A(n,n) = ((-4/3)*a1(j))+(-4*a2)+((8/3)*a2)/(1+BiZ); % self coupling
A(n,n+Nr) = (4/3)*a2; % top neighbor
B(n) = ((4/3)*a2)*(BiZ/(1+BiZ));

% Upper Left
i = 1;
j = Nz;
n = i+(j-1)*Nr;
A(n,n+1) = (4/3)*a1(j); % right neighbor
A(n,n) = (-4/3*a1(j))+(-4*a2)+((8/3)*a2)/(1+BiZ); % self coupling
A(n,n-Nr) = (4/3)*a2;
B(n) = ((4/3)*a2)*(BiZ/(1+BiZ)); % bottom and top neighbors

% Lower Right
i = Nr; j = 1;
n = i+(j-1)*Nr;
A(n,n-1) = ((8/3)+(4/27))*a1(j); % left neighbor
A(n,n) = -4*(a2 +
a1(j))+((8/3)*a1(j))/(1+BiR(j))+(4/27)*a1(j)*((1/(1+BiR(j))))+((8/3)*a2)/(1+B
iZ); % self coupling
A(n,n+Nr) = (4/3)*a2; % top neighbor
B(n) = (8/3)*a1(j)*((BiR(j))/(1+BiR(j)))-
(4/27)*a1(j)*((BiR(j))/(1+BiR(j)))+((8/3)*a2)*(BiZ/(1+BiZ)); % bottom and
right neighbors

% Upper Right
i = Nr;
j = Nz;
n = i+(j-1)*Nr;
A(n,n-1) = ((4/3)+(4/27))*a1(j); % left neighbor
A(n,n) = -
4*(a1(j)+a2)+((8/3)*a1(j))/(1+BiR(j))+(4/27)*a1(j)*((1/(1+BiR(j))))+((8/3)*a2
)/(1+BiZ); % self coupling
A(n,n-Nr) = (4/3)*a2; % bottom neighbor
B(n) = (8/3)*a1(j)*((BiR(j))/(1+BiR(j)))-
(4/27)*a1(j)*((BiR(j))/(1+BiR(j)))+((8/3)*a2)*(BiZ/(1+BiZ)); % right and top
neighbors



%% Additional matrices for linear system
C = eye(50);
D = zeros(50,1);
sys=ss(A,B,C,D);
```

```
%% Calculate temperature change with time
% Time Vector, picking 1 sec arbitrarily
t=[0:1:Totaltime]';
% input is constant across the time vector
u=Tinf*ones(length(t),1);
% State initial conditions
x0=T0*ones(50,1);
% Using |LSIM| to simulate the linear system, and it plots automatically
[yy,tt,xx]=lsim(sys,u,t,x0);

%End of 2-D finite difference coding for heating profile of shrimp as a
frustum cone.
```

B.2 MATLAB PROGRAM

Computation of the Heating Profile in Pan Fried Salmon (3-D slab)

```
%% 3-D Rectanglular Slab Heat Transfer Model - Pan Fried Salmon

% The heating profile of pan fried Atlantic salmon is simulated using the
finite difference method in the x-y-z plane.  The coding simulates a slipping
process after 4-minutes by 'flipping' the slab in the y-direction.

clear all

%% Thermal Properties and Initial Constants

h = 10; % heat transfer coeff (W/m^2*K)
k = .429; % thermal conductivity of block (W/m*K)
Cp = 3620; % Specific Heat capacity J/kg*K
rho = 1124.5; % Density kg/m^3

Tpan=210; % heat temperature (C)
Lx = 55; % width of block in x direction (mm)
Ly = 15; % height of block in y direction (mm)
Lz = 90; % depth of block in z direction (mm)
Totaltime=420; %total heating time in (sec)
T0=5; % initial temperature throughout block;

%% Determine spatial grid for the geometry
Nx = 5;  % number of nodes in the x-direction
dx = Lx/Nx;
Ny = 5; % number of nodes in the y-direction
dy = Ly/Ny;
Nz = 5; % number of nodes in the z-direction
dz = Lz/Nz;

alpha=k/rho/Cp*10^6; % thermal diffusivity (m^2/sec * 10^6)
a1=alpha/(dx*dx);  % combined values to simplify matrix setup
a2=alpha/(dy*dy);
a3=alpha/(dz*dz);
BiX=h*(dx)/k;
BiY=h*(dy)/k;
BiZ=h*(dz)/k;

%% Allocate storage space
N = Nx*Ny*Nz;
A = zeros(N,N);
B = zeros(N,1);

%% Central Nodes

for p = 2:Nz-1
    for j = 2:Ny-1
        for i = 2:Nx-1
            n = i+(j-1)*Nx+(p-1)*Nx*Ny;
            A(n,n-1) = a1;
```

```matlab
            A(n,n+1) = a1; % left and right neighbors
            A(n,n) = -2*(a1 + a2 + a3); % self coupling
            A(n,n-Nx) = a2;
            A(n,n+Nx) = a2; % bottom and top neighbors
            A(n,n-25) = a3;
            A(n,n+25) = a3; % z-direction neighbors
        end
    end
end

%% Outer Boundaries (Excluding Corners/Sides)
% Left Boundary
i = 1;
for p = 2:Nz-1
    for j = 2:Ny-1
        n = i+(j-1)*Nx+(p-1)*Nx*Ny;
        A(n,n+1) = (2/3)*a1; % right neighbor
        A(n,n) = -2*((2/3)*a1 + a2 + a3); % self coupling
        A(n,n-Nx) = a2;
        A(n,n+Nx) = a2; % bottom and top neighbors
        A(n,n-25) = a3;
        A(n,n+25) = a3;
        B(n)=0;
    end
end

% Bottom Boundary
j = 1;
for p = 2:Nz-1
    for i = 2:Nx-1
        n = i+(j-1)*Nx+(p-1)*Nx*Ny;
        A(n,n-1) = a1;
        A(n,n+1) = a1; % left and right neighbors
        A(n,n) = -2*((2/3)*a2+a1+a3)+((4/3)*a2)/(1+BiY); % self coupling
        A(n,n+Nx) = (4/3)*a2; % top neighbor
        A(n,n-25) = a3;
        A(n,n+25) = a3;
        B(n) = ((4/3)*a2*(2/7)*((BiY)/(1+BiY)));%/(0.4*dy);
    end
end

% Right Boundary
i = Nx;
for p = 2:Nz-1
    for j = 2:Ny-1
        n = i+(j-1)*Nx+(p-1)*Nx*Ny;
        A(n,n-1) = (4/3)*a1;
        A(n,n) = -2*(a2 + (2/3)*a1 + a3); % self coupling
        A(n,n-Nx) = a2;
        A(n,n+Nx) = a2; % bottom and top neighbors
        A(n,n-25) = a3;
        A(n,n+25) = a3;
        B(n) =0; % left and right neighbors
    end
end
```

```matlab
% Top Boundary
j = Ny;
for p = 2:Nz-1
    for i = 2:Nx-1
        n = i+(j-1)*Nx+(p-1)*Nx*Ny;
        A(n,n-1) = a1;
        A(n,n+1) = a1; % left and right neighbors
        A(n,n) = -2*(a1+(2/3)*a2+a3); % self coupling
        A(n,n-Nx) = (4/3)*a2;
        A(n,n-25) = a3;
        A(n,n+25) = a3;
        B(n) =0; % bottom and top neighbors
    end
end

% Front Boundary
p = 1;
for j = 2:Ny-1
    for i = 2:Nx-1
        n = i+(j-1)*Nx+(p-1)*Nx*Ny;
        A(n,n-1) = a1;
        A(n,n+1) = a1;
        A(n,n) = -2*(a1+a2+(2/3)*a3);
        A(n,n-Nx) = a2;
        A(n,n+Nx) = a2;
        A(n,n+25) = (4/3)*a3;
        B(n) =0;
    end
end

% Back Boundary
p = Nz;
for j = 2:Ny-1
    for i = 2:Nx-1
        n = i+(j-1)*Nx+(p-1)*Nx*Ny;
        A(n,n-1) = a1;
        A(n,n+1) = a1;
        A(n,n) = -2*(a1+a2+(2/3)*a3);
        A(n,n-Nx) = a2;
        A(n,n+Nx) = a2;
        A(n,n-25) = (4/3)*a3;
        B(n) =0;
    end
end


%% Outer Boundaries: Sides

% z-direction sides (x and y surface contact)
% lower left
i = 1; j = 1;
for p = 2:Nz-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n+1) = (2/3)*a1; % right neighbor
    A(n,n) = -2*(a1+a2+a3)+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY); % self
coupling
```

```
    A(n,n+Nx) = (2/3)*a2; % top neighbor
    A(n,n-25) = a3;
    A(n,n+25) = a3;
    B(n) = ((4/3)*a1)*(BiX/(1+BiX))+((4/3)*a2)*(BiY/(1+BiY));
end

% lower right
i = Nx; j = 1;
for p = 2:Nz-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n-1) = (2/3)*a1; % left neighbor
    A(n,n) = -2*(a1+a2+a3)+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY); % self
coupling
    A(n,n+Nx) = (2/3)*a2; % top neighbor
    A(n,n-25) = a3;
    A(n,n+25) = a3;
    B(n) = ((4/3)*a1)*(BiX/(1+BiX))+((4/3)*a2)*(BiY/(1+BiY));
end

% upper left
i = 1; j = Ny;
for p = 2:Nz-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n+1) = (4/3)*a1; % right neighbor
    A(n,n) = -2*((2/3)*a1+(2/3)*a2+a3); % self coupling
    A(n,n-Nx) = (4/3)*a2; % bottom neighbor
    A(n,n-25) = a3;
    A(n,n+25) = a3;
    B(n) = 0;
end

% upper right
i = Nx; j = Ny;
for p = 2:Nz-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n-1) = (4/3)*a1; % left neighbor
    A(n,n) = -2*((2/3)*a1+(2/3)*a2+a3);
%+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY); % self coupling
    A(n,n-Nx) = (4/3)*a2; % bottom neighbor
    A(n,n-25) = a3;
    A(n,n+25) = a3;
    B(n) = 0;
end

%y-direction sides
% front left
i = 1; p = 1;
for j = 2:Ny-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n+1) = (4/3)*a1; % right neighbor
    A(n,n) = -2*((2/3)*a1+a2+(2/3)*a3);
%+((4/3)*a1)/(1+BiX)+((4/3)*a3)/(1+BiZ); % self coupling
    A(n,n+25) = (4/3)*a2; % z-deep neighbor
    A(n,n-Nx) = a2;
    A(n,n+Nx) = a2;
    B(n) = 0;
```

133

```
end

% front right
i = Nx; p = 1;
for j = 2:Ny-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n-1) = (4/3)*a1; % left neighbor
    A(n,n) = -2*((2/3)*a1+a2+(2/3)*a3);
%+((4/3)*a1)/(1+BiX)+((4/3)*a3)/(1+BiZ); % self coupling
    A(n,n+25) = (4/3)*a3; % z-deep neighbor
    A(n,n-Nx) = a2;
    A(n,n+Nx) = a2;
    B(n) = 0;
end

% back left
i = 1; p = Nz;
for j = 2:Ny-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n+1) = (4/3)*a1; % right neighbor
    A(n,n) = -2*((2/3)*a1+a2+(2/3)*a3);
%+((4/3)*a1)/(1+BiX)+((4/3)*a3)/(1+BiZ); % self coupling
    A(n,n-25) = (4/3)*a3; % z-in neighbor
    A(n,n-Nx) = a2;
    A(n,n+Nx) = a2;
    B(n) = 0;
end

% back right
i = Nx; p = Nz;
for j = 2:Ny-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n-1) = (4/3)*a1; % left neighbor
    A(n,n) = -2*((2/3)*a1+a2+(2/3)*a3);
%+((4/3)*a1)/(1+BiX)+((4/3)*a3)/(1+BiZ); % self coupling
    A(n,n-25) = (4/3)*a3; % z-in neighbor
    A(n,n-Nx) = a2;
    A(n,n+Nx) = a2;
    B(n) = 0;
end

%x-direction sides
% front bottom
j = 1; p = 1;
for i = 2:Nx-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n+Nx) = (2/3)*a2; % top neighbor
    A(n,n) = -2*(a1+a2+(2/3)*a3)+((4/3)*a2)/(1+BiY); %+((4/3)*a3)/(1+BiZ); %
self coupling
    A(n,n+25) = (4/3)*a3; % z-deep neighbor
    A(n,n-1) = a1;
    A(n,n+1) = a1;
    B(n) = ((4/3)*a2)*(BiY/(1+BiY));
end

% front top
```

```
j = Ny; p = 1;
for i = 2:Nx-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n-Nx) = (4/3)*a2; % bottom neighbor
    A(n,n) = -2*(a1+(2/3)*a2+(2/3)*a3); %+((4/3)*a2)/(1+BiY);
%+((4/3)*a3)/(1+BiZ); % self coupling
    A(n,n+25) = (4/3)*a3; % z-deep neighbor
    A(n,n-1) = a1;
    A(n,n+1) = a1;
    B(n) = 0;
end

% back bottom
j = 1; p = Nz;
for i = 2:Nx-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n+Nx) = (2/3)*a2; % top neighbor
    A(n,n) = -2*(a1+a2+(2/3)*a3)+((4/3)*a2)/(1+BiY); %+((4/3)*a3)/(1+BiZ); %
self coupling
    A(n,n-25) = (4/3)*a3; % z-in neighbor
    A(n,n-1) = a1;
    A(n,n+1) = a1;
    B(n) = ((4/3)*a2)*(BiY/(1+BiY));
end

% back top
j = Ny; p = Nz;
for i = 2:Nx-1
    n = i+(j-1)*Nx+(p-1)*Nx*Ny;
    A(n,n-Nx) = (4/3)*a2; % bottom neighbor
    A(n,n) = -2*(a1+(2/3)*a2+(2/3)*a3);
%+((4/3)*a1)/(1+BiX)+((4/3)*a3)/(1+BiZ); % self coupling
    A(n,n-25) = (4/3)*a3; % z-in neighbor
    A(n,n-1) = a1;
    A(n,n+1) = a1;
    B(n) = 0;
end

%% 8 Corner Nodes
% Lower Front Left
i=1; j=1; p=1;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n+1) = (2/3)*a1; % right neighbor
A(n,n+Nx) = (2/3)*a2; % top neighbor
A(n,n+25) = (2/3)*a3; % deep neighbor
A(n,n) = -
2*(a1+a2+a3)+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ);
B(n) =
((4/3)*a1)*(BiX/(1+BiX))+((4/3)*a2)*(BiY/(1+BiY))+((4/3)*a3)*(BiZ/(1+BiZ));

% Lower Front Right
i=Nx; j=1; p=1;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n-1) = (2/3)*a1; % left neighbor
A(n,n+Nx) = (2/3)*a2; % top neighbor
A(n,n+25) = (2/3)*a3; % deep neighbor
```

135

```
A(n,n) = -
2*(a1+a2+a3)+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ);
B(n) =
((4/3)*a1)*(BiX/(1+BiX))+((4/3)*a2)*(BiY/(1+BiY))+((4/3)*a3)*(BiZ/(1+BiZ));


% Upper Front Left
i=1; j=Ny; p=1;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n+1) = (4/3)*a1; % right neighbor
A(n,n-Nx) = (4/3)*a2; % bottom neighbor
A(n,n+25) = (4/3)*a3; % deep neighbor
A(n,n) = -
2*(2/3)*(a1+a2+a3);%+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ)
;
B(n) = 0;


% Upper Front Right
i=Nx; j=Ny; p=1;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n-1) = (4/3)*a1; % left neighbor
A(n,n-Nx) = (4/3)*a2; % bottom neighbor
A(n,n+25) = (4/3)*a3; % deep neighbor
A(n,n) = -
2*(2/3)*(a1+a2+a3);%+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ)
;
B(n) = 0;


% Lower Back Left
i=1; j=1; p=Nz;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n+1) = (2/3)*a1; % right neighbor
A(n,n+Nx) = (2/3)*a2; % top neighbor
A(n,n-25) = (2/3)*a3; % inner neighbor
A(n,n) = -
2*(a1+a2+a3)+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ);
B(n) =
((4/3)*a1)*(BiX/(1+BiX))+((4/3)*a2)*(BiY/(1+BiY))+((4/3)*a3)*(BiZ/(1+BiZ));


% Lower Back Right
i=Nx; j=1; p=Nz;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n-1) = (2/3)*a1; % left neighbor
A(n,n+Nx) = (2/3)*a2; % top neighbor
A(n,n-25) = (2/3)*a3; % inner neighbor
A(n,n) = -
2*(a1+a2+a3)+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ);
B(n) =
((4/3)*a1)*(BiX/(1+BiX))+((4/3)*a2)*(BiY/(1+BiY))+((4/3)*a3)*(BiZ/(1+BiZ));


% Upper Back Left
i=1; j=Ny; p=Nz;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n+1) = (4/3)*a1; % right neighbor
A(n,n-Nx) = (4/3)*a2; % bottom neighbor
A(n,n-25) = (4/3)*a3; % inner neighbor
```

```matlab
A(n,n) = -
2*(2/3)*(a1+a2+a3);%+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ)
;
B(n) = 0;

% Upper Back Right
i=Nx; j=Ny; p=Nz;
n = i+(j-1)*Nx+(p-1)*Nx*Ny;
A(n,n-1) = (4/3)*a1; % left neighbor
A(n,n-Nx) = (4/3)*a2; % bottom neighbor
A(n,n-25) = (4/3)*a3; % inner neighbor
A(n,n) = -
2*(2/3)*(a1+a2+a3);%+((4/3)*a1)/(1+BiX)+((4/3)*a2)/(1+BiY)+((4/3)*a3)/(1+BiZ)
;
B(n) = 0;




%% Additional matrices for linear system
C = eye(125);
D = zeros(125,1);
sys=ss(A,B,C,D);

%% Calculate temperature change with time
% Time Vector, picking 1 sec arbitrarily
t=[0:1:240]';
% input is constant across the time vector
u=Tpan*ones(length(t),1);
% State initial conditions
x0=T0*ones(125,1);

% Using |LSIM| to simulate the linear system, and it plots automatically
[yy,tt,xx]=lsim(sys,u,t,x0);

%% Flipping!
%flipping the fillet upside-down by simply flipping the current temperature
%profile in the y direction
C2=eye(125);
D2=zeros(125,1);
sys2=ss(A,B,C2,D2);
t2=[0:1:179]';
u2=Tpan*ones(length(t2),1);
x02=[yy(240,21) yy(240,22) yy(240,23) yy(240,24) yy(240,25) yy(240,16)
yy(240,17) yy(240,18) yy(240,19) yy(240,20)...
    yy(240,11) yy(240,12) yy(240,13) yy(240,14) yy(240,15) yy(240,6)
yy(240,7) yy(240,8) yy(240,9) yy(240,10)...
    yy(240,1) yy(240,2) yy(240,3) yy(240,4) yy(240,5) yy(240,46) yy(240,47)
yy(240,48) yy(240,49) yy(240,50)...
    yy(240,41) yy(240,42) yy(240,43) yy(240,44) yy(240,45) yy(240,36)
yy(240,37) yy(240,38) yy(240,39) yy(240,40)...
    yy(240,31) yy(240,32) yy(240,33) yy(240,34) yy(240,35) yy(240,26)
yy(240,27) yy(240,28) yy(240,29) yy(240,30)...
    yy(240,71) yy(240,72) yy(240,73) yy(240,74) yy(240,75) yy(240,66)
yy(240,67) yy(240,68) yy(240,69) yy(240,70)...
```

```
    yy(240,61) yy(240,62) yy(240,63) yy(240,64) yy(240,65) yy(240,56)
yy(240,57) yy(240,58) yy(240,59) yy(240,60)...
    yy(240,51) yy(240,52) yy(240,53) yy(240,54) yy(240,55) yy(240,96)
yy(240,97) yy(240,98) yy(240,99) yy(240,100)...
    yy(240,91) yy(240,92) yy(240,93) yy(240,94) yy(240,95) yy(240,86)
yy(240,87) yy(240,88) yy(240,89) yy(240,90)...
    yy(240,81) yy(240,82) yy(240,83) yy(240,84) yy(240,85) yy(240,76)
yy(240,77) yy(240,78) yy(240,79) yy(240,80)...
    yy(240,121) yy(240,122) yy(240,123) yy(240,124) yy(240,125) yy(240,116)
yy(240,117) yy(240,118) yy(240,119) yy(240,120)...
    yy(240,111) yy(240,112) yy(240,113) yy(240,114) yy(240,115) yy(240,106)
yy(240,107) yy(240,108) yy(240,109) yy(240,110)...
    yy(240,101) yy(240,102) yy(240,103) yy(240,104) yy(240,105)];


[yy2,tt2,xx2]=lsim(sys2,u2,t2,x02); % Finishes the cooking process after
flipping

%End of 3-D finite difference coding for heating profile of Atlantic salmon
slab
```