AN ABSTRACT OF THE THESIS OF

Ainong (Ellen) Su for the degree of Master of Science in Bioresource Engineering presented on June 27, 1996. Title: Comparative Methods of Determining Heat Transfer Coefficients over Moist Food Materials.

Redacted for privacy

Abstract approved: ___

Edward R. Kolbe

Production of surimi represents a potential utilization of a number of low-valued fish species, one of which, Pacific whiting, represents the largest biomass off the West Coast of the United States. However, a protease enzyme softens the fish flesh in Pacific whiting and limits the expansion of surimi production.

Many studies have demonstrated the importance of time and temperature in minimizing the texture softening. An optimal design of the surimi seafood process is possible only when an accurate prediction of the time-varying temperature distribution throughout the surimi product can be obtained. This provides a measure of the heating rate and the extent of thermal processing. Such a prediction necessitates a study of the surface heat transfer coefficient which is one of the most important parameters for the heat transfer analysis.

Associated with automated-machinery processing of surimi seafoods, a full understanding of the heat transfer coefficient (h) is especially important because high-quality surimi products using Pacific whiting only can be obtained through rapid and

controlled heating. This study was intended to determine transient surface heat transfer coefficients in a steam heating environment, simulating the widely-used steam heating of thin-sheet surimi paste in the seafood industry.

In determining the heat transfer coefficient, many different methods have been used including the inverse calculation method, the lumped mass method and the heat flux method. This study employed all three to measure and model the heat transfer coefficient (h) under similar steam conditions. A comparative evaluation was made to define the best method and model for the h determination. The inverse calculation method produced an h model which, when applied to a heat transfer analysis, provided the best agreement between predicted and experimental temperature profiles at three locations in surimi paste during a 1000-sec cooking period. The lumped mass method overestimated the heat transfer coefficients to food; the heat flux method gave inconsistent measurements.

It is a classic inverse problem to estimate surface heat transfer coefficients from temperature measurements inside a product, a procedure which involves solution of the inverse heat conduction problem and parameter optimization. A whole domain function specification procedure was developed for the inverse calculation method. This procedure simulates heat transfer coefficients as specified functions by estimating all the unknown parameters in the functions over the total time interval. A nonlinear regression computer program was written for the inverse calculation of surface heat transfer coefficients, incorporating the implict Crank-Nicolson scheme for the finite-difference formulation of the one-dimensional heat conduction problem and the downhill simplex method for parameter optimization. This inverse calculation method provided relatively accurate models of the surface heat transfer coefficient.

Comparative Methods of Determining Heat Transfer Coefficients
over Moist Food Materials

by

Ainong (Ellen) Su

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 27, 1996
Commencement June 1997

Master of Science thesis of Ainong (Ellen) Su presented on June 27, 1996

APPROVED:

Redacted for privacy

Major Professor, representing Bioresource Engineering

Redacted for privacy

Chair of Department of Bioresource Engineering

Redacted for privacy

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University Libraries. My signature below authorizes release of my thesis to any reader upon request.

Redacted for privacy

Ainong (Ellen) Su, Author

ACKNOWLEDGMENTS

This thesis could never be completed successfully without the input and support of many individuals whom I am sincerely indebted to. Now, I would like to take this opportunity to show my gratefulness to them.

I would like to express my sincere gratitude to my major professor, Dr. Edward Kolbe for your years of guidance, patience and support throughout this graduate study.

I would like to thank my minor professor, Dr. Jae Park for his concern of this research, assistance in constructing the testing equipment, and supply of surimi samples.

I would like to thank my committee members, Dr. Ajoy Velayudhan and Dr. Solomon Yim for their assistance.

I am grateful to Ken Stewart, Robert Schnekenburger and John Guida for their help in setting-up the testing equipment.

My gratitude is extended to my husband, my sister and my brother-in-law for their human support so vitally necessary for me to complete this thesis.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

NOMENCLATURE

A_s	Surface area, m^2
b	Thickness of composite surimi and stainless steel slab, m
Bi	Biot number (= hL/k)
c_i	Constant
C_p	Specific heat, J/kg °C
D	Diameter of tube, m
g	Gravitational acceleration, 9.807 m/s^2
h	Surface heat transfer coefficient, W/m^2 °C
h_{fg}	Latent heat of vaporization, J/kg
k	Thermal conductivity, W/m °C
k_f	Thermal conductivity of liquid phrase, W/m °C
L	Significant dimension, thickness of insulated slab, m
m	Number of locations for internal temperature measurements
M	General time index
n	Number of data points at each interior location
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
S	The sum of least square; Steam content
t	Time, sec

T	Product Temperature, ^{o}C
T_a	Ambient temperature, ^{o}C
T_i	Initial temperature, ^{o}C
T_s	Surface temperature, ^{o}C
T_{ij}	Predicted value of temperature at position i and time j, ^{o}C
T_s	Surface temperature of test subject, ^{o}C
T_i^n	Temperature at location i and time level n, ^{o}C
T_0^n	Surface temperature of surimi at time n, ^{o}C
Δt	Timestep of temperature measurement, sec
v	Velocity of the fluid, m/s
V	Volume, m^3
x	Variable distance coordinate
Δx	Grid size, m
Y_{ij}	Measured value of temperature at position i and time j, ^{o}C
α	Thermal diffusivity, m^2/s
ρ	Density, kg/m^3
ρ_f	Liquid density, kg/m^3
ρ_v	Vapor density (kg/m^3)
ω	Angular rotation, radians/s
ε	Emissivity
σ	Stefan-Boltzmann constant, 5.670×10^{-8} W/m^2K^4
μ_f	Steam viscosity, N s/m^2

Subscripts and Superscripts

a	Ambient
f	Liquid phase
i	Location index of temperature measurement and calculation
I	Location index of temperature calculation for boundary condition
j	Time index of temperature measurement and calculation
n	Time index of temperature calculation
s	Surface of solid
0	Initial or surface condition

COMPARATIVE METHODS OF DETERMINING HEAT TRANSFER COEFFICIENTS OVER MOIST FOOD MATERIALS

1. INTRODUCTION

Background

Surimi is a minced fish flesh that is washed to remove most of the oil, blood, enzymes and sarcoplasmic protein and then stabilized for frozen storage by the addition of cryoprotectants. Although the art of making surimi has been practiced in Asia for many centuries, only during the past 36 years has the tradition evolved into a major industrial operation (Sonu, 1986). As an intermediate raw material, surimi has been widely used for fabricating new food items which require specific textural attributes because of its distinguishing gel-forming capacity. Surimi-based products are providing the consumer with novel, nutritious, and convenient foods. More importantly, surimi is a potential utilization of under-utilized fish species such as arrowtooth flounder and Pacific whiting, the latter representing the largest biomass off the West Coast of the United States. The abundance in resources and the opportunity to produce high-quality surimi from low-valued fish make it desirable for the seafood industry to expand surimi production.

However, these low-valued fish species have a number of intrinsic quality problems that are difficult to overcome. The principal process problem of surimi from the fish mentioned above results from a heat stable protease enzyme that is present throughout its muscle tissue and causes rapid softening of the flesh (Patashnik et al., 1982; Nelson et al., 1985; Greene and Babbitt, 1990; Morrissey, 1992). Different cooking rates for surimi would cause significant differences in texture of the cooked product (Yongsawatdigul and Park, 1996). Rapid and controlled heating could inactivate the protease enzyme before the proteolysis occurs, minimizing damage to the flesh. On the other hand, a slow heat transfer allows the protease enzymes to actually increase in activity near the enzyme activation zone (40 - 60 ^{o}C) before heat denaturation occurs (Yongsawatdigul et al., 1995). Consequently, an accurate prediction of the heating rate is especially important for good control of the surimi process, to obtain high-quality surimi seafood products.

A current commercial method to rapidly heat surimi paste is the use of steam and radiant heating of thin sheets. In many seafood companies, highly automated machinery has been used for surimi processing. Continuous production of surimi is carried out by means of a stainless-steel belt on which surimi is conveyed through a steam-filled chamber and/or a gas-fired heating section (Park, 1995). As observed in a local manufacturing plant, Kyotaru Oregon in Salem, thin sheets of surimi paste (about 2 mm) are thermally processed by steadily moving through the gas-fired burner section and the steam chamber. It is not uncommon to use steam as a sole heating element (Park, 1995).

Operational control of the surimi seafood process is limited to adjusting the belt speed, steam flow rate, steam temperature, and product thickness. These factors determine the steam condition in the steam chamber and the quality of the final products. Optimal adjustment of them is economically significant for maximizing quality retention and throughput, and minimizing energy and time consumption. The basis for this optimization is an accurate prediction of temperature history distribution, providing an estimate of heating rate and the extent of the thermal process.

Limitations of Present Models

The surface heat transfer coefficient (h) is known to be one of the most important parameters required for the analysis and simulation of thermal processes. A model of this coefficient refers to a mathematical equation correlating the heat transfer coefficient (h) with some of the influencing factors that can be measured.

The surface heat transfer coefficient encompasses all the factors that influence convection heat transfer. In particular, it depends on conditions in the boundary layer which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties. To model the heat transfer coefficient (h) in steam, any factors that affect the boundary conditions may be taken into account; examples are flow velocity, ambient temperature, surface temperature, temperature difference between the surface and the ambient, steam density, steam content, geometrical shape of the product and orientation factor.

Nu-Re Correlation. For convective heat transfer in fluids, the strong dependence of the coefficient (h) on velocity of the heating medium has caused investigators to represent their findings in a power relationship between Nusselt (Nu) and Reynolds (Re) numbers for general application (Arce and Sweat, 1980). The Nusselt number (hL/k) characterizes the heat transfer and contains the surface heat transfer coefficient, a characteristic dimension and the thermal conductivity of the fluid at the surface temperature conditions. The Reynolds number ($Lv\rho/\mu$) characterizes the dynamic properties of the fluid and has the same characteristic dimension L, the velocity of the fluid v, and the density and viscosity of the fluid at the average film temperature conditions. The Prandtl number, $C_p\mu/k$, characterizes the heat transfer properties of the fluid at average film temperature conditions.

A general form of the Nu-Re correlation was obtained by Kays and Crawford (1980), assuming a constant free stream velocity with laminar flow under forced convection

$$Nu = c\,Pr^{1/3}\,Re^{1/2} \tag{1.1}$$

where c equals 0.644 or 0.906 for a constant temperature or a constant heat flux boundary, respectively. However, this correlation is not for steam condensation heat transfer, even although other conditions are quite similar to those important in this study.

Similar dimensionless relationships are often used as tools for convection heat transfer in food refrigeration processes, but they have the limitations as it is only the mean values that are obtained and in many cases may give misleading results causing over- or under-treatment of the products (Hallstrom et al., 1988). In studying food steam process, this kind of Nu-Re dimensionless relationship is rarely used. This would be due to the small effect of the steam velocity on the heat transfer coefficient (h) under normal steam cooking environment.

Empirical h Models. Empirical models of the heat transfer coefficient (h) are generally used to do condenser design calculations. These h models were developed for film-wise condensation which involves a series of assumptions (Collier, 1981): the flow of condensate in the film is laminar; the fluid properties are constant; subcooling of the condensate may be neglected; momentum changes through the film are negligible; the vapor is stationary; heat transfer is only by conduction. The application of these models is limited by the geometrical shape and the orientation of the product. For a vertical plate, an empirical model has been developed (Incropera and Dewitt, 1990):

$$h = 0.943\left[\frac{\rho_f g(\rho_f - \rho_v) h_{fg} k_f^{\,3}}{(T_a - T_s)\mu_f L}\right]^{0.25} \tag{1.2}$$

where

g = Gravitational acceleration (9.807 m/s^2)

L = Length of vertical plate (m)

T_a = The ambient temperature (°C)

T_s = The surface temperature (°C)

h_{fg} = Latent heat of vaporization (J/kg)

k_f = Thermal conductivity of liquid phase (W/m °C)

ρ_f = Liquid density (kg/m^3)

ρ_v = vapor density (kg/m^3)

μ_f = Steam viscosity of liquid condition (N s/m^2)

The surimi sheet to be processed and cooked can be regarded as a horizontal plate under steam condensing conditions. One model developed for a rotating horizontal disc has been formulated by Nandapurkar and Beatty (1960).

$$h = 0.904\left[\frac{\rho_f^{\,2}\omega^2 h_{fg} k_f^{\,3}}{(T_a - T_s)\mu_f}\right]^{0.25} \tag{1.3}$$

where

ω = Angular rotation (radians/s)

For a vertical tube under film condensation, the heat transfer coefficient (h) can be calculated according to McCabe et al. (1985):

$$h = 0.943\left[\frac{\rho_f^{\,2} g h_{fg} k_f^{\,3}}{(T_a - T_s)\mu_f L}\right]^{0.25} \tag{1.4}$$

where

L = Length of vertical tube (m)

Another h model is for horizontal tube (McCabe et al., 1985):

$$h = 0.725\left[\frac{\rho_f^{\,2} g h_{fg} k_f^{\,3}}{(T_a - T_s)\mu_f D}\right]^{0.25} \tag{1.5}$$

where

D = Diameter of the tube (m)

Zhang and Cavalieri (1991) modified this equation and obtained a similar h model for steam blanching of green beans

$$h = 0.06\left[\frac{\rho_f^{\,2} g h_{fg} k_f^{\,3}}{(T_a - T_s)\mu_f L}\right]^{0.25} \tag{1.6}$$

where

L = Length of a horizontal cylinder representing the beans (m)

They reported this modification to be necessary, because the h results from the empirical model (1.5) overpredicted the heat transfer coefficient to green beans by a factor of 12. The reduction was attributed to the presence of non-condensable gas and food surface conditions.

The empirical models described above cannot be directly used to estimate the heat transfer coefficient (h) for food processes. This would be explained by the following reasons: (1) the empirical models were based upon the assumption of ideal film-wise condensation; (2) they were developed for condenser designs, not for food; (3) none exactly match surimi process conditions of a horizontal plate steadily moving through the steam chamber. However, such empirical models provide us with good information on how one might model the heat transfer coefficient (h) for steam heating of moist foods. These empirical equations have shown that the heat transfer coefficient (h) is determined by the geometry of the product, the orientation of the product, the thermal properties of the heating medium which depends on steam temperature and pressure, and the temperature difference between the surface and the ambient. The flow velocity is not included in the equations because for film condensation vapor is assumed stationary. Although the flow velocity is generally considered to be a major factor affecting convective heat transfer coefficients under a normal steam-cooking condition, saturated steam at about 100 ^{o}C and 1atm, steam velocity only has a small effect on heat transfer (McAdams, 1954; Ling et al., 1974; Ling et al., 1976).

Experimental h Models. Many investigators have reported that the surface heat transfer coefficient (h) is significantly affected by the steam composition, represented by steam content (Ramaswamy et al., 1982; Ramaswamy et al., 1983; Tung et al., 1984; Tung et al., 1989) or air percentage by volume (Othmer, 1929; DeVuono and Christensen, 1984). The studies of Tung et al. (1984) and Tung et al. (1989) reported a relationship between the heat transfer coefficient (h) and the steam content,

$$h = a\exp(bS) \tag{1.7}$$

where a and b are dependent upon steam retort type (horizontal or vertical retort), flow rate, flow direction and test subject orientation; S is the steam content represented as the ratio of saturated steam pressure (absolute) corresponding to the retort temperature, and the total retort pressure (absolute). They studied the influence of steam content by introducing air to the retort to adjust steam content. In this manner of evaluating the steam composition, the steam content is 100% when the steam temperature is 100 ^{o}C and pressure is 1 atm. By this model, if the steam pressure is constant then we just need to measure the steam temperature to calculate the heat transfer coefficient (h). However, the application of this model to surimi steam process is limited by the following factors: (1) this model is originally developed for steam process in overpressured retort; (2) the resulted heat transfer coefficient (h) is only an average value that may be not adequate for an accurate prediction of heat transfer in food.

Two additional models were experimentally derived under overpressure: one is by Othmer (1929) relating the heat transfer coefficient (h) with steam temperature, the temperature difference between steam and the surface, and the percent air by volume; another by DeVuono and Christensen (1984) is a function of the temperature difference, air percentage and the pressure in the steam container. These models are not applicable to surimi paste production under atmospheric steam conditions, because they were developed for tubes not plates, and food has very different surface conditions and thermal properties from metal. Moreover, steam heat transfer is strongly dependent on the geometrical shape and the orientation of the test product.

Objectives

As a part of the research project of "Processing alternatives to reduce protease-related muscle softening in seafoods" (Kolbe et al., 1993), the long-term purpose of this research was to minimize the tendency of enzymes to soften seafood texture during cooking.

This study focused on three objectives: 1) to develop an accurate model of the heat transfer coefficient (h) for the design and optimization of a surimi steam cooking process; 2) to develop a technique for the inverse calculation of transient heat transfer coefficients (h) from interior temperature measurements in food product; 3) to compare the inverse calculation method, the lumped mass method and the heat flux method in determining the heat transfer coefficient (h) under similar steam conditions.

Outline of This Study

In this study, a whole-domain function specification procedure was developed for the inverse calculation method, simulating heat transfer coefficients by means of estimating all the unknown parameters of a specific function representing the coefficients for the time history; a nonlinear regression computer program was designed for the solution of the heat conduction problem and parameter optimization; the lumped mass method was employed to determine the coefficients for three orientations and then temperature-dependent models were fitted; a thin-foil heat flux sensor with integral thermocouple was selected to measure the coefficients, which is called the heat flux method in this study; advantages and limitations were cited for each method at the end. All the modeling results of the heat transfer coefficient from this study were checked by a finite element package PDEase (Macsyma Inc., Arlington, MA).

The content of the following sections is:

2. Experimental Development, including experimental designs and procedures for the three different methods.
3. Analytical Methodology, including a literature review for each method and the development of the analytical approaches used in this study.
4. Results and Discussion, in the form of a manuscript to be submitted for publication.
5. Other results and recommendation for future study.

Appendices Computer programs and a description of the development of the programs.

2. EXPERIMENTAL DEVELOPMENT

Introduction

A survey of the literature indicates that the study of the surface heat transfer coefficient (h) is based upon either the measurement of interior temperature or the measurement of surface heat flux and surface temperature. Methods for determining the heat transfer coefficient (h) can be categorized as the inverse calculation method, the lumped mass method and the heat flux method. Among these, the inverse calculation method and the lumped mass method are related to measuring the internal temperatures, while the heat flux method is associated with measuring the surface heat flux and surface temperature.

It has been reported that the estimation of the heat transfer coefficient (h) using the inverse calculation method is most accurate because the surface conditions and thermal properties of food are continuously changing during the heating process (Arce and Sweat, 1980; Chavarria and Heldman, 1984; Scott et al., 1992). The inverse calculation method estimates the heat transfer coefficient (h) from interior temperature measurements at one or more locations in the food product. It involves the solution of the heat conduction problem and the optimization of parameters used to define a specific function for the heat transfer coefficient (h). In this study, a nonlinear regression computer program was developed to model the time-dependent heat transfer coefficients by minimizing the difference between predicted and experimental temperatures. In an attempt to increase the accuracy of the modeling results, a large number of interior temperatures were used for the inverse calculation. The temperature data were collected once per second for a 1000-sec process at three interior locations of specific distances from the surimi surface. Moreover, temperature-dependent thermophysical properties of surimi paste were evaluated at each time level using the property models developed by AbuDagga and Kolbe (1996).

The lumped mass method is much simpler than the inverse calculation method. It utilizes a high-conductivity metal transducer instead of food to evaluate the heat transfer coefficient (h) from interior temperature measurement. The main assumption for the lumped mass method is that the temperature gradient inside the transducer is negligible. Such a temperature can be measured at any interior location of the transducer. Using this method, the heat transfer coefficient (h) was calculated by formulating an overall energy balance on the test product. The inherent simplicity of this method renders it the preferred method for studying the surface heat transfer coefficient.

The calculation of the heat transfer coefficient (h) is most simplified when we know the surface heat flux and the surface temperature. The heat flux method uses a heat flux sensor and a thermocouple to measure the surface heat flux and the surface temperature, then calculates the transient heat transfer coefficient (h) by definition. The RdF Industrial Micro-Foil Heat Flux Sensor (RdF Corporation, Hudson, NH) used in this investigation was developed using a new micro-foil technology and materials. A foil-type thermocouple was built into the sensor to provide the surface temperature measurement at the same time the heat flux measurement is made. The unique structure of the foil-type sensors provides the sensors with the lowest thermal capacity, fastest response time and least disturbance to heat flux.

Test Materials

Surimi samples. Pacific whiting (*Merluccius productus*) surimi was taken from Point Adams Packing Co. (Hammond, OR) and mixed with 4% sucrose, 4% sorbitol (ICI Specialties, New Castle, DE), and 0.3% sodium tripolyphosphate (B.K. Ladenburg Corp., Cresskill, NJ) at the OSU Seafood Laboratory in Astoria, OR. Samples had been frozen and kept in a -30 °C room for 2 months before our experiments.

Frozen surimi was tempered 2-3 hr at room temperature. Partially thawed surimi was then chopped with 2% NaCl, 1.5% enzyme inhibitor (beef plasma protein, BPP) and some ice water for 4 min in a Stephan vertical vacuum chopper (Model UM 5 universal, Stephan Machinery Co., Columbus, OH) to obtain a final mixture of 80% moisture content. The temperature was maintained below 8 °C during chopping. The moisture content of surimi samples was measured by an infrared moisture determination balance (Model AD-4714A, A&D Company, Limited, Tokyo, Japan). Upon completion of chopping, the surimi paste was stuffed into PVC containers (about 0.5 kg each) and held below 10 °C in a styrofoam box until cooking. (Radio Shack) was put on

Copper block. A piece of pure copper (15.2 cm x 15.2 cm x 0.635 cm) (Figure 2.1) was embedded in styrofoam with only one surface exposed to the ambient. The temperature measurements were taken at three locations of different distances from the exposed surface to verify the uniformity of the temperature distribution in the copper block for the application of the lumped mass method. Three small horizontal holes were drilled in three sides for inserting the 30 gage thermocouples in the block. Before locating the thermocouples, some highly conductive heat sink compound the tip of the

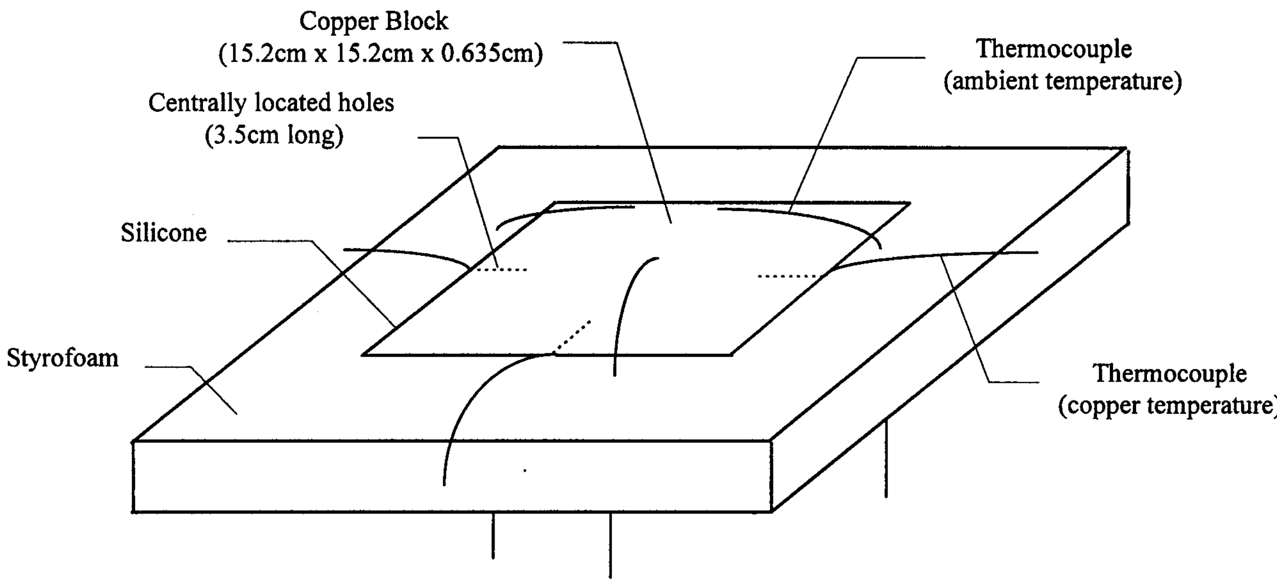


Figure 2.1—Schematic diagram of the experimental set-up for copper block.

thermocouple junctions to insure a complete bond between the junctions and the copper and to minimize the delay of the temperature measurements. Finally, the edge around the insulated copper block was filled with silicone sealant to prevent steam leakage and to fix the thermocouples. The property data for pure copper are as following: thermal conductivity = 400 W/m ^{o}K, specific heat = 385 J/kg ^{o}K, and density = 8933 kg/m^3 (Incropera and Dewitt, 1990) which were evaluated at 85 ^{o}C, the average temperature of the copper block during the test.

Apparatus and Procedure

Steam chamber. All the tests were conducted in an insulated stainless-steel chamber (900 mm x 900 mm x 600 mm) (Figure 2.2) in which steam uniformly shot down on to the test subject from two steam tubes (1″ diameter) with many small holes evenly positioned on the bottom surfaces. To obtain a constant steam condition in the steam chamber for all the tests, the same opening was held to allow steam to exit the chamber freely. The steam flow into the chamber was controlled by a globe valve, adjusted to achieve a good circulation of saturated steam. A temperature gage was mounted on the steam chamber and the sensor detected the steam temperature near the test subject surface. A nearby on-line steam pressure gage was used to monitor the pressure of the steam source. A consistent steam condition was assumed if both the temperature and the pressure monitored by the gages were constant.

Surimi paste cooking tray. This tray (Figure 2.3) was fabricated from a piece of stainless steel plate (1/8″ thick) with two nylon spacers (cross section 20 mm x 13 mm)

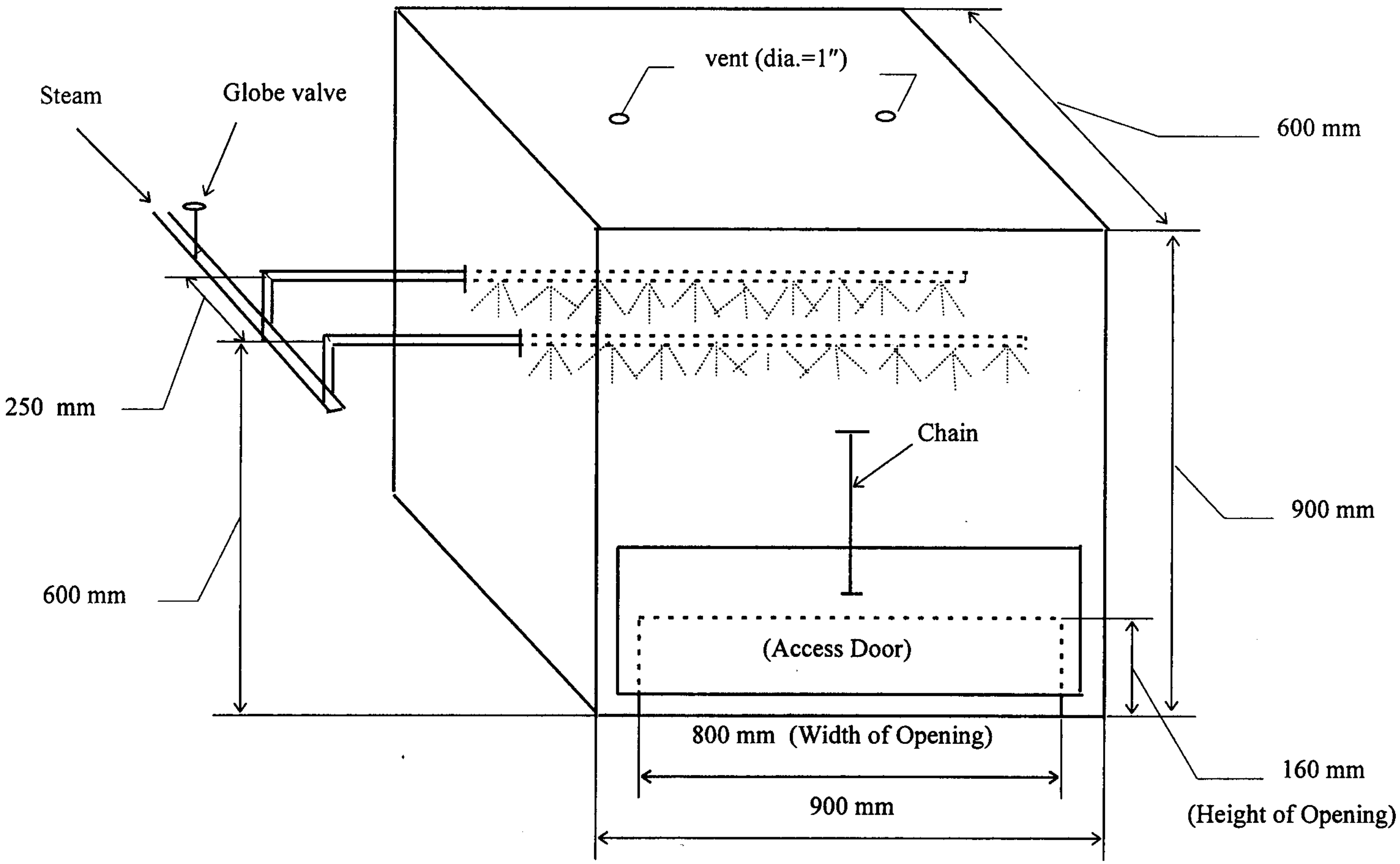
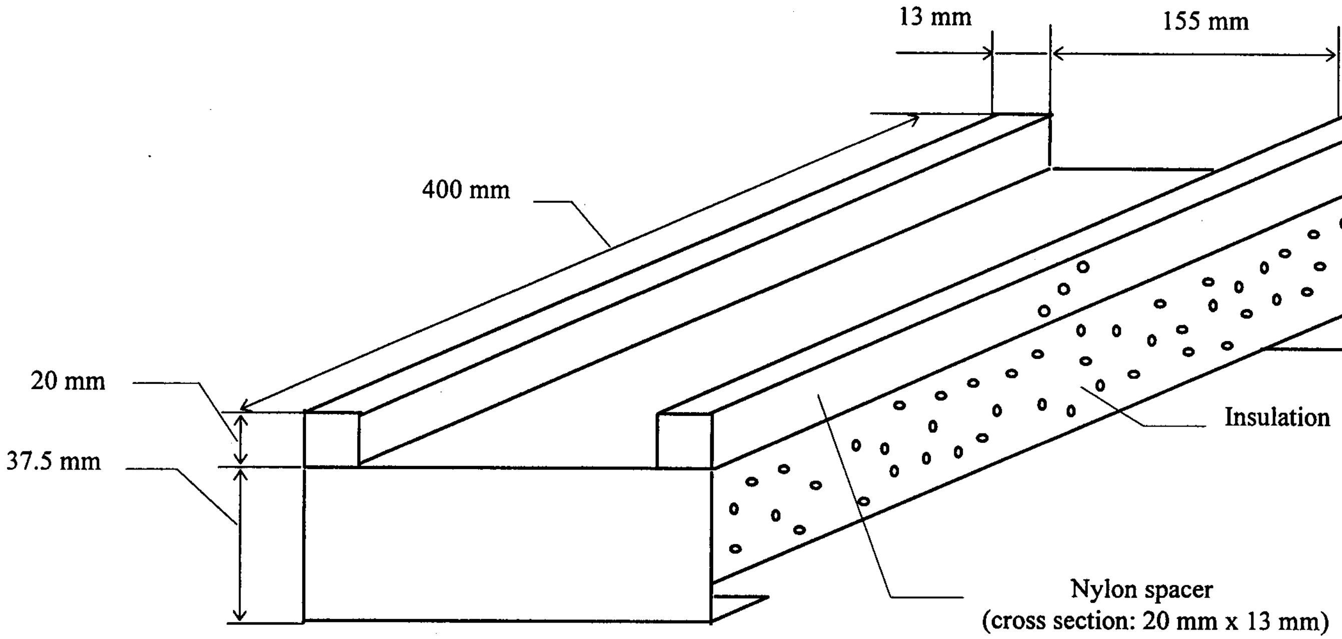


Figure 2.2—Schematic diagram of steam chamber.



(The distances from the holes in the Nylon spacer to its top surface are 5mm, 10mm and 15mm, respectively.)

Figure 2.3—Schematic diagram of cooking tray.

mounted on two sides to form a uniform surimi slab. Through one of the nylon spacers, three small holes were evenly drilled (one at the center, one near the surface and one near the bottom) to accurately locate thermocouple probes (TMQSS-032-3, ungrounded, Omega Engineering Inc.) used to measure the interior temperatures of surimi paste. The bottom of this tray was well insulated by DAP KWIK foam (DAP Inc., Dayton, OH). The surimi paste (20 mm thick) formed on this tray (400 mm x 155 mm x 20 mm) could be assumed to be a part of an infinite slab so that the assumption of one-dimensional heat conduction held.

Heat flux sensor. The heat flux sensor for our experiments was Model RdF 27070-1 Industrial Micro-Foil Heat Flux Sensor (RdF Corporation, Hudson, NH) with integral thermocouple for measuring surface temperature. Its dimensions were 35.1 mm x 28.5 mm x 0.15 mm. This flat heat flux sensor is specifically designed for the precise measurement of heat loss or gain through the surface. To install the sensor on the surface of the surimi paste, the usual technique is to recess the sensor an amount equal to its thickness, thus making the installation flush with the surrounding area (Ortolano and Hines, 1983).

Prestabilized steam condition. It is important to prestabilize the steam condition in the chamber, because a constant steam environment is necessary to allow a comparison of the three methods used to determine the heat transfer coefficient (h). For this reason, the heating medium was allowed to stabilize for more than one hour after the globe valve was regulated. The resulting saturated steam environment was assumed to simulate surimi seafood production condition in industry. The steam condition was monitored by the pressure gage, the temperature gage and several thermocouples (about 25 mm from test surface) attached to a Campbell 21X datalogger (Logan, UT). The experimental temperature of the steam was controlled to 100 °C.

Tests with surimi paste. The surimi tests were used to support the inverse calculation method and the heat flux method. These surimi tests were repeated 15 times under similar steam conditions. A quick preparation for the test was important to ensure a uniform temperature distribution throughout the surimi slab. When making the surimi slab, care was taken to ensure that the tray was uniformly filled with surimi paste and that the surimi surface was as smooth as possible so that one-dimensional heat conduction could be assumed. After making the surimi slab, both the heat flux sensor and the thermocouple probes were carefully located on and in the surimi slab. The initial uniform temperature of the surimi slab was in the range of 12-14 °C. The positions of the tips of the three thermocouple probes were checked and adjusted relative to the surface of the stainless steel tray before each test without surimi on the tray. A second check of the positions were taken immediately after each test by carefully cutting three cross sections along the sensing tips of the probes and measuring the distances by an optical micrometer. This was important, because the temperature measurements and numerical calculations were sensitive to the distance of the thermocouple probes from the surface of surimi paste.

Tests with copper. The copper tests were used to support the lumped mass method. The specific set-up of the copper block made it possible to test the orientation effect on the heat transfer coefficients (h). This was done by placing the test copper surface horizontal (facing up, down) and vertical in the chamber. The three orientations were easily obtained by the means of a wire basket, 15 test runs for each.

Data collection. Data collection was carried out by a Campbell 21X microvoltmeter datalogger (Logan, UT) bidirectionally interfaced with a PC so measurement could be programmed on a microcomputer. Data were recorded twice per second for the copper test and once per second for the surimi test. For all the tests, three 30 gage type T thermocouples attached to the test subjects were used to monitor the steam temperature (ambient temperature) around the test subject, required to be uniform for this study. The distance between the junctions of the thermocouples and the test surface was about 25 mm. Three small rubber shields were used to block junctions from "seeing" the initial cold surfaces of the test materials, thus reducing the radiation effect on the measurements.

All tests were carried out during one day after the steam condition in the chamber was stabilized. The surimi tests and the copper tests were conducted alternately to assure that the copper and the surimi were heated under a similar steam condition. To ensure a uniform steam condition and a uniform initial temperature, the test subjects were instantly introduced to the steam chamber with the slide door quickly moved up and down to the same opening.

3. ANALYTICAL METHODOLOGY

The inverse calculation method, the lumped mass method and the heat flux method are different not only in experimental design, but also in analytical approach. Since different methods may result in different results of the heat transfer coefficient (h), a comparative evaluation of the methods would be valuable for a good understanding of this study's results and to guide future research.

Inverse Calculation Method

Beck et al. (1985) defined the inverse heat conduction problem as determining surface conditions, such as surface temperature, surface heat flux and heat transfer coefficient, from internal temperature measurements. This is in contrast to the direct problem in which internal temperature distributions are found from known boundary conditions.

The inverse estimation of the heat transfer coefficient is based on the following considerations: (1) it is extremely difficult to measure surface conditions (surface heat flux, surface temperature) accurately, however, internal temperatures can be measured accurately; (2) accurate internal temperature measurements provide the most reliable information of a food thermal process, which involves a coupled heat and mass transfer; (3) modern computers and accurate finite difference methods make it possible to solve inverse problems accurately and efficiently. The inverse calculation method developed in this study was a procedure for the modeling of transient heat transfer coefficients from transient temperature measurements inside a product. It involves the solution of the inverse heat conduction problem and parameter optimization.

Literature Review

To solve the transient heat conduction problem, we need to first discretize the partial differential equations, including the heat conduction and boundary condition equations. Implicit numerical methods are generally used for this discretization and one of these, the Crank-Nicolson scheme is most popularly used for the finite difference formulation of the heat conduction equation (Beck, 1966; Narayana and Murthy, 1981; Arce et al., 1983; Chavarria et al., 1984; Beck et al., 1985; Scott et al., 1992); it is consistent, unconditionally stable and convergent (Hoffman, 1990). The high accuracy of solution gained by using this implicit finite difference method, however, is at the expense of heavy computational endeavor because that a system of equations must be solved to obtain the solution at each time level.

After discretization of the equations, the inverse heat conduction problem is still nonlinear if any one of the thermal properties (k, ρ, C_p) or the heat transfer coefficient (h) varies with temperature. A series of methodologies have evolved to solve the nonlinear inverse heat conduction problem with parameter estimation. As described by Beck et al. (1985), the two basic classes of methods for the solution of nonlinear inverse heat conduction problems are function specification and regularization methods. These methods were originally developed for the estimation of surface heat flux and/or temperature. It is important to note that same procedures can be used to determine the heat transfer coefficient. In the function specification method, a functional form for the unknown heat transfer coefficient is assumed; the unknown parameters in the function are estimated utilizing the method of least squares. The second called the regularization method, is a procedure which modifies the least squares approach by adding factors that are intended to reduce excursions in the unknown function and improve convergence.

Both the functional specification method and the regularization method can be employed in sequential and whole domain estimation forms (whole time domain). To establish the functional forms obtained from the function specification method and the regularization method, either the whole domain estimation procedure (the whole domain function specification method, the whole domain regularization method) or the sequential estimation procedure (the sequential function specification method, the sequential regularization method) can be used to estimate the unknown parameters contained in the functions. Frank (1963) and Davies (1966) were the early proponents of the whole domain method estimating all the parameters for the total time interval.

The whole domain method assures the stability and accuracy of the solution, but at the expense of solving a large set of nonlinear algebraic equations iteratively. Especially in the case when the solution is needed over a long period of time, the dimension of the matrices and the number of computations involved increase accordingly. The sequential method differs from the whole domain method in that the solution is found sequentially at each time level, greatly improving computational efficiency. In the sequential methods, a functional form of the future heat flux/heat transfer coefficient was assumed; only a limited number of future time steps are used and only one component of the heat flux/heat transfer coefficient vector is found at each step (Beck, 1968; Beck, 1970; Beck, 1979; Osman and Beck, 1987; Scott and Beck, 1989; Scott et al., 1992). The sequential method is preferred by researchers since it is more computationally efficient and gives only slightly different results from the whole domain method.

Beck et al. (1985) presented a function specification method in which the heat transfer coefficient (h) is represented as a function of time. The functional form contains a number of unknown parameters that are estimated utilizing the method of least squares to minimize the temperature difference between the experimental data and calculated values. The sequential function specification method was discussed in a series of papers by Beck (Beck, 1961; Beck,1968; Beck, 1970; Beck, 1979). Osman and Beck (1987) proposed a sequential function specification method to represent h as a function of position.

The regularization method is a procedure which modifies the least-squares approach by adding factors that are intended to provide stability, reducing the influence of measurement errors in the data. It has a number of forms and has been studied by many researchers (Miller, 1970; Tikhonov and Arsenin, 1977; Alifanov, 1975; Cozdoba and Crykowsky, 1982; Bell and Wardlaw,1981; Beck and Murio, 1986; Scott and Beck, 1985). Scott and Beck (1989), and Scott et al. (1992) presented their studies of the sequential regularization solution of the inverse heat conduction problem. It was pointed out by Beck et al. (1985) that the results produced by the sequential regularization method and the function specification method are quite similar.

Beck and Murio (1986) proposed a combined function specification-regularization method. This method used the sequential feature of the function specification method and the special function minimized in the regularization method. The combined procedure is much more computationally efficient than the usual regularization procedure.

Parameter estimation is involved in both the function specification and the regularization methods. Parameter estimation is a discipline that provides tools for the efficient use of data in the estimation of constants appearing in a specified function (Beck and Arnold, 1977). It can be accomplished through minimizing the sum of squares functions, which is the sum of least squares function for the function specification method, and a modified sum of least squares function for the regularization method. Methods for minimizing the sum of squares function can be divided into methods that need only evaluations of the function to be minimized and methods that also require evaluations of the derivative of that function (Press et al., 1992). The simplest procedure for minimizing the function is the trial and error method (Beck et al., 1985), which is effective for one-parameter estimation. Other methods requiring only function evaluation include the downhill simplex method and Powell's method (Press et al., 1992). These methods are valid only for the function specification method in minimizing the sum of least-squares. If the experimental data curve of the heat transfer coefficient (h) is approximately smooth, then the procedure for only function evaluation without the derivative evaluation would be a better choice because the computation is greatly reduced. However, derivative evaluation is necessary for scattered data when employing the regularization method. The Marquardt method (Marquardt, 1963) gained wide application in parameter estimation. It is one of the modifications of the Gauss method, including the Box-Kanemasu interpolation, Levenberg damped least squares, Marquardt, halving-doubling and interpolation-extrapolation methods (Beck and Arnold, 1977). In minimizing the squares function, these methods specify direction and size of corrections to the parameter vector.

The inverse calculation of the heat transfer coefficient (h) is both an inverse heat conduction problem as well as parameter estimation. A nonlinear program is necessary for the inverse calculation, which must include the procedures for the discretization of the partial differential equations, the solution of the nonlinear heat conduction problem, and parameter optimization by the means of minimizing the sum of squares functions.

Due to the temperature-dependent thermal properties of food during processing, researchers have resorted to using inverse calculation methods to estimate surface heat transfer coefficients. This nonlinear numerical approach is known to provide the most accurate solution if small space and time increments are used (Arce and Sweat, 1980). However, the difficulties in measuring temperature-dependent thermal properties of food cause researchers to use food substitutes of known thermal properties instead of foods in applying this method. Chavarria and Heldman (1984) used an acrylic transducer of known $C_p(T)$ and k(T) in their study of heat transfer coefficients for food freezing processes, and a nonlinear program to established a constant estimate of the heat transfer coefficient (h). Scott et al. (1992) used the Karlsruhe Test Substance (the Federal Research Institute, West Germany) as a substitute food product in studying transient heat transfer coefficients in frozen foods during storage. The Karlsruhe Test Substance is a highly concentrated methyl-cellulose mixture, has thermal properties and freezing characteristics similar to those of common food products. To get a full knowledge of a food thermal process, it is desirable to examine the food itself rather than a transducer because of the unique surface conditions and thermal properties of food products.

Rumsey et al. (1980) presented a work in a different manner for the inverse calculation of the heat transfer coefficients to steam-cooked sweet potato. They employed two analytical methods, Laplace transformation technique and the finite difference technique, to calculate the coefficients from central temperatures inside sweet potato. Another important application of the inverse calculation method for food process is evaluating thermal properties (Beck, 1966; Narayana and Murthy, 1981).

This study developed a whole domain function specification method for the inverse calculation of the heat transfer coefficient (h). This approach assured the stability and the accuracy of the nonlinear estimation through following considerations:

(1) the whole-domain method has advantage over sequential method in dealing with a large set of temperature data during a long time history, because it establishes a specific h function for the entire time history, however, the sequential method evaluates only one component of the heat transfer coefficients at each time level;

(2) simple function evaluation method for the minimization of the sum of least squares, which would greatly simplify the computer programming without derivative evaluation, more importantly reducing the computation time;

(3) implicit finite difference methods used for discretizing the partial differential equations: one-dimensional heat conduction equation, insulated boundary condition equation, and convective boundary condition equation;

(4) temperature-dependent thermophysical properties for surimi.

Analytical Approach

This study expanded a great effort to assure the accuracy of the solution of the inverse heat conduction problem, meantime reducing the computation time. Modeling of the heat transfer coefficient was carried out by a nonlinear regression computer program (Appendix B), developed from the solution of the inverse heat conduction problem and parameter optimization.

The Crank-Nicolson finite difference method was used for the finite-difference formulation of the one-dimensional heat conduction equation. The Extrapolation method, a modification of Taylor series expansions, was used to linearize the derivative boundary conditions (Hoffman, 1990). The procedure developed in this study for the solution of the inverse heat conduction problem is a whole domain function specification method. The functional form assumed for the heat transfer coefficient was a modification of empirical models and included the ambient temperature and the surface temperature as independent variables. The unknown parameters (coefficients and exponents) in the function were estimated by the method of sum of least squares. Because our experiments were conducted under fairly steady-state steam conditions, the curve of the heat transfer coefficient profile was expected to be relatively smooth. This enabled the use of the simple function evaluation methods, the trial and error method for one parameter (Tarantola, 1987) and the downhill simplex method for more than one parameter (Press et al., 1992), in minimizing the sum of least squares.

The temperature-dependent thermal properties ($\rho(T)$, $C_p(T)$ and $k(T)$) of surimi paste were calculated using the property models developed by AbuDagga and Kolbe

(1996). The samples of surimi paste were made following the same procedures. In this study, the nonlinearity associated with temperature-dependent thermal properties was readily accommodated by re-evaluating all thermal properties at temperatures corresponding to the previous time step.

Basically, one-dimensional heat conduction was assumed for heat transfer in the composite structure of surimi paste and the insulated stainless-steel plate (Figure 3.1). The slab (thickness of surimi and steel slab: b = 20.0 + 2.0 mm) between the surface of the surimi paste and the bottom of the stainless-steel plate was divided into 44 elements, giving 45 nodes for the finite difference calculation (node 0 at the surface of surimi paste surface, node I = 44 at the bottom of the stainless-steel plate). One node was specifically

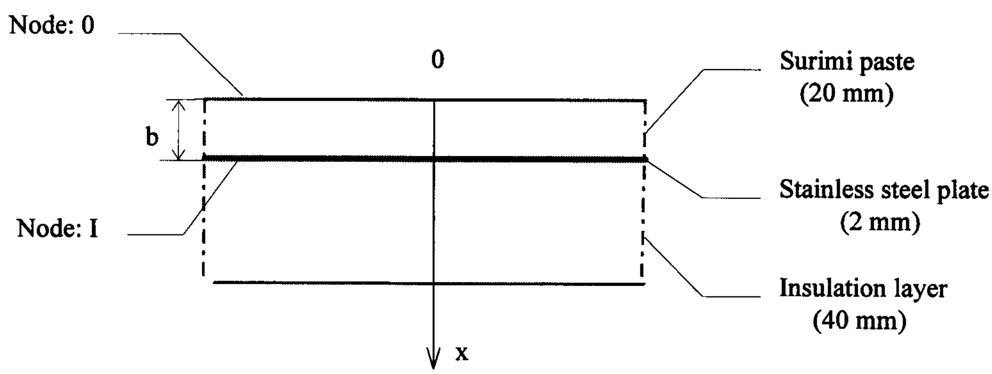


Figure 3.1–One-dimensional heat transfer by conduction.

assigned to the interface between surimi paste and stainless-steel and was represented as a node of surimi paste. The thermal contact resistance between surimi paste and stainless-steel was considered negligible. The temperature distribution at all nodes was iteratively calculated once per second for a 1000-sec cooking period. The nonlinear program approached the optimal unknown parameters in the function representing the heat transfer coefficient by continually improving the agreement between the temperature measurements at the three locations inside surimi paste and temperature calculations at the corresponding nodes.

The mathematical description of this heat conduction problem is illustrated below. The one-dimensional heat conduction equation for heat transfer in surimi paste:

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[k(T)\frac{\partial T}{\partial x}] \tag{3.1}$$

Thermophysical properties of AISI 304 stainless steel (density $\rho = 7900$ kg/m^3, specific heat $C_p = 477$ J/kg ^oK, thermal conductivity k = 14.9 W/m ^oK) were evaluated at 40 ^oC (Incropera and Dewitt, 1990), the average temperature of this insulated tray during the 1000-sec surimi cooking. The heat conduction equation for heat transfer in the stainless steel plate is:

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \tag{3.2}$$

The transient heat transfer coefficient (h) is involved in the boundary condition as:

$$-k(T)\frac{\partial T}{\partial x} = h(t)[T_a(t) - T_s(t)] \quad \text{heat convection on surimi surface} \tag{3.3}$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{insulated stainless steel surface} \tag{3.4}$$

A uniform initial temperature (T_0) distribution was assumed for surimi and stainless steel tray as:

$$T(x,0) = T_0 \quad (0 \le x \le b) \tag{3.5}$$

T(x, 0) denotes temperature at time t = 0 in any position x of the surimi-steel plate.

The heat conduction equations (3.1) and (3.2) were discretized by the Crank-Nicolson method as (Hoffman, 1990):

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = \alpha \frac{1}{2}\left(\frac{T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1}}{\Delta x^2} + \frac{T_{i+1}^{n} - 2T_i^{n} + T_{i-1}^{n}}{\Delta x^2}\right) \tag{3.6}$$

Where, α denotes the thermal diffusivity of surimi and stainless steel.

$$\alpha = \alpha_i^n = \frac{k_i^n}{\rho_i^n (C_p)_i^n} \qquad \text{for surimi} \tag{3.7}$$

$$\alpha = \frac{k}{\rho C_p} \qquad \text{for stainless steel} \tag{3.8}$$

The discretization of the insulated stainless-steel boundary condition, was based on the following two Taylor series expansions:

$$T_{i-1}^{n+1} = T_i^{n+1} + (-\Delta x)\frac{\partial T_i^{n+1}}{\partial x} + \frac{(-\Delta x)^2}{2}\frac{\partial^2 T_i^{n+1}}{\partial x^2} + 0(-\Delta x)^3 \tag{3.9}$$

$$T_{i-2}^{n+1} = T_i^{n+1} + (-2\Delta x)\frac{\partial T_i^{n+1}}{\partial x} + \frac{(-2\Delta x)^2}{2}\frac{\partial^2 T_i^{n+1}}{\partial x^2} + 0(-\Delta x)^3 \tag{3.10}$$

Equation (3.11) was obtained by combining the two equations [4 x (3.9) - (3.10)]. The higher-order space derivatives were eliminated because Δx (0.022/44 = 0.0005 m) was very small, and the approximation was $0(\Delta x^3)$.

$$4T_{i-1}^{n+1} - T_{i-2}^{n+1} = 3T_i^{n+1} - 2\Delta x \frac{\partial T_i^{n+1}}{\partial x} \tag{3.11}$$

The discretization of the convective surface boundary condition was based on the following two Taylor series expansions:

$$T_{i+1}^{n+1} = T_i^{n+1} + \Delta x \frac{\partial T_i^{n+1}}{\partial x} + \frac{\Delta x^2}{2} \frac{\partial^2 T_i^{n+1}}{\partial x^2} + 0(\Delta x^3) \tag{3.12}$$

$$T_{i+2}^{n+1} = T_i^{n+1} + (2\Delta x) \frac{\partial T_i^{n+1}}{\partial x} + \frac{(2\Delta x)^2}{2} \frac{\partial^2 T_i^{n+1}}{\partial x^2} + 0(\Delta x^3) \tag{3.13}$$

Modifying the above two equations [4 x (3.12) - (3.13)], it was obtained

$$4T_{i+1}^{n+1} - T_{i+2}^{n+1} = 3T_i^{n+1} + 2\Delta x \frac{\partial T_i^{n+1}}{\partial x} \tag{3.14}$$

It is called the Extrapolation method to use Equations (3.11) and (3.14) for the finite-difference formulation of boundary conditions.

Based on key equations (3.6), (3.11) and (3.14), heat conduction and boundary condition equations were represented by simultaneous linear equations. Rearranging equation (3.6), equation (3.15) was obtained for interior nodes in surimi and stainless steel plate:

$$-dT_{i-1}^{n+1} + 2(1+d)T_i^{n+1} - dT_{i+1}^{n+1} = dT_{i-1}^{n} + 2(1-d)T_i^{n} + dT_{i+1}^{n} \tag{3.15}$$

where,

$$d = d_i^n = \frac{\alpha_i^n \Delta t}{\Delta x^2} \qquad \text{for surimi} \tag{3.16}$$

$$d = \frac{\alpha \Delta t}{\Delta x^2} \qquad \text{for stainless steel} \tag{3.17}$$

It was assumed that no heat is released through the insulated surface of the cooking tray,

$$\frac{\partial T_i^{n+1}}{\partial x} = 0 \tag{3.18}$$

then, Equation (3.11) becomes

$$3T_I^{n+1} - 4T_{I-1}^{n+1} + T_{I-2}^{n+1} = 0 \tag{3.19}$$

In equation (3.19), node I represents the insulated surface of the stainless steel tray. The slab representing the surimi paste and the stainless steel was evenly divided into I elements, from node 0 to node I (Figure 3.1). For convective heat transfer on the surimi surface,

$$-k_i^n \frac{\partial T_0^{i+1}}{\partial x} = h_{simulated}(T_a^{n+1} - T_0^{n+1}) \tag{3.20}$$

or

$$\frac{\partial T_0^{i+1}}{\partial x} = \frac{h_{simulated}}{k_i^n}(T_0^{n+1} - T_a^{n+1}) \tag{3.21}$$

thus at the surimi surface, equation (3.14) becomes

$$(-3 - 2\Delta x \frac{h_{simulated}}{k_i^n})T_0^{n+1} + 4T_1^{n+1} - T_2^{n+1} = -2\Delta x \frac{h_{simulated}}{k_i^n} T_a^{n+1} \tag{3.22}$$

The term $h_{simulated}$ was the unknown heat transfer coefficient which was represented as a specific function with unknown parameters. It can be seen at this point that modeling the heat transfer coefficient was estimating the unknown parameters in solving the simultaneous equations (3.15), (3.19) and (3.22) with the h function and the initial uniform temperature. The matrix equation (3.23) shown in next page was formulated by the three simultaneous equations, and solved by LU decomposition and Gauss elimination methods (Hoffman, 1990).

The whole-domain function specification estimation of the heat transfer coefficient (h) was based on a target h function, for example:

$$
\begin{bmatrix}
-3-2\cdot\Delta x\cdot\dfrac{h_{simulated}}{k(T)} & 4 & -1 & 0 & \ldots & 0 & 0 & 0 & 0 \\
-d(T) & 2\cdot(1+d(T)) & -d(T) & 0 & \ldots & 0 & 0 & 0 & 0 \\
0 & -d(T) & 2\cdot(1+d(T)) & -d(T) & \ldots & 0 & 0 & 0 & 0 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
0 & 0 & 0 & 0 & \ldots & -d & 2\cdot(1+d) & -d & 0 \\
0 & 0 & 0 & 0 & \ldots & 0 & -d & 2\cdot(1+d) & -d \\
0 & 0 & 0 & 0 & \ldots & 0 & 1 & -4 & 3
\end{bmatrix}
\cdot
\begin{bmatrix}
T_{0,n+1} \\ T_{1,n+1} \\ T_{2,n+1} \\ \ldots \\ T_{42,n+1} \\ T_{43,n+1} \\ T_{44,n+1}
\end{bmatrix}
=
\begin{bmatrix}
-2\cdot\Delta x\cdot\dfrac{h_{simulated}}{k(T)}\cdot T_a \\
d(T)\cdot T_{0,n}+2\cdot(1-d(T))\cdot T_{1,n}+d(T)\cdot T_{2,n} \\
d(T)\cdot T_{1,n}+2\cdot(1-d(T))\cdot T_{2,n}+d(T)\cdot T_{3,n} \\
\ldots \\
d\cdot T_{41,n}+2\cdot(1-d)\cdot T_{42,n}+d\cdot T_{43,n} \\
d\cdot T_{42,n}+2\cdot(1-d)\cdot T_{43,n}+d\cdot T_{44,n} \\
0
\end{bmatrix}
\qquad (3.23)
$$

$$h_{simulated} = c_1(T_a - T_0)^{c_2} \tag{3.24}$$

where, T_0 is the surface temperature. The sum of least squares of the prediction error of n data points at m (= 3) locations was given by

$$S = \sum_{i=1}^{m}\sum_{j=1}^{n}(Y_{ij} - T_{ij})^2 \tag{3.25}$$

The predicted temperatures depend implicitly on the parameters (c_1, c_2)

$$T_{ij} = T_{ij}(c_1, c_2) \tag{3.26}$$

The object was to choose (c_1, c_2) such that least squares S was minimized. The downhill simplex method lead the S function to converge to a minimum, and the nonlinear program established the best estimate of the parameters in the h function. Finally, a similar numerical calculation program (Appendix C) was used to test the accuracy of the nonlinear regression estimation, then calculate surface heat transfer coefficients and time-dependent temperature distributions throughout the entire product based on the optimized heat transfer coefficient function, which was viewed as the h model. And a finite element package (PDEase, Macsyma Inc., Arlington, MA) was used to double check the modeling results.

Lumped Mass Method

In determining the surface heat transfer coefficient, most studies use the lumped mass method, which is also called the lumped capacitance method. Such a wide preference is attributed to its experimental and analytical simplicity.

Literature Review

The lumped mass method is usually associated with the use of a metal transducer of high thermal conductivity to ensure that a uniform temperature is distributed across the subject. The Biot number (hL/k), a dimensionless parameter, plays a fundamental role in evaluating the uniformity of temperatures. A suitable criterion is to maintain the Biot number below 0.1 so the resistance to conduction within the subject is much less than the resistance to convection across the boundary layer, and the temperature gradient in the subject is negligible (Incropera and Dewitt , 1990).

Khairullah and Singh (1991) used copper spheres of the same size as food particles (green peas, cherries and radishes) to study the transient heat transfer coefficient for fluidized bed freezing. They pointed out that a constant ambient temperature is necessary for the validity of the lumped mass method. Reid and Meybeck (1991) used a copper block to evaluate the effective surface heat transfer coefficients for fish freezing in the mechanical air blast freezer and cryogenic freezer, respectively. During their experiments, the cooling medium was controlled to a constant temperature and circulation rate. Cowell and Namor (1974) adopted a brass slab to study the effect of packaging materials on the overall heat transfer coefficient in plate freezing of foods. Flores and Mascheroni (1988) performed their h study with continuous air blast belt freezers using a copper disk to represent foods. In applying this lumped mass method, Gruda and Kasieczka (1991) carried out their study of heat transfer coefficients (h) for fluidized and fixed bed freezing of foodstuffs using two different approaches. In their first approach, a copper sphere was warmed up before testing then subjected to a constant-temperature cooling medium. For the second approach, they presented a novel set-up for the copper sphere in the center of which they installed a small electrical heater during freezing. A constant heat flux on the surface was assumed. The copper temperature was measured just beneath the sphere surface and the h calculation was carried out by $h = q/(T_a - T_s)$. Identical to this second approach, Clary and Nelson (1970) introduced the lumped mass method for irregularly-shaped foodstuffs which were modeled as ellipsoids. Sastry (1984) and Chau and Snyder (1988) used mushroom- and shrimp-shaped aluminum castings, to investigate mushroom and shrimp heating processes. Ramaswamy et al. (1983) developed a quick release system to suddenly introduce an aluminum test brick to the steam retort in which steam remained at a constant temperature.

Heat conduction in the absence of a temperature gradient would imply the existence of infinite thermal conductivity. Such a condition is clearly impossible. However, although the condition is never satisfied exactly, it is closely approximated if the resistance to conduction within the solid is small compared with the resistance to heat transfer between the solid and its surroundings. In neglecting temperature gradients within the solid, we can no longer consider the problem from within the framework of the heat conduction equation. Instead, the transient temperature response is determined by formulating an overall energy balance on the solid (Incropera and Dewitt, 1990). This balance relates the rate of the heat loss at the surface E_{out} to the rate of change of the internal energy E_{st}, generally, not considering any surface mass transfer effects.

$$-E_{out} = E_{st} \tag{3.27}$$

or

$$-hA_s(T(t)-T_a)=\rho VC_p\frac{dT(t)}{dt} \tag{3.28}$$

Introducing the temperature difference

$$\theta \equiv T-T_a \tag{3.29}$$

and recognizing that $(d\theta / dt)=(dT / dt)$, it follows that

$$\frac{\rho VC_p}{hA_s}\frac{d\theta}{dt}=-\theta \tag{3.30}$$

Separating variables and integrating from the initial condition, for which T(0) = T_i,

$$\frac{\rho VC_p}{hA_s}\int_{\theta_i}^{\theta}\frac{d\theta}{\theta}=-t \tag{3.31}$$

where

$$\theta_i \equiv T_i-T_a \tag{3.32}$$

Evaluating the integrals it follows that

$$\frac{T(t)-T_a}{T_i-T_a}=\exp[-(\frac{h(t)A_s}{\rho VC_p})t] \tag{3.33}$$

Equation (3.33) indicates that the heat transfer coefficient h(t) is explicitly correlated with temperature T. It is important to note that the coefficient computed by Equation (3.29) is the effective/overall coefficient over the processing period t.

There are some other methods used in dealing with the time derivative in Equation (3.28). Sastry (1984) rewrote it into the form of Equation (3.34) and solved using a fourth-order Runge-Kutta procedure starting from the initial temperature value and using a range of trial values for the effective h.

$$\frac{dT(t)}{dt}=-\frac{hA_s}{\rho VC_p}(T(t)-T_a) \tag{3.34}$$

Khairullah and Singh (1991) included the explicit effect of radiation in the energy balance (Equation 3.35), and then calculated the transient heat transfer coefficient using a finite difference interpretation (Equation 3.37).

$$hA_s(T - T_a) + \varepsilon A_s\sigma(T^4 - T_a^4) = \rho VC_p \frac{dT}{dt} \tag{3.35}$$

Finite difference formulation of temperature derivative

$$\left.\frac{dT}{dt}\right|_{i+1} = \frac{T_{i+2} - T_i}{2\Delta t} \tag{3.36}$$

$$h_{i+1} = \frac{\rho VC_p(\frac{T_{i+2} - T_i}{2\Delta t}) - \varepsilon A_s\sigma(T_{i+1}^4 - T_a^4)}{A_s(T_{i+1} - T_a)} \tag{3.37}$$

Reid and Meybeck (1991) computed the effective surface heat transfer coefficient from the relationship (3.38).

$$h = \frac{(\rho V)C_p}{A_s} \frac{T_i - T_t}{\int_0^{t_f}(T(t) - T_a(t))dt} \tag{3.38}$$

This is a modification of Equation (3.28), and the time derivative is modified by

$$\frac{dT(t)}{[T(t) - T_a(t)]dt} = \frac{T_i - T_f}{\int_0^{t_f}[T(t) - T_a(t)]dt} \tag{3.39}$$

where T_f is the final temperature at t_f ending the process.

Cowell and Namor (1974) developed a very different analytical approach for the h calculation. The main difference from other methods was that this approach did not assume zero gradient. The test plate was considered to be part of an infinite slab of thickness l with an arbitrary temperature distribution at time t = 0. The face at $x = l$ was in contact with a stirred fluid maintained at temperature T_0 for t > 0 and the surface at x = 0 was perfectly insulated. First, they obtained Equation (3.40), which is the reduction of an expression developed by Carslaw and Jaeger (1959) for the temperature T(t) at time t in the plane at distance x from the insulated face of the slab. The important assumption is $t \rightarrow \infty$,

$$T(t) - T_a = C\exp[-(\frac{k\alpha_1^2}{\rho C_p l^2})t] \tag{3.40}$$

Where, the quantity C is constant independent of temperature, and α_1 is the first real positive root of

$$\alpha \tan\alpha = \frac{hl}{k} \tag{3.41}$$

At any depth x, a plot of $\ln(T(t)-T_a)$ against t is asymptotic to a line of slope

$$S = \frac{-\alpha_1^2 k}{\rho C_p l^2} \tag{3.42}$$

It is reported that if k, ρ, C_p and l are known in (3.42), α_1 can be obtained from an experimental value of S and inserted into (3.41) to give h (Pflug et al., 1965). Then, expanding tan α, (3.41) was modified

$$\alpha\{\alpha + \frac{\alpha^3}{3} + \frac{2\alpha^5}{15} + \cdots\} = \frac{hl}{k} \tag{3.43}$$

Depending on the magnitude of α, the heat transfer coefficient (h) can be calculated as retaining only one term or two terms in Equation (3.44).

$$h = -S\rho C_p l \tag{3.44}$$

or

$$h = -S\rho C_p l + \frac{S^2\rho^2 C_p^2 l^3}{3k^2} \tag{3.45}$$

They also point out that if Biot (= hl/k) $\leq$ 0.1, the maximum error in h due to using (3.44) instead of (3.41) and (3.42) is 3.2%, thus (3.44) would be adequate in many cases.

Ramaswamy et al. (1983) developed a fairly complicated iterative procedure for the calculation of the heat transfer coefficient (h) by the lumped mass method. In their tests, a metal brick initially at a uniform temperature, T_i, was plunged into a constant ambient temperature, T_a at t = 0. The temperature history at the center of the brick, T, was calculated by considering the general equation for unsteady state heat transfer into a metal plate of infinite dimension (Carslaw and Jaeger, 1959):

$$U = \sum_{n=1}^{\infty} \frac{2\sin\alpha_n}{\alpha_n + \sin\alpha_n \cos\alpha_n} \cos(\alpha_n x / d) \cdot \exp(-\alpha_n{}^2 Fo) \tag{3.46}$$

where α_n is the nth positive root of

$$\beta \cdot \tan\beta = Bi \tag{3.47}$$

where U is the unaccomplished temperature ratio, $(T_a\text{-}T)/(T_a\text{-}T_i)$, Fo is the Fourier number, $\alpha t/d^2$ and Bi is the Biot number, hd/k; d, α and k are the significant dimension, thermal diffusivity and thermal conductivity of the plate material, respectively. When Fo > 0.2, at the center of the infinite plate, x = 0, the infinite summation series can be approximated by the first term of the series as

$$U = R \cdot \exp(-S \cdot Fo) \tag{3.48}$$

where

$$R = \frac{2\sin\alpha_1}{\alpha_1 + \sin\alpha_1 \cos\alpha_1} \tag{3.49}$$

$$S = \alpha_1{}^2 \tag{3.50}$$

A finite brick-shaped object may be thought of as being formed by the intersection of three infinite plates. If U(b) represents the temperature ratio at the center of a brick, so

$$U(b) = U(p1) \cdot U(p2) \cdot U(p3) \tag{3.51}$$

where U(p1), U(p2) and U(p3) are the temperature ratios at the centers of the three constituent infinite plates from which the finite brick is formed. Equation (3.49) can be expanded as

$$U(b) = R(p1) \cdot R(p2) \cdot R(p3) \cdot \exp\{-[\frac{S(p1)}{a^2} + \frac{S(p2)}{b^2} + \frac{S(p3)}{c^2}] \cdot \alpha \cdot t\} \tag{3.52}$$

where 2a, 2b and 2c are the length, width and thickness of the brick.

When the center temperature of the brick is plotted against time as $\log(T_a - T)$ vs t, the equation for the straight line portion of the curve can be written as

$$\log(T_a - T) = \log[j \cdot (T_a - T_i)] - t / f_h \tag{3.53}$$

where f_h is the negative reciprocal slope of the straight line portion of the curve and j is the lag factor defined by $j = (T_a - T_{pi}) / \log(T_a - T_i)$. T_{pi} is the pseudo-initial temperature obtained from the intercept of the straight line portion of the curve extended to the beginning of the heating process. By rearrangement, Equation (3.53) can be written as

$$\frac{T_a - T}{T_a - T_i} = j \cdot 10^{-(t/f_h)} = j \cdot \exp(-2.303 \cdot t / f_h) \tag{3.54}$$

Recognizing that the temperature ratio in Equation (3.54) is the same as U(b) in Equation (3.52), and comparing the two equations, it is evident that j = R(p1)R(p2)R(p3) and that arguments of the exponential functions can be equated, thus the final equation is

$$f_h = \frac{2.303}{\alpha \cdot [\frac{S(p1)}{a^2} + \frac{S(p2)}{b^2} + \frac{S(p3)}{c^2}]} \tag{3.55}$$

Equation (3.55) indicates that for a given material of specified dimensions, f_h is inversely proportional to the sum of the S values which are dependent on the Biot number associated with the three dimensions of the brick which in turn depend on the heat transfer coefficient. Equation (3.55) has to be solved for h by an interative procedure.

<u>Procedure for h Determination</u>

The lumped mass method is valid only when the temperature of the solid can be assumed spatially uniform at any instant during the transient process (Incropera and Dewitt, 1990). For our experiments, a piece of pure copper (thickness L = 0.635 cm) was used to keep the Biot number small (Bi = hL/k < 0.1) and to ensure the accuracy of this method. Transient heat transfer coefficients were determined by formulating an overall energy balance on the copper brick:

$$-h(t)A_s(T(t) - T_a) = \rho V C_p \frac{dT}{dt} \tag{3.56}$$

Where, V is the volume of the copper block and A_s is the surface temperature. The thickness of the copper block,

$$L = \frac{V}{A_s} \tag{3.57}$$

The time derivative was assumed to be

$$\frac{dT}{dt} = \frac{T(t + \Delta t) - T(t - \Delta t)}{2\Delta t} \tag{3.58}$$

Where, $\Delta t = 0.5$ sec is the time interval for our data collection. Thus, time-dependent heat transfer coefficient can be calculated by the following equation,

$$h(t) = -\frac{\rho L C_p}{2\Delta t} \frac{T(t+\Delta t) - T(t-\Delta t)}{T(t) - T_a} \tag{3.59}$$

where, L is the thickness of the copper block; ρ is the density; C_p is the specific heat; T_a is the ambient temperature; $T(t+\Delta t)$, $T(t)$ and $T(t-\Delta t)$ are the copper temperatures at time $t+\Delta t$, t and $t-\Delta t$.

Equation (3.59) is actually a modification of Equation (3.56) which is originally used to calculate a constant effective heat transfer coefficient for the whole time history (0-t). The initial temperature is the product temperature before heating. In this study, it was possible to calculate the heat transfer coefficient at each time level (every 0.5 sec) since the timestep for temperature measurements was small (0.5 sec). The product temperature of each time level was used as the initial temperature of next time level. In this manner, the calculated heat transfer coefficients were approximately treated as time-dependent heat transfer coefficients.

Heat Flux Method

The heat flux method is the simplest and most convenient for determining the heat transfer coefficient, because h values are directly calculated from the measurements of surface heat flux and surface temperature. The measuring device used herein is the Model 27070-1 RdF Industry Micro-Foil Heat Flux Sensor with a foil-type thermocouple.

Instrumentation

The Micro-Foil heat flux sensor (RdF Corporation, Hudson, NH) is a differential thermocouple type sensor which utilizes a thin foil type thermopile bonded to both sides of a known thermal barrier. Its dimension is 35.1 mm x 28.5 mm x 0.15 mm. The difference in temperature across the thermal barrier is proportional to heat flux through the sensor. The foil-type sensor and the thermocouple were developed using a new micro-foil technology and materials. The sensor is unique because it is very thin and provide minimal thermal perturbations to the heat flux. Using this heat flux sensor, a microvoltmeter is needed to resolve the output signal in microvolts yielded by the sensor. A Campbell 21X microvoltmeter datalogger (Logan, UT) was used in this study. The accuracy of the measurement with this sensor is optimized by proper installation and the ability to adequately couple the sensor to the materials surrounding it as well as to any prevailing thermal conditions. The usual technique for installation is to recess the sensor an amount equal to its thickness, thus making the installation flush with the surrounding area (Ortolano and Hines, 1983). This heat flux sensor is unique in using an integral foil-type thermocouple to measure the surface temperature. However, the direct measurements of surface heat flux and surface temperature would involve some uncertainty. The performance specifications of the heat flux sensor are listed below:

Upper Temperature Limit: 400 ^{o}F (204 ^{o}C)

Number of Junctions: 40

Thermocouple: Type K

Carrier: Polyimide Film (Dupont Kapton)

Nominal Thickness: 0.006 inches

Sensor Resistance: 300 ohms approx.

Lead Wires: #30 AWG Solid Copper, Teflon insulated

Response time: 0.60 sec

Nominal sensitivity: 1.0 $\mu V/(W/m^2)$

Maximum Recommended Heat Flux: 95,000 W/m^2

Thermal Capacitance: (600 $W\text{-}s/m^2)/^oC$

Thermal Resistance: 0.002 $^oC/(W/m^2)$

Calculation of h

Since the surface temperature can be measured at the time the heat flux measurement is made by this device, the calculation of transient heat transfer coefficients becomes the most convenient. According to Beck et al. (1985), time-dependent heat transfer coefficient (h) can be calculated as

$$h(t) = \frac{q(t)}{T_a(t) - 0.5[T_s(t) + T_s(t - \Delta t)]} \tag{3.60}$$

where, q(t) is surface heat flux, $T_s(t)$ and $T_a(t)$ are surface and ambient temperatures.

The heat flux method is seldom used for h study because of the uncertainty of measurements. The deviation of either surface temperature or heat flux would result in appreciable inaccuracy. One study using this method is by Federov et al. (1972) who utilized a heat flux pickup to measure the time-dependent heat flux and surface temperature. Their study indicated that the mere presence of the device alters the surface of the test subject, thus making the readings approximate (Arce and Sweat, 1980).

4. COMPARATIVE METHODS OF DETERMINING HEAT TRANSFER COEFFICIENTS OVER STEAM-COOKED SURIMI PASTE

E. SU, E.R. KOLBE and J.W. PARK

ABSTRACT

A comparative evaluation employed the inverse calculation method, the lumped mass method and the heat flux method to determine time-dependent heat transfer coefficients (h) over food while simulating a surimi steam cooking process. The inverse calculation method was developed to model the coefficients from temperature histories at three interior locations in surimi paste during a 1000-sec cooking period. The application of this inverse calculation method provided an accurate estimation of time-dependent heat transfer coefficients, and a good agreement between predicted and experimentally determined temperatures. The lumped mass method which overestimated the heat transfer coefficient is inappropriate for heat transfer analysis associated with steam as the heating medium. The heat flux method gave inconsistent h results under steam conditions and is not an accurate method.

INTRODUCTION

Surimi, a washed and refined form of minced fish meat, is widely used for fabricating new food items which require specific textural attributes because of its distinguishing gel-forming capacity. Production of surimi represents a potential utilization of a number of under-utilized fish species of which Pacific whiting represents the largest biomass off the West Coast of the United States. However, a protease enzyme softens the fish flesh in Pacific whiting and limits the expansion of surimi production.

Many studies have demonstrated the importance of heating rate and product temperature in minimizing texture softening of fish flesh (Greene and Babbitt, 1990; Hamann et al., 1990; Kinoshita et al., 1990; Shimizu et al., 1992; Wasson, 1992; Bertak and Karahadian, 1995). An optimal design of surimi seafood process is possible only when time-varying temperature distributions in the product can be accurately predicted which provide a measure of the heating rate and the extent of thermal processing. The surface heat transfer coefficient is one of the most important parameters for such a temperature prediction. This study was intended to measure and model the heat transfer coefficient (h) over thin-sheets of surimi paste horizontally cooked in a steam heating environment, simulating the direct steam heating generally utilized for surimi seafood production.

Many factors influence the surface heat transfer coefficient over steam-cooked food. In the heat transfer study of steam blanching of green bean, Zhang and Cavalieri (1991) presented the coefficient as a function of the temperature difference between ambient and the food surface, thermal properties of steam, and diameter of green bean.

$$h = 0.06\left[\frac{\rho_f^{\,2} g h_{fg} k_f^{\,3}}{(T_a - T_s)\mu_f L}\right]^{0.25} \tag{4.1}$$

The equation is a modification of an empirical correlation generally used for condenser design calculations of horizontal tubes; the coefficient of 0.725 for the condenser has reduced to 0.06 for application to the green bean case. A similar empirical correlation for a rotating horizontal plate was developed by Nandapurkar and Beatty (1960), except that the dimension of the plate was not included.

Ramaswamy et al. (1983) and Tung et al. (1984) have directed much effort toward the study of the heat transfer coefficient utilizing an aluminum brick in steam retorts and developed an exponential equation between the heat transfer coefficient and the steam content using lumped mass analysis. They pointed out that the steam content of a steam/air mixture was the major factor influencing the heat transfer coefficient, and the steam flow rate/velocity, steam flow direction and product orientation also influenced the coefficient. On the other hand, the medium flow velocity over the product surface, normally a major factor affecting the convective heat transfer, has only a small effect on the heat transfer coefficient under a normal steam cooking condition (McAdams, 1954; Ling et al., 1974; Ling et al., 1976). Ling et al. (1976) tested the effect and reported that increasing steam velocity did not have a drastic effect on overall heating rate of sweet potato. They found that a ten-fold increase in steam velocity only improved temperature change by 3-4 ^{o}C.

Methods for determining the heat transfer coefficient can be divided into the inverse calculation method, the lumped mass method and the heat flux method. The estimation of surface conditions from temperature measurements inside a heat-conducting solid involves the solution of the heat conduction problem and nonlinear parameter optimization. Beck et al. (1985) defined it as the inverse heat conduction problem, and summarized a number of methods for the inverse calculation of the heat flux and/or surface temperature. It is important to note that the same methods can be used for inverse calculation of the heat transfer coefficient.

As described by Beck et al. (1985), the two basic classes of methods for the solution of the inverse heat conduction problem are function specification and regularization methods. In the function specification method, a functional form for the unknown heat transfer coefficient is assumed; the unknown parameters in the function are estimated utilizing the method of least squares. The regularization method modifies the least squares approach by adding factors that are intended to reduce excursions in the unknown function. After choosing a function (h model) representing the heat transfer coefficient, either the whole domain estimation procedure or the sequential estimation procedure has been used by researchers to estimate the unknown parameters contained in the function. The whole domain parameter estimation method is a powerful procedure, because very small time steps can be taken and all the parameters for the complete time history are simultaneously estimated. However, the whole-domain procedure is not as computationally efficient as the sequential method which uses only a few future temperatures. The results produced by the function specification method and the sequential regularization method are quite similar (Beck et al., 1985).

The inverse estimation of the heat transfer coefficient for a food thermal process is usually accompanied by the use of a food substitute of known thermal properties. Scott et al. (1992) applied the sequential regularization method in studying time-dependent surface heat transfer coefficients in frozen foods using the Karlsruhe Test Substance (the Federal Research Institute, West Germany), a highly concentrated methyl-cellulose mixture having thermal properties similar to those of common food products. Chavarria and Heldman (1984) estimated a constant heat transfer coefficient for food freezing processes using an acrylic transducer of known $C_p(T)$ and $k(T)$. In this case, the inverse problem was actually simplified as a one-parameter estimation. Bonacina and Comini (1972) also assumed a constant value for the surface heat transfer coefficient during cooling using "Tylose", a gel having strongly temperature-dependent thermal properties.

The inverse calculation method is considered to be the most accurate method, however, the application of this method is limited by its analytical complexity and difficulty in computer programming (Arce and Sweat, 1980; Chavarria and Heldman, 1984; Scott et al., 1992). Simpler methods are desirable in many cases. One of these, the lumped mass method, is much simpler and has been widely used in studying the heat transfer coefficient. And perhaps the most convenient method is the heat flux method from which the heat transfer coefficient (h) can be directly calculated from the measurements of the surface heat flux and surface temperature.

The objectives of this study were: (1) to develop an accurate heat transfer coefficient model for the design and optimization of surimi steam process; (2) to develop an inverse calculation method to accurately model the heat transfer coefficient; (3) to compare the inverse calculation method, the lumped mass method and the heat flux method in determining heat transfer coefficients associated with steam as the heating medium.

MATERIALS & METHODS

Theoretical Consideration

Inverse calculation method. The procedure developed in this study for the inverse calculation of the heat transfer coefficient is a whole domain function specification method. The functional form assumed for the heat transfer coefficient was a modification of empirical models found in the literature (Nandapurkar and Beatty, 1960) and included the ambient temperature and the surface temperature as independent variables. Using this method, unknown parameters in the function were estimated simultaneously by minimizing differences between predicted and experimental temperatures at three internal locations in surimi paste during a 1000-sec cooking period. A nonlinear regression computer program (Appendix B) was written for this inverse calculation method. In this computer program, the heat conduction equation is discretized using the implicit Crank-Nicolson numerical method; the boundary condition equations are implicitly discretized through modifying Taylor series expansions (Hoffman, 1990); and the nonlinear parameter optimization is carried out using the downhill simplex method (Press et al., 1992).

Temperature-dependent thermophysical properties of surimi paste were evaluated using the property models developed by AbuDagga and Kolbe (1996) for the same whiting surimi paste. Thermophysical properties of AISI 304 stainless steel (ρ=7900 kg/m^3, C_p=477 J/kg ^{o}C, k=14.9 W/m ^{o}C, Incropera and Dewitt, 1990) were evaluated at 40 ^{o}C, the average temperature of the stainless-steel insulated tray during cooking.

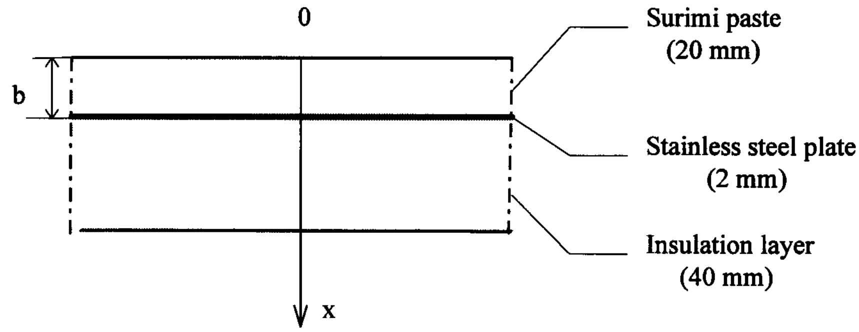


Figure 4.1—One-dimensional heat transfer by conduction.

One-dimensional heat conduction was assumed for heat transfer in surimi paste cooked on an insulated stainless-steel tray (Figure 4.1).The mathematical description of this one-dimensional heat transfer problem is:

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[k(T)\frac{\partial T}{\partial x}] \qquad \text{for surimi paste} \qquad (4.2)$$

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \qquad \text{for stainless steel plate} \qquad (4.3)$$

The heat transfer coefficient (h) is involved in the boundary conditions,

$$-k(T)\frac{\partial T}{\partial x} = h(T)[T_a(t) - T_s(t)] \qquad \text{for convection on surimi surface} \qquad (4.4)$$

$$\frac{\partial T}{\partial x} = 0 \qquad \text{for insulated stainless steel surface} \qquad (4.5)$$

A uniform initial temperature distribution was assumed for surimi and stainless steel tray,

$$T(x,0) = T_0 \qquad (0 \le x \le b) \qquad (4.6)$$

The sum of least squares for total m (= 3) locations with n (= 1000) data points (data were collected once per second for 1000 sec) at each location is:

$$S = \sum_{i=1}^{m}\sum_{j=1}^{n}(Y_{ij} - T_{ij})^2 \qquad (4.7)$$

Lumped mass method. The essence of the lumped mass method is the assumption that the temperature of the heated solid is spatially uniform at any instant during the transient process (Incropera and Dewitt, 1990). A piece of pure copper (thickness: L = 0.635 cm) was used to keep the Biot number small ($Bi = hL/k < 0.1$) and to ensure the accuracy of this method. The heat transfer coefficient was determined by formulating an overall energy balance on the copper block:

$$-h(t)A_s[T(t) - T_a(t)] = \rho V C_p \frac{dT}{dt} \tag{4.8}$$

For a small time increment Δt, it is assumed that

$$\frac{dT}{dt} = \frac{T(t+\Delta t) - T(t-\Delta t)}{2\Delta t} \tag{4.9}$$

The thickness of the copper block is,

$$L = \frac{V}{A_s} \tag{4.10}$$

where, V is the volume of the block and A_s is the surface area. The heat transfer coefficient was calculated by the following equation,

$$h(t) = -\frac{\rho L C_p}{2\Delta t} \frac{T(t+\Delta t) - T(t-\Delta t)}{T(t) - T_a(t)} \tag{4.11}$$

The time interval of the temperature measurements was $\Delta t = 0.5$ sec.

Heat flux method. The heat flux method determined the time-dependent heat transfer coefficient utilizing a heat flux sensor with integral thermocouple to measure both the surface heat flux and the surface temperature. The calculation of the heat transfer coefficient was straightforward when the surface heat flux and surface temperature are known (Beck et al., 1985).

$$h(t) = \frac{q(t)}{T_a(t) - 0.5[T_s(t) + T_s(t - \Delta t)]} \tag{4.12}$$

Test Materials

Surimi samples. Pacific whiting (*Merluccius productus*) surimi was taken from the process line of a local manufacturer, mixed with 4% sucrose, 4% sorbitol (ICI Specialties, New Castle, DE), and 0.3% sodium tripolyphosphate (B.K. Ladenburg Corp., Cresskill, NJ) and frozen at the OSU Seafood Laboratory in Astoria, OR. Samples had been stored in a -30 °C room for 2 months before our experiments.

To make surimi paste, frozen surimi was tempered 2-3 hr at room temperature. Partially thawed surimi was then chopped with 2% NaCl, 1.5% enzyme inhibitor (beef plasma protein) and some ice water for 4 min in a Stephan vertical vacuum chopper (Model UM 5 universal, Stephan Machinery Co., Columbus, OH) to obtain a final mixture of 80% moisture content. The temperature was maintained below 8 °C. The moisture content of surimi samples was measured by an infrared moisture determination balance (Model AD-4714A, A&D Company, Limited, Tokyo, Japan). Upon completion of chopping, the surimi paste was stuffed into PVC containers (about 0.5 kg each) and held below 10 °C in a styrofoam box until cooking.

Copper block. A piece of pure copper (152 mm x 152 mm x 6.35 mm) was embedded in styrofoam with only one surface exposed to the ambient (Figure 4.2). Internal temperature measurements were taken at three different distances from the exposed surface to verify the uniformity of the temperature distribution in the copper

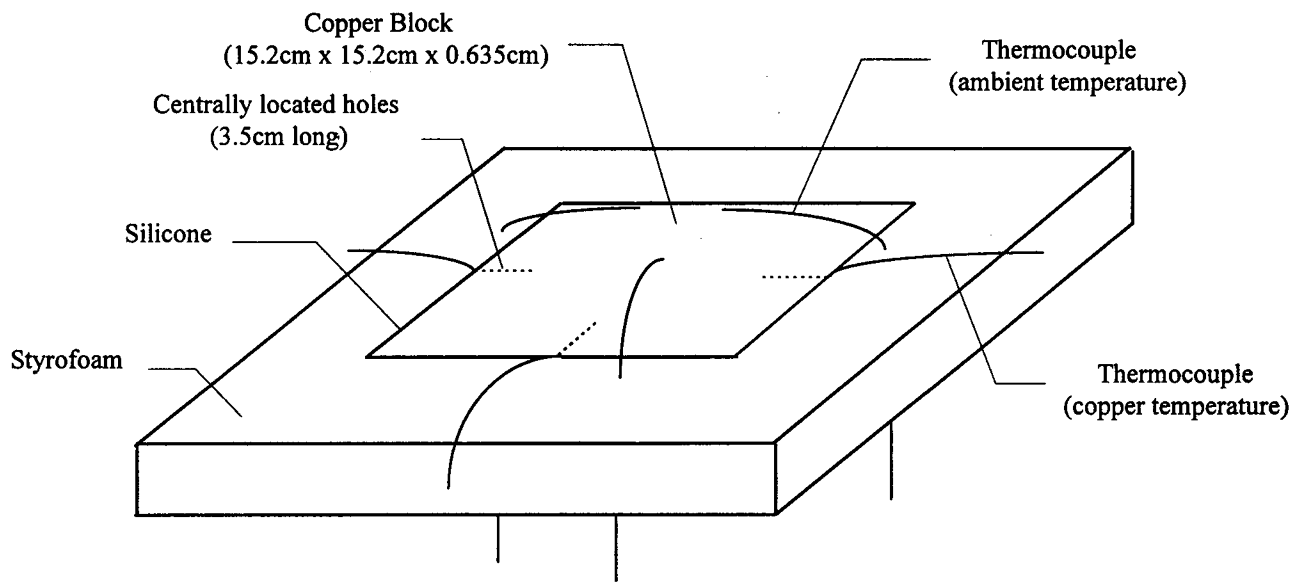


Figure 4.2—Schematic diagram of the experimental set-up for copper block.

block for the application of the lumped mass method. Three small horizontal holes were drilled in three sides for inserting the 30 gage thermocouples. Before locating the thermocouples, highly conductive heat sink compound (Radio Shack) was put on the tips of the thermocouple junctions to minimize thermal resistance and time-delay between the junctions and the copper. The boundary around the insulated copper block was filled with silicone sealant to prevent steam leakage and to fix the thermocouples. The ambient temperature was detected by three 30 gage thermocouples which were about 25 mm from the test surface. The property data was taken as the following: thermal conductivity = 400 W/m ^{o}K, specific heat = 385 J/kg ^{o}K, and density = 8933 kg/m^3 (Incropera and Dewitt, 1990); properties were evaluated at 85 ^{o}C, the average temperature of the copper block during the test.

Experimental Apparatus

Steam chamber. All the tests were conducted in an insulated stainless-steel chamber (900 mm x 900 mm x 600 mm) (Figure 4.3). Steam shot uniformly down on the test subject from two steam 1″ pipes with small holes evenly positioned on the bottom sides. To obtain a constant steam condition in the chamber for all tests, the same opening was maintained for the slide door of the chamber to allow steam to freely exit the chamber. The steam flow into the chamber was controlled by a globe valve, adjusted to achieve a good circulation of steam. The steam temperature reached 100 ^{o}C after a period of preheating. A temperature gage was mounted on the steam chamber to detect the steam temperature next to the test subject surface. A nearby on-line steam pressure gage

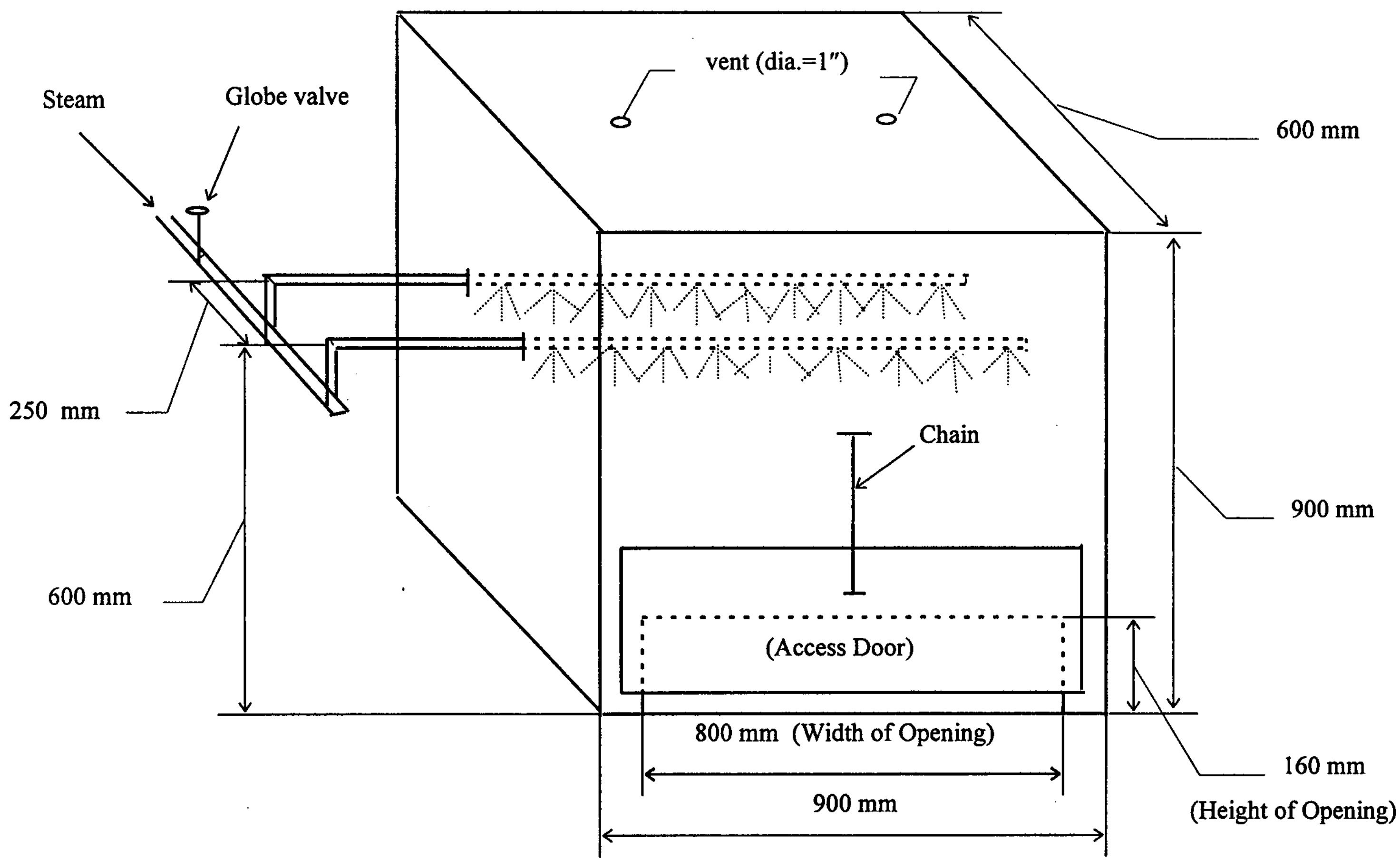
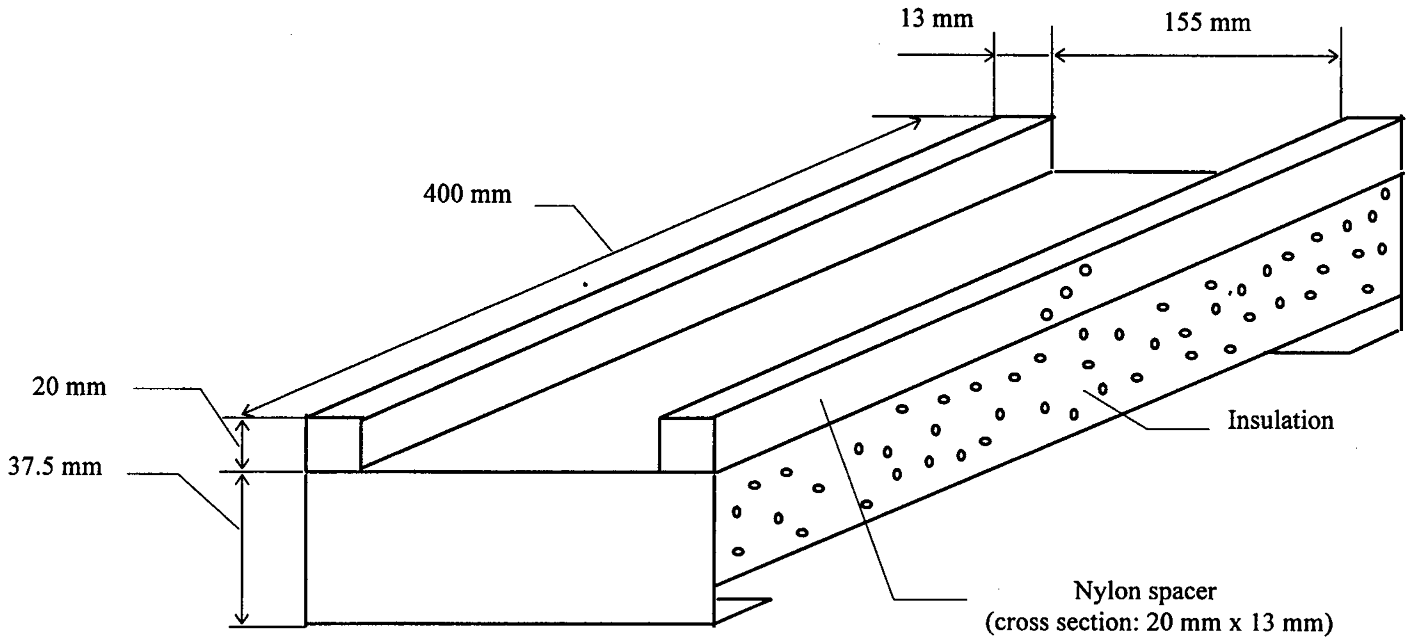


Figure 4.3—Schematic diagram of steam chamber.

was used to monitor the pressure of the steam source. A consistent steam condition was assumed if both the temperature and the pressure monitored by the gages were constant.

Surimi paste cooking tray. This tray was fabricated from a piece of 1/8″ stainless steel plate with two nylon bars (cross section: 20 mm x 13 mm) mounted on two sides to form a uniform surimi slab (Figure 4.4). Through one of the nylon bars, three small holes were evenly drilled for thermocouple probes (TMQSS-032-3, ungrounded, Omega Engineering Inc.) to measure interior temperatures of the surimi paste. The probes were 3″ long so that their tips could reach the central locations of the surimi paste which were expected to be 5 mm, 10 mm and 15 mm from the surimi surface respectively. These were the same distances from the holes in the nylon bar to its top surface. The bottom of this tray was well insulated by DAP KWIK foam (DAP Inc., Dayton, OH). The surimi paste (20 mm thick) formed on this tray (400 mm x 155 mm x 20 mm) could be assumed to be a part of an infinite slab so that the assumption of one-dimensional heat conduction would hold in this case.

Heat flux sensor. The heat flux sensor (35.1 mm x 28.5 mm x 0.15 mm) used in this study was a Model RdF 27070-1 Industrial Micro-Foil Heat Flux Sensor (RdF Corporation, Hudson, NH) with integral thermocouple for measuring surface temperature. It is a differential thermocouple type sensor which utilizes a thin foil type thermopile bonded to both sides of a known thermal barrier. The difference in temperature across the thermal barrier is proportional to heat flux through the sensor. The sensor is unique because it is very thin and provides minimal thermal perturbations to the heat flux. Using this heat flux sensor, a microvoltmeter is needed to resolve the output signal in microvolts



(The distances from the holes in the Nylon spacer to its top surface are 5mm, 10mm and 15mm, respectively.)

Figure 4.4—Schematic diagram of cooking tray.

yielded by the sensor. The usual technique for installation is to recess the sensor an amount equal to its thickness, thus making the installation flush with the surrounding area (Ortolano and Hines, 1983).

Testing Procedures

Prestabilized steam condition. It was important to prestabilize the steam condition in the chamber, because a constant steam environment was necessary to allow a comparison of the three methods used to determine the heat transfer coefficient. For this reason, the heating medium was allowed to stabilize for more than one hour.

Tests with surimi. The surimi tests were conducted to support the inverse calculation method and the heat flux method. The surimi tests were repeated 15 times under similar steam conditions. A quick preparation for the test was important to ensure a uniform temperature distribution throughout the surimi slab. When making the surimi slab, care was taken to ensure that the tray was uniformly filled with surimi paste and that the surimi surface was as smooth as possible so that one-dimensional heat conduction could be assumed. After making the surimi slab, both the heat flux sensor and the thermocouple probes were carefully located on and in the surimi slab. The initial uniform temperature of the surimi slab was between 12 and 14 ^{o}C. The positions of the tips of the three thermocouple probes were checked and adjusted relative to the surface of the stainless steel tray before each test without surimi on the tray. A second check of the positions were taken immediately after each test by carefully cutting three cross sections along the sensing tips of probes and measuring the distances by an optical micrometer.

Tests with copper. The copper tests were used to support the lumped mass method. Since the lumped mass method was valid only when the temperature measurements across the entire copper block were uniform at any instant, each tests was carried out very quickly. Data from 15 test runs were used for the lumped mass analysis.

Data collection. Temperature measurements were recorded by a Campbell 21X microvoltmeter datalogger (Campbell Scientific, Logan, UT), interfaced with an IBM PC. Data were collected twice per second for the copper test and once per second for the surimi test. For all the tests, three 30 gage type T thermocouples were used to monitor the ambient steam temperature around the test subject which had to be uniform for this heat transfer analysis. The distance between the junctions of the thermocouples and test surface was about 25 mm. Three small rubber shields were used to block junctions from “seeing” the initial cold surfaces of the test materials, thus reducing the radiation error. All tests were carried out during one day. The surimi tests and the copper tests were conducted alternately to assure that the copper and the surimi were heated under a similar steam condition. To ensure a uniform steam condition and a uniform initial temperature, the test subjects were “instantly” introduced to the steam chamber with the slide door quickly moved up and down to the same opening.

RESULTS & DISCUSSION

In evaluating the modeling results of the heat transfer coefficient obtained from the three methods, the h models were used to predict temperatures within the surimi paste and the temperature prediction was then compared with measurement. A typical comparison was carried out between the simulated and experimental temperatures at a central location of the surimi slab to evaluate the measuring and modeling results of the heat transfer coefficient and the related methods.

Inverse Calculation Method

Many different functional forms were used to model the heat transfer coefficient by the inverse calculation method. It was found that the resulted h model (Equation 4.13) from the function $h = c_1(T_a - T_s)^{c_2}$ produced the best agreement between the predicted and measured temperatures when the model was used in the heat transfer analysis of one surimi test. The h model developed for surimi paste under steam processing is:

$$h = 0.594\left[\frac{k_f^{\,3}\rho_f^{\,2}h_{fg}}{\mu_f}\right]^{0.25}\frac{1}{(T_a - T_s)^{0.70}}, \qquad R^2 = 0.95 \qquad (4.13)$$

The model was developed from the experimental temperature data of 15 tests. For each test, a similar h model was developed, which was the result of a two-parameter (c_1, c_2) optimization by the downhill simplex method. Model (4.13) is the optimized result of the 15 models. Since the steam temperature was maintained at 100 °C and 1 atm, the thermal properties of the steam were constant. The steam properties were included in the equation in the same fashion as in the empirical models. A comparison between the temperature prediction and measurement in surimi paste was shown in Figure 4.5.

Zhang and Cavalieri (1991) reported that surface heat transfer coefficients on steam-blanched green bean had a steady increase from about 400 to 1100 W/m^2 °C during

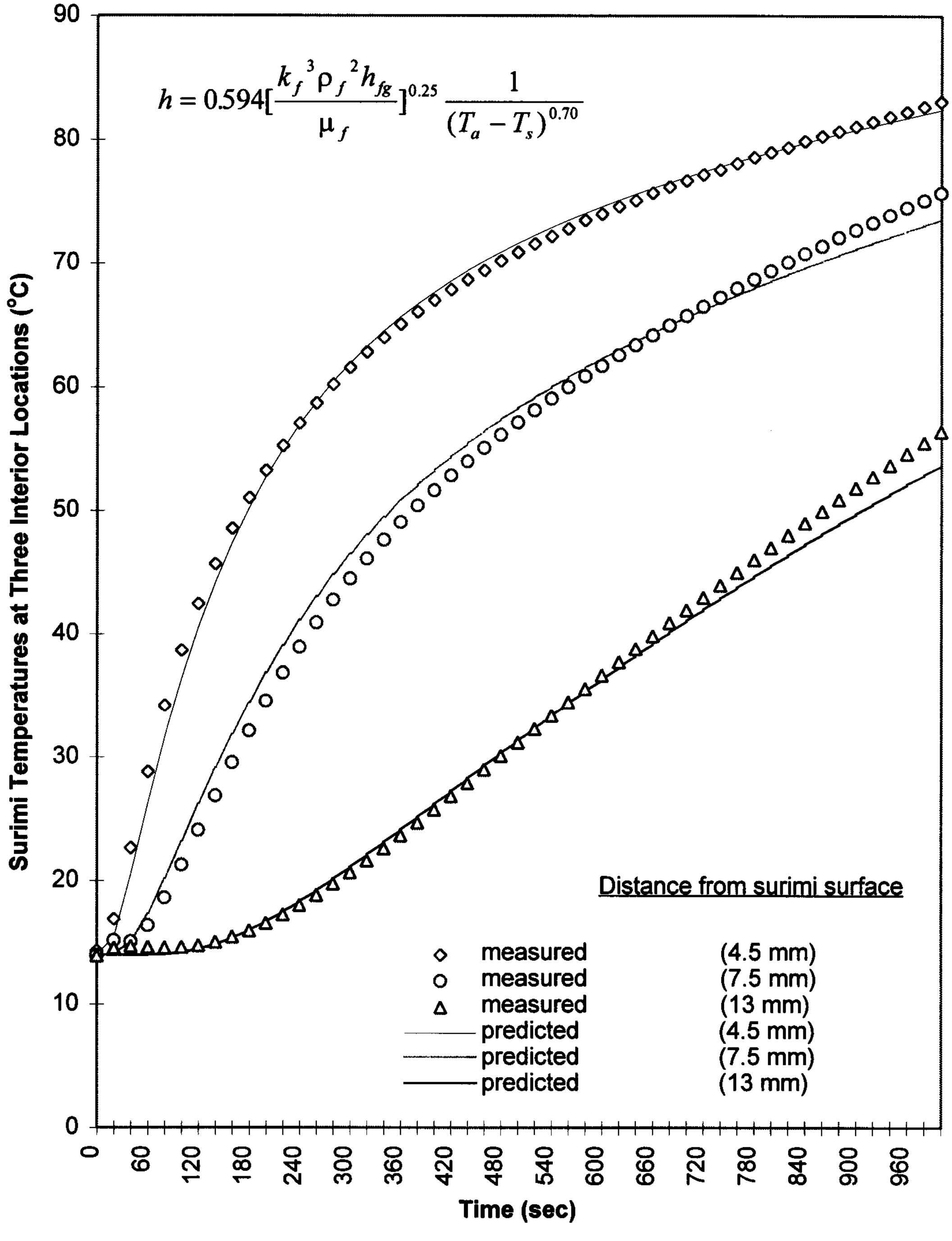


Figure 4.5—Comparison of measured and predicted temperatures in surimi. (Inverse Calculation Method)

the heating period from 100 sec to 250 sec after the 100-sec natural convection for which no steam was introduced to the steam retort. This was fairly consistent with our modeling results; during the same period of time, the heat transfer coefficient varied from 500 to 1150 W/m^2 °C. In the literature, little effort has been directed to the study of transient heat transfer coefficients associated with steam. This study was unique in modeling transient heat transfer coefficients over a long period of heating of 1000-sec for real food involving temperature-dependent thermophysical properties.

In performing inverse calculations, many researchers have evaluated the heat transfer coefficient as a constant value. It would be important to know whether or not an optimal constant h value can give a good temperature prediction. In this study, the best agreement of the temperature profiles occurred when the heat transfer coefficient was 900 W/m^2 °C, the average value of 15 tests (h values were in the range of 800-1000 W/m^2 °C for the 15 tests). Figure 4.6 presents a comparison between the temperature prediction and measurement for the same surimi test measured above, when h = 900 W/m^2 °C. Such a constant h value is much lower than that normally expected (5700-17,000 W/m^2 °C) for condensing steam (Ling et al., 1974). The significant reduction of heat transfer coefficient may be explained by mass transfer between the moist food and steam, that is, the evaporation from surimi would decrease the values of the heat transfer coefficient. The same significant reduction was found by Ling et al. (1974); surface heat transfer coefficients were respectively 1135 W/m^2 °C and 284 W/m^2 °C for steam blanching of carrots and vegetable tissues at atmospheric pressure. They stated that the h reductions were attributed to noncondensable gases from the vegetables (Ling et al., 1976).

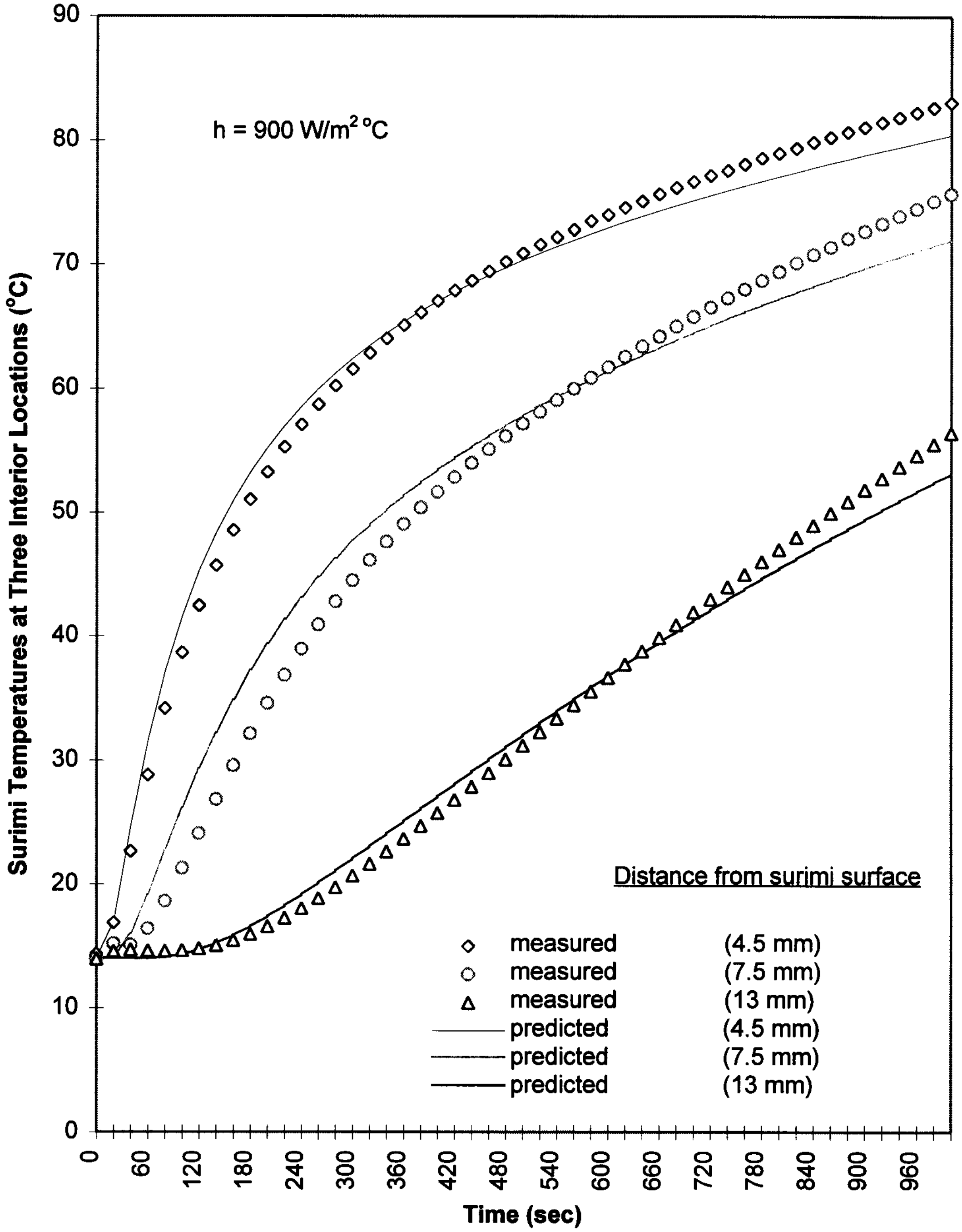


Figure 4.6—Comparison of measured and predicted temperatures in surimi, $h = 900$ W/m^2 °C. (Inverse Calculation Method)

It is evident that an appropriate functional form is better than a constant in modeling the heat transfer coefficient. However, the constant approach needs less computation and it may be acceptable in some cases. As indicated in the literature, the uncertainty of locations of interior sensors is a major factor influencing the modeling results of this inverse heat conduction problem. Using this inverse calculation method, the locations of the temperature measurements can be accurately determined, thus minimizing error resulted from the uncertainty of sensor locations.

Lumped Mass Method

The power-law relationship also performed well in relating the heat transfer coefficient to temperature difference (T_a - T_s) between the ambient and the copper.

$$h = 1.746\left[\frac{k_f^{\,3}\rho_f^{\,2}h_{fg}}{\mu_f}\right]^{0.25}\frac{1}{(T_a - T_s)^{0.42}}, \qquad R^2 = 0.89 \qquad (4.14)$$

Applying this model to the same surimi test, the temperature prediction is compared with the temperature measurement in Figure 4.7. The difficulty in using the lumped mass method to study steam heating is to maintain a uniform initial and processing temperature. For this reason, Ramaswamy et al. (1983) designed a quick release system to accomplish the instantaneous exposure of the metal transducer to the heating medium.

Heat Flux Method

The calculated values of heat transfer coefficient varied from 500 W/m^2 °C to 2000 W/m^2 °C under similar steam conditions. To reduce such a variation which

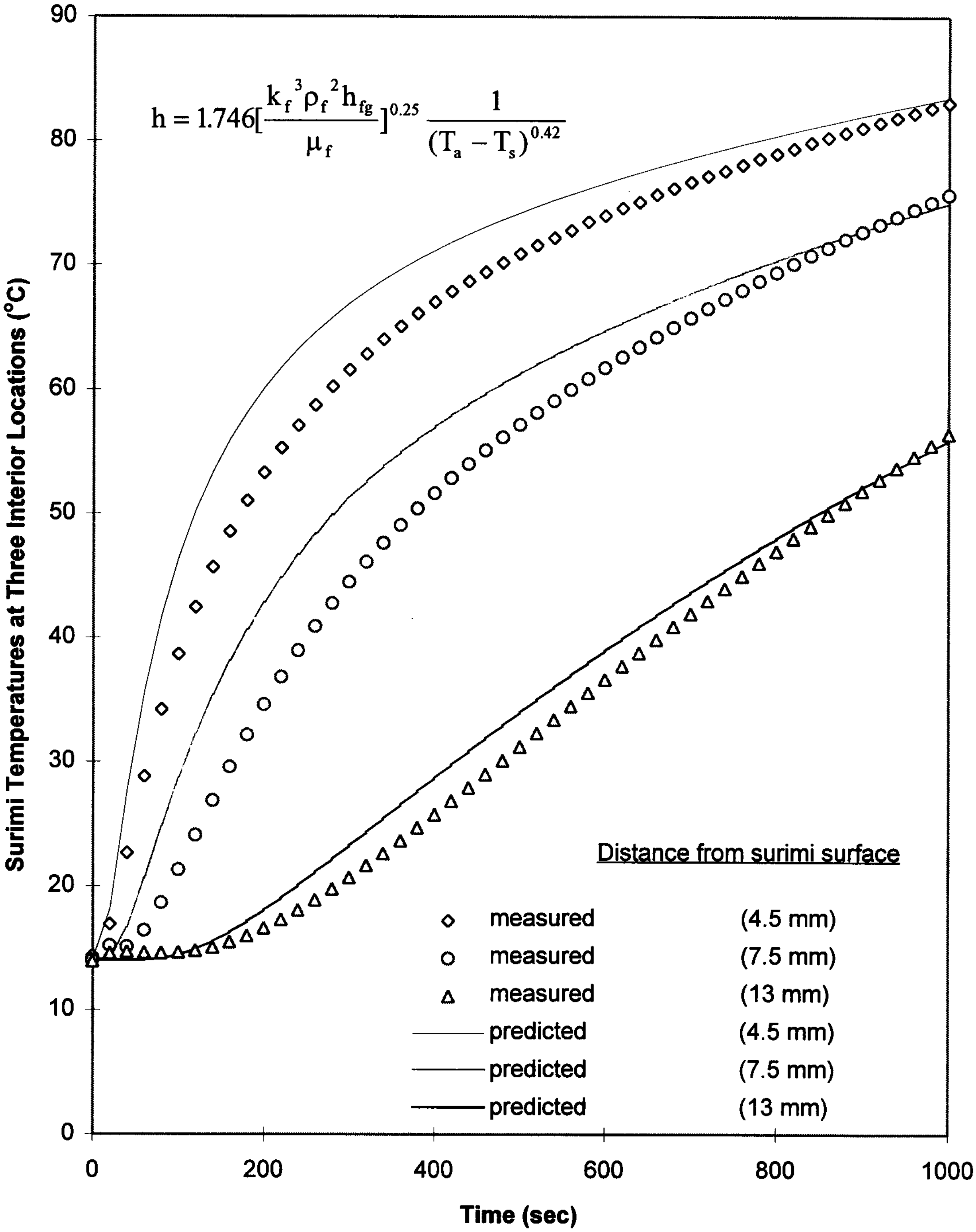


Figure 4.7—Comparison of measured and predicted temperatures in surimi. (Lumped Mass Method)

appeared to result from random steam condensation, it is recommended that tests be repeated many times and an intermediate value of heat transfer coefficient selected. Figure 4.8 is a comparison of the temperature prediction with the temperature measurement for the same surimi test, in which h = 1500 $W/m^2\ ^oC$ was used. It is important to note that the heat flux method could not provide accurate estimation of the heat transfer coefficient and it would not be appropriate for the thermal analysis of a surimi steam process. The measurement of boundary conditions by this method would involve considerable uncertainty under steam conditions.

Comparison of Methods

Figure 4.9 presents the results of the heat transfer coefficient determined by the three methods. It can be seen that the lumped mass method produced a much higher heat transfer coefficient than the inverse calculation method. Such a big difference could be explained by different surface conditions of the test subjects and different mass transfer between the medium and the test surfaces. The h curve representing the heat flux method is made up of the average values of h obtained from 15 tests. For the heat flux method, the power-law relationship was not appropriate, however h could be approximated as h = 1500 $W/m^2\ ^oC$, the value used in Figure 4.8.

The similarity of curves from the inverse calculation method and the lumped mass method was that the heat transfer coefficient experienced a small steady increase when the temperature difference was significant. It then began more rapid increase when the difference became small. As indicated in most of the published studies, higher values of

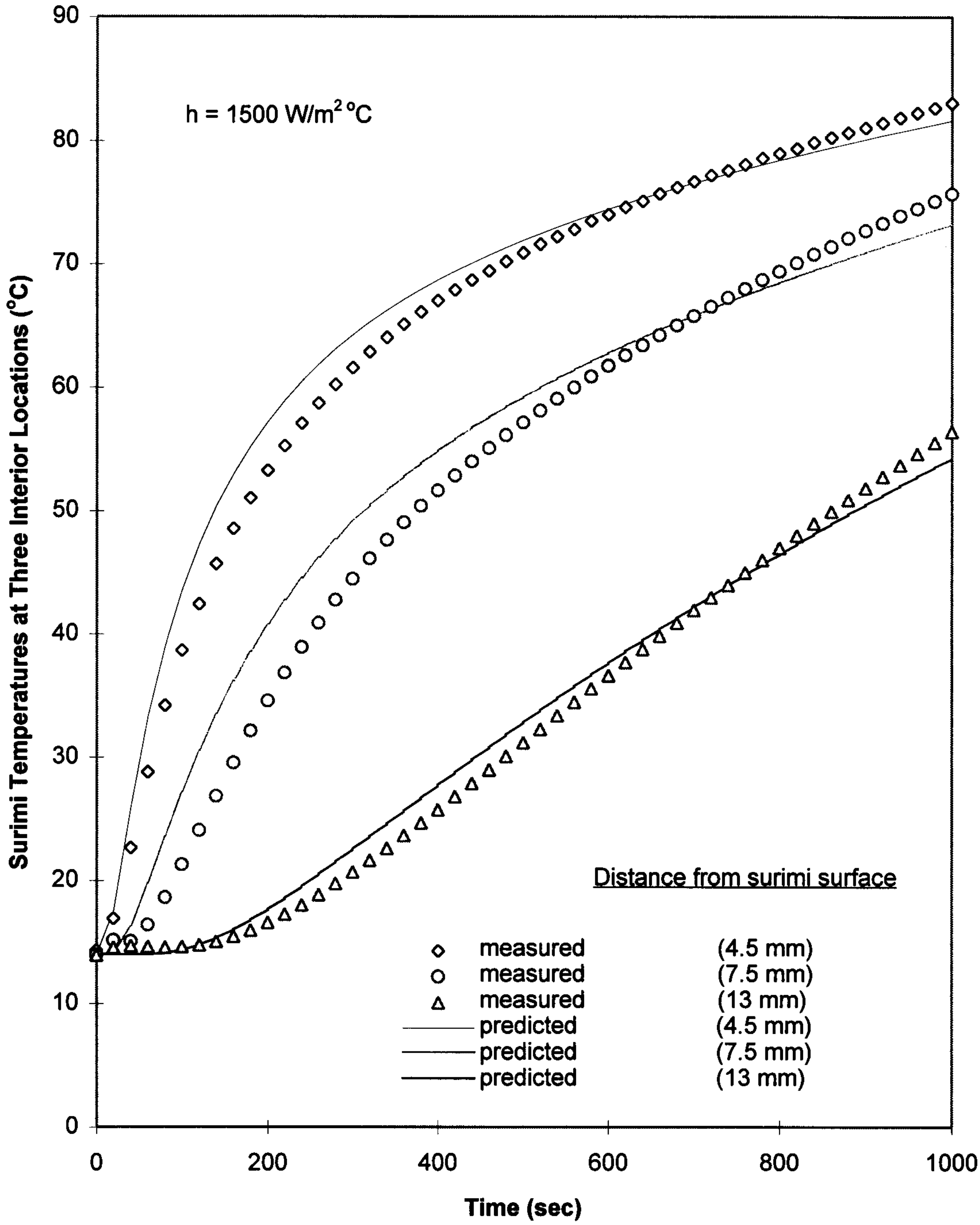


Figure 4.8—Comparison of measured and predicted temperatures in surimi. (Heat Flux Method)

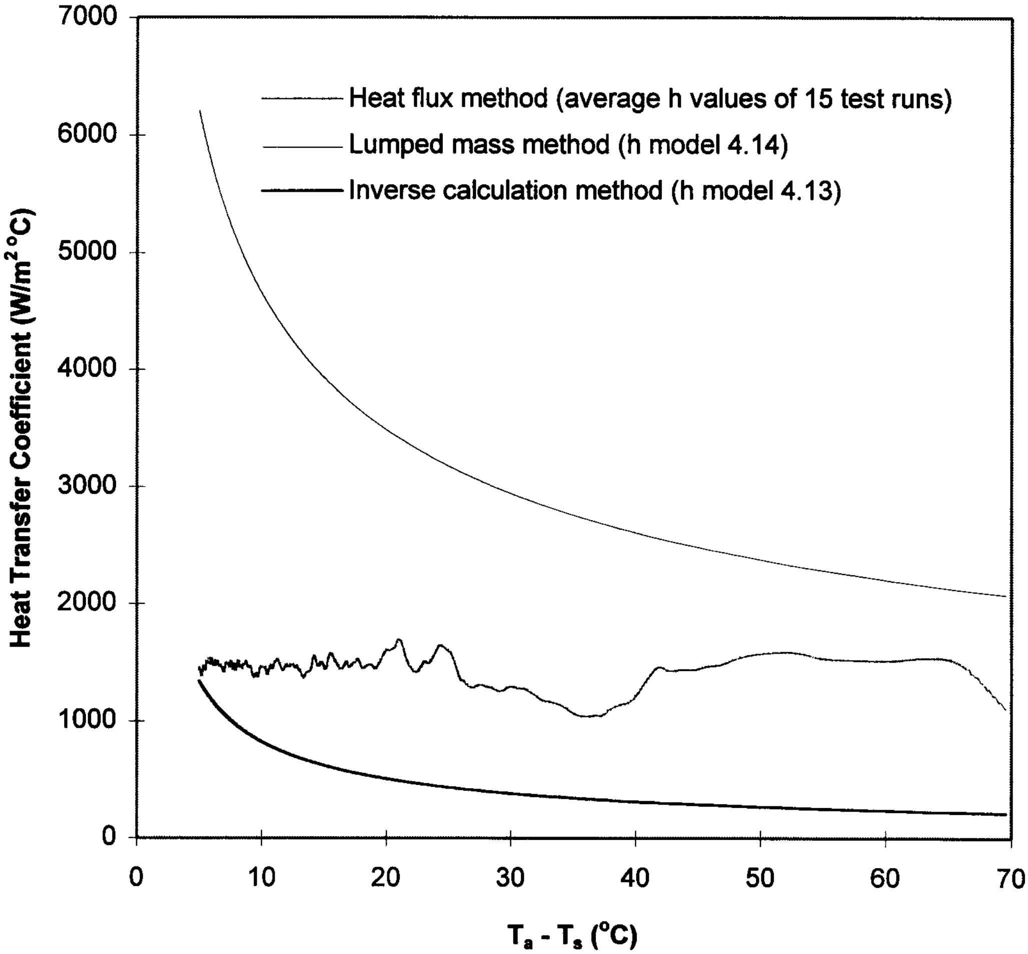


Figure 4.9—Comparison of heat transfer coefficients estimated by three methods.

the surface heat transfer coefficient were associated with small temperature difference between the heating medium and the test surface (Ramaswamy et al., 1983).

Figure 4.10 presents the difference between the predicted ($T_{predicted}$) and the measured temperatures ($T_{measured}$) when applying the h models resulting from the three methods. Using the h models to predict temperatures for the surimi paste, Table 4.1

Table 4.1

Methods	Heat Transfer Coefficient (W/m^2 °C)	max(ΔT) (°C)	ave(ΔT) (°C)
Inverse Calculation Method	$h = 0.594[\frac{k_f^3 \rho_f^2 h_{fg}}{\mu_f}]^{0.25} \frac{1}{(T_a - T_s)^{0.70}}$	2.2	1.3
	900	5.5	2.4
Lumped Mass Method	$h = 1.746[\frac{k_f^3 \rho_f^2 h_{fg}}{\mu_f}]^{0.25} \frac{1}{(T_a - T_s)^{0.42}}$	8.5	3.7
Heat Flux Method	1500 (500-2000)	6.7	2.7

compares the three methods; max(ΔT) is the maximum temperature difference and ave(ΔT) is the average temperature difference (absolute values) occurring at the central location during the 1000-sec cook.

It is obvious that the temperature prediction is more accurate using the inverse calculation method than either the lumped mass or the heat flux method. A similarity among the three methods was that their predicted temperatures were higher than the experimental ones at the beginning of the heating, but subsequently, they were lagging behind the experimental measurements. A similar temperature discrepancy was observed in the study of Stoforos and Merson (1995).

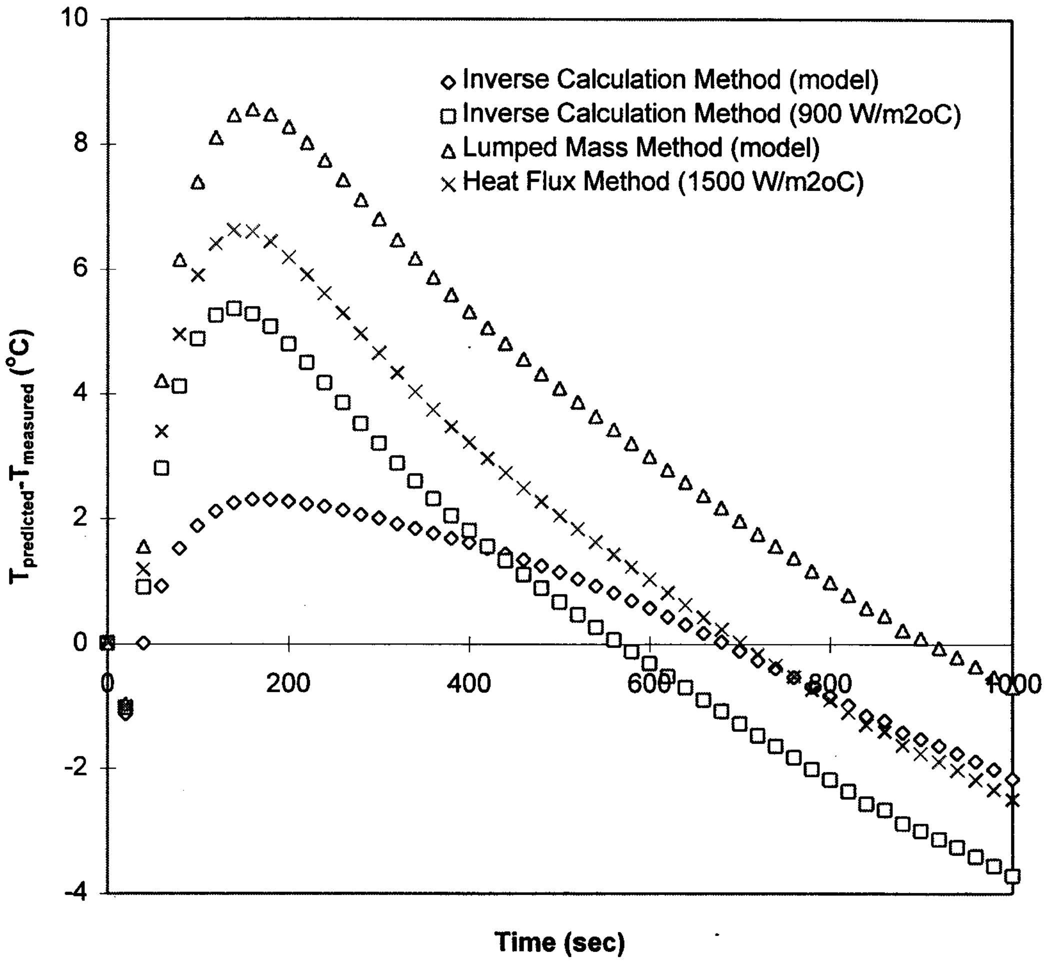


Figure 4.10—Comparison of temperature difference ($T_{predicted}$-$T_{measured}$) at a central location of surimi paste.

Among the three methods, the inverse calculation method is most accurate because the nonlinear optimization is based on transient interior temperature measurements and temperature-dependent thermophysical properties. The ultimate goal of estimating heat transfer coefficient is to predict heating rate and temperature history distributions for the process. Inversely matching the temperature prediction with the experimental measurement to establish the heat transfer coefficient model is practically the most reliable method. The main advantage of the heat flux method and the lumped mass method is the simplicity and convenience in analysis and calculation.

CONCLUSIONS

It can be concluded from this study that different methods might produce different results of the heat transfer coefficient. The inverse calculation method gave much better estimate for the heat transfer coefficient than both the inverse calculation method and the lumped mass method. The lumped mass method overestimated the heat transfer coefficient and gave poor temperature prediction for surimi paste. The heat flux method provided inconsistent measurements of the surface heat transfer coefficient. Neither the lumped mass method nor the heat flux method are recommended for thermal analysis of steam cooking of moist food materials.

The inverse calculation method utilized a whole domain function specification procedure to simulate surface heat transfer coefficients based on interior temperature measurements in a food product. The main advantages of this procedure in assuring the accuracy of h modeling include: (1) it can handle a large number of temperature data to assure the reliability of parameter estimation; (2) it enables simultaneous and accurate estimation of time-dependent heat transfer coefficient and locations of temperature measurements, the uncertainty of which is known to be a major factor influencing the solution of inverse heat conduction problem.

NOMENCLATURE

A_s	Convective surface area, m^2
b	Thickness of surimi slab with stainless steel plate, m
Bi	Biot number (= hL/k)
C_p	Specific heat, J/kg ^{o}C
g	Gravitational acceleration, m/s^2
h	Steam surface heat transfer coefficient, $W/m^2\,^{o}C$
h_{fg}	Latent heat of vaporization, J/kg
k	Thermal conductivity, W/m ^{o}C
k_f	Thermal conductivity of liquid phrase, W/m ^{o}C
L	Significant dimension, thickness or diameter, m
m	Number of locations for internal temperature measurements
n	Number of data points at each interior location
q	Heat flux, W/m^2
S	The sum of least square
T	Solid Temperature, ^{o}C
T_a	Ambient temperature, ^{o}C
T_{ij}	Predicted value of temperature at position i and time j, ^{o}C
T_0	Initial temperature of test subject, ^{o}C
T_s	Surface temperature of test subject, ^{o}C
t	Time, sec

Δt	Timestep of temperature measurement, sec
V	Volume of solid, m^3
x	Variable distance coordinate
Y_{ij}	Measured value of temperature at position i and time j, ^{o}C
ρ	Density, kg/m^3
ρ_f	Liquid density, kg/m^3
μ_f	Steam viscosity of liquid condition, $N\ s/m^2$

REFERENCES

AbuDagga, Y. and Kolbe, E. 1996. Thermophysical properties of surimi paste at cooking temperature. J. Food Eng., In press.

Arce, J. and Sweat, V.E. 1980. Survey of published heat transfer coefficients encountered in food refrigeration processes. ASHRAE Transactions. 86(2): 235.

Beck, J.V. and Arnold, K.J. 1977. "Parameter estimation in engineering and science." John Wiley & Sons, Inc., New York.

Beck, J.V., B. Litkouhi, and C. R. St. clair, Jr. 1985. "Inverse Heat Conduction Problems." John Wiley & Sons, Inc., New York.

Bertak, J.A. and Karahadian, C. 1995. Surimi-based imitation crab characteristics affected by heating method and end point temperature. J. Food Sci. 60(2): 292.

Bonacina, C. and Comini, G. 1972. Calculation of convective heat transfer coefficients from time-temperature curves. Proceedings of the XII International Congress of Refrigeration. PP. 157-166.

Chavarria, V.M. and Heldman D.R. 1984. Measurement of convective heat transfer coefficients during food freezing processes. J. Food Sci. 49(3): 810.

Greene, D. and Babbitt, J. 1990. Control of muscle softening and protease-parasite interactions in Arrowtooth flounder (*Atheresthes stomias*). J. Food Sci. 55(2): 579.

Hamann, D.D., Amato, P.M., Wu, M.C., Foegeding, E.A. 1990. Inhibition of Modori (gel weakening) by plasma hydrolysate and egg white. J. Food Sci. 55(3): 665.

Hoffman, J.D. 1990. "Numerical Methods for Engineers and Scientists." McGraw Hill Book Co., New York.

Incropera F.P. and Dewitt D.P. 1990. "Fundamentals of Heat and Mass Transfer." 3rd ed. John Wiley & Sons.

Kays, W.M. and Crawford, M.E. 1980. "Convective Heat and Mass Transfer." second edition, McGraw Hill Book Company, New York, Chap. 9, pp. 133-160.

Kinoshita, M., Toyohara, H. and Shimizu, Y. 1990. Proteolytic degradation of fish gel (Modori-phenomenon) during heating process. Proceedings Comm. C2; IIR. Aberdeen: 61-67.

Ling, C.A., Bomben, J.L., Farkas, D.F. 1974. Heat transfer from condensing steam to vegetable pieces. J. Food Sci. 39: 692.

Ling, C.A., Lung, D.B. and Lightfoot, E.N. 1976. Estimation of the surface heat transfer coefficient with the presence of noncondensable gases. 41: 1345.

McAdams, W.H. 1954. "Heat Transmission." McGraw-Hill Book Company, Inc., New York.

Nandapurkar, S.S. and Beatty, K.O. 1960. Chem. Eng. Prog. Symp. Series No. 30, 56: 129.

Ortolano, D.J. and Hines, F.F. 1983. A simplified approach to heat flow measurement. Proceedings of the ISA International Conference and Exhibit, Houston, Texas.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. 1992. "Numerical Recipes in C." Cambridge University Press.

Ramaswamy, H.S., Tung, M.A., and Stark, R. 1983. A method to measure surface heat transfer from steam/air mixture in batch retorts. J. Food Sci. 48(3): 900.

Scott, E.P., Beck, J.V. and Heldman, D.R. 1992. Estimation of transient heat transfer coefficients in frozen foods during storage. J. Food Eng. 15(2): 99.

Shimizu, Y., Toyohara, H., Lanier, T.C. 1992. Surimi production from fatty and dark-fleshed fish species. Surimi technology. T.C. Lanier and C.M. Lee, eds. Dekker, New York.

Stoforos, N. G. and Merson, R.L. 1995. A solution to the equations governing heat transfer in agitating liquid/particulate canned foods. J. Food Pro. Eng. 18: 165.

Tarantola, A. 1987. "Inverse Problem Theory." Elsevier Science Publishing Company Inc., New York.

Tung, M.A., Ramaswamy, H.S., Smith, T. and Stark, R. 1984. Surface heat transfer coefficients for steam/air mixtures in two pilot scale retorts. J. Food sci. 49: 939.

Wasson, D.H. 1992. Fish muscle proteases and heat-induced myofibrillar degradation: a review. J. Aquatic Food Prod. Tech. 1(2): 23.

Zhang, Q. and Cavalieri, R.P. 1991. Thermal model for steam blanching of green beans and determination of surface heat transfer coefficient. Transactions of ASAE. 34(1): 182.

5. OTHER RESULTS AND RECOMMENDATIONS FOR FUTURE STUDY

Other Results

Inverse calculation method. Although other functional forms were examined for modeling the heat transfer coefficient (h), the one we used in this study gave the best agreement between the modeling temperatures and the experimental temperatures. Other options we examined included the following:

$$h = \frac{c_0 (\ln T_s)^{c_1}}{c_3 + (T_a - T_s)^{c_2}} \tag{5.1}$$

$$h = \frac{c_0 (\ln T_s)^{c_1}}{(T_a - T_s)^{c_2}} \tag{5.2}$$

$$h = \frac{c_0 \ln T_s}{(T_a - T_s)^{1/2}} \tag{5.3}$$

$$h = \frac{c_0 \ln T_s}{(T_a - T_s)^{3/4}} \tag{5.4}$$

$$h = \frac{c_0 T_s}{(T_a - T_s)^{1/4}} \tag{5.5}$$

Lumped mass method. In order to evaluate the overall effects of heat transfer on a copper surface within the steam chamber, the orientation effect on the heat transfer coefficient (h) was examined. With steam flow downward in the chamber, three orientations of the copper block were adjusted to be horizontal (facing up, down) and vertical. The power-law equations performed well in relating the heat transfer coefficient (h) to temperature difference (T_a-T_s) between the ambient and the copper.

Test surface facing up

$$h = 1.746[\frac{k_f^{\ 3}\rho_f^{\ 2}h_{fg}}{\mu_f}]^{0.25}\frac{1}{(T_a - T_s)^{0.42}}\ , \qquad R^2 = 0.89 \qquad (5.7)$$

Test surface facing down

$$h = 0.830[\frac{k_f^{\ 3}\rho_f^{\ 2}h_{fg}}{\mu_f}]^{0.25}\frac{1}{(T_a - T_s)^{0.39}}\ , \qquad R^2 = 0.93 \qquad (5.8)$$

Test surface vertical

$$h = 2.802[\frac{k_f^{\ 3}\rho_f^{\ 2}h_{fg}}{\mu_f}]^{0.25}\frac{1}{(T_a - T_s)^{0.63}}\ , \qquad R^2 = 0.92 \qquad (5.9)$$

For convenience, the same function was used to establish the h model for the vertical case, and a good fitness was demonstrated by the R^2 value. Figure 5.1 shows that the orientation is an important factor influencing heat transfer coefficients (h). As can be seen from the figure, the values were highest when the test surface was facing up and lowest when the test surface was facing down. The higher values could be due to a faster steam flow over the test surface, thus reducing the thickness of the condensate film while enhancing heat transfer. release system to accomplish the instantaneous exposure of the metal transducer to the heating medium. Ramaswamy et al. (1983) and Tung et al. (1989) investigated the orientation effect on heat transfer in two ways: in a positive flow retort a metal transducer was placed vertically and flow of the medium was adjusted to be

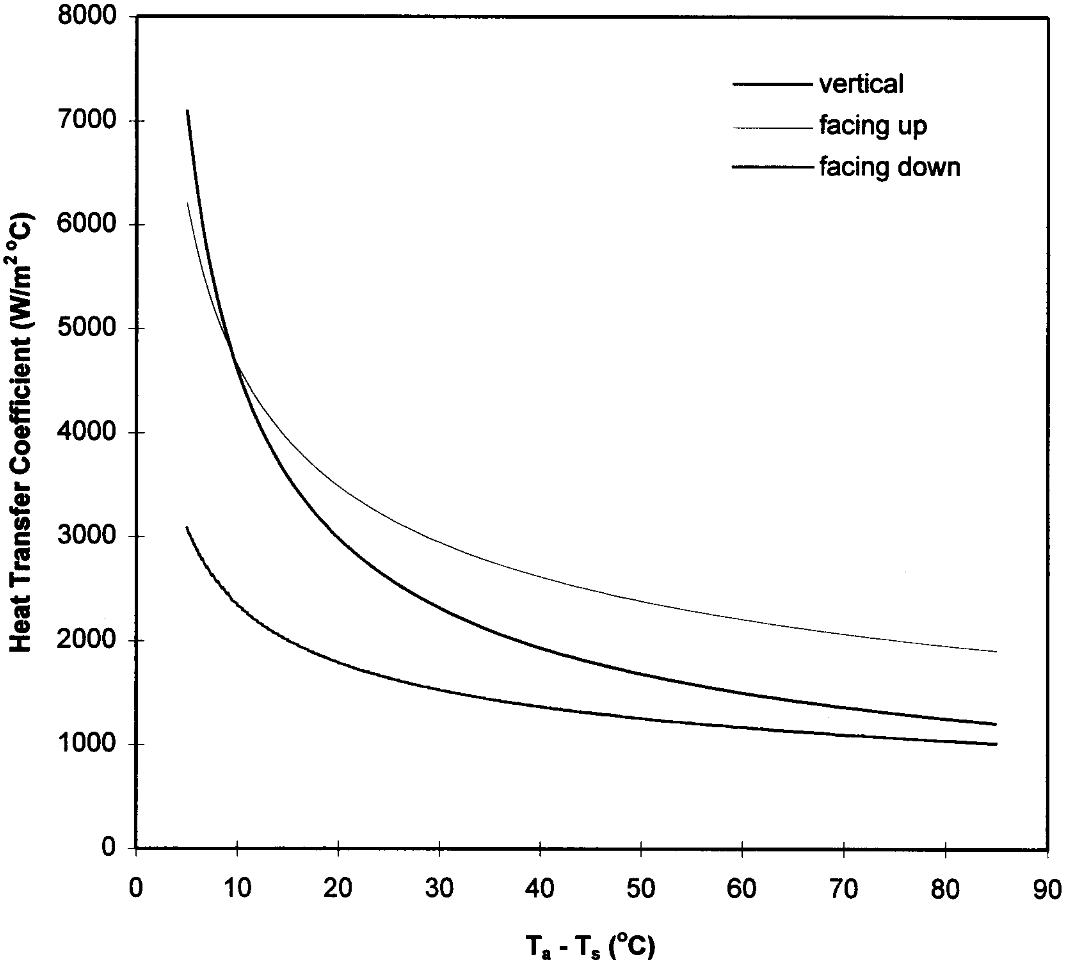


Figure 5.1—Orientational effect on the heat transfer coefficient. (Lumped Mass Method)

upwards or downwards; in a lagarde retort flow of the medium was horizontal and the transducer was adjusted to be vertically or horizontally placed. The significant influence of orientation on the heat transfer coefficient (h) indicates that a good circulation of steam over the product surface is very important to assure a rapid heating.

Heat flux method. Figures 5.2 and 5.3 present the measurements of heat flux and the calculated heat transfer coefficients (h) in 6 different tests.

Recommendations for Future Study

Originally, we sought to test the factor of steam velocity, however, appropriate measuring device was not available. The effect of steam velocity on the heat transfer coefficient would be of interest to understand. The experimental temperature was kept at 100 °C in this study. Future study should examine the steam temperature effect under different steam temperature conditions. The orientation effect of the surimi product should be tested using surimi. Although the orientation is an important factor influencing the heat transfer coefficient over copper block, its effect on surimi is uncertain because of the unique surface condition and thermal properties of food.

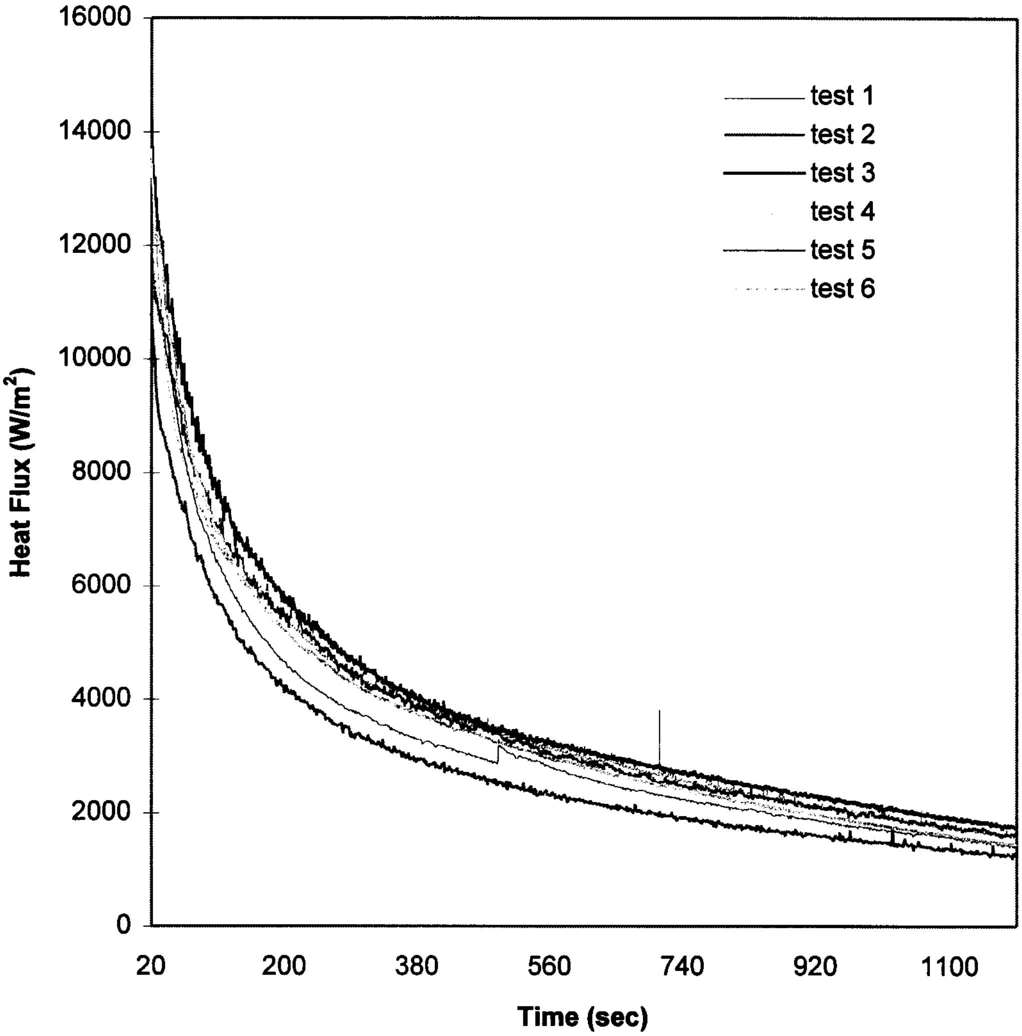


Figure 5.2—Measurements of heat flux by heat flux sensor.

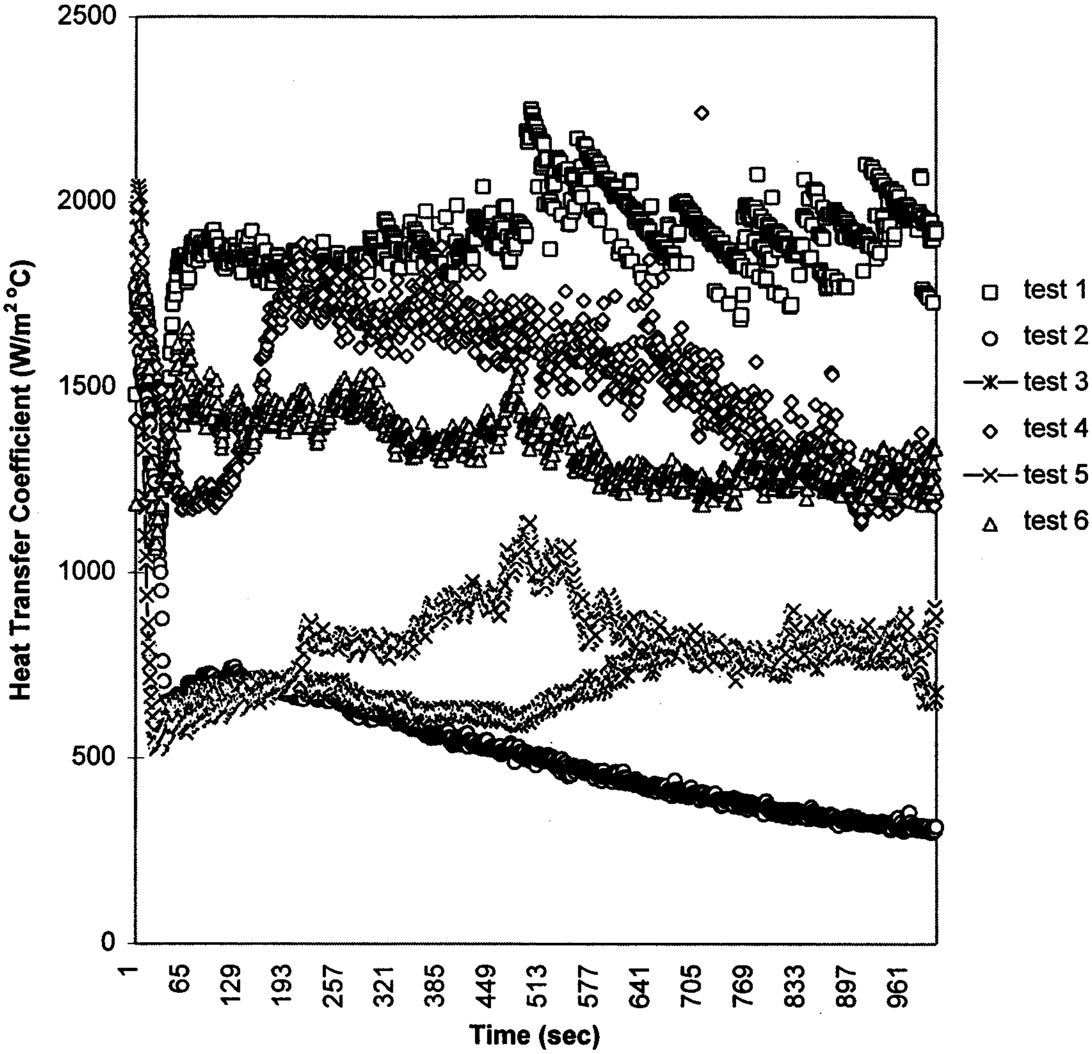


Figure 5.3—Heat transfer coefficients determined by heat flux method.

BIBLIOGRAPHY

AbuDagga, Y. and Kolbe, E. 1996. Thermophysical properties of surimi paste at cooking temperature. In press, J. of Food Eng.

Alifanov, O.M. and Artyukhin, F.A. 1975. Regularized numerical solution of the nonlinear inverse heat-conduction problem. J. Eng. Phy. 29: 934.

Arce, J.A., Potluri, P.L., Schneider, K.C., Sweat, V.E. and Dutson, T.R. 1983. Modeling beef carcass cooling using a finite element technique. Transactions of ASAE. 83: 950-954 and 960.

Arce J. and Sweat, V.E. 1980. Survey of published heat transfer coefficients encountered in food refrigeration processes. Transactions of ASHRAE. 86(2): 235.

Bard, Y. 1974. "Nonlinear Parameter Estimation." Academic Press, Inc., New York.

Beck, J.V. 1961. Correction of transient thermocouple temperature measurements in heat conducting solids, Part II, The calculation of transient heat fluxes using the inverse convolution, AVCO Corp., Res. and Adv. Dev. Div., Wilmington, MA, Tech. Report RADTR-7-60-38 (Part II), March 30, 1961.

Beck, J.V. 1966. Analytical determination of optimum transient experiments for measurement of thermal properties. Proc. 3rd Int. Heat Transfer Conference, IV, 74-80.

Beck, J.V. 1968. Surface heat flux determination using an integral method. Nucl. Eng. Des. 7: 170.

Beck, J.V. 1970. Nonlinear estimation applied to the nonlinear inverse heat conduction problem. International Journal of Heat and Mass Transfer. 13: 703.

Beck, J.V. and Arnold, K.J. 1977. "Parameter Estimation in Engineering and Science." John Wiley & Sons, Inc., New York.

Beck, J.V. 1979. Criteria for comparison of methods of solution of the inverse heat conduction problem, Nucl. Eng. Des. 53: 11.

Beck, J.V., B. Litkouhi, and C. R. St. Clair, Jr.. 1982. Efficient sequential solution of the nonlinear inverse heat conduction problem. Numerical Heat Transfer. 5: 275.

Beck, J.V., B. Litkouhi, and C. R. St. clair, Jr. 1985. "Inverse Heat Conduction Problems." John Wiley & Sons, Inc., New York.

Beck, J.V. and Murio, D. 1986. Combined function specification-regularization procedure for solution of inverse heat conduction problem. AIAA Journal. 24: 180.

Bell, J.B. and Wardlaw, A.B. 1981. Numerical solution of an ill-posed problem arising in wind tunnel heat transfer data reduction. Naval surface weapons center, NSWC TR 82-32, Dec. 1981.

Bertak, J.A. and Karahadian, C. 1995. Surimi-based imitation crab characteristics affected by heating method and end point temperature. J. Food Sci. 60(2): 292.

Bonacina, C. and Comini, G. 1972. Calculation of convective heat transfer coefficients from time-temperature curves. Proceedings of the XII International Congress of Refrigeration. PP. 157-166.

Brown, G.E. 1974. Importance of surface heat transfer during steam heat and heat/hold process. J. Food Sci. 39: 1066.

Carslaw, H.S and Jaeger, J.C. 1959. Conduction of heat in solids. 2nn ed. Clarenden Press: Oxford. PP. 92-93 and 120.

Chau, K.V. and Snyder, G.V. 1988. Mathematical model for temperature distribution of thermally processed shrimp. Transactions of ASAE.

Chavarria, V.M. and Heldman D.R. 1984. Measurement of convective heat transfer coefficients during food freezing processes. J. Food Sci. 49(3): 810.

Clary, B.L. and Nelson, G.L. 1969. The ellipsoidal model as an adequate model for determining the forced convective heat transfer coefficients from irregular shapes. ASAE paper No. 69-374.

Clary, B.L. and Nelson, G.L. 1970. Determining convective heat transfer coefficients from ellipsoidal shapes. Transactions of ASAE. 13(3): 309.

Collier, J.G. 1981. "Convective Boiling and Condensation." McGraw-Hill Book Co., New York.

Cowell, N.D. and Namor, M.S.S. 1974. Heat transfer coefficients in plate freezing: the effect of packaging materials. I.I.F.-I.I.R.-- Commissions B1, C1, C2--Bressanone 1974-3.

Cozdoba, L.A. and Crykowsky, P.G. 1982. Methods of solution to the inverse problem. Scientific Publisher, Kiev, 1982 (in Russian).

Davies, J.M. 1966. Input power determined from temperatures in simulated skin protected against thermal radiation. J. Heat Transfer. 88: 154.

DeVuono, A.C. and Christensen, R.N. 1984. Experimental investigation of the pressure effects on film condensation of steam-air mixtures at pressure above atmospheric. 38: 73.

Evans, K.E. and Mannapperuma, J.D. and Singh, R.P. 1991. Freezing of foods under surface boiling boundary conditions. Rev. Int. Froid 1991 Vol 14 Juillet.

Federov, V.G., Il'Inskiy, D.N., Gerashchenko, O.A. and Andreyeva, L.D. 1972. Heat transfer accompanying the cooling and freezing of meat carcasses. Heat Transfer-Soviet Research. 4(4): 55.

Feldmann, C. 1976. Part 1: Transfert de chaleur et de masse entre une sphere et de l'air a basse temperature. Conservatoire national des arts et metiers, Paris. Memoire No. 6.

Flores, E.S. and Mascheroni, R.H. 1988. Determination of heat transfer coefficients for continuous belt freezers. J. Food Sci. 53(6): 1872.

Frank, I. 1963. An application of least square methods to the solution of the inverse problem of heat conduction. J. Heat Transfer. 85: 378.

Greene, D. and Babbitt, J. 1990. Control of muscle softening and protease-parasite interactions in Arrowtooth flounder (*Atheresthes stomias*). J. Food Sci. 55(2): 579.

Gruda, Z., and Kasieczka, W. 1991. Effect of the process parameter on particle-to-air heat transfer coefficient in fluidized and fixed bed freezing. XVIIIth International congress of refrigeration. August 10-17, 1991. No de la communication / paper No. 377.

Hallstrom, B., Skjoldebrand, C. and Tragardh. 1988. "Heat Transfer & Food Products." Elsevier Applied Science, London and New York.

Hamann, D.D., Amato, P.M., Wu, M.C., Foegeding, E.A. 1990. Inhibition of Modori (gel weakening) by plasma hydrolysate and egg white. J. Food Sci. 55(3): 665.

Hoffman, J.D. 1990. "Numerical Methods for Engineers and Scientists." McGraw Hill Book Co., New York.

Incropera F.P. and Dewitt D.P. 1990. "Fundamentals of Heat and Mass Transfer." 3rd ed. John Wiley & Sons.

Kays, W.M. and Crawford, M.E. 1980. "Convective Heat and Mass Transfer." second edition, McGraw Hill Book Company, New York, Chap. 9, pp. 133-160.

Khairullah, A. and Singh, R.P. 1991. Optimization of fixed and fluidized bed freezing processes. Int. J. Refrig. vol. 14.

Kinoshita, M., Toyohara, H. and Shimizu, Y. 1990. Proteolytic degradation of fish gel (Modori-phenomenon) during heating process. Proceedings Comm. C2; IIR. Aberdeen: 61-67.

Kolbe, E., Morrissey, M. T. and Park, J. W. 1993. Processing alternatives to reduce protease-related muscle softening in seafoods. Project: R/SF-2. Sea Grant. US Dept. of Commerce.

Ling, C.C.A., Bomben, J.L., Farkas, D.F. 1974. Heat transfer from condensing steam to vegetable pieces. J Food Sci. 39: 692.

Ling, A.C., Lung, D.B. and Lightfoot, E.N. 1976. Estimation of the surface heat transfer coefficient with the presence of noncondensable gases. J Food Sci. 41: 1345.

McAdams, W.H. 1954. "Heat Transmission." McGraw-Hill Book Company, Inc., New York.

McCabe, W.L., Smith, J.C. and Harriott, P. 1985. "Unit Operations of Chemical Engineering." 4th ed. McGraw-Hill Book Company, New York.

Marquardt, D.W. 1963. An algorithm for least squares estimation of nonlinear parameters. J. Soc. Ind. Appl. Math. 11: 431-441.

Miller, K. 1970. Least squares methods for the ill-posed problems with a prescribed bound. SIAM Journal of Mathematical Analysis. 1: 52-74.

Morrissey, M.T. 1992. Pacific whiting report. Report prepared for the Oregon Trawl Commission, Astoria, Oregon.

Nandapurkar, S.S. and Beatty, K.O. 1960. Chem. Eng. Prog. Symp. Series No. 30, 56: 129.

Narayana, K.B. and Murthy, M.V. 1981. Heat and mass transfer characteristics and the evaluation of thermal properties of moist food materials. Transactions of ASAE. 24(3): 789.

Nelson, R.W., Barnett, H.J. and Kudo, G. 1985. Preservation and processing characteristics of Pacific whiting (*Merluccius productus*). Marine Fisheries Review. 47(2): 60.

Ortolano, D.J. and Hines, F.F. 1983. A simplified approach to heat flow measurement. Proceedings of the ISA International Conference and Exhibit, Houston, Texas.

Osman, A.M. and Beck, J.V. 1987. Nonlinear inverse problem for the estimation of time- and -space dependent heat transfer coefficients. AIAA-87-0150. Presented at the 25th Annual Aerospace Sciences Meeting, January, 12-15, Reno, NE.

Othmer, D.F. 1929. "The Condensation of Steam." Ind. and Eng. Chem. 21(6): 576.

Park, J. 1995. "Processing of Surimi and Surimi Seafoods." Oregon State University Seafood Lab. Astoria, OR.

Patashnik, M., Groninger, H.S., Barnett, H., Kudo, G., Koury, B. 1982. Pacific whiting (*Merluccius Productus*): abnormal muscle texture cause by myxosporidian-induced parasite. Marine Fisheries Review. 44(5): 1.

Pflug I.J., Blaisdell J.L. and Kopelman J. 1965. Transactions of ASHRAE. 71(1): 238.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. 1992. "Numerical Recipes in C." Cambridge University Press.

Ramaswamy, H.S., Lo, K.V. and Tung, M.A. 1982. Simplified equations for transient temperature in conductive foods with convective heat transfer at the surface. J. Food Sci. 47(6): 2042.

Ramaswamy, H.S., Tung, M.A., and Stark, R. 1983. A method to measure surface heat transfer from steam/air mixture in batch retorts. J. Food Sci. 48: 900.

Reid, D.S. and Meybeck, A. 1991. Comparison of weight loss and quality changes between cryogenic and mechanical freezing of catfish. Written for the XVIII th International Congress of Refrigeration.

Rumsey, T. Farkas, D.F. and Hudson, J.S. 1980. Measuring the steam heat transfer coefficient to vegetables. Transactions of ASAE. 23(4): 1048.

Sastry, S.K. 1984. Convective heat transfer coefficients for canned mushrooms processed in still retorts. Presented at the 1984 Winter Meeting ASAE.

Scott, E.P. and Beck, J.V. 1985. Analysis of order of sequential regularization solution of inverse heat conduction problem. ASME paper No. 85-WA/HT-43.

Scott, E.P. and Beck, J.V. 1989. Analysis of order of sequential regularization solutions of inverse heat conduction problems. J. Heat Transfer. 111: 218.

Scott, E.P., Beck, J.V. and Heldman, D.R. 1992. Estimation of transient heat transfer coefficients in frozen foods during storage. J. Food Eng. 15(2): 99.

Shimizu, Y., Toyohara, H., Lanier, T.C. 1992. Surimi production from fatty and dark-fleshed fish species. "Surimi Technology." T.C. Lanier and C.M. Lee, eds. Dekker, New York.

Sonu, S.C. 1986. Surimi. NOAA Technical Memorandum NMFS. U.S. Department of Commerce.

Stoforos, N. G. and Merson, R.L. 1995. A solution to the equations governing heat transfer in agitating liquid/particulate canned foods. J. Food Pro. Eng. 18: 165.

Sylvia, G. and Morrissey, M.T. 1992. "Pacific whiting." Oregon Sea Grant, Corvallis, OR.

Tarantola, A. 1987. "Inverse Problem Theory." Elsevier Science Publishing Company Inc., New York.

Templtron, J. and Nicholson, F.J. 1972. Heat transfer and flow characteristics of freezer plates refrigerated with trichoroethylene, calcium chloride brine and pump-circulated refrigerant 22.

Tikhonov, A.N. and Arsenin, V.Y. 1977. Solutions of ill-posed problems. V.H. Winston & Sons, Washington, D.C.

Tung, M.A., Ramaswamy, H.S., Smith, T. and Stark, R. 1984. Surface heat transfer coefficients for steam/air mixtures in two pilot scale retorts. J. Food Sci. 49: 939.

Tung, M.A. and Morello, G.F. 1989. "Food Properties and Computer-aided Engineering of Food Processing Systems." Food Properties, Heat transfer conditions and Sterilization Considerations in Retort Processes. 49-71.

Vetterling, W.T., Teukolsky, S.A., Press, W.H. and Flannery, B.P. 1992. "Numerical Recipes, Example Book [c]". 2rd edition. Cambridge University Press.

Wasson, D.H. 1992. Fish muscle proteases and heat-induced myofibrillar degradation: a review. J. Aquatic Food Prod. Tech. 1(2): 23.

Yongsawatdigul, J. and Park, J.W. 1996. Linear heating rate affects gelation of Alaska pollock and Pacific whiting surimi. J. Food Sci.. 61: 149.

Yongsawatdigul, J. and Park, J.W., and Kolbe, E. 1995. Ohmic heating maximizes gel functionality of Pacific whiting surimi. J. Food Sci. 60: 10.

Zhang, Q. and Cavalieri, R.P. 1991. Thermal model for steam blanching of green beans and determination of surface heat transfer coefficient. Transactions of ASAE. 34(1): 182.

APPENDICES

Appendix A Description of the Computer Programs

The nonlinear regression computer program was used for simultaneous solution of matrix equation (3.19) and parameter optimization in the h function using downhill simplex method (Press et al., 1992). The matrix equation is a finite-difference formulation of the one-dimensional heat conduction problem by the implicit Crank-Nicolson and Extrapolation methods (Hoffman, 1990). The equation is solved by the LU decomposition and Gauss elimination methods. The outputs from this program, a whole domain function specification procedure, are the optimized parameters of the h model. The thickness (20 cm) of surimi paste formed on the tray was divided into 40 elements, and that of the stainless steel was divided into 4 elements. The total nodes for the composite structure of surimi and stainless-steel plate was N (45), for surimi was N1 (41). With these many nodes, we found that the temperature results were quite stable and that almost no change resulted from increasing the number of nodes. The interface point was represented by a node of surimi. The thermal properties of surimi paste were evaluated for each time level according to the temperatures of previous time level. The analytical procedures of the nonlinear regression program have been given in detail under section Analytical Approach of the inverse calculation method (Page 28-35).

This C code is valid only when the files in the Numerical Recipe disk are installed (Press et al., 1992) in PC. This is because the parameter optimization by the downhill simplex method was carried out by using two files, “nr.h” and “nrutil.h”, from the Numerical Recipe. The “main” procedure of this code is a copy of “int main(void)” in Chapter10 page 172-173, Numerical Recipes, Example Book [C] (Press et al., 1992).

After giving initial values to the parameters of the assumed h function in the "main" procedure, the nonlinear regression program searches the optimal parameters by reducing the sum of least squares (temperature difference) between the calculated and the experimental temperatures interactively.

The experimental temperature data were introduced as *.txt file on spreadsheet. In accordance to that the surimi internal temperatures were measured once per second for 1000 sec, we used one second as the timestep to calculate temperature distributions for the 45 nodes for 1000-sec history. The temperature difference between the experimental and calculated temperatures was minimized in a least squares sense. The experimental and predicted temperatures used for the sum of least squares were respectively 51 (ROWS) from 1000 data points for each of the 3 (COLS) internal locations (one datum every 20 sec of 1000 sec).

The numerical calculation program is similar to the nonlinear regression program. The main difference is that the parameter optimization procedures are not included in the numerical calculation program. Since some symbols cannot be typed in the C program, we used different ones from those used in section Analytical Approach of the inverse calculation method (Page 28-35). Following is a list of some symbols used in the computer programs,

<u>N</u> = total nodes for surimi and the stainless-steel plate

<u>N1</u> = total nodes for surimi slab

<u>ROWS</u> = number of experimental temperatures used for optimization

<u>COLS</u> = three interior locations of temperature measurements

<u>MP</u>, <u>NP</u> are for parameter optimization (MP = 3, NP = 2 for 2-parameter optimization)

xx[N] = one-dimensional temperature matrix of equation (3.19) (nonlinear regression)

x[N] = one-dimensional temperature matrix of equation (3.19) (numerical calculation)

a[][N] = two-dimensional matrix of equation (3.19)

b[N] = one-dimensional matrix in right side of equation (3.19)

Tb = ambient temperature

T0 = initial temperature

r = thickness of surimi and stainless-steel composite slab

dt = timestep for temperature calculation

dr = grid size

m = moisture content of surimi paste

h = simulated surface heat transfer coefficient

k [N1]= time- and position-dependent thermal conductivity of surimi

cp[N1] = time- and position-dependent specific heat of surimi

roh[N1] = time- and position-dependent density of surimi

af[N1] = time- and position-dependent thermal diffusivity of surimi

ks = thermal conductivity of stainless steel

cps = specific heat of stainless steel

rohs = density of stainless steel

afs = thermal diffusivity of stainless steel

LS = the sum of least squares

Appendix B Nonlinear Regression Program

/* **** C CODE FOR THE SOLUTION OF INVERSE HEAT CONDUCTION PROBLEM AND ***************************** PARAMETER ESTIMATION ***************************** */**

```
#include <stdio.h>
#include <math.h>
#include "nr.h"
#include "nrutil.h"

#define N  45
#define N1 41
#define ROWS 51
#define COLS 3
#define MP 3
#define NP 2
#define FTOL 1.0e-2

void    lu(double l[][N], double u[][N], double a[][N]);
void    back(double b[N], double l[][N],  double u[][N], double xx[N]);
double  xx[N], b[N];
double  l[N][N], u[N][N], a[N][N];

/* The main() file is a modification of the file in "Numerical Recipes, Example Book [C]", chapter 10
   page 172-173. The whole program is valid with the installation of files in the individual "Numerical
   Recipes" disk */

/* Parameter optimization */

int main(void)
{
  int i, nfunc, j, ndim=NP;
  float *x, *y, **p;

  x=vector(1,NP);
  y=vector(1,MP);
  p=matrix(1,MP,1,NP);
  for(i=1; i<=MP; i++){
    for(j=1; j<=NP; j++)

/*Starting guess of the unknown parameters in two methods, you need to choose one of them */

         /* method 1 */
          x[j]=p[i][j]=(i == (j+1) ? 0.5:0.0);

         /* method 2 */
/*        p[1][1]=4480,   p[1][2]=0.6;
          p[2][1]=4350,   p[2][2]=0.7;
          p[3][1]=5000,    p[3][2]=0.8;   */

  y[i]=func(x);
```

```
  }
  amoeba(p,y,ndim,FTOL,func,&nfunc);
  printf("\nNumber of function evaluations: %3d\n", nfunc);
  printf("Vertices of final 3-d simplex and\n");
  printf("function values at the vertices:\n\n");
  printf("%3s %10s %12s %12s %14s\n\n",
          "i","x[i]","y[i]","z[i]","function");
  for(i=1;i<=MP;i++) {
    printf("%3d ",i);
    for(j=1;j<=NP;j++)
          printf("%12.6f ",p[i][j]);
    printf("%12.6f\n",y[i]);
  }
  free_matrix(p,1,MP,1,NP);
  free_vector(y,1,MP);
  free_vector(x,1,NP);
  return 0;
}
```

/* Solve the Inverse Calculation Problem */

```
float func(float x[])
{
  double  Tb=100, T0=14, T0_tray=14;
  double  r = 0.02 + 0.002;
  double  dt=1, dr;
  double  m = 80;
  double  h;
  double  k[N1], cp[N1], roh[N1], af[N1], d[N1];
  double  ks = 14.9, cps = 477, rohs = 7900, afs, ds;
  double  data[ROWS][COLS], LS = 0;
  int     i, j, i1, counter = 0, time = 1;
  FILE    *fp;
```

/* Open and read experimental data file in spreadsheet */

```
  fp = fopen("data.txt", "r");
    if (fp == NULL) {
      puts("\n Error opening files\n");
          return 0;
    }
    for (i=0; i < ROWS; i++)
      for (j=0; j < COLS; j++) {
            float  val = 0;
            fscanf(fp, "%f", &val);
            data[i][j] = val;
          }
    fclose (fp);
```

/* Define the initial temperature */

```
  dr = r/(N - 1);
  afs = ks / (rohs * cps);
```

```
  ds = (afs * dt)/(dr * dr);
  for(i = 0; i <= N1 - 1; i++)
    xx[i] = T0;
  for(i = N1; i <= N - 1; i++)
    xx[i] = T0_tray;          /* the temp. of the cooking tray can be approximated as surimi temp. T0 */

/* Solve the one-dimensional conduction problem with a model for the heat transfer coefficient */

while(time <= 1000) {

/* Temperature-dependent properties of surimi are evaluated at each time level */

  for(i = 0; i <= N1 - 1; i++) {
    k[i] = 1.33 - 0.0224 * m + 0.000158 * m * m - 0.00448 * xx[i] +
                   0.000046 * xx[i] * xx[i] + 0.000022 * m * xx[i];
    cp[i] = 1000 * (2.33 + 0.006 * xx[i] + 0.0149 * m);
    roh[i] = 1511.2 - 1.16 * xx[i] - 5.43 * m;
    af[i] = k[i] / (roh[i] * cp[i]);
    d[i] = af[i] * dt / (dr * dr);
  }

/* Unknown parameters contained in the h function can be estimated by this C code */

  h=x[1]/(pow((Tb-xx[0]),x[2]));
/* x[1] and x[2] are unknown parameters, xx[0] is surimi surface temp. */

/* Forming matrix A (N x N) by Crank-Nicolson and extrapolation schemes*/

    a[0][0] = -3.0 - 2 * dr * (h / k[0]);
    a[0][1] = 4.0;
    a[0][2] = -1;
    for(j = 3; j <= N - 1; j++)
         a[0][j] = 0.0;
    for(i = 1; i <= N1 - 1; i++)
         for(j = 0; j <= N - 1; j++)
           if(i == j)
             a[i][j] = 2.0 * (1 + d[i]);
           else if(i - 1 == j)
             a[i][j] = -d[i];
           else if(i + 1 == j)
             a[i][j] = -d[i];
           else
             a[i][j] = 0.0;
    for(i = N1; i <= N - 2; i++)
         for(j = 0; j <= N - 1; j++)
           if(i == j)
             a[i][j] = 2.0 * (1 + ds);
           else if(i - 1 == j)
             a[i][j] = -ds;
           else if(i + 1 == j)
             a[i][j] = -ds;
           else
             a[i][j] = 0.0;
    a[N-1][N-1] = 3;
```

```
    a[N-1][N-2]  = -4.0;
    a[N-1][N-3]  = 1.0;
    for(j = 0; j <= N - 4; j++)
          a[N-1][j] = 0.0;

/* Forming initial matrix B (N x 1) */

    b[0] = -2.0 * dr * (h / k[0]) * Tb;
    for(i = 1; i <= N1 - 1; i++)
          b[i] = d[i] * xx[i - 1] + 2 * (1 - d[i]) * xx[i] + d[i] * xx[i + 1];
    for(i = N1; i <= N - 2; i++)
          b[i] = ds * xx[i - 1] + 2 * (1 - ds) * xx[i] + ds * xx[i + 1];
    b[N-1] = 0;

/* Calling for subroutines to calculate temperature at each time level, [T] = [A]^-1 [B] */

    lu(l, u, a) ;
    back(b, l, u, xx);

/* Sum of least square */

     if ((time-1) % 20 == 0){
           i1 = time/20;
     LS = LS + (data[i1][0]- xx[9])*(data[i1][0]- xx[9]) + (data[i1][1]- xx[15])*
              (data[i1][1]- xx[15]) + (data[i1][2]- xx[26])*(data[i1][2]- xx[26]);
/* numbers 9, 15 and 26 are sensor locations of temp. measurements inside surimi paste, these numbers
must be adjusted for different tests */
     }
   }
return LS;
}


/*  LU DECOMPOSITION */

void lu(double l[][N], double u[][N], double a[][N])
{
  int  i, j, k;
  double sum0, sum1;

  for(i = 0; i <= N - 1; i++)
    l[i][0] = a[i][0];

  for(j = 0; j <= N - 1; j++)
    u[0][j] = a[0][j] / l[0][0];

  for(j = 1; j <= N - 1; j++) {
    for(i = j; i <= N - 1; i++) {
          sum0 = 0.0;
          for(k = 0; k <= j - 1; k++)
            sum0 = sum0 + l[i][k] * u[k][j];
          l[i][j] = a[i][j] - sum0;
    }
    u[j][j] = 1.0;
```

```
    for(i = j + 1; i <= N - 1; i++) {
      sum1 = 0.0;
      for(k = 0; k <= j - 1; k++)
            sum1 = sum1 + l[j][k] * u[k][i];
      u[j][i] = (a[j][i] - sum1) / l[j][j];
    }
  }
}
```

```
/* GAUSS ELIMINATION */

void back(double b[N], double l[][N], double u[][N], double xx[N])
{
  int  i, j, k;
  double sum2, sum3;

  b[0] = b[0] / l[0][0];
  for(i = 1; i <= N - 1; I++) {
    sum2 = 0.0;
    for(k = 0; k <= i - 1; k++)
          sum2 = sum2 + l[i][k] * b[k];
    b[i] = (b[i] - sum2) / l[i][i];
  }

  xx[N - 1] = b[N - 1];

  for(j = N - 2; j >= 0; j--) {
    sum3 = 0.0;
    for(k = j + 1; k <= N - 1; k++)
          sum3 = sum3 + u[j][k] * xx[k];
    xx[j] = b[j] - sum3;
  }
}
```

Appendix C Numerical Calculation Program

/* FOR NUMERICAL CALCULATION OF TEMPERATURE HISTORY DISTRIBUTIONS AND ESIMATION OF THE HEAT TRANSFER COEFFICIENT AS A CONSTANT VALUE */

```
#include <stdio.h>
#include <math.h>

#define N  45
#define N1  41
#define ROWS 51
#define COLS 3

void   lu(double l[][N], double u[][N], double a[][N]);
void   back(double b[N], double l[][N],  double u[][N], double x[N]);
double  x[N], b[N];
double  l[N][N], u[N][N], a[N][N];

main()
{
  double  Ta = 100, T0 = 14, T0_tray = 14, T;
  double  r = 0.02 + 0.002;
  double  dt=1, dr;
  double  m = 80;
  double  h;
  double  k[N1], cp[N1], roh[N1], af[N1], d[N1];
  double  ks = 14.9, cps = 477, rohs = 7900, afs, ds;
  double  data[ROWS][COLS];
  double  LS = 0;
  int      i, j, i1, counter = 0, time = 1;
  FILE   *fp;
```

/* Open and read experimental data file in spreadsheet */

```
  fp = fopen( "data.txt", "r" );
  if (fp == NULL) {
    puts( "\nError opening file\n" );
    return 0;
  }
  for ( i=0; i < ROWS; i++)
    for (j=0; j < COLS; j++) {
      float val = 0;
      fscanf(fp, "%f", &val );
      data[i][j] = val;
    }
  fclose (fp);
```

/* Print temperature data */

```
 for(i=0; i<=50; i++)
   printf("%7.2lf%7.2lf%7.2lf\n", data[i][0], data[i][1], data[i][2]);
```

/* Define the initial temperature */

```
dr = r/(N - 1);
T = T0;
afs = ks / (rohs * cps);
ds = (afs * dt)/(dr * dr);

for(i = 0; i <= N1 - 1; i++)
  x[i] = T0;
for(i = N1; i <= N - 1; i++)
  x[i] = T0_tray;
```

/* Solve the one-dimensional conduction problem with a model for the heat transfer coefficient */

```
while(time <= 1000){
```

/* Temperature-dependent properties of surimi are evaluated at each time level */

```
  for(i = 0; i <= N1 - 1; i++) {
    k[i] = 1.33 - 0.0224 * m + 0.000158 * m * m - 0.00448 * x[i] +
              0.000046 * x[i] * x[i] + 0.000022 * m * x[i];
    cp[i] = 1000 * (2.33 + 0.006 * x[i] + 0.0149 * m);
    roh[i] = 1511.2 - 1.16 * x[i] - 5.43 * m;
    af[i] = k[i] / (roh[i] * cp[i]);
    d[i] = af[i] * dt / (dr * dr);
  }
      /* Predict temperature distribution using the developed h model */
       h = 4130/(pow(Ta-x[0],0.70));

      /* Or, you can use this program to estimate h as a constant value for the entire time history
      manually by minimizing the sum of least squares, it is what we call here, the trial and error
      method */
      /* h = 900;  */
```

/* Forming matrix A (N x N) by Crank-Nicolson and extrapolation schemes*/

```
  a[0][0] = -3.0 - 2 * dr * (h / k[0]);
  a[0][1] = 4.0;
  a[0][2] = -1;
  for(j = 3; j <= N - 1; j++)
    a[0][j] = 0.0;
  for(i = 1; i <= N1 - 1; i++)
    for(j = 0; j <= N - 1; j++)
      if(i == j)
        a[i][j] = 2.0 * (1 + d[i]);
      else if(i - 1 == j)
        a[i][j] = -d[i];
      else if(i + 1 == j)
        a[i][j] = -d[i];
      else
        a[i][j] = 0.0;
  for(i = N1; i <= N - 2; i++)
    for(j = 0; j <= N - 1; j++)
      if(i == j)
```

```
            a[i][j] = 2.0 * (1 + ds);
          else if(i - 1 == j)
            a[i][j] = -ds;
          else if(i + 1 == j)
            a[i][j] = -ds;
          else
            a[i][j] = 0.0;
      a[N-1][N-1] = 3;
      a[N-1][N-2]  = -4.0;
      a[N-1][N-3]  = 1.0;
      for(j = 0; j <= N - 4; j++)
        a[N-1][j] = 0.0;
```

/* Forming initial matrix B (N x 1) */

```
      b[0] = -2.0 * dr * (h / k[0]) * Tb;
      for(i = 1; i <= N1 - 1; i++)
        b[i] = d[i] * x[i - 1] + 2 * (1 - d[i]) * x[i] + d[i] * x[i + 1];
      for(i = N1; i <= N - 2; i++)
        b[i] = ds * x[i - 1] + 2 * (1 - ds) * x[i] + ds * x[i + 1];
      b[N-1] = 0;
```

/* Calling for subroutines to calculate temperature at each time level, [T] = [A]$^{-1}$ [B] */

```
      lu(l, u, a) ;
      back(b, l, u, x);
```

/* Print numerical-calculated temperature distribution at the same locations of temperature measurements */

```
       time = dt * (++counter);
     /*  print(" %7.2lf\n", x[0]);  */                    /* Surface temperature of surimi */
      if((time-1) % 20 == 0) {
        printf(" %7.2lf%7.2lf%7.2lf\n", x[9], x[14], x[29]);
      }
```

/* Sum of least square—a check of the modeling result, it should be the same as that obtained from the nonlinear program */

```
      if ((time-1) % 20 == 0){
        i1 = time/20;
      LS = LS + (data[i1][0]-x[9])*(data[i1][0]-x[9]) + (data[i1][1]- x[14])*
           (data[i1][1]- x[14]) + (data[i1][2]- x[29])*(data[i1][2]- x[29]);
      }
    }
    printf(" %8.2lf", LS);
    return 0;
}
```