Effect of Thermal Treatment on Moisture Transport during Steam Cooking of Skipjack Tuna (Katsuwonas pelamis)

J.W. Bell, B.E. Farkas, S.A. Hale, and T.C. Lanier

ABSTRACT: Moisture and mass loss were determined during atmospheric steam cooking of skipjack tuna by measurement of muscle moisture content in whole fish and on-line measurement of mass and temperature in fillets. Thermal denaturation temperatures of muscle proteins were measured by differential scanning calorimetry. Muscle moisture content and mass loss were dependent on muscle temperature. Temperature distribution was predicted and mass loss rates were calculated in fillets. A decreasing rate of mass loss was followed by a steady rate period and a resumption of a decreasing rate period. The increased loss of mass during the steady period corresponded to thermal denaturation temperatures of muscle proteins. Changes in mass loss rates resulted from a gradient of muscle changes produced by the temperature gradient created during cooking.

Key Words: thermal, transport, cooking, skipjack, tuna

Introduction

In 1998 the U.S. canned tuna processing industry produced 26.4 million standard cases, or over 1.2 billion cans, of light meat tuna from 242,000 tons of fish, accounting for over a half-billion dollars (NMFS 1999). In response to economic and environmental pressure, the predominant tuna species for production of light meat tuna has shifted from the larger yellowfin to smaller skipjack. The majority of tuna canned in the United States is produced by a traditional, labor-intensive process. After receipt and storage of frozen tuna at the cannery, the fish are thawed, butchered, atmospheric steam cooked, and cooled. During the subsequent cleaning process, fish components of light meat, red meat, skin, and scales are manually separated. Cans are filled with the cooked light meat, plus vegetable broth and oil or water, then seamed, retorted, and labeled. This process must accommodate the variability of a wild-caught raw product, including differences in availability, species, fish size, and maturity. Harvest conditions, post-harvest handling, and physical condition have been shown to affect raw and frozen tuna quality (Crawford and others 1970; Burns 1985; Price and others 1991, 1992; Watson and others 1992).

Control of the unit operation of atmospheric steam cooking is critically important to producing cooked muscle for canning. Thermal changes and moisture loss that occur during this process step significantly impact final canned yields and quality. Historically, industry and academic research has focused on physiology and quality studies of yellowfin tuna (Brown and others 1967; Hatae and others 1984, 1990; Kanoh and others 1988; Watson and others 1992), with little fundamental research reported on the thermal processing of skipjack tuna (Crawford and others 1970).

The most drastic changes in meat during heating are caused by changes in the muscle proteins (Hamm 1977). Water loss during cooking results from changes to both myofibrillar and collagen muscle proteins (Offer and others 1988; Foegeding and others 1996). Thermal denaturation temperatures of muscle proteins for mammals and fish can be obtained by differential scanning calorimetry (DSC) (Wright and others 1977; Kijowski and Mast 1988; Park and Lanier 1989), while microscopy has been used to observe structural changes of heated fish proteins (Lampila and Brown 1986; Ofstad and others 1993).

Characterizing the effects of thermal treatment on muscle and understanding the dynamics of moisture loss during cooking is important for process control and improvement of final product yield and quality in meat processing industries. Mass and heat transfer studies have been conducted to investigate water loss rates and temperature changes during dry oven roasting of beef muscle. This research resulted in an improved understanding of the relationships between the physical mechanisms and biochemical changes that occur during industrial cooking of beef (Bengtsson and others 1976; Godsalve and others 1977a). The loss of moisture and mass from edible portions of the tuna muscle during atmospheric steam cooking is an important effect of the tuna cannery process. This edible, light meat used for canning is the white muscle primarily located in the tuna loins. This loin meat can also be removed from raw skipjack as fillets. The objective of this work was to investigate the effects of thermal protein denaturation and moisture loss in skipjack tuna loin muscle during steam cooking of fillets and whole fish.

Materials and Methods

Frozen cannery grade skipjack tuna, 3.0 kg to 4.5 kg in mass, were captured by purse seine vessels and frozen in brine in the Western Tropical Pacific using the common commercial practices. These fish were shipped from the cannery frozen storage overnight to North Carolina State Univ., Dept. of Food Science, and were stored at −30 °C until sampling.

Moisture content

Six skipjack were thawed in still ambient temperature water to a backbone temperature of 0 °C. Individual whole skipjack tuna were placed in a wire basket and suspended through the lid of an unseamed vertical pilot plant retort. Cook temperature of the fish was monitored during steam cooking...
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Moisture transport during cooking of tuna was measured using a thermocouple wire inserted into the dorsal loin muscle adjacent to the fish backbone ("backbone temperature"). This wire was attached to a digital thermometer (Model HH21, Omega Engineering Inc., Stamford, Conn., U.S.A.). Four pairs of muscle samples were removed during steam cooking for moisture content (MC) determination for each fish. Removal sites for all samples were located along both dorsal loins (Figure 1). Selection of a particular location was randomly determined for each sampling time. Muscle core samples were removed by means of a serrated cork borer. Each 3-cm dia core sample contained only white loin muscle, excluding red muscle, skin, and backbone. After removal, each sample was packed in a polyethylene bag and stored in ice until MC analysis.

A pair of muscle samples was removed from each thawed fish prior to cooking. The fish was then placed in the basket, suspended through the closed retort lid, and steam was introduced. Upon reaching a fish backbone temperature of 49°C, the steam was turned off, and the fish was removed from the retort. A core sample from 1 of the 3 remaining sample locations on each dorsal loin was removed and stored. The fish and basket were returned to the retort, and steam cooking continued until reaching a backbone temperature of 65°C. The muscle sample removal procedure was then repeated. After return to the retort and continued cooking, muscle was removed from the final sample location of each dorsal loin at a backbone temperature of 82°C. Each sampling produced muscle cores for that temperature and location from both dorsal loins.

Each chilled muscle core was then bisected with a scalpel to produce sub-samples of muscle from the interior near the backbone and exterior near the surface or skin. Each sample was then finely minced before determining moisture content using AOAC air-drying method 950.46B (AOAC 1995).

Fillet mass

Four fish were thawed as described in the previous section. Each fish was cut to produce 2 fillets. Mass and dimension were recorded for each fillet before cooking. The fillets ranged from 820 g to 1,030 g in mass, 9.5 cm to 11.3 cm in length, and 3.8 cm to 4.4 cm in maximum thickness.

An individual skipjack fillet was placed in a wire basket and suspended through the closed lid of an unsealed retort. The basket was attached by chain to an aluminum platform scale. The scale included 4 load cells (Tedea-Huntleigh, Canoga Park, Calif., U.S.A.), and the platform was positioned over the center hole of the closed retort lid during atmospheric steam cooking (Figure 2). Sheet metal shields were attached to the platform, and a fan was used to sweep away steam from the load cells to prevent moisture interference to the scale electronics.

Results and Discussion

Moisture content in whole fish

The percent moisture content, wet basis, of skipjack tuna muscle during steam cooking was determined at 2 depths of...
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the dorsal loin tissue (Figure 3). Measuring loin muscle temperatures at the fish backbone monitored the extent of cooking. Initial moisture levels for thawed, uncooked tuna were similar to those reported for skipjack caught in warm waters (George 1975; Balogun and Talabi 1986). The lower MC measured in raw loin muscle near the skin was likely caused by surface dehydration from commercial brine freezing and dry frozen storage practices. The difference in MC between the interior and surface raw muscle samples decreased during cooking, and approached zero at extended cook time and temperature.

The reduction of the difference in MC between muscle samples at the 2 depths during cooking resulted from the sharper decline in MC of the interior muscle, notably after the 48 °C backbone temperature samples. Muscle near the surface reached higher temperatures much more rapidly than the internal muscle. Moisture content reduction produced by heating occurs in the surface muscle before the interior muscle. Above 48 °C backbone temperature, the rate of MC decrease was greater in the interior than the muscle near the surface.

Heat transfer in fillets

During steam cooking of fillets, ambient temperatures quickly rose as the retort filled with steam, remaining near 100 °C throughout the remaining cook period (Figure 4). Due to the very high heat transfer capacity of condensing steam, the surface temperature of the muscle fillet rapidly reached the ambient temperature (data not shown), while the temperature increase at the center depends primarily on the dimension of the food product and its thermal diffusivity (Dagerskog 1977).

While Dagerskog reported values for convective heat transfer coefficient (h) to range from 1,500 to 10,000 W/m² °C for saturated steam, research on steam blanching of carrots and steam cooking of surimi gels reported “h” values to be near or below the low end of this range as a result of gas film or gel formation (Ling and others 1974; Su and others 1999). Zhang and others (2001) reported thermal conductivity (k) values of 0.57 W/m °C for skipjack. These thermal properties and the thickness of the muscle fillets (about 4 cm) produced a Biot number (N_Bi = hD/k) that is greater than 40. Thus, this system of steam cooking tuna results in negligible surface resistance to heat transfer and produces surface temperatures similar to the ambient steam temperatures (Singh and Heldman 1993). The similarity of surface and ambient temperatures was verified by measurement of ambient and sub-skin temperatures during ancillary studies of steam cooking eviscerated tuna. The fillet center temperature data (Figure 4) indicates that a temperature gradient was quickly produced between the fillet surface and center, and then decreased during cooking as the center temperature increased. This gradient may be mathematically modeled by using the 1-dimensional Fourier equation (Geankoplis 1993):

\[ \rho C_p \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} \right) \]  

(1)

The thermal diffusivity (\( \alpha \)) incorporates the physical and thermal properties of skipjack tuna muscle and was assumed to remain constant for this study:

\[ \alpha = \frac{k}{\rho C_p} \]  

(2)

where (Zhang and others 2001):

- \( k = 0.57 \) W/m °C
- \( \rho = 1100 \) kg/m³
- \( C_p = 3500 \) J/kg °C

Defining \( x = 0 \) at the loin center, and \( x = L \) at either edge, and assuming symmetry of the slab:

\[ IC: T = T_o \text{ at } 0 \leq x \leq L \quad t = 0 \]  

(3)

\[ BC1: \frac{\partial T}{\partial x} = 0 \text{ at } x = 0 \quad t > 0 \]  

(4)

\[ BC2: T = T_o \text{ at } x = L \quad t > 0 \]  

(5)

Using Equations 2 through 5 for solution of Equation 1 yields (Geankoplis 1993):

\[ \frac{T - T_o}{T_e - T_o} = \frac{1}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n+1} \frac{\sin \left[ (2n+1) \pi x / 2L \right]}{(2n+1) \pi x / 2L} \]  

(6)
Equation 6 can be used to determine the approximate temperature $T$ at any position $x$ and time $t$, and thus temperature distribution, for a skipjack muscle loin of known thickness and thermal diffusivity. Center temperatures for a skipjack loin of 4-cm thickness during 42 min of steam cooking at atmospheric pressure are calculated using Equations 2 and 6 with conditions of Equations 3 through 5 (Figure 5). The center temperature data for fillets of similar thickness indicate heating curves similar to that for the calculated temperatures and validates the 1-dimensional Fourier equation for determining temperature distribution through the fillet thickness. Higher center temperatures for the calculated curve than the actual fillets at given times result from the 2nd boundary condition, which assumes an initial ambient temperature of 100 °C. Retort temperature data recorded during steam cooking (Figure 5) indicate that an initial period of 5 min was required to reach ambient temperatures near 100 °C. This heating delay during steam cooking of the fillets explains the lower center temperatures for the actual data.

Mass loss and thermal denaturation

Turbulence inherent in the steam cooking and weighing system resulted in scatter in the mass data (Figure 4). A spline function (SAS 1989) was developed (smval = 45; 200 data points) to eliminate inherent system variability due to turbulence in steam cooking. This statistical smoothing procedure was used to generate the spline fit curve that represents the raw mass data (Figure 4). The initial increase in fillet mass shown resulted from moisture condensing on the fillet and basket and chain apparatus. This increase was followed by a rapid decrease in mass due to streaming off of the condensate as surface temperatures reached ambient steam temperatures.

As expected, mass was lost from the muscle fillet during heating. Rates of change in mass over time were calculated to increase understanding of the effects of cooking temperature on muscle changes. This rate of mass loss from the fillets is shown with fillet center temperature (Figure 6). This curve is the negative derivative of the mass and time data, or $-\Delta M/\Delta t$, as calculated from the spline function derived data, and reflects the rate of mass loss.

The maxima and minima of this curve indicate changes in the rate in which mass was lost from the muscle fillet. Investigations of beef muscle during dry oven cooking showed that changes in moisture loss rates resulted from boiling fronts and evaporation. Loss of moisture also resulted from thermal denaturation of muscle proteins, which produced a mechanical force to effect transport of moisture to the muscle surface (Bengtsson and others 1976; Godsalve and others 1977a, b). The process of steam cooking of tuna occurs in a saturated moisture environment. These conditions do not provide temperatures above boiling nor produce a moisture gradient at the fillet surface to cause the evaporation that occurs in a dry cooking system. Thus, the use of saturated steam creates a cooking system where thermal denaturation of muscle proteins is the primary mechanism in moisture loss.

Differential scanning calorimetry was utilized to investigate thermal denaturation temperatures of tuna loin muscle proteins. A DSC plot shows 3 peaks and indicates the denaturation of 3 muscle proteins as thermal events (Figure 7). The 1st thermal event occurs over a range of temperatures from 40 °C to 55 °C, the 2nd from 55 °C to 64 °C, and the 3rd from 64 °C to 71 °C. The 1st peak corresponds to myosin denaturation and is similar to thermal denaturation temperature ranges for beef and fish muscle (Martens and others 1977a, b). The process of steam cooking of tuna occurs in a saturated moisture environment. These conditions do not provide temperatures above boiling nor produce a moisture gradient at the fillet surface to cause the evaporation that occurs in a dry cooking system. Thus, the use of saturated steam creates a cooking system where thermal denaturation of muscle proteins is the primary mechanism in moisture loss.

The 2nd peak corresponds to collagen, with $T_{\text{max}}$ at 59 °C. Although lower denaturation and shrinkage temperatures have been associated with fish collagens (Sikorski and others 1984; Ofstad and others 1993), the environmental habitat temperature of the species has been found to strongly affect collagen thermal stability in fish (Foegeding and others 1996). A thermal study of yellowfin tuna muscle found collagen to denature and melt during heating to 60 °C (Kanoh and others 1988). Samples of collagen-containing tendon and skin from skipjack were also heated by DSC and showed thermal event peaks near 60 °C (data not shown). The 3rd peak corresponds to actin, with a $T_{\text{max}}$ at 68 °C. Thermal analysis studies of muscle proteins of fish, beef, rabbit, and chicken all show actin to have the higher thermal denaturation temperatures for...
Muscle proteins (Wright and others 1977; Martens and others 1982; Park and Lamer 1988; Kijowski and Mast 1988).

Collagen is a long, cylindrical protein arranged in fibrils that thermally shrink to less than 1/3rd of their original length. Myosin is an elongated protein molecule chain contained in the myofibrils in muscle fibers (Foegeding and others 1996). During heating, both of these structural muscle proteins decrease in dimension upon reaching their thermal denaturation temperatures and cause shrinkage of the muscle fibrils and tissue. This shortening is associated with many biochemical and physical changes in cooked meat, including moisture loss and mechanical properties (Bouton and others 1974; Hamm 1977; Offer and Knight 1988). These changes in protein structure generate mechanical forces, or pressure gradients, in the muscle that result in moisture movement through the tissue (Godsalve and others 1977a).

Thermal response of the muscle proteins to increased temperature is fundamental to the mass loss dynamics taking place in the tuna loin fillets during steam cooking. The average rate of mass loss (\( \frac{\partial M}{\partial t} \)) for 8 steam cooked skipjack tuna fillets was calculated and shown versus center temperature (Figure 8). The vertical lines show 95% confidence intervals for the mean data. This curve does not include the initial mass gain due to condensation and shows the initial increasing rate of mass loss due to the streaming off of condensate. A component of this initial increasing rate of mass loss was also due to denaturation of proteins in the surface muscle. Moisture forced out of the muscle at and near the surface was quickly lost from the fillet.

A decline in the mass loss rate occurred as cooking continued (Figure 8). This falling rate period exhibits a steady declining rate of loss until the fillet center temperature approached 40°C. The decline in rate slowed, and the curve flattened, as the center temperature increased to 47°C. This period of reduced decline in rate of mass loss, or an increasing rate of mass loss, provides insight into the effects of increased temperature on the protein structure and moisture transport in the tuna muscle. This period occurred when the fillet center reached the temperature range of myosin denaturation changes (Figure 7). Previous studies for beef and fish muscle have associated greatest mass loss at myosin denaturation temperatures and myofibril shrinkage (Hamm 1977; Ofstad and others 1993). This denaturation results in shrinkage of the muscle cell myofibrils (Offer and others 1988). As the center of the fillet reached myosin shrinkage and denaturation temperatures, this region also began to reach the range of collagen denaturation temperatures. Thermal denaturation of the collagen protein in the endomysial sheaths generates tension and lateral shrinkage on the muscle cells (Bailey 1988; Offer and others 1983). This tension produces a mechanical force within the muscle tissue, allowing the transport of the moisture from the muscle interior towards the surface.

After the sustained period of increased mass loss, or slowing of the decline rate of mass loss between fillet center temperatures of 37°C and 47°C, the rate of mass loss entered a 2nd falling rate period and continued to decrease until the end of the cook period (Figure 8). These temperature effects on changes in the mass loss rate data can be better understood by the heat transfer dynamics in the fillet (Figure 9). These curves show temperature distribution across a 4-cm thick fillet determined by the 1-dimensional model expressed by Equations 1 to 6 at different lengths of steam cooking. After cooking for 13 min, the center temperature of the fillet reaches 40°C, and the center half of the muscle thickness (from 0.01 m to 0.03 m) is between 40°C and 57°C. The denaturation of myosin and shrinkage of the myofibrillar network occur at this time in this large section of the muscle, and the association of moisture, or water holding ability, of the myofibrils is greatly decreased. Denaturation and shrinkage of the collagen also begins during the latter range of the myosin thermal denaturation.

The mechanical force produced by contraction of myofibrils and structural proteins in the muscle tissue was responsible for the increased moisture transport and slowing rate of decline of mass loss during this period (Figure 8). The conclusion of the leveling rate period at a fillet center temperature of 47°C was followed by the return of declining mass loss. This center temperature was reached after cooking the fillet for approximately 15 min (Figure 9). At this time, only the central 1/3rd of the muscle thickness was below the \( T_{\text{max}} \) for myosin (52°C), and less than half of the fillet had not yet reached the \( T_{\text{max}} \) of collagen (59°C). This decreasing level of protein denaturation reduced the applied mechanical...
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force, resulting pressure gradient, and moisture transport to the fillet surface. Increasing internal muscle temperatures and expansion of the external, previously-denatured region of muscle resulted in the decreasing rate of mass loss.

Changes in mass transfer properties in the near-surface region also affected mass loss rates. Increased resistance to moisture flow resulted in muscle cooked above thermal denaturation temperatures of these muscle proteins. Thermal changes to non-structural muscle proteins and the continued shrinkage of myosin in heated muscle can also affect transport properties. Previous microstructure studies using scanning electron microscopy on thermally processed skipjack muscle showed that aggregations of denatured sarcoplasmic proteins and collagen were formed in the interstices between the shrunken muscle fibers and the endomysium at 60 °C (Figure 10) (Lampila and Brown 1986). These authors also noted increased muscle fiber shrinkage and aggregate formation after higher temperature treatment during canning.

Additional studies on yellowfin tuna (Hatae and others 1984, 1990; Kanoh and others 1988) indicated that final drip loss was affected by amount of muscle fiber shrinkage and coagulated sarcoplasmic proteins in interstitial spaces. Kanoh and others (1988) also reported increased fiber shrinkage and disruption of other muscle proteins when yellowfin tuna muscle was cooked to 100 °C. These aggregated and coagulated muscle protein components deposited between shrunken muscle fibers create physical barriers to moisture flow and liquid transport, and can be described as increased tortuosity in the muscle structure. Tortuosity increases the resistance to moisture flow in the exterior muscle region. This increased resistance to flow will affect the rate of moisture lost at the surface, as less water is available from the reduced amount of the central muscle undergoing denaturation. These heat and mass transfer dynamics also help explain the higher moisture content of the less denatured interior muscle region found for the cooked whole fish surrounded by the denatured muscle with higher resistance to transport during the cooking process.

Conclusion

Moisture or cook loss during steam cooking of skipjack tuna is a critical factor in process performance and final product quality in the canned tuna industry. Understanding the dynamics of mass loss during steam cooking of tuna muscle is important to the control and improvement of canned tuna production. Controlling moisture responses during the subsequent canning and retorting processes of the cooked tuna muscle can be improved by increased understanding of the thermal effects on the tuna muscle proteins. Surface evaporation and moisture gradient diffusion are not involved in moisture transport and loss from tuna muscle during steam cooking utilized by the canned tuna industry. The thermal gradient produced by steam cooking affected thermal changes in muscle proteins and the dynamics of increasing transport force and resistance in different regions of the muscle tissue.

Moisture transport through and out of the tuna muscle resulted primarily from the denaturation of muscle proteins and the mechanical force produced by these changes. The resulting pressure gradient in the muscle tissue increased as the amount of muscle mass undergoing denaturation of myosin and collagen increased. The temperature gradient resulted in a gradient of protein denaturation and produced a pressure gradient through the muscle. As increasing temperature moved from the surface to the interior of the muscle, the non-denatured region grew smaller in the muscle center, and the moisture transport distance to the muscle surface increased. Changes in other muscle proteins in the higher temperature surface region increased the tortuosity of this muscle, resulting in an increased moisture transport path and resistance to flow.

Thermal changes to muscle protein structures and their ability to transport and retain water could provide opportunities for balancing cooking losses with texture qualities important to further processing and cleaning of cooked tuna loins. Industrial skipjack tuna cooking can be controlled to produce cooked muscle with optimal muscle moisture content for further cleaning and fill compliance. Cooking schedules can be based on protein thermal denaturation temperatures and moisture transport properties. These effects on moisture transport in the skipjack muscle affect cook loss and the yield and quality of the final canned tuna product.

Nomenclature and Units

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>Cp</td>
<td>Specific heat</td>
<td>J/kg °C</td>
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<tr>
<td>D</td>
<td>Fillet characteristic dimension</td>
<td>m</td>
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<tr>
<td>h</td>
<td>Convective heat transfer coefficient</td>
<td>W/m² °C</td>
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\[ k \] thermal conductivity 
\[ L \] fillet half-thickness 
\[ M \] mass 
\[ N_{Bi} \] Riots number 
\[ t \] time 
\[ T \] temperature 
\[ T_i \] initial fillet temperature 
\[ T_{amb} \] ambient temperature 
\[ x \] position across fillet thickness 
\[ \alpha \] thermal diffusivity 
\[ \rho \] density 

W/m°C 
m 
kg 
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°C 
°C 
m 
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kg/m³

References


This research was funded by StarKist Seafood Inc. and the U.S. Dept of Agriculture National Needs Fellowship Grant 495-38420-2141. The authors also wish to thank Heather Stewart, Penny Amato, Elizabeth Webb, and Janet Zhang for data assistance and Dr. Francis Giesbrecht for statistical support.

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