

**MEASUREMENT OF THERMAL PROPERTIES OF SEAFOOD**

by

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(ABSTRACT)

Thermal properties of ten different seafood were measured in this research. They included bluefish (*Pomatomus saltatrix*), croaker (*Micropogonias undulatus*), spanish mackerel (*Scomberomorus maculatus*), pink salmon (*Oncorhynchus gorbuscha*), black seabass (*Atractoscion nobilis*), spot (*Leiostomus xanthurus*), shrimp (*Pandalus borealis*), tilapia (*Tilapia aurea*), grey sea trout (*Cynoscion regalis*), and yellow fin tuna (*Thunnus albacares*) (Wheaton, et al. 1985). Thermal properties measured were thermal conductivity, thermal diffusivity, and specific heat from 5 to 30 °C. Enthalpy was measured from -40 to 30 °C. Moisture and fat content were measured. Thermal conductivity and thermal diffusivity were measured by a rapid transient technique using a bead thermistor probe. Specific heat and enthalpy were measured using a differential scanning calorimeter. Moisture content and fat content were measured by the AOAC specified oven dry method and ether extraction method, respectively.

The measured thermal properties agreed well with the scarcely available literature values. They were then statistically correlated with moisture and fat content. Based on statistical analysis, mathematical models relating thermal properties and composition were proposed and compared with the models available in the literature. Models for thermal conductivity and specific heat were recommended to predict these properties of meats and fish with similar composition.

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# CHAPTER 1

## INTRODUCTION

Knowledge of thermal properties are essential in the efficient and economical design of all food processing operations involving heat transfer. Some of the common processes involving heat transfer are heating, cooling, freezing, thawing, and frying. It is also of great importance in the development of thermal models for generating accurate numerical results. Besides thermal properties, heat transfer rates, and mechanisms are also very important in the proper design of these processes.

Several researchers including Hill, et al. (1967), Qashou, et al. (1972), Choi and Okos (1983), Sweat (1975) and Rahman (1993) have emphasized the need for thermal properties of foods in general and seafood in particular. These properties greatly depend on the physical characteristics of food such as temperature, size, shape, state (frozen or unfrozen), compositional parameters, (moisture content, fat content, protein, and ash) and fiber orientation. As these properties vary widely with temperature and composition, it is essential to report the measured properties in concert with these parameters. But several researchers including Lentz (1961) and Reidy and Rippen (1971) have reported that these parameters are more often not reported. In addition to this Balaban and Pigott (1992) reported that thermal data are more often reported, either as a function of moisture content or fat content. However models that include both these variables are rare.

An extensive literature search revealed that very limited data were available for seafood in general and for under-utilized fish species like bluefish, croaker, tilapia, etc. in particular. So the study was aimed at the measurement of thermal properties of common mid- atlantic finned fishes. Thermal properties of these species were measured for the above mentioned reasons and also based on the fact that these fishes are more likely to be commercially processed in future due to increasing cost and consumption of other fishes like cod, herring, salmon etc.

Thermal properties like thermal conductivity and thermal diffusivity can be measured by various steady state (guarded hot plate, concentric cylinder, concentric sphere, Woodams, et al. 1968) and unsteady state methods (line source probe, thermal comparator, thermistor probe etc.). All these methods have several advantages and disadvantages. Reidy (1968) and Qashou (1970) each listed in detail the sources of error in thermal property measurements of the various methods.

Steady state techniques pose two major problems for experiments with high moisture products, though they generally require simple mathematical relations to calculate the properties. Firstly, the time required for the temperature distribution to reach a steady state value takes a long time. Secondly, moisture diffusion can occur from high temperature regions to low temperature regions, altering the composition of the sample. The moisture migration might be quite substantial because of the long tests. Transient techniques eliminate both these major problems as the test period mostly varies from a few seconds to a few minutes. Since thermal conductivity is

greatly dependant on physical and chemical composition, which is most often considered as porosity, moisture content, and fat content, transient techniques are recommended for high moisture agricultural materials.

Specific heat unlike thermal conductivity and thermal diffusivity is independent of mass density of the product. Specific heat and enthalpy are often measured by different types of calorimeters, which are direct applications of the enthalpy equation,  $Q = m C_p (T_1 - T_2)$  and energy balance occurring between the sample and the calorimeter. Several researchers have also discussed the use of various thermal models developed from statistical analyses on experiments measuring chemical compositional parameters. Mohsenin (1980) has discussed in detail several other methods used in specific heat measurements of agricultural materials. Mohsenin (1980) and Sweat (1986) suggested the differential scanning calorimeter as the best practical tool for these measurements on foods.

## **1.1 OBJECTIVES**

Taking the above factors into consideration, the objectives of the study were as follows:

- (1) to measure thermal conductivity and thermal diffusivity of the available mid-atlantic seafood by a rapid transient technique using a bead thermistor probe at temperatures from 5 to 30 °C;
- (2) to measure specific heat and enthalpy by a differential scanning calorimeter at temperatures from 5 to 30 °C and from -40 to 30 °C respectively;
- (3) to measure moisture content by the AOAC specified oven-dry method and fat content by the AOAC specified ether-extraction method;
- (4) to statistically correlate the thermal properties with moisture and fat content;
- (5) to develop a mathematical model relating thermal conductivity, thermal diffusivity, enthalpy and specific heat to temperature, moisture content, and specific heat.

# CHAPTER 2

## REVIEW OF LITERATURE

This chapter presents a review of the common methods employed in determining the thermal conductivity, thermal diffusivity, and specific heat of foods and a brief compilation of the thermal properties of seafood from the literature. Lentz (1961) reported that the literature on thermal properties of meats and associated animal fats were limited and often conflicting. Reidy and Rippen (1971) reported the lack of values for experimental parameters such as moisture content and direction of heat flow in addition to the measured thermal properties. This was further supported by many others including Mattea, et al. (1989) and Sweat (1986).

### 2.1 REVIEW OF METHODS FOR THERMAL CONDUCTIVITY AND DIFFUSIVITY

#### 2.1.1 GUARDED HOT PLATE METHOD

Lentz (1961) described the use of a modified guarded hot plate apparatus in measuring the thermal conductivity of meats, fats, gelatin gels, and ice. The standard guarded hot plate method is based on the steady-state longitudinal heat flow principle which determines the thermal conductivity of the material by applying Fourier's law. As described in the ASTM Standards C177-45 (1955), the experimental setup consisted of placing the sample material on each side of a hot plate. This assembly was then sandwiched between cold plates maintained at lower temperatures by liquids circulating through them. Thermal conductivity was determined by measuring the heat flux through the samples for a resulting temperature gradient. The apparatus is so called, because of the edge losses from the sample being prevented by a guard ring. Lentz, in his tests, used an insulation material of known thermal conductivity on one side of the hot plate instead of introducing a second sample to minimize the error. Lentz (1961) used the guarded hot plate apparatus in measuring thermal conductivity of different types of meat such as fish and poultry over a range of temperatures between 5 and -25 °C. He reported that above freezing temperatures, the thermal conductivity of the measured meats were about equal to each other and slightly lower than water. Mohsenin (1980) reported that with this method, the measurements would take a considerable amount of time because of the several hours needed for the sample to reach a steady state condition and because of larger sample sizes. This will eventually promote moisture migration within the sample. So, it was proven more successful especially for dry homogenous samples in the form of slabs. It can be used only for determining thermal conductivity and so thermal diffusivity can only be calculated if the density and specific heat of the sample are known.

### 2.1.2 LINE HEAT SOURCE PROBE METHOD

Sweat and Haugh (1974) reported the use of a thermal conductivity probe for the measurement of thermal conductivity of small food samples based on the theory of the line heat source method. This is based on a linear heat source of infinite length and infinitesimal diameter. It essentially consisted of a thermocouple with a constantan heater wire running along its length, which is the heat source and a copper constantan thermocouple as the temperature recorder. The entire assembly was then enclosed in a 21 gage stainless steel tubing 3.9 cm long and 0.07 mm outer diameter. The basic theory has been discussed in detail by Nix, et al. (1967). Annamma and Rao (1974) also used a line heat source probe for thermal conductivity measurement of fish. They reported a linear relationship between thermal conductivity and moisture content up to about 55%. The linear correlation model is discussed in section 2.3.1 in detail. Wang and Kolbe (1990) reported thermal conductivity measurements of surimi at various cryoprotectant levels using a similar type of thermal conductivity probe. Rahman and Potluri (1991) reported the use of a modified line source probe for thermal conductivity measurements of fresh and dried squid meat. They found that thermal conductivities of fresh and dried squid meat varied from 0.52 to 0.04 W/m·°C at 30 °C and that it decreased with decreasing moisture. The probe consisted of a teflon insulated constantan heater wire in double length acting as a heat source and a chromel - constantan thermocouple. Both were inserted in a stainless steel syringe needle. In both the cases the probes were inserted into the sample of interest initially at uniform temperature. The line source is heated at a constant rate and the probe temperature closest to the line source is monitored. Temperature versus logarithmic time was plotted and the slope determined. The thermal conductivity was calculated using the following formula.

$$k = \frac{Q}{4\rho S} \quad (2.1)$$

where, k = thermal conductivity, W/m·°C,

Q = heat input per unit length of line source, W/m,

S = slope of the line, temperature versus log of time.

Khandan, et al. (1981) had also reported the use of similar type of probe made with a sewing needle instead of a hypodermic needle for better accuracy in thermal conductivity measurements of foods. Nix, et al. (1967) presented a simultaneous measurement technique for both thermal conductivity and diffusivity based on the line source probe method. Kumbhar, et al. (1981) used the technique in measuring thermal properties of 12 different species of fishes over temperatures of -20 °C to 40 °C. Their results indicated that both thermal conductivity and thermal diffusivity are directly dependent on temperature, variety of species, and are directly proportional to the temperature above freezing point. Balaban and Pigott (1992) used the same heated thermocouple method in measuring the thermal conductivity of ocean perch at different temperatures between 20 and 80 °C at different moisture contents. Their results also showed that thermal conductivity increased with temperature and moisture.

### 2.1.3 ACALORIMETER METHOD

The use of acalorimeter or the regular regime method for thermal diffusivity measurement of fish was reported only by Annamma and Rao (1974). It is a transient technique. It is based on the fact that when the heat transfer coefficient of the surrounding medium approaches infinity, the logarithm of the rate of change of temperature becomes constant in time and space, and is proportional to the thermal diffusivity of the sample. Canned samples were used for the measurement of thermal diffusivity by using the equation:

$$a = \frac{2.3026}{f \left[ \left( \frac{2.4048}{a} \right)^2 + \left( \frac{p}{2b} \right)^2 \right]} \quad (2.2)$$

where,

$\alpha$  = thermal diffusivity,  $m^2/s$ ,

$f$  = slope of the heating curve from a time-temperature plot drawn on an inverted semi-log paper,

$a$  = finite cylinder radius,  $m$ ,

$2b$  = length of the cylinder,  $m$ .

### 2.1.4 THERMISTOR PROBE METHOD

The use of thermistor probes in the measurement of thermal properties of foods is very limited. The use of thermistors for the determination of thermal conductivity of biomaterials was reported as early as in 1968 by Chato (1968). Thereafter it was used for the measurement of thermal properties of biomaterials and of tissue perfusion, but not for food. Kravets (1988) used thermistors to measure the thermal conductivity of various milk products at high temperatures. He concluded that the method was very practical and thermal conductivity measurements correlated well with the physical changes occurring in milk at higher temperatures. Van Gelder and Diehl (1996) measured thermal conductivity and thermal diffusivity of tomato products and nutritional supplements at high temperatures. Thermal conductivity values for the tomato products agreed quite well with the reported values, but thermal diffusivity values were much larger than literature values. They also reported a positive relation between temperature and moisture content.

A thermistor is a thermally sensitive resistor which exhibits a change in electrical resistance with a change in temperature (Thermometrics, 1980). These are ceramic semiconductors made of oxides of manganese, nickel, cobalt, copper, iron, and titanium. Some of the commonly available thermistors are bead type, disk type, wafer and chip type, flake and rod thermistors (Thermometrics, 1980). Kravets (1988) and Van Gelder and Diehl (1996) used self-heated bead type thermistors in thermal properties measurements.

Solution of a coupled thermal model for a finite thermistor placed in a continuous, homogenous, infinite perfused medium described by Valvano, et al. (1984) was used to determine the thermal conductivity and thermal diffusivity. Balasubramaniam (1975) and Valvano, et al. (1985) described in detail the theory behind the coupled thermal model. The model was based on the assumptions that the thermistor is spherical, heat is generated in all the regions of the bead, heat is generated uniformly in the bead (Hayes and Valvano, 1985), there is no contact resistance between the thermistor and the medium, and the mode of heat transfer is only by conduction.

Thermal conductivity of the medium was determined from the steady state solution of the coupled thermal model by the following equation (Van Gelder and Diehl, 1996):

$$\frac{1}{k_m} = \frac{4\pi a R_f \Delta T_b}{V_{ss}^2} - \frac{1}{5k_b} \quad (2.3)$$

where,

$k_m$  = thermal conductivity of the medium, W/m•°C,

$a$  = radius of the thermistor, m,

$R_f$  = final resistance of the thermistor,  $\Omega$ ,

$\Delta T_b$  = Temperature of the thermistor - Temperature of the medium, °C,

$V_{ss}^2$  = Square of the voltage in the steady state condition, V<sup>2</sup>,

$k_b$  = thermal conductivity of the bead, W/m•°C.

Thermal diffusivity was determined from the transient state solution of the thermal model by:

$$a_m = \left[ \frac{a}{(\beta / t) \left( 1 + \frac{k_m}{5k_b} \right) \sqrt{\rho}} \right]^2 \quad (2.4)$$

where,  $\alpha_m$  = thermal diffusivity of the medium, m<sup>2</sup>/s,

$\beta$  = slope of the heat generation equation,

$\Gamma$  = intercept of the heat generation equation.

## 2.2 REVIEW OF METHODS FOR SPECIFIC HEAT AND ENTHALPY

### 2.2.1 SPECIFIC HEAT FROM CHEMICAL COMPOSITION

Mohsenin (1980) reported that the need for data on specific heat of food materials had been recognized as early as 1892. Siebel (1892) in order to provide some experimental values for products like meat, egg, fruits, and vegetables calculated the specific heat based on the assumption that food materials mainly comprised of water and solids as their major constituents. So, the specific heat of the material was calculated as the sum of the specific heat of water and solid matter. Based on the calculated values, he proposed an equation for specific heat of foods above freezing temperatures as:

$$C_p = 0.008a + 0.20 \quad (2.5)$$

where  $C_p$  is the specific heat of the substance containing “a” percent of water. It was assumed uniformly that 0.2 represented the specific heat of the solid matter. For frozen foods since the specific heat of frozen water is nearly half that of the water, it can be calculated from another equation as:

$$C_p = 0.003a + 0.20 \quad (2.6)$$

Several other thermal models developed based on chemical composition for specific heat have been listed in Section 2.3.3

### 2.2.2 METHOD OF MIXTURES OR THE DIRECT WATER IMMERSION METHOD

Rahman (1993) reported the method of mixtures as the most common method for food materials. The method of mixtures consists of dropping a specimen of known mass and temperature into a calorimeter of known specific heat and water of known mass and temperature. The unknown specific heat is then calculated from a heat balance equation after the thermal equilibrium has reached. Mohsenin (1980) reported the calculation of the average specific heat of the sample from:

$$C_s = \frac{C_w W_w (t_e - t_w) - C_c W_c (t_i - t_e)}{W_s (t_i - t_e)} \quad (2.7)$$

where,

$C_s$ ,  $C_w$  and  $C_c$  = specific heat of sample, water and calorimeter, kJ/kg•K, respectively,

$W_w$ ,  $W_c$ , and  $W_s$  = weight of water, calorimeter and sample, kg, respectively,

$T_e$  = equilibrium temperature of the mixture, K,

$T_w$  = initial temperature of water, K,

$T_i$  = initial temperature of the sample and calorimeter, K.

Rahman (1993) reported the range for specific heat of fresh seafood from 3.29 to 3.79 kJ/kg•K. Balaban and Pigott (1992) also reported the use of the same method in heat capacity calculations of ocean perch. They summarized the results with an empirical equation for heat capacity of ocean perch at different moisture contents and temperatures

Lewis (1987) had mentioned that the heat losses to the surroundings was the greatest concern in such experimental units. To avoid heat losses the calorimeter was maintained at the same temperature as that of the surroundings. The calorimeter developed based on this principle is referred to as the adiabatic calorimeter. Several researchers, including Jason and Long (1955) also reported the use of an adiabatic calorimeter in the measurement of specific heat of fish muscle at freezing temperatures. Pham, et al. (1993) also used the same technique in the enthalpy measurement of 27 types of food materials such as fish and processed meat over the temperature range of -40 to 40 °C. They found that their values agreed well with Schwartzberg model which calculated enthalpy by adding enthalpies of individual components.

### **2.2.3 DIFFERENTIAL SCANNING CALORIMETER**

Though several food related experiments have been carried out using differential scanning calorimeter, it was Wang and Kolbe (1991) who reported the use of this rapid measuring technique in the measurement of thermal properties like initial freezing point, unfreezable water, enthalpy and apparent specific heat. As discussed by Mohsenin (1980), the differential scanning calorimeter produces a thermogram in accordance to the heat energy gained or lost by the sample. This is done by a scanner which scans the sample at the desired rate over a specified temperature level of interest. The test material and the reference material are held in a cell. They are heated by individual heaters but maintained at the same temperature and the amount of heat energy required to maintain this temperature is recorded.

## **2.3 REVIEW OF EMPIRICAL MODELS FOR THERMAL PROPERTIES OF SEAFOODS**

Sweat (1986) discussed the various empirical models used in the prediction of thermal properties of foods in general. Some of the thermal models, which were later used by other researchers in the prediction of seafoods are listed below.

### **2.3.1 THERMAL CONDUCTIVITY MODELS**

The following equation was originally developed by Chato (1966) from experimental results using biomaterials. Later on it was used by Sahriri, et al. (1981) in determining thermal conductivity of different fish species such as mackerel, tilapia and sardine.

$$k = 0.0324 + 0.329W \quad (2.8)$$

where,

$k$  = thermal conductivity, W/m•°C,

$W$  = water content, in decimal.

Sweat (1975) predicted one equation each for temperature above and below freezing based on all the available thermal conductivity of meats, poultry, and fish up to 1975. The equation mentioned below is used for calculating thermal conductivity of foods above freezing temperatures.

$$k = 0.080 + 0.52W \quad (2.9)$$

where,

$k$  = thermal conductivity, W/m•°C,

$W$  = water content, in decimal.

Sweat (1986) developed a general equation for solid and liquid foods from a data set of about 430 points:

$$k = 0.48X_w + 0.155X_p + 0.25X_c + 0.16X_f + 0.135X_a \quad (2.10)$$

where,

$k$  = thermal conductivity, W/m•°C,

$X_w$  = water content, decimal,

$X_p$  = protein content, decimal,

$X_c$  = carbohydrate, decimal,

$X_f$  = fat content, decimal,

$X_a$  = ash, decimal.

The model mentioned is valid for a narrow temperature range above freezing as the temperature term was not included in the model. Sweat (1986) computed the average deviation as

$$\sum (k_e - k_p)^2 / n$$

where,

$k_e$  = experiment value,

$k_p$  = predicted value,

$n$  = number of data points.

### **2.3.2 THERMAL DIFFUSIVITY MODELS**

The following equation was developed by Charm (1971). It was cited and used by Sahriri and co-researchers (1981) in determining thermal diffusivity of mackerel, tilapia and sardine.

$$a = \frac{0.398}{\left(\frac{1}{a^2} + \frac{0.427}{b^2}\right)f_h} \quad (2.11)$$

$\alpha$  = thermal diffusivity, in.<sup>2</sup>/min,

where  $2a$  = diameter of the can, in.,

$2b$  = inside length of the can, in.,

$f_h$  = reciprocal of the slope index of heating curve, min.

### 2.3.3 SPECIFIC HEAT MODELS

Reidel (1956) developed the model based on calorimetric investigations on fish meat for temperature above freezing.

$$C_p = 1.672 + 2.508W \quad (2.12)$$

where,

$C_p$  = Specific heat, kJ/kg•K,

$W$  = water content, in decimal.

The following equation was developed by Zaitesev, et al. (1969). It was cited and used by Sahriri and co-researchers (1981) in determining specific heat of mackerel, tilapia and sardine.

$$C_p = W + 0.5F + 0.36P \quad (2.13)$$

where,

$C_p$  = Specific heat, Btu/lb<sub>m</sub>•°F,

$W$ ,  $F$ , and  $P$  are the water content, fat content and protein fractions respectively.

Rahman, 1993 measured the specific heat of selected fresh seafood (calamari, cuttle, prawn, octopus, and squid) by method of mixtures and fitted the data to several models proposed by him. Based on the model that gave the lowest f-ratio, the model mentioned below was recommended to predict specific heat of related seafood. Details of the several other models are elaborately discussed by Rahman (1993).

$$C_p = 35.06 - 81.33X_w + 52.88X_w^2 \quad (2.14)$$

$C_p$  = Specific heat, kJ/kg•K,

where  $X_w$  is the mass fraction of water.

## 2.4 REVIEW OF THERMAL PROPERTIES OF SEAFOODS

A literature search revealed the limited availability of data on thermal properties like thermal conductivity, thermal diffusivity, enthalpy, and specific heat for seafood in general. A brief compilation of the available thermal property data from the literature is listed in Table A.1 of Appendix A.

Interest in thermal properties of seafood dates back to 1892 when Siebel (1892) calculated the specific heat of eels, whitefish, and lobster using thermal models given in section 2.2.1 developed from compositional parameters such as water content and solids. Sanz, et al. (1987) reported the work of Lobsin (1939) in thermal conductivity measurements of pike perch. In 1944 Short, et al. (sited by Polley, et al. 1980) measured the specific heat of shrimp and redfish by a bomb calorimeter. Griffiths, et al. (1948) measured thermal conductivity of whale blubber using the parallel plate apparatus. In 1952 Smith et al. conducted measurements to determine thermal conductivity of herring, perch, and whale meat also using the parallel plate apparatus. Jason and Long (1955) used the principle of an adiabatic calorimeter to measure the specific heat of cod muscle. Lentz (1961) used a modified version of the parallel plate or the guarded plate apparatus in determining thermal conductivity of salmon. In 1974, Annamma and Rao used the line source technique and a calorimeter in measuring thermal conductivity and thermal diffusivity respectively of prawn, sardine, and mackerel. Later in 1981, Kumbhar, et al. experimentally measured thermal conductivity and thermal diffusivity of various fish species using the line heat source method. Rahman and Potluri (1991) also measured thermal conductivity of dry and fresh squid using the line heat source probe. In 1992, Balaban and Pigott measured thermal conductivity of ocean perch by the heated thermocouple method and heat capacity by direct water immersion technique. In 1993, Rahman extended his work on thermal property measurement by measuring specific heat of selected fresh seafood like calamari, squid, prawn, and cuttle by the method of mixtures method. Pham, et al. (1993) reported the use of an adiabatic calorimeter for enthalpy measurements of Gurnard and Tarakihi fillets in their experiments.

# CHAPTER 3

## MATERIALS AND METHODS

This chapter summarizes the techniques used in the measurement of thermal properties of ten different species of seafood. Thermal conductivity, thermal diffusivity, specific heat and enthalpy were measured for bluefish (*Pomatomus saltatrix*), croaker (*Micropogonias undulatus*), spanish mackerel (*Scomberomorus maculatus*), pink salmon (*Oncorhynchus gorbuscha*), black seabass (*Atractoscion nobilis*), spot (*Leiostomus xanthurus*), shrimp (*Pandalus borealis*), tilapia (*Tilapia aurea*), grey sea trout (*Cynoscion regalis*), and yellow fin tuna (*Thunnus albacares*). Moisture and fat content were also measured.

### 3.1 SAMPLE PREPARATION

When available, whole fish were purchased, headed, and gutted. Each was then cut perpendicular to the backbone into sections of about three inches long. One section was used for the thermal conductivity and thermal diffusivity tests and the other section was frozen and used later for all the other tests. Three fish were handled in this way resulting in three replications for thermal conductivity, thermal diffusivity, specific heat, and enthalpy tests. For shrimp, three different headed specimens were used for all tests. The shells were removed and used for all tests. Due to the unavailability of whole tuna, a single large steak was cut into three pieces of about one inch thick and each piece was used for all tests. For salmon, three steaks, each about an inch thick, were purchased and each was used for all tests. The shrimp, salmon, and tuna specimens were frozen immediately after thermal conductivity and thermal diffusivity tests, and used later for other tests.

### 3.2 MEASUREMENT OF THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY

This section summarizes the techniques involved in measuring the thermal conductivity and thermal diffusivity of seafood.

#### 3.2.1 SELECTION OF THERMISTOR

Number of factors are to be considered in choosing a probe. Valvano, et al. (1985) reported that larger probes are necessary to increase the effective volume of measurement, reduce the effect of thermal contact and to improve the accuracy and durability, but he also added that smaller probes were necessary to increase the time response of the probe. Considering these factors, glass encapsulated Thermometrics P100 (Edison, NJ) bead thermistor probes with a diameter of 0.1 inches and a resistance of 1000  $\Omega$  at 25 °C was chosen. The probe lead wires were soldered to insulated wires at the ends. The soldered junctions were wrapped with heat shrink tubing and the

ends were coated with epoxy to minimize entry of moisture into the probe. The thermistors were examined under a microscope for proper shape and presence of water or air globules.

### 3.2.2 TEMPERATURE CALIBRATION OF THE THERMISTOR

To measure the temperature of the medium in the sensing mode, the thermistor probe must be calibrated for temperature. This was accomplished by the simultaneous measurement of resistance and temperature by a Keithley model 2000 multimeter (Cleveland, Ohio) and a Guildline model 9540 digital platinum resistance thermometer (Ontario, Canada) traceable to National Bureau of Standards respectively (Table B.4 of Appendix B). The thermometer along with the probe was placed in a sample holder. It was then immersed partly in a Haake model A82 constant temperature bath (Saddle Brook, New Jersey) to maintain constant temperature conditions. The resistance was measured at about 5, 10, 15, 20, 25, 30 °C.

An inverse log function was used to calculate the thermistor temperature T, from the thermistor resistance by:

$$T = \frac{1}{H_0 + H_1 \ln R + H_3 (\ln R)^3} \quad (3.1)$$

where, T is the temperature of the thermistor in °C.  $H_0$ ,  $H_1$ , and  $H_3$  are calibration coefficients, which were determined by non-linear regression analysis using the Statistical Analysis Software (SAS Systems, Cary, North Carolina) using the calibration data. The SAS code for performing the non-linear regression is included in D.1 of Appendix D. This procedure was repeated for three different thermistors. Two of them were kept in reserve for future use in case of breakage and one was calibrated for thermal conductivity and thermal diffusivity using the circuit described in the section 3.2.3

### 3.2.3 CIRCUIT

The test for measuring thermal conductivity and thermal diffusivity of the medium consists essentially of imbedding the thermistor probe into the medium of interest and maintaining the probe at a prescribed temperature elevation above the temperature of the medium throughout out the experiment. This is accomplished by a special electronic circuit originally designed by Balasubramaniam (1975), which was used in the conductivity and diffusivity measurements. The circuit operates as follows.

A current is sent through the thermistor and the resulting voltage drop is measured with a data acquisition unit. The resistance is calculated and converted into a temperature using the equation 3.1. A temperature step of 2.5 °C is chosen and added to this temperature to calculate the desired final temperature. This is converted into final resistance using equation 3.1. This resistance is matched with the resistance of the resistor bank consisting of nine resistors, of which eight resistors are fixed and sums up to a total resistance of approximately 255 Ω and the ninth resistor is adjusted to a resistance between 500 and 3500Ω, to match the total resistance of the thermistor. The resolution of the resistor bank is such that the final temperature is within 0.03 °C

of the intended final temperature. The resistance is measured to calculate the final attained temperature. The realized temperature step  $\Delta T$  in equation 2.3 is then calculated as the difference between the final and the initial temperature.

For this research, the measurement control and data acquisition took place through software written in Turbo Pascal 4.0 (Van Gelder and Diehl, 1996). The circuit described above was assembled by Van Gelder and was interfaced to a personal computer with a Metrabyte Corporation PIO-12 input/output board (Taunton, MA) and a Metrabyte Corporation DAS-20 analog digital converter (Taunton, MA).

When data collection began voltages of opposite sign were applied across the thermistor and the resistor bank. The circuit was designed such that voltages applied across the thermistor and the resistor bank equilibrated within 0.1 seconds. The voltage across the sample was measured at a rate of 100 Hz for a period of 30 seconds. The data was plotted as voltage squared versus inverse of square root of time. A linear regression was done on the data to give the intercept of this plot which is the steady state voltage squared achieved at infinite time (Kravets, 1988).

### **3.2.4 THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY CALIBRATION OF THE THERMISTOR**

To measure the thermal properties from equations 2.3 and 2.4, the thermistor coefficients, effective probe radius "a" and effective thermal conductivity " $k_b$ " must be determined. This is accomplished by calibrating the thermistors with thermal standards of known thermal properties in the measurement range, at each temperature. Distilled water, Fisher Scientific glycerin (Pittsburg, PA) and Union Carbide UCON 500 heat transfer fluid (Danbury, CT) were used as thermal standards. Their thermal properties are listed in Tables A.2 of Appendix A. Calibration data of thermistors with these thermal standards have been tabulated in Tables B.1, B.2, and B.3 of Appendix B. 0.5% agar was added to water as a thickener to prevent convection around the probe at higher temperatures. Valvano et al. (1985) had established the fact that thermal properties of water remained unaltered with the addition of very low concentrations of agar. Fiber glass pipe insulation material in a concentration of 1.5 % weight per volume was used in the sample holder to prevent convection around the probe when the heat transfer fluid and glycerin were used as the calibrating medium. It was assumed that the thermal properties were not affected by the presence of such low concentrations of fiber glass insulation material. The probe was imbedded into the media and the parameters were measured at about 5, 10, 15, 20, 25 and 30 °C in each liquid. A cylindrical jacketed sample holder adapted from a Brookfield viscometer unit (Stoughton, Massachusetts) of height 60.15 mm and diameter 20.9 mm was used in all the calibration procedures. Three replicates were taken at each temperature. Sufficient time was allowed between each measurement for the medium and the thermistor to reach a state of equilibrium. A temperature step of 2.5 °C was used. The sample was scanned for 30 seconds at a speed of 100 Hz. Valvano et al. (1985) reported that heating intervals of more than 20 seconds are required to increase the effective volume of measurement and improve the statistics of linear regression. Regression analysis was performed to determine  $R_f \Delta T_b / V_{ss}^2$  in equation 2.3 and  $\beta / \tau$  in equation 2.4. Regression was done for sample points collected from 3 seconds to 15 seconds.

This particular time region was chosen to ensure better linearity. Avoidance may result in a non-linear curvature because of thermal equilibration still occurring in the initial period and convection in latter period. The final resistance ( $R_f$ ), temperature step ( $\Delta T_b$ ), steady state voltage squared ( $V_{ss}^2$ ) and the reference medium thermal conductivity were all used in equation 2.3 to determine the bead thermal conductivity ( $1/k_b$ ) as a function of effective radius. This data was then plotted for each reference material at temperatures of 5, 10, 15, 20, 25 and 30 °C. The intersection point of the three standardization lines yielded the effective radius and thermal conductivity of the thermistor bead probe. This entire procedure was done by a computer program written in Pascal. It was determined statistically that temperature was insignificant with regard to the bead parameters. So the bead parameters were averaged across temperatures and each single averaged value was used as the effective radius and effective thermal conductivity respectively of the thermistor probe. The slope and the intercept values were calculated to define the steady state  $\tau$  and the transient state  $\beta$  parameters in the heat generation equation, which is a function of thermal properties of the medium.

### **3.2.5 EXPERIMENTAL PROCEDURE**

The calibrated probe was used for the measurement of thermal conductivity and diffusivity of the seafood samples. Except as noted, the sample holder was a rectangular aluminum bread pan 9.25 inches long and 5.25 inches wide for all thermal conductivity and thermal diffusivity measurements. The sample holder was partially immersed in the constant temperature bath. Each of the three pieces of fish was placed side by side on the pan. Except as noted below, the probe was inserted into the side above and parallel to the backbone for all the samples. In the case of salmon the probe was inserted into the side and perpendicular to the backbone. For tuna the probe was inserted from the side. The shrimp samples were placed side by side on the sample holder, and the probe was inserted parallel to the axial direction of the body. The samples were covered with three layers of saran wrap above and below and with fiber glass pipe insulation material on top to minimize heat losses. The procedure described in the calibration section was repeated for each fish and shrimp at each temperature. Since all the parameters in equation 2.3 and 2.4 were known, thermal conductivity and thermal diffusivity of the samples could be calculated. Three replicates were taken at each temperature of about 5, 10, 15, 20, 25 and 30 °C and the data was recorded for thermal conductivity and thermal diffusivity calculations. The constant temperature bath was held at a lower temperature, so that the sample would reach temperatures approximately 5, 10, 15, 20, 25 and 30 °C. The probe was used to monitor temperature equilibration, and the actual temperature of the sample was read from the thermistor. These temperatures were used in all the statistical analyses. Sufficient time was given for the medium and thermistor to equilibrate. It normally ranged from fifteen to twenty minutes between replicates and one to two hours between each temperature measurement.

### **3.3 SAMPLE PREPARATION FOR MOISTURE CONTENT, FAT CONTENT, ENTHALPY AND SPECIFIC HEAT TESTS**

The preserved pieces were thawed and only the flesh was removed. It was then ground using a Warring model 7011 commercial blender (New Hartford, Connecticut) to get an uniform sized material. About 5 - 6 g of the sample was used for determining moisture and fat content and about 25-30 mg was used for determining enthalpy and specific heat. Each sample was tested once for moisture and fat content measurements.

### **3.4 MEASUREMENT OF MOISTURE CONTENT**

The moisture content was measured by the standard procedure described in the AOAC Official methods of analysis (1990) for meat and meat products by the oven dry method.

### **3.5 MEASUREMENT OF FAT CONTENT**

Fat was defined as an ether extractable material and so was determined by the standard ether extraction method described in the AOAC Official methods of analysis (1990) for meat and meat products. This was accomplished by a Tecator AB, Soxtec System HT2 1045, ether extraction unit (Hoganas, Sweden).

### **3.6 MEASUREMENT OF ENTHALPY AND SPECIFIC HEAT**

Both specific heat and enthalpy were measured with a DSC 30 Mettler TC 11 TA processor differential scanning calorimeter (Hightstown, New Jersey). The instrument was calibrated for temperature and heat flow with a standard aluminum pan containing a measured quantity of lead, zinc and calcium. Heat flow calibration was also done with a standard aluminum pan containing a measured quantity of indium. Since enthalpy was measured at temperatures below freezing, a special three point calibration was done with high purity acetone, gallium, and mercury. The melting points are -94.6, 29.8 and -38.9 °C, respectively (CRC, 1985). Samples were weighed on a Sartorius model 1712 MP 8 digital analytical balance (Westbury, New York). Samples weighing about 25 - 30 mg were sealed in Mettler aluminum pans (Highstown, New Jersey). The samples were scanned at a heating rate of 5 °C/min over the range of -40 to 30 °C for enthalpy measurements and at a heating rate of 10 °C/min over the range of 5 to 30 °C for specific heat measurements. In all the cases, reference pans were empty aluminum pans. Liquid nitrogen was used as a purge gas during all the experiments.

### **3.7 STATISTICAL ANALYSIS**

All statistical analyses related to this study were done using the Statistical Analysis Software (SAS Systems, Cary, North Carolina). Details of the analysis can be found in the appropriate sections of chapter 4. All the analysis were carried out at measured temperatures at a significance

level of 0.05. Tuna was excluded from the analysis, since data taken using a single steak cannot represent the population.

# CHAPTER 4

## RESULTS AND DISCUSSION

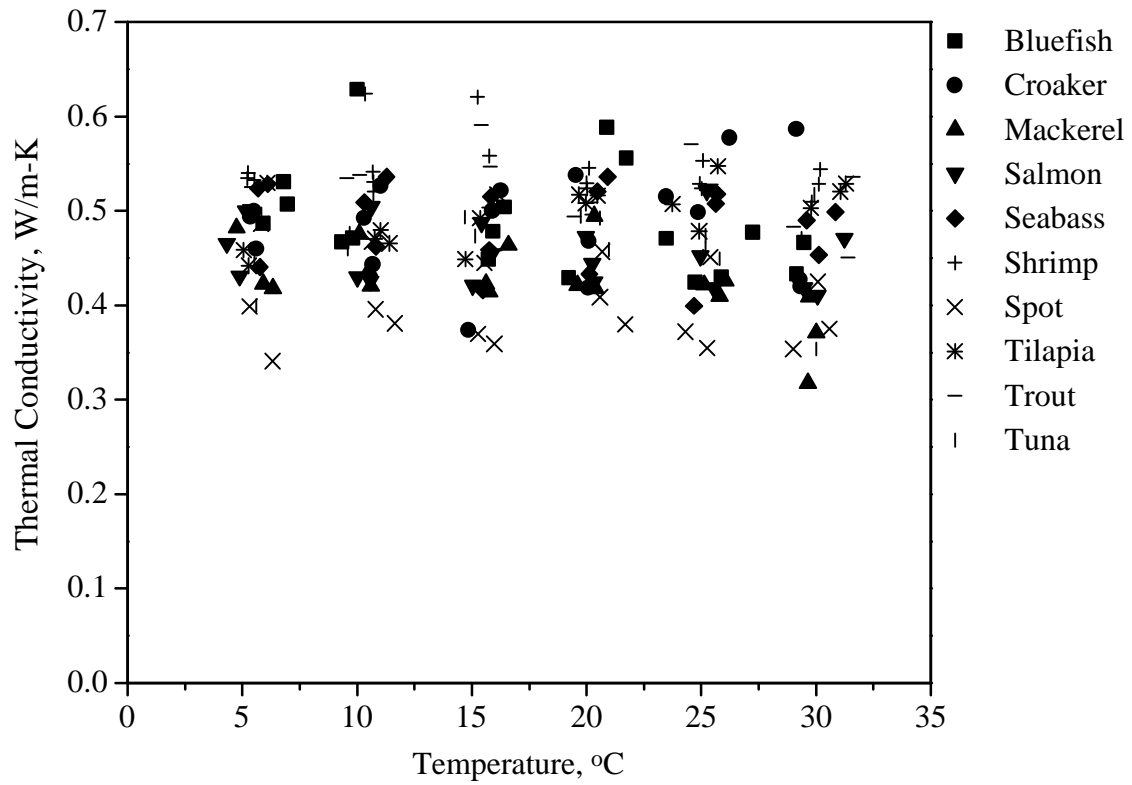
This chapter discusses the various results obtained during thermal conductivity(k), thermal diffusivity ( $\alpha$ ), specific heat ( $C_p$ ), enthalpy (H), moisture content, and fat content measurements. These measurements were carried out with ten different types of seafood that included bluefish, croaker, salmon, seabass, shrimp, spanish mackerel, spot, tilapia, trout, and tuna.

### 4.1 THERMAL CONDUCTIVITY TESTS

The measured thermal conductivity values are presented in Tables C.1 - C.10 of Appendix C. The values in general ranged from 0.4 to 0.6 W/m•K. Kumbhar, et al. (1981) had reported values ranging from 0.416 to 0.459 W/m•K for mackerel at temperatures 0 to 30 °C, which compared well with the measured readings (Table C.6 of Appendix C). The only other data available was for salmon of the British Columbia variety (Lentz, 1961). The only value that could be compared to was 0.502 W/ m•K at about 4 °C, which agreed well with the measured value (Table C.3 of Appendix C). All the other values were reported for the freezing range. An extensive literature search revealed that thermal conductivity values were not available for the direct comparison of other species of seafood measured during this study. But in general it can be concluded that the resulting thermal conductivity values agreed well with the values found in the literature for seafood in general (Table A.1 of Appendix A).

#### 4.1.1 EFFECT OF TEMPERATURE, FAT CONTENT, AND MOISTURE CONTENT ON THERMAL CONDUCTIVITY

Statistical analysis was done to study the effect of temperature, moisture content, and fat content on thermal conductivity and to formulate a model for thermal conductivity including these three parameters. Individual regressions for each fish regressing temperature with thermal conductivity was done. The SAS code written to accomplish a general linear model (GLM) is included in D.2 of Appendix D. All tests were performed at  $\alpha = 0.05$  significance level. The probability (p) values for 27 runs were larger than 0.05. Except for three runs the probability values were significant. So, overall it was concluded that the effect of temperature was insignificant with regard to thermal conductivity in the range studied. This can be observed well in Figure 1, where the values of thermal conductivity did not change much with temperature. The underlying basis for the lack of temperature effect may be because of the influence of thermal conductivity of water. Since most of the product is water, thermal conductivity of water would dominate the most. Since thermal conductivity of water varies very little (Kreith and Bohn, 1993) in the measured range of 5 to 30 °C, temperature remains insignificant. This was also stated by Sweat (1975), who concluded from several models that temperature had little effect on thermal



**Figure 1. Thermal conductivity versus temperature for all species. At each temperature, values for the three samples are shown.**

conductivity above freezing for meats. As a result the values for thermal conductivity were averaged across temperatures.

A regression analysis was done with the averaged thermal conductivity values and moisture and fat content. The SAS code for this regression analysis is included in the D.3 of Appendix D. A significance level of  $\alpha = 0.05$  was considered for these tests. Individual models for thermal conductivity versus fat and thermal conductivity versus moisture content were studied. In both the models fat and moisture content were significant. A model including both the moisture content and fat was proposed to study the combined effect of these parameters on thermal conductivity. The effect of moisture content was barely significant (probability value = 0.0638) and that of fat was barely significant (probability value = 0.0983). This can be due to the masking effect of moisture and fat content on each other in the combined model. Based on the results, a model for thermal conductivity was proposed as:

$$k = 0.2223 - 0.0036F + 0.0035M \quad (4.1)$$

where,

$k$  = thermal conductivity, W/m•K,

$F$  = fat content, %,

$M$  = moisture content, %.

The R-square for the model was 0.7248 and the root mean square error was 0.02575. This model was compared to the model (4.2) proposed by Sweat (1975) for meats and fish from 230 data points found in the literature:

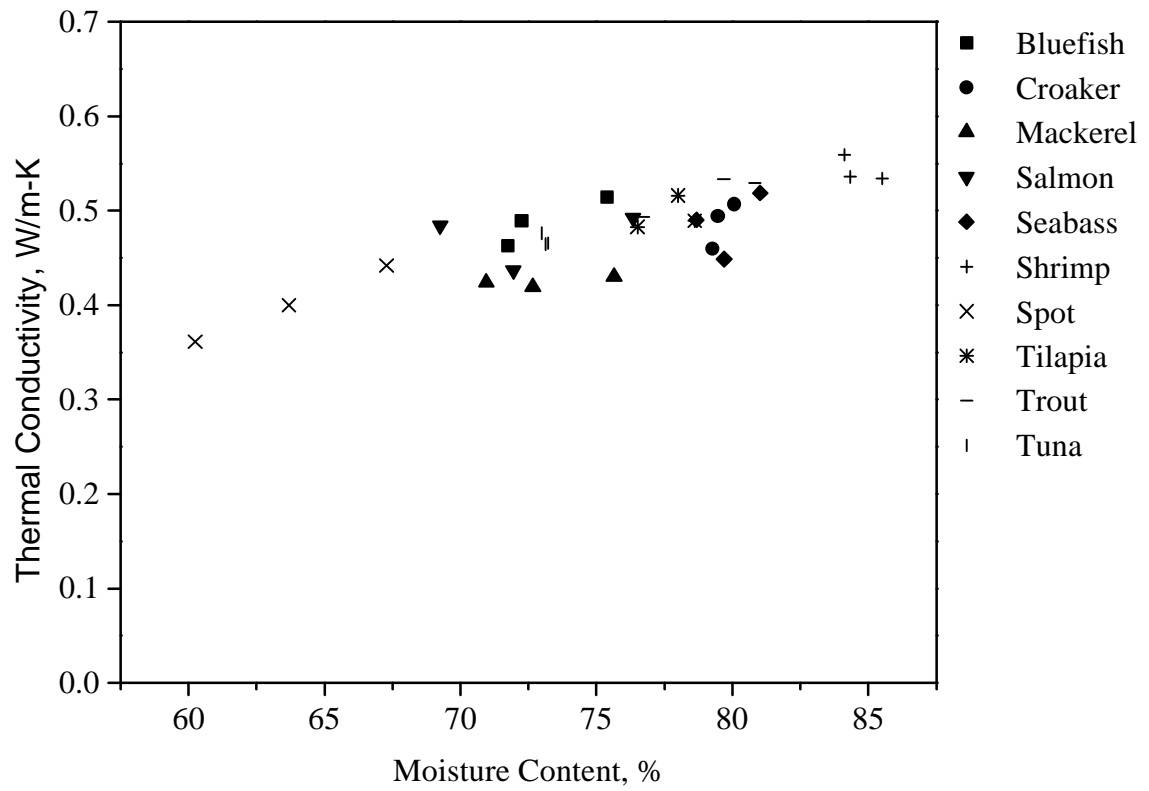
$$k = 0.080 + 0.0052M \quad (4.2)$$

Equation 4.1 and equation 4.2 cannot be compared directly, because of the additional term for fat content in equation 4.1. So the average fat content of 3.7534% was substituted into 4.1 and then compared. The resulting equation was

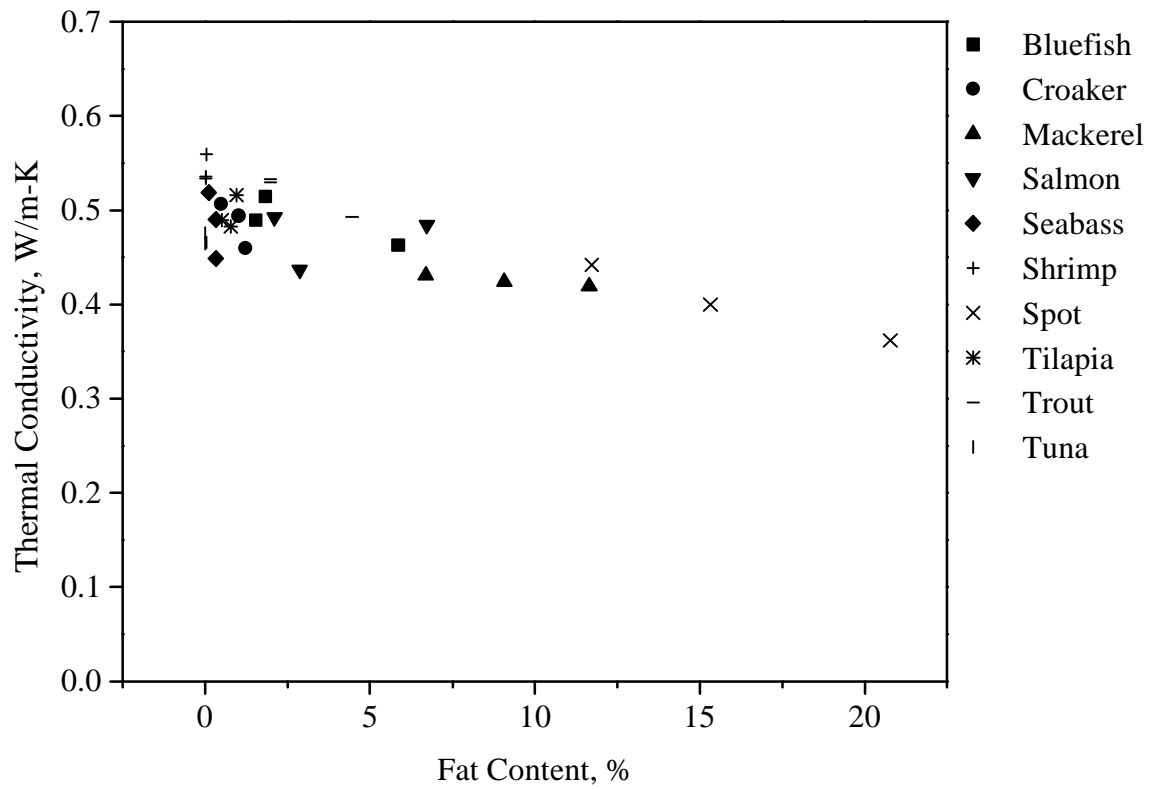
$$k = 0.2088 + 0.0035M \quad (4.3)$$

and this agreed well with the equation 4.2. The minor discrepancy may be accounted due to different set up of experiments and other unknown parameters like fat content.

The significance of moisture and fat content with regard to thermal conductivity can also be observed in Figures 2 and 3. In the figure for thermal conductivity versus moisture content, an increasing trend can be noticed in general, which agreed well with the positive correlation reported in most of the literature for thermal conductivity and moisture (Sweat, 1986). The main basis for this trend can be explained by the increased thermal conductivity' due to increased quantity of water. More water results in a higher thermal conductivity for moisture rich products. This is also explained by the positive sign in equation 4.1. On the other hand, Figure 3 for thermal



**Figure 1. Thermal conductivity versus moisture content for all species. Thermal conductivity values are averaged across the temperature range of 5 to 30 °C**



**Figure 2. Thermal conductivity versus fat content for all species. Thermal conductivity values are averaged across the temperature range of 5 to 30 °C**

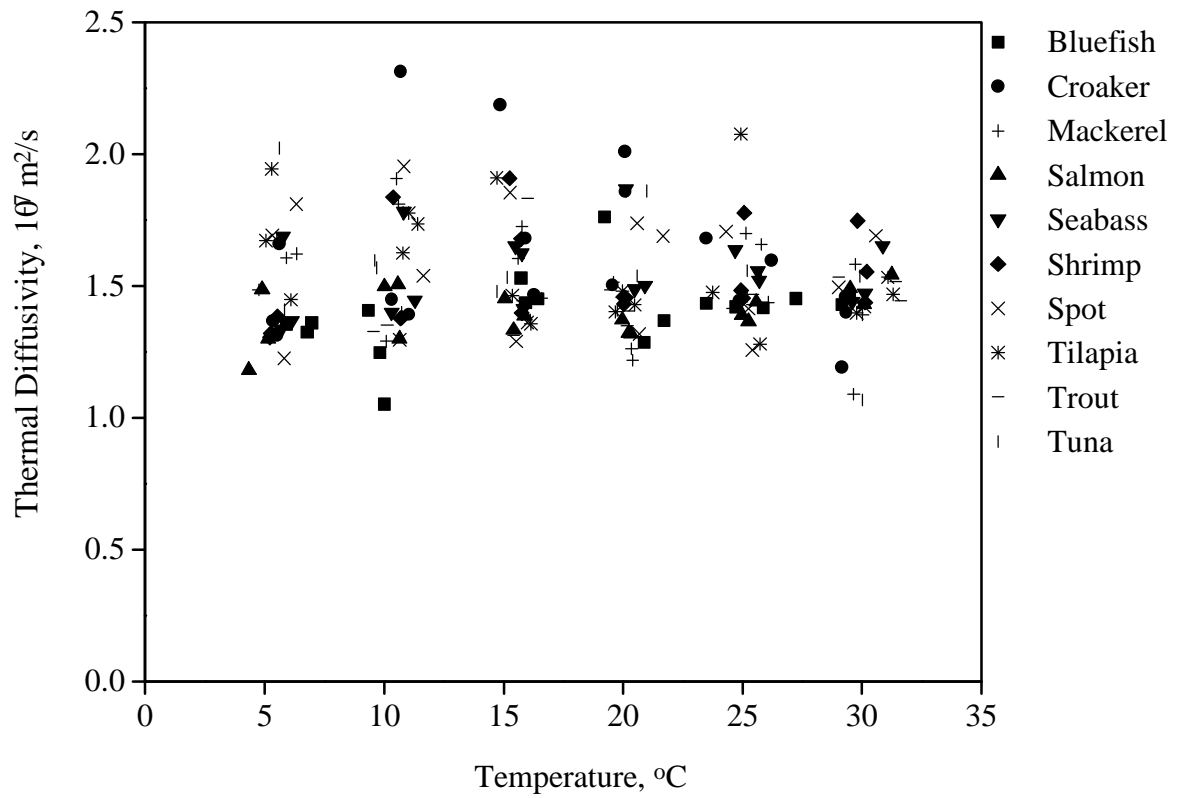
conductivity versus fat content shows a negative trend. This can be substantiated by the layers of fat acting as an insulation and reducing heat conduction, which is explained by the negative sign for the fat content in the model.

## **4.2 THERMAL DIFFUSIVITY TESTS**

Thermal diffusivity was measured for the same range of temperature as that of conductivity experiments. They ranged from 1.1 to  $1.9 \times 10^{-7} \text{ m}^2/\text{s}$  for the ten different species of seafood measured during the study. In general, thermal diffusivity values were rarely found in the literature which made it difficult for direct comparison. Kumbhar, et al. (1981) had reported diffusivity values for 12 different species of fishes which included values for mackerel at 10, 20 and 30 °C. These reported values ranged from 1.086 to  $1.875 \times 10^{-7} \text{ m}^2/\text{s}$  for a temperature range of 0 to 30 °C, which compared well with the measured values. The measured thermal diffusivity values for salmon (Table C.3 of Appendix C) also agreed well with the value reported by Dickerson (1968). He had reported a value of  $1.45 \times 10^{-7} \text{ m}^2/\text{s}$  for temperatures ranging from 0 to 27 °C.

### **4.2.1 EFFECT OF TEMPERATURE, FAT CONTENT, AND MOISTURE CONTENT ON THERMAL DIFFUSIVITY**

Statistical analysis was done to observe the effects of temperature, fat, and moisture content on thermal diffusivity for the ten different seafoods measured during this research. The analysis was carried out in the same manner as described in the section 5.1.1 for thermal conductivity. Individual regressions, regressing thermal diffusivity and temperature for each fish, except for three proved that temperature was insignificant. This can also be seen in Figure 4 for thermal diffusivity versus temperature, where thermal diffusivity did not change much with temperature. This can be explained based on thermal diffusivity of water varying very little within the range of 5 to 30 °C (Kreith and Bohn, 1993). Therefore thermal diffusivity was averaged across temperatures. The SAS code for the above GLM procedure is included in D.2 of Appendix D.



**Figure 3. Thermal diffusivity versus temperature for all species. At each temperature, values for the three samples are shown.**

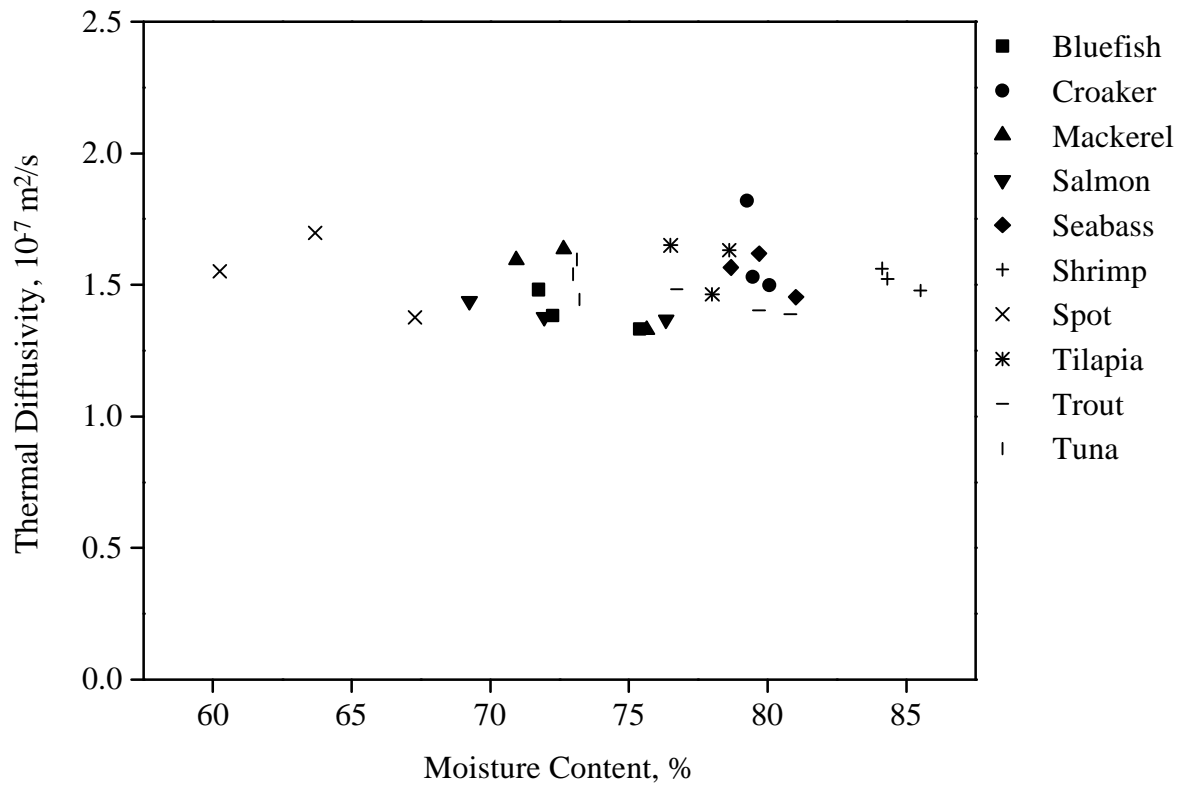
Regression analysis was then performed with fat and moisture content individually and as combined models with the averaged thermal diffusivity. In all the models 0.05 was considered as the significance level. In all the models the effect of fat and moisture content on thermal diffusivity was insignificant. The model fat versus thermal diffusivity resulted in a probability value of 0.6260 and that with moisture content resulted in a probability value of 0.9804. The combined model which included both fat and moisture content with thermal diffusivity also resulted in large probability values of 0.3053 and 0.3641 for fat and moisture content respectively. This lack of significance can be due to the large scatter in the recorded data. This can also be observed well in figures 5 and 6. Since the parameters moisture and fat content were insignificant in all the models, a thermal model for thermal diffusivity was not proposed.

### **4.3 SPECIFIC HEAT TESTS**

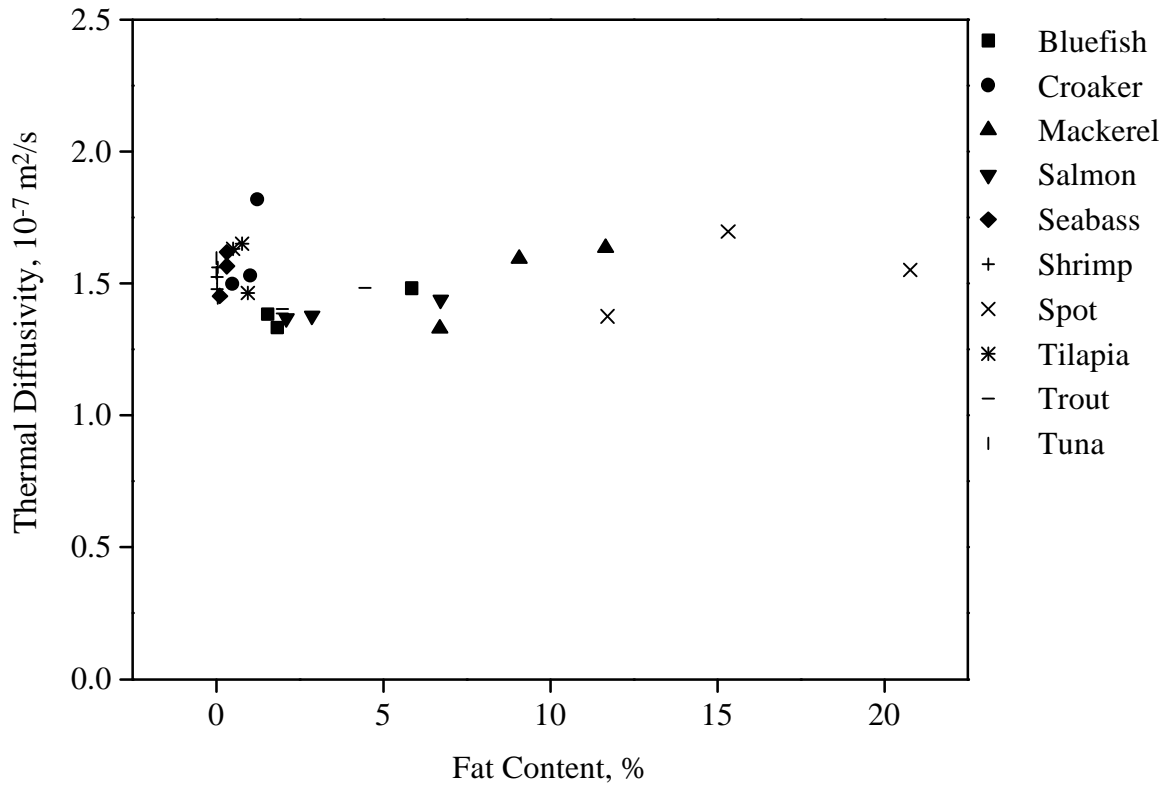
In general the specific heat values did not differ much within the measured temperature range for each sample, and ranged from 3.1 to 3.8 kJ/kg• °C (Table C.11 of Appendix C). These values agreed well with the literature values. Rahman (1993) had reported values ranging from 3.29 to 3.79 kJ/ kg•K for fresh seafood at a temperature about 17 °C (Table A.1 of Appendix A).

#### **4.3.1 EFFECT OF TEMPERATURE, FAT CONTENT, AND MOISTURE CONTENT ON SPECIFIC HEAT**

Statistical analysis was carried out to study the effect of temperature, moisture content, and fat content on specific heat. Individual regressions, regressing specific heat with temperature were



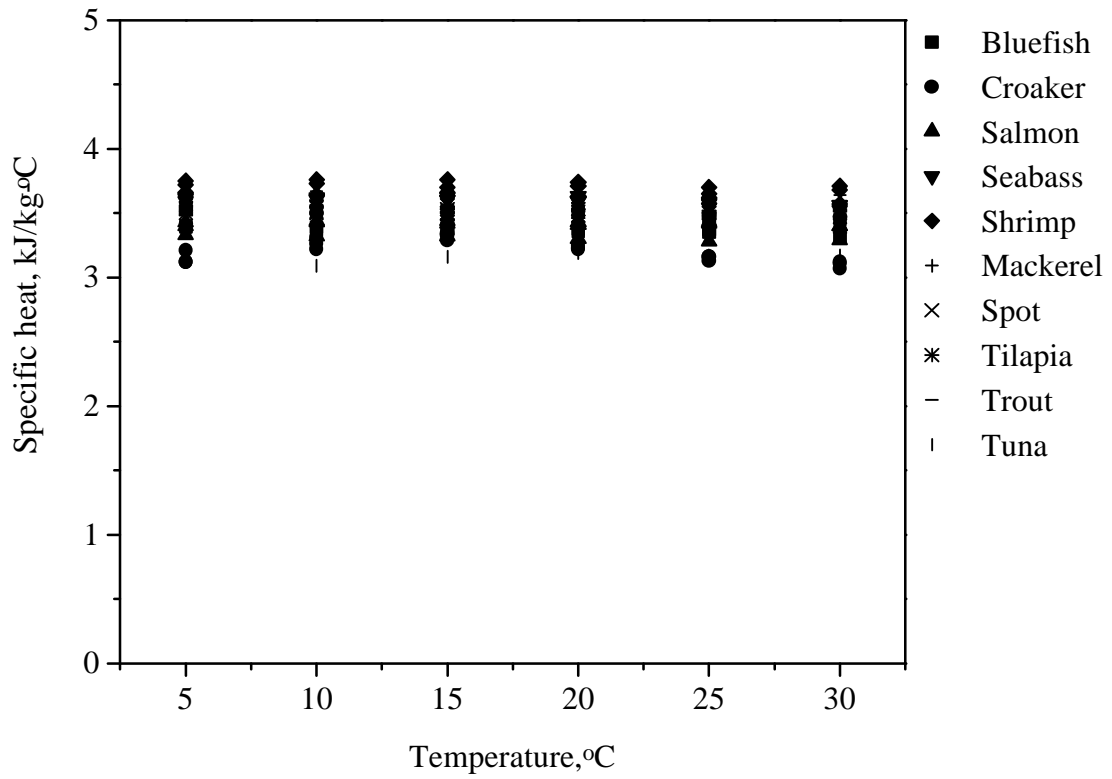
**Figure 4. Thermal diffusivity versus moisture content for all species. Thermal diffusivity values are averaged across the temperature range of 5 to 30 °C**



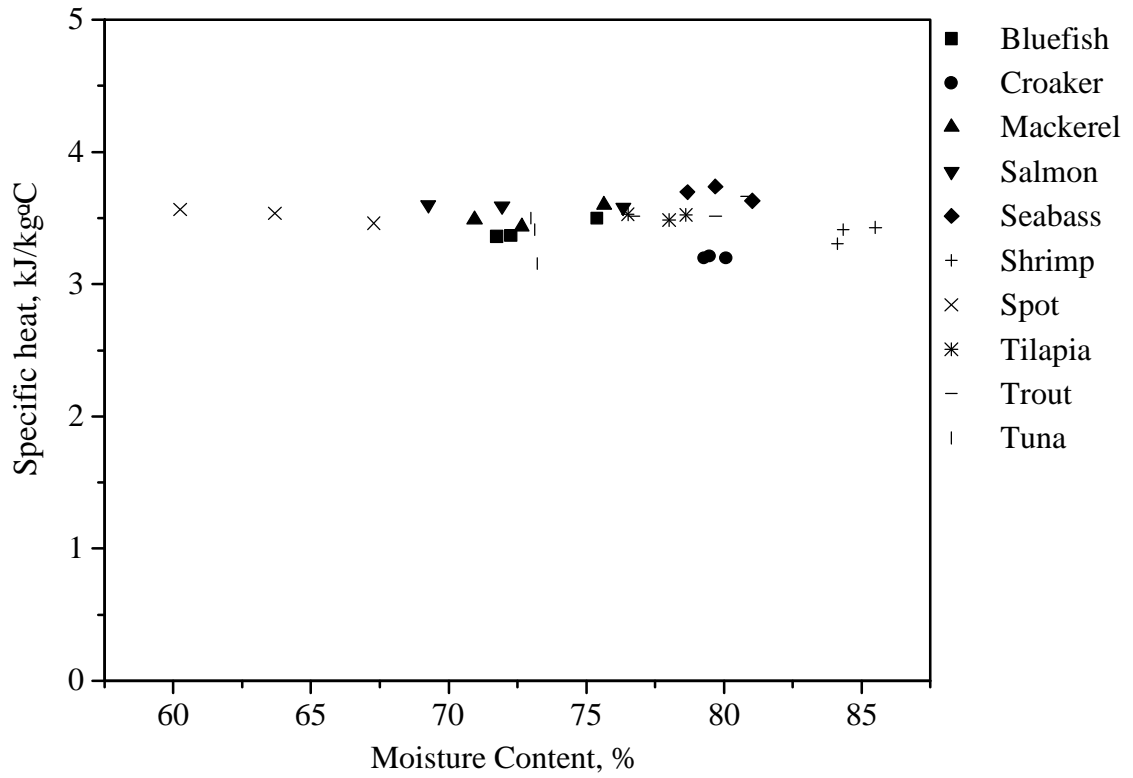
**Figure 5. Thermal diffusivity versus fat content for all species. Thermal diffusivity values are averaged across the temperature range of 5 to 30 °C**

done on each fish. In some cases temperature proved to be significant and in some it did not. The distribution was nearly half as against the three seen in thermal conductivity and thermal diffusivity measurements. So, temperature could not be averaged. So, instead of an ordinary regression or least squares procedure, the "genmod" procedure or the generalized least square procedure was done to give a generalized estimating equation (GEE) for specific heat based on temperature, moisture content, and fat content. This method was preferred as the correlation arising due to repeated measurements on the same fish across temperatures as well as the individual fat and moisture content measurements could be accounted within the model. Thus the effect of temperature, moisture content, and fat content on specific heat could be statistically studied. The effect of these parameters on specific heat are graphically represented in Figures 7, 8, and 9. The SAS code used to accomplish this is included in D.2 of Appendix D. Temperature, moisture content, and fat content had a significant effect on temperature at a significance level of 0.05. Though, it is difficult to observe the negative correlation for specific heat versus temperature in the Figure 7, it can be seen in Table C.11 of Appendix C, where the specific heat values decrease with the increase in temperature for the measured range. The difficulty may be due to the very small decrease in specific heat value with increase in temperature. This may be because of influence of water, whose specific heat also decreases with increase in temperature in the measured range (Kreith and Bohn, 1993). So, a model was proposed for specific heat which included these parameters as follows.

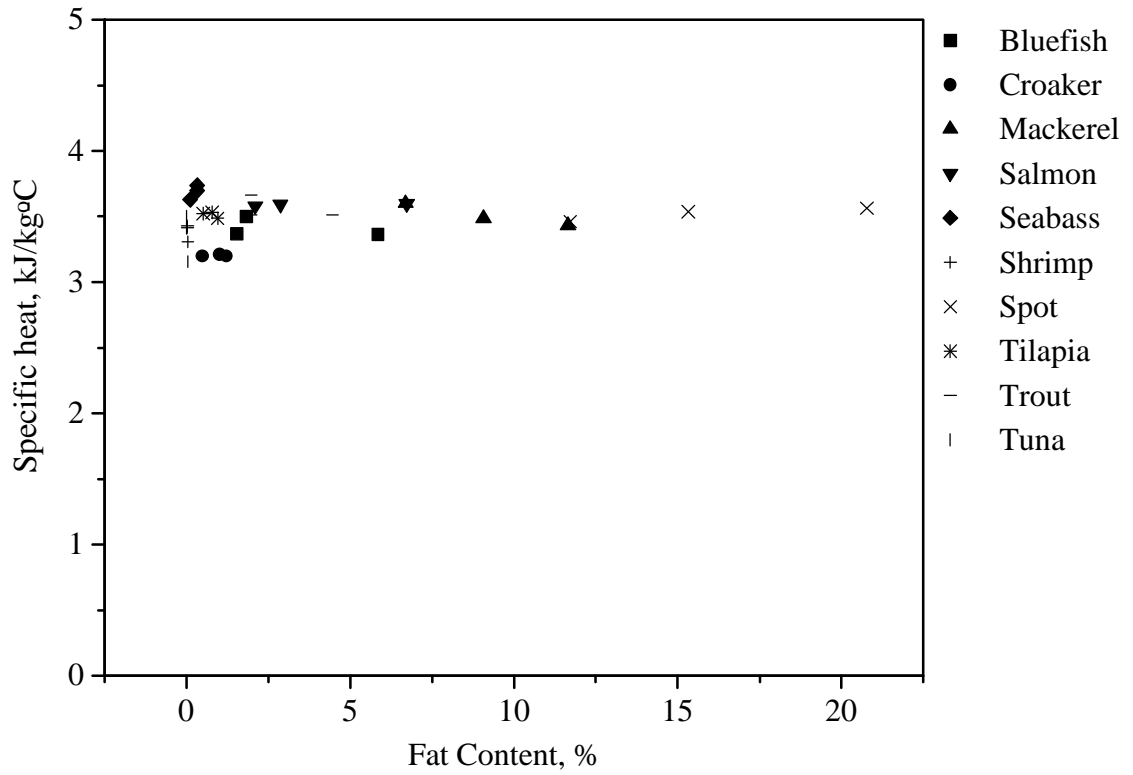
$$C_p = 1.5050 - 0.0024T + 0.0258F + 0.0252M \quad (4.4)$$



**Figure 6. Specific heat versus temperature for all species. At each temperature, values for the three samples are shown.**



**Figure 7. Specific heat versus moisture content for all species. Specific heat values are averaged across the temperature range of 5 to 30 °C**



**Figure 8. Specific heat versus fat content for all species. Specific heat values are averaged across the temperature range of 5 to 30 °C**

where,

$C_p$  = Specific heat, kJ/kg·°C,

$T$  = Temperature, °C,

$F$  = Fat content, %,

$M$  = Moisture content, %.

The goodness of fit for the model was assessed by the Pearson chi - square value. With a low value of 0.0164, it was concluded that the proposed model fitted very well.

Since specific heat models, containing all these parameters could not be found in the literature, equation 4.4 could not be directly compared. So the average temperature of 17.5 °C and average fat content of 3.7534 % was substituted in the above equation and was then compared to the equation (2.12) proposed by Reidel (1956) for fresh meat above freezing temperatures. Both the models agreed well.

#### **4.4 ENTHALPY TESTS**

Taking the temperature datum as -40 °C, enthalpy was calculated upto 30 °C. In general, the enthalpy values ranged from 242.12 to 376.57 kJ/kg at 0 °C. This agreed well with the reported values of 318 to 323 kJ/kg at 0 °C for cod, haddock, and perch (Sweat, 1986).

##### **4.4.1 EFFECT OF TEMPERATURE, FAT CONTENT, AND MOISTURE CONTENT ON ENTHALPY**

It is obvious that enthalpy is a function of temperature, since enthalpy refers to the energy content of the food measured. This can also be seen in Figure 10,. To study the effect of moisture and fat content on enthalpy, a regression analysis (D.5 of Appendix D) was done using enthalpy values separately at 0 °C and 30 °C for each fish.

At 30 °C a model for enthalpy was proposed as

$$H = 101.9221 + 4.0202F + 4.0814M \quad (4.5)$$

where,

$H$  = Enthalpy, kJ/kg,

$F$  = Fat content, %,

$M$  = Moisture content, %.

Fat content (probability value = 0.0609) was barely significant, but moisture content (probability value = 0.0313) was significant at an alpha level 0.05. The r-square for the model was 0.1789 and the root mean square error was 28.6798. A correlation analysis was done to study the degree of correlation between enthalpy, moisture content, and fat content. The Pearson correlation coefficients for enthalpy versus moisture content and enthalpy versus fat content was 0.2795 and 0.9880 respectively. Though a model is proposed, it is not recommended for future use because of the low r-square value and low correlation between enthalpy and moisture content.

At the 0 °C temperature, the model for enthalpy was proposed as

$$H = 47.7908 + 3.3746F + 3.4408M \quad (4.6)$$

where,

H = Enthalpy, kJ/kg,

F = Fat content, %,

M = Moisture content, %.

Fat content (probability value = 0.0674) was barely significant, but moisture content (probability value = 0.0348) was significant at an alpha level 0.05. The r-square for the model was 0.1726 and the root mean square error was 24.7148. A correlation analysis gave a Pearson correlation coefficient of 0.2826 for enthalpy versus moisture content and 1.0 for enthalpy versus fat content. This model is not recommended for calculation of enthalpy of products with similar moisture and fat content because of the low r-square value and poor correlation with moisture content.

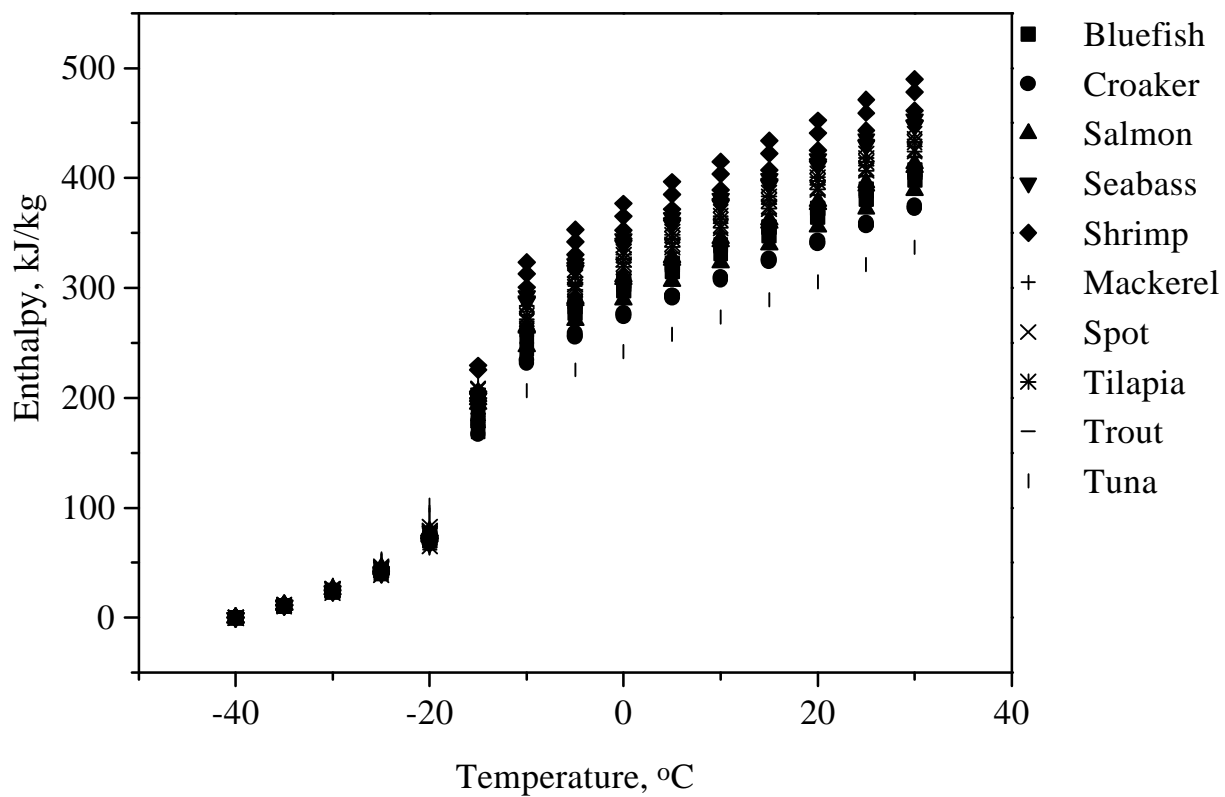
## 4.5 MOISTURE CONTENT AND FAT CONTENT TESTS

The measured moisture content was expressed as percentage wet basis for all seafood. The measured fat content was expressed in percentage, and this was calculated based on the wet raw meat initially taken. All values for the measured fat and moisture content can be found in Tables C.1 - C.10 in Appendix C. The values for bluefish, mackerel, salmon, seabass, and trout were well within the ranges reported by Sidwell, et al. (1974), Wheeler, et al. (1981) and Wheaton, et al. (1985). The value for tilapia could not be compared because of unavailability of data in literature. For spot, Sidwell, et al. (1974) reported only one value of 3.1% for fat. While this value is much lower than the measured average of 15.94%, it should be noted that the thermal conductivity of spot, was the lowest of all species tested (Figure 3). This low value is logical for a high fat content food material. In case of shrimp, moisture content compared well within the range reported by Wheeler, et al. (1981), but the average fat content was slightly lower, 0.031 %, than the lowest value in the range reported by Wheeler. In case of croaker, values for fat content compared well with the values reported by Sidwell, et al. (1974), but data for moisture content was unavailable for comparison. For tuna, the moisture content value agreed well with those reported by Sidwell, et al. (1974), but the fat content was very low at an average of 0.016 %.

This compares with a range of 0.1 to 9.5 % reported by Sidwell. This may be due to the sample being the loin of tuna marketed for sashimi or due to experimental error.

#### **4.6 COMPILATION OF THERMAL PROPERTIES**

Table 1 summarizes the measured thermal properties of seafood. Thermal conductivities of the seafood measured in this study ranged from 0.40 to 0.55 W/m• °C, which agreed well with the literature values (Table A.1 of Appendix A). Thermal diffusivity values ranged from 1.39 to  $1.62 \times 10^{-7}$  m<sup>2</sup>/s, which were also comparable to literature values. Specific heat measured ranged from 3.2 to 3.6 kJ/kg• °C, which compared well with the available data in the literature. Enthalpy values also agreed well with those reported by Sweat(1986) for fish.



**Figure 9. Enthalpy versus temperature for all species. At each temperature, values for the three samples are shown.**

**Table 1. Compilation of thermal properties of seafood**

Species	Moisture Content %	Fat Content %	Thermal Conductivity* W/m•°C	Thermal Diffusivity* 10 <sup>-7</sup> m <sup>2</sup> /s	Enthalpy** kJ/kg	Specific Heat* kJ/kg•°C
Bluefish	78.125	3.740	0.4890	1.4007	302.27	3.4095
Croaker	79.605	0.915	0.4866	1.6155	275.65	3.2028
Salmon	72.513	3.898	0.4711	1.3944	302.58	3.5894
Seabass	79.800	0.253	0.4859	1.5462	341.17	3.6883
Shrimp	84.655	0.031	0.5430	1.5212	364.75	3.3828
Mackerel	73.081	9.138	0.4246	1.5197	322.79	3.5061
Spot	63.737	15.938	0.4011	1.5417	331.04	3.3550
Tilapia	77.712	0.747	0.4961	1.5816	325.15	3.5133
Trout	79.080	2.857	0.5186	1.4247	333.24	3.5639
Tuna	73.107	0.016	0.4687	1.5275	287.81	3.3567

\* Average values of thermal properties measured at about 5, 10, 15, 20, 25 and 30 °C.

\*\* Values at 0 °C. Temperature datum at -40 °C

Note: All thermal property values are the average of three replications.

# CHAPTER 5

## CONCLUSIONS

The following conclusions can be drawn from this study.

1. Thermistor probe technique is another suitable rapid technique for measuring thermal conductivity and thermal diffusivity of meats similar to those tested in the study for a temperature range of 5 to 30 °C.
2. Centering of probe is a critical factor in thermal conductivity and thermal diffusivity measurements, especially for small diameter sample like shrimp. The thermistor was sensitive to pick up the thermal properties of the metal sample holder, if placed otherwise.
3. Convection currents around the thermistor probes had to be taken care when using liquid samples by thickeners. Otherwise the slope of power versus time was altered remarkably.
4. The approximate time taken for the medium and thermistor to equilibrate ranged from fifteen to twenty minutes between replicates and one to two hours between each temperature measurement.
5. Temperature had no significant effect on thermal conductivity and thermal diffusivity as measured with the bead thermistor for the measured temperature range of 5 to 30 °C.
6. The study showed a positive correlation between thermal conductivity and moisture content.
7. A negative correlation was observed between thermal conductivity and fat content.
8. Thermal conductivity data was fitted into a mathematical model, which can be used for predicting thermal conductivity of meats with similar composition as those researched in this study.
9. Fat content and moisture content had a significant effect on enthalpy, but the degree of significance was small in case of moisture content and high in case of fat content.
10. Temperature was negatively correlated with specific heat, while fat and moisture content was positively correlated with specific heat.

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# **APPENDIX A**

## **THERMAL PROPERTY DATA FROM LITERATURE**

### A.1 List of thermal properties of seafood as found in literature

Material	Temperature, °C, Moisture Content, %	Thermal Conductivity, W/m•K	Thermal Diffusivity, $10^{-3} \text{m}^2/\text{hr}$	Specific Heat, kJ/kg •K	Reference
Black Bhitki	-20,77.70	1.563	2.712	-	Kumbhar, et al. (1981)
	-10, 77.70	1.487	1.585	-	
	0, 77.70	0.416	0.520	-	
	10, 77.70	0.425	0.587	-	
	20, 77.70	0.436	0.683	-	
	30, 77.70	0.454	0.710	-	
	40, 77.70	0.464	0.749	-	
Black Pomphret	-20,75.00	1.315	2.428	-	Kumbhar, (1981)
	-10, 75.00	1.244	1.217	-	
	0, 75.00	0.412	0.501	-	
	10, 75.00	0.418	0.546	-	
	20, 75.00	0.417	0.566	-	
	30, 75.00	0.442	0.647	-	
	40, 75.00	0.452	0.706	-	
Calamari (mantle)	80.02, 17+2	-	-	3.41	Rahman, (1993)
	79.98, 17+2	-	-	3.47	Rahman, (1993)
	81.59, 17+2	-	-	3.35	Rahman, (1993)
Calamari (tentacle)	83.09, 17+2	-	-	3.43	Rahman, (1993)
	83.91, 17+2	-	-	3.69	Rahman, (1993)

Material	Temperature, °C, Moisture Content, %	Thermal Conductivity, W/m•K	Thermal Diffusivity, 10 <sup>-3</sup> m <sup>2</sup> /hr	Specific Heat, kJ/kg •K	Reference
Calamari (wing)	84.18, 17+2	-	-	3.78	Rahman, (1993)
	83.38, 17+2	-	-	3.79	Rahman, (1993)
Cod	0-10, 83	0.549	-	-	
Cuttle (mantle)	80.92, 17+2	-	-	3.59	Rahman, (1993)
Cuttle (skin)	86.99, 17+2	-	-	3.79	Rahman, (1993)
Eels	Above 0, 62.07	-	-	2.889	Siebel, (1892)
Herring	-19.0, -	0.796	-	-	Smith, et al. (1952)
Hilsa	-20, 74.70	1.328	2.350		Kumbhar, et al. (1981)
	-10, 74.70	1.234	1.547		
	0, 74.70	0.409	0.599	-	
	10, 74.70	0.416	0.592	-	
	20, 74.70	0.430	0.764	-	
	30, 74.70	0.450	0.769	-	
	40, 74.70	0.461	0.796	-	
King Prawn	75.63, 17+2	-	-	3.45	Rahman, (1993)
	76.49, 17+2	-	-	3.41	Rahman, (1993)
Lobster	Above 0, 76.62	-	-	3.391	Siebel, (1892)
Mackerel	0-20, 77.35	0.409-0.419	-	-	Kumbhar, (1981)
Mackerel	-20, 77.35	1.237	1.940	-	Kumbhar, et al.(1981)

Material	Temperature, °C, Moisture Content, %	Thermal Conductivity, W/m•K	Thermal Diffusivity, $10^{-3} \text{m}^2/\text{hr}$	Specific Heat, kJ/kg •K	Reference
	-10, 77.35	1.088	1.145	-	Kumbhar, et al. (1981)
	0, 77.35	0.416	0.391	-	
	10, 77.35	0.423	0.422	-	
	20, 77.35	0.438	0.498	-	
	30, 77.35	0.459	0.575	-	
Malli	-20, 78.20	-	-	-	Kumbhar, et al. (1981)
	-10, 78.20	1.356	1.184	-	
	0, 78.20	0.411	0.443	-	
	10, 78.20	0.424	0.493	-	
	20, 78.20	0.460	0.560	-	
	30, 78.20	0.453	0.694	-	
Perch	-29.0, -	0.0225	-	-	Smith, et al. (1952)
Red Bhitki	-20, 79.53	1.358	2.009	-	Kumbhar, et al. (1981)
	-10, 79.53	1.207	1.465	-	
	0, 79.53	0.413	0.454	-	
	10, 79.53	0.436	0.512	-	
	20, 79.53	0.440	0.579	-	
	30, 79.53	0.449	0.675	-	
	40, 79.53	0.466	0.772	-	
Redfish	-40, 84.7	-	-	1.716	Short, et al. (1951)
	-34.4, 84.7	-	-	1.785	
	-28.8, 84.7	-	-	1.842	
	-23.3, 84.7	-	-	1.925	
	-17.7, 84.7	-	-	2.135	
	-12.2, 84.7	-	-	2.972	

Material	Temperature, °C, Moisture Content, %	Thermal Conductivity, W/m•K	Thermal Diffusivity, $10^{-3} \text{m}^2/\text{hr}$	Specific Heat, kJ/kg •K	Reference
	-6.66, 84.7	-	-	5.065	
Rohu	-20, 75.20	1.535	1.955	-	Kumbhar, et al. (1981)
	-10, 75.20	1.284	1.412	-	
	0, 75.20	0.421	0.489	-	
	10, 75.20	0.446	0.529	-	
	20, 75.20	0.442	0.560	-	
	30, 75.20	0.461	0.644	-	
	40, 75.20	0.463	0.692	-	
Salmon (British Columbia)	-15.0, 73.00	1.151	-	-	Lentz, (1961)
	-13.0, 73.00	1.256	-	-	
	-10.0, 73.00	1.109	-	-	
	-13.0, 73.00	1.256	-	-	
	-4.0, 73.00	1.194	-	-	
	3.88, 73.00	0.502	-	-	
Saman	-20,77.30	1.428	2.314	-	Kumbhar, et al. (1 981)
	-10,77.30	1.334	1.415	-	
	0, 77.30	0.409	0.464	-	
	10, 77.30	0.419	0.466	-	
	20, 77.30	0.422	0.547	-	
	30, 77.30	0.431	0.674	-	
	40, 77.30	0.454	0.725	-	
Singara	-20, 77.87	1.284	1.899	-	Kumbhar, et al. (1981)
	-10, 77.87	1.254	1.063	-	

Material	Temperature, °C, Moisture Content, %	Thermal Conductivity, W/m•K	Thermal Diffusivity, $10^{-3}m^2/hr$	Specific Heat, kJ/kg •K	Reference
	0, 77.87	0.420	0.314	-	
	10, 77.87	0.417	0.419	-	
	20, 77.87	0.418	0.477	-	
	30, 77.87	0.450	0.526	-	
	40, 77.87	0.461	0.592	-	
Shrimp	-40, 78.6	-	-	1.883	Short, et al. (1944)
	-34.4, 78.6	-	-	1.9676	
	-28.8, 78.6	-	-	2.093	
	-23.3, 78.6	-	-	2.302	
	-17.7, 78.6	-	-	2.721	
	-12.2, 78.6	-	-	3.642	
	-6.66, 78.6	-	-	6.531	
Sol	-20, 77.60	1.365	2.219	-	Kumbhar, et al. (1981)
	-10, 77.60	1.294	1.462	-	
	0, 77.60	0.398	0.529	-	
	10, 77.60	0.434	0.598	-	
	20, 77.60	0.476	0.659	-	
	30, 77.60	0.452	0.736	-	
	40, 77.60	0.459	0.882	-	
Squid (dried)*	80.9, 30	0.52			Rahman, et al. (1991)
Squid (fresh)*	82.6, 30	0.49			Rahman, et al. (1991)
Squid (tentacle)	82.63, 17+2	-	-	3.58	Rahman, (1993)
	79.61, 17+2	-	-	3.50	Rahman, (1993)

Material	Temperature °C, Moisture Content, %	Thermal Conductivity, W/m•K	Thermal Diffusivity, $10^{-3}m^2/hr$	Specific Heat, kJ/kg •K	Reference
Surama	83.02, 17+2	-	-	3.53	Rahman, (1993)
-20, 78.00	1.327	1.858	-	Kumbhar, et al. (1981)	
	-10, 78.00	1.067	1.089	-	
	0, 78.00	0.415	0.408	-	
	10, 78.00	0.433	0.447	-	
	20, 78.00	0.433	0.554	-	
	30, 78.00	0.446	0.581	-	
	40, 78.00	0.468	0.640	-	
Whale, blubber	18.0, -	0.209	-	-	Griffiths, et al. (1948)
Whale, meat	-12.0, -	1.28	-	-	Smith, et al. (1952)
Whitefish	Above 0, 78.00	-	-	3.433	Siebel, (1892)
White Pomphret	-20, 74.83	1.395	2.735	-	Kumbhar, et al. (1981)
	-10, 74.83	1.118	1.218	-	
	0, 74.83	0.390	0.487	-	
	10, 74.83	0.400	0.565	-	
	20, 74.83	0.435	0.676	-	
	30, 74.83	0.453	0.782	-	
	40, 74.83	0.475	0.816	-	

## A.2 Thermal properties of water, glycerin, and UCON 500

### Thermal properties of water \*

Temperature °C	Thermal Conductivity W/m•°C	Specific Heat J/kg•K	Density kg/m <sup>3</sup>	Thermal Diffusivity m <sup>2</sup> /s
5.0	0.5795	4180.399	1004.056	1.38E-7
10.0	0.5855	4181.376	1001.870	1.40E-7
15.0	0.5912	4182.315	999.771	1.41E-7
20.0	0.5969	4183.272	997.628	1.43E-7
25.0	0.6026	4184.211	995.529	1.45E-7
30.0	0.6084	4185.169	993.387	1.46E-7

\*Source: Incropera, F.P. and De Witt, D. P. 1985. Fundamentals of Heat and Mass Transfer. 2 nd ed., John Wiley & Sons, New York.

### Thermal properties of glycerin\*

Temperature °C	Thermal Conductivity W/m•°C *	Specific Heat J/kg•K **	Density kg/m <sup>3</sup> ***	Thermal Diffusivity m <sup>2</sup> /s
5.0	0.2848	2264.264	1271.213	9.9E-8
10.0	0.2848	2292.648	1267.706	9.8E-8
15.0	0.2848	2319.919	1264.337	9.71E-8
20.0	0.2848	2347.747	1260.900	9.62E-8
25.0	0.2848	2375.018	1257.531	9.54E-8
30.0	0.2848	2402.846	1254.093	9.45E-8

\* Source: Touloukian, Y.S., Liley, P.E., and Saxena, S.C. 1970. Thermal Conductivity: Nonmetallic Liquids and Gases. The TPRC Data Series, Vol. 3, IFI/Plenum Press, New York.

\*\* Source: Touloukian, Y.S., 1970. Specific Heat: Non metallic Liquids and Gases. The TPRC Data Series, Vol.6, IFI/Plenum Press, New York.

\*\*\* Source: Incropera, F.P. and De Witt, D. P. 1985. Fundamentals of Heat and Mass Transfer. 2 nd ed., John Wiley & Sons, New York.

### Thermal properties of UCON 500\*

Temperature	Thermal Conductivity	Specific Heat	Density	Thermal Diffusivity
°C	W/m•°C	J/kg•K	kg/m <sup>3</sup>	m <sup>2</sup> /s
5.0	0.1697	1854.073	1048.352	8.73E-8
10.0	0.1690	1855.976	1044.773	8.71E-8
15.0	0.1683	1857.805	1041.335	8.70E-8
20.0	0.1676	1859.672	1037.826	8.68E-8
25.0	0.1669	1861.501	1034.388	8.67E-8
30.0	0.1662	1863.367	1030.879	8.65E-8

\*Source: UCON Heat Transfer Fluid 500, 1989. Union Carbide Chemicals and Plastics Company Inc., Specialty Chemicals Division, Danbury, CT.

**APPENDIX B**

**THERMISTOR CALIBRATION**

### B.1 Calibration of thermistor with water

Temperature °C	Slope (S)	Intercept(I)	S/I	Average	Experiment Value	Average
30.184	1.6696	6.9878	0.2389		275.332	
30.180	1.4346	7.0232	0.2043	0.2547	273.599	277.469
30.183	2.1758	6.7803	0.3209		283.476	
25.036	2.7255	8.2753	0.3294		278.639	
24.963	2.0441	7.9361	0.2576	0.2898	292.040	283.323
25.132	2.3419	8.2932	0.2824		279.290	
20.202	2.4555	10.4298	0.2354		265.902	
20.102	2.5700	10.1260	0.2538	0.2708	275.688	274.852
20.084	3.1814	9.8425	0.3232		282.967	
15.218	3.1395	12.4359	0.2525		272.528	
15.159	3.6740	11.9707	0.3069	0.2819	282.450	278.519
15.161	3.4471	12.0436	0.2862		280.581	
10.347	4.4099	14.8707	0.2965		277.259	
10.281	4.8194	14.4551	0.3334	0.3280	285.043	282.870
10.276	5.1060	14.4188	0.3541		286.309	
5.274	6.1338	17.8529	0.3436		284.204	
5.249	5.2558	18.1069	0.2903	0.3411	281.160	280.810
5.260	5.2141	18.3871	0.3895		277.066	

### B.2 Calibration of thermistor with glycerin

Temperature °C	Slope (S)	Intercept (I)	S/I	Average	Experiment Value	Average
30.020	1.3554	4.7647	0.2899		414.248	
30.006	2.0152	5.8938	0.3419	0.3422	326.364	360.355
30.040	2.2270	5.6410	0.3947		340.453	
25.158	1.9002	7.1612	0.2653		323.338	
25.156	1.8947	7.0785	0.2677	0.2790	324.662	325.388
25.149	2.1382	7.0283	0.3042		328.164	
20.240	3.2616	8.3510	0.3906		330.555	
20.212	2.4513	8.5397	0.2870	0.3213	323.367	326.354
20.205	2.4448	8.5360	0.2864		325.141	
15.253	3.1208	10.4655	0.2981		321.065	
15.246	3.7979	10.2236	0.3715	0.3158	329.827	324.051
15.234	2.9146	10.4932	0.2778		321.261	
10.325	4.3436	12.6645	0.3430		324.963	
10.314	3.7230	12.8316	0.2901	0.3358	320.963	325.126
10.301	4.6803	12.5067	0.3742		329.982	
5.215	6.1559	15.6666	0.3930		326.801	
5.178	4.9114	16.0769	0.3055	0.3305	318.627	321.010
5.171	4.7148	16.0819	0.2932		317.601	

### B.3 Calibration of thermistor with UCON 500

Temperature °C	Slope (S)	Intercept (I)	S/I	Average	Experiment Value	Average
30.244	2.4895	4.8037	0.5182		397.497	
30.229	2.0298	4.9379	0.4111	0.4737	388.550	394.575
30.234	2.3661	4.8091	0.4920		397.675	
25.250	2.4210	5.9537	0.4066		386.203	
25.111	2.3214	6.1149	0.3796	0.4166	376.702	385.688
25.036	2.7242	5.8746	0.4637		394.161	
20.214	3.1979	7.1025	0.4502		390.525	
20.204	2.9297	7.2140	0.4061	0.4058	386.569	385.544
20.201	2.6548	7.3523	0.3611		379.539	
15.282	3.5903	8.8313	0.4065		380.648	
15.265	3.1986	8.9858	0.3560	0.4004	376.194	381.345
15.278	3.8176	8.7040	0.4386		387.194	
10.389	3.9828	11.0083	0.3618		372.615	
10.343	4.4021	10.8279	0.4066	0.3866	379.705	376.832
10.347	4.2654	10.8991	0.3914		378.175	
5.128	3.9920	11.0036	0.3628		466.081	
5.496	10.8871	8.9810	1.2122	0.9286	562.344	529.751
5.492	10.8636	8.9717	1.2108		560.830	

#### B.4 Resistance versus temperature data for thermistors

Temperature, °C	Resistance, k $\Omega$		
	Thermistor 1	Thermistor 2	Thermistor 3
35.1	0.7038	0.7335	0.7435
30.1	0.8401	0.8756	0.8888
25.1	1.0201	1.0508	1.0677
20.1	1.2286	1.2805	1.3011
15.1	1.4953	1.5629	1.5898
10.2	1.8393	1.9168	1.9501
5.3	2.2664	2.3610	2.4045

**APPENDIX C**

**EXPERIMENTAL RESULTS**

### C.1 Compiled data on thermal conductivity and thermal diiffusivity for bluefish

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	29.154	75.391	1.83	0.5855	344.84	0.43335	1.43E-07
2	29.475	72.244	3.536	0.5528	334.484	0.46692	1.461E-07
3	27.237	71.74	5.855	0.5465	331.457	0.47774	1.452E-07
1	23.473			0.5549	333.369	0.47085	1.435E-07
2	25.862			0.5908	345.878	0.43025	1.417E-07
3	24.731			0.5949	347.882	0.42438	1.421E-07
1	20.875			0.5059	306.83	0.58873	1.285E-07
2	21.727			0.5094	313.01	0.5563	1.369E-07
3	19.216			0.5303	346.149	0.42944	1.762E-07
1	15.91			0.549	331.283	0.47838	1.437E-07
2	16.42			0.5283	324.65	0.50401	1.451E-07
3	15.719			0.554	339.877	0.44881	1.529E-07
1	9.999			0.5342	300.062	0.62888	1.052E-07
2	9.812			0.5949	333.226	0.47136	1.247E-07
3	9.335			0.563	334.359	0.46736	1.407E-07
1	5.905			0.5589	329.066	0.48665	1.356E-07
2	6.967			0.5433	323.819	0.50741	1.36E-07
3	6.782			0.5344	318.405	0.53077	1.325E-07

### C.2 Compiled data on thermal conductivity and diffusivity for croaker

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	29.159	80.069	0.493	0.5266	307.232	0.58651	1.192E-07
2	29.333	79.471	1.023	0.6035	349.413	0.42001	1.398E-07
3	29.303	79.276	1.23	0.5846	346.85	0.42738	1.459E-07
1	24.871			0.5334	326.051	0.49837	1.444E-07
2	26.222			0.46	308.928	0.57731	1.597E-07
3	23.471			0.4841	322.012	0.51498	1.68E-07
1	20.092			0.4896	334.172	0.46802	1.857E-07
2	20.0775			0.5046	349.968	0.41845	2.009E-07
3	19.551			0.4973	316.88	0.53775	1.503E-07
1	15.902			0.4934	325.603	0.50016	1.68E-07
2	16.268			0.5137	320.543	0.5213	1.468E-07
3	14.86			0.5174	367.822	0.37371	2.185E-07
1	10.308			0.5366	327.545	0.49249	1.449E-07
2	11.032			0.5241	319.326	0.52665	1.391E-07
3	10.694			0.4542	341.688	0.44304	2.312E-07
1	5.352			0.5515	327.238	0.49369	1.367E-07
2	5.511			0.5586	325.739	0.49961	1.312E-07
3	5.608			0.524	336.578	0.45972	1.659E-07

### C.3 Compiled data on thermal conductivity and thermal diffusivity for salmon

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	30.083	71.943	2.87	0.6055	352.988	0.41014	1.43E-07
2	29.498	69.252	6.723	0.5864	350.098	0.41808	1.489E-07
3	31.24	76.345	2.101	0.5356	333.428	0.47064	1.541E-07
1	24.969			0.5789	338.972	0.45175	1.389E-07
2	25.57			0.5965	350.136	0.41798	1.44E-07
3	25.253			0.5328	320.574	0.52116	1.365E-07
1	20.246			0.5998	341.378	0.44402	1.322E-07
2	20.338			0.618	347.943	0.42421	1.317E-07
3	19.965			0.5669	333.006	0.47214	1.37E-07
1	15.047			0.5918	349.165	0.42071	1.451E-07
2	15.874			0.5776	338.246	0.45414	1.386E-07
3	15.415			0.5636	328.889	0.48732	1.331E-07
1	10.021			0.5753	346.114	0.42955	1.497E-07
2	10.58			0.5771	347.601	0.4252	1.506E-07
3	10.637			0.5582	324.601	0.50421	1.299E-07
1	4.327			0.6167	334.973	0.46522	1.18E-07
2	4.884			0.5764	345.795	0.43049	1.487E-07
3	5.142			0.5616	325.769	0.49949	1.299E-07

#### C.4 Compiled data on thermal conductivity and diffusivity for seabass

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	30.123	79.695	0.325	0.5611	338.468	0.45341	1.472E-07
2	29.589	81.026	0.110	0.5399	328.186	0.49001	1.44E-07
3	30.861	78.679	0.325	0.4986	325.983	0.49864	1.651E-07
1	24.693			0.5751	357.043	0.3995	1.635E-07
2	25.638			0.508	323.802	0.50748	1.555E-07
3	25.691			0.5069	321.318	0.51794	1.52E-07
1	20.487			0.5107	320.74	0.52044	1.488E-07
2	20.92			0.4986	317.241	0.53608	1.502E-07
3	20.124			0.5125	344.94	0.43305	1.868E-07
1	15.498			0.5587	350.775	0.41619	1.65E-07
2	15.831			0.5281	322.049	0.51482	1.412E-07
3	15.763			0.5304	336.915	0.45858	1.624E-07
1	10.825			0.5038	335.793	0.46239	1.781E-07
2	11.278			0.5084	317.25	0.53604	1.444E-07
3	10.313			0.5343	323.369	0.50927	1.399E-07
1	5.764			0.5336	342.526	0.44042	1.687E-07
2	6.121			0.5276	318.92	0.52846	1.367E-07
3	5.673			0.5371	320.027	0.52355	1.335E-07

### C.5 Compiled data on thermal conductivity and diffusivity for shrimp

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	30.124	84.123	0.039	0.5145	318.963	0.52827	1.438E-07
2	30.188	85.51	0.026	0.4853	315.54	0.54403	1.554E-07
3	29.812	84.331	0.028	0.4779	323.269	0.50969	1.747E-07
1	25.016			0.5147	319.985	0.52374	1.453E-07
2	24.93			0.5061	318.825	0.52889	1.484E-07
3	25.061			0.4489	313.641	0.55319	1.776E-07
1	20.03			0.5186	319.972	0.52379	1.431E-07
2	20.114			0.5007	315.291	0.54521	1.456E-07
3	20.007			0.5099	318.642	0.52971	1.459E-07
1	15.248			0.4004	301.392	0.62057	1.908E-07
2	15.723			0.4914	324.778	0.50349	1.679E-07
3	15.764			0.5031	312.599	0.55835	1.397E-07
1	10.368			0.4066	300.829	0.62406	1.836E-07
2	10.682			0.5176	316.152	0.54114	1.376E-07
3	10.721			0.5237	318.402	0.53079	1.379E-07
1	5.22			0.5357	317.563	0.5346	1.306E-07
2	5.253			0.5291	316.317	0.54037	1.319E-07
3	5.529			0.5216	317.959	0.5328	1.383E-07

### C.6 Compiled data on thermal conductivity and diffusivity for spanish mackerel

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	30.026	70.942	9.072	0.6514	369.047	0.37099	1.39E-07
2	29.653	75.647	6.691	0.803	397.455	0.31739	1.089E-07
3	29.718	72.653	11.65	0.5766	353.444	0.40892	1.582E-07
1	25.795			0.563	353.285	0.40934	1.657E-07
2	26.066			0.5899	347.271	0.42615	1.438E-07
3	25.135			0.5462	348.835	0.42165	1.699E-07
1	20.35			0.5735	327.074	0.49433	1.262E-07
2	20.4			0.6485	350.177	0.41786	1.218E-07
3	19.607			0.579	349.042	0.42106	1.514E-07
1	15.763			0.5481	351.537	0.41409	1.725E-07
2	16.594			0.5567	335.436	0.46362	1.454E-07
3	15.609			0.5618	348.669	0.42212	1.604E-07
1	10.511			0.5049	343.833	0.4364	1.906E-07
2	10.095			0.5816	332.063	0.47554	1.29E-07
3	10.606			0.5303	349.319	0.42028	1.809E-07
1	6.332			0.5619	350.141	0.41796	1.623E-07
2	4.75			0.5375	330.389	0.48168	1.486E-07
3	5.914			0.561	348.537	0.4225	1.607E-07

### C.7 Compiled data on thermal conductivity and thermal diffusivity for spot

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	30.094	67.282	11.718	0.5945	347.684	0.42495	1.42E-07
2	29.018	60.241	20.773	0.6455	377.288	0.35366	1.496E-07
3	30.583	63.689	15.322	0.5872	367.281	0.37492	1.69E-07
1	24.32			0.5874	368.639	0.37189	1.705E-07
2	25.255			0.6624	376.554	0.35514	1.414E-07
3	25.412			0.609	339.166	0.45112	1.257E-07
1	20.681			0.5899	337.415	0.4569	1.319E-07
2	21.677			0.5831	365.116	0.37987	1.688E-07
3	20.58			0.5504	353.607	0.40848	1.739E-07
1	15.536			0.6067	341.185	0.44463	1.29E-07
2	15.993			0.6707	374.658	0.35901	1.362E-07
3	15.266			0.5654	369.777	0.36939	1.855E-07
1	10.655			0.5868	334.401	0.46721	1.296E-07
2	11.637			0.6098	364.671	0.3809	1.539E-07
3	10.813			0.5289	358.451	0.39593	1.954E-07
1	5.817			0.5881	329.154	0.48632	1.226E-07
2	6.318			0.5991	383.873	0.34094	1.809E-07
3	5.322			0.5663	357.459	0.39843	1.692E-07

### C.8 Compiled data on thermal conductivity and diffusivity for tilapia

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	29.777	76.51	0.784	0.539	324.914	0.50293	1.397E-07
2	31.312	78.617	0.503	0.5088	318.842	0.52881	1.468E-07
3	31.07	78.008	0.954	0.5031	320.712	0.52056	1.533E-07
1	23.75			0.5218	323.933	0.50694	1.476E-07
2	24.913			0.4566	331.223	0.4786	2.076E-07
3	25.732			0.5326	314.789	0.54762	1.279E-07
1	19.683			0.5287	321.554	0.51693	1.401E-07
2	19.966			0.5202	323.643	0.50814	1.48E-07
3	20.481			0.5239	321.696	0.51632	1.429E-07
1	14.715			0.4958	339.879	0.44881	1.909E-07
2	15.365			0.534	327.608	0.49225	1.464E-07
3	16.13			0.5371	321.466	0.51731	1.356E-07
1	11.024			0.493	330.98	0.47949	1.776E-07
2	10.778			0.5217	333.514	0.47034	1.626E-07
3	11.402			0.5082	334.85	0.46565	1.735E-07
1	5.285			0.4961	342.033	0.44196	1.944E-07
2	5.06			0.5226	336.888	0.45867	1.672E-07
3	6.088			0.512	318.672	0.52957	1.447E-07

### C.9 Compiled data on thermal conductivity and diffusivity of trout

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	31.397	76.729	4.456	0.5547	339.274	0.45077	1.517E-07
2	31.61	80.824	2.133	0.5084	317.319	0.53572	1.446E-07
3	29.021	79.687	1.983	0.5283	330.0787	0.48284	1.533E-07
1	25.433			0.5093	319.065	0.52781	1.469E-07
2	25.407			0.5201	320.458	0.52167	1.431E-07
3	24.577			0.4926	310.14	0.57091	1.414E-07
1	20.248			0.5427	326.69	0.49584	1.404E-07
2	20.168			0.544	323.359	0.50932	1.349E-07
3	19.46			0.529	327.192	0.49387	1.485E-07
1	16.007			0.4996	337.019	0.45823	1.832E-07
2	15.807			0.5015	314.96	0.5468	1.446E-07
3	15.421			0.4993	306.432	0.59095	1.313E-07
1	10.756			0.5314	320.765	0.52033	1.375E-07
2	10.128			0.5242	316.78	0.53821	1.351E-07
3	9.553			0.5314	317.602	0.53442	1.327E-07
1	5.323			0.5547	324.049	0.50646	1.307E-07
2	5.424			0.5426	319.678	0.52509	1.303E-07
3	5.407			0.5347	319.616	0.52536	1.341E-07

### C.10 Compiled data on thermal conductivity and diffusivity of tuna

Species Number	Temperature °C	Moisture Content %	Fat Content %	Slope/ Intercept	Experiment Value	Conductivity W/m•°C	Diffusivity m <sup>2</sup> /s
1	30.018	73.215	0.045	0.7638	377.326	0.35359	1.068E-07
2	29.37	73.128	0.002	0.5507	333.331	0.47099	1.456E-07
3	29.915	72.978	0.002	0.5044	321.379	0.51768	1.537E-07
1	25.196			0.5404	336.507	0.45996	1.558E-07
2	25.189			0.5473	332.422	0.47424	1.462E-07
3	25.798			0.5498	339.686	0.44943	1.55E-07
1	20.975			0.4949	336.662	0.45944	1.861E-07
2	20.587			0.5209	327.659	0.49205	1.539E-07
3	19.745			0.5432	327.136	0.49409	1.408E-07
1	16.101			0.5402	323.466	0.50887	1.37E-07
2	15.15			0.535	332.648	0.47343	1.533E-07
3	14.708			0.5305	327.337	0.4933	1.479E-07
1	10.728			0.5297	321.813	0.51582	1.4E-07
2	9.681			0.5267	331.815	0.47644	1.569E-07
3	9.598			0.534	336.526	0.4599	1.596E-07
1	5.828			0.5412	326.56	0.49635	1.41E-07
2	5.607			0.517	356.953	0.39973	2.022E-07
3	5.52			0.5328	341.287	0.44431	1.674E-07

### C.11 Measured specific heat data for all seafood

Variety	Number	Specific Heat, kJ/kg•K					
		Temperature, °C					
		5	10	15	20	25	30
Bluefish	1	3.53	3.52	3.52	3.51	3.45	3.45
	2	3.39	3.39	3.38	3.38	3.37	3.31
	3	3.40	3.37	3.38	3.36	3.35	3.31
Croaker	1	3.21	3.22	3.29	3.23	3.13	3.11
	2	3.12	3.31	3.34	3.22	3.16	3.12
	3	3.12	3.26	3.33	3.25	3.16	3.07
Salmon	1	3.62	3.62	3.62	3.59	3.57	3.52
	2	3.61	3.61	3.60	3.63	3.58	3.56
	3	3.59	3.60	3.60	3.59	3.54	3.56
Seabass	1	3.75	3.76	3.76	3.74	3.70	3.71
	2	3.66	3.64	3.66	3.63	3.62	3.57
	3	3.72	3.73	3.70	3.71	3.65	3.68
Shrimp	1	3.33	3.32	3.32	3.30	3.28	3.29
	2	3.43	3.44	3.44	3.43	3.43	3.40
	3	3.40	3.43	3.42	3.41	3.42	3.40
Mackerel	1	3.55	3.49	3.50	3.49	3.46	3.43
	2	3.63	3.62	3.61	3.60	3.57	3.57
	3	3.48	3.42	3.44	3.46	3.40	3.39
Spot	1	3.47	3.50	3.49	3.48	3.44	3.40
	2	3.58	3.59	3.58	3.57	3.55	3.52
	3	3.53	3.55	3.56	3.53	3.53	3.52
Tilapia	1	3.54	3.55	3.53	3.53	3.52	3.51
	2	3.56	3.54	3.50	3.51	3.50	3.53
	3	3.50	3.51	3.50	3.48	3.46	3.47
Trout	1	3.53	3.52	3.53	3.53	3.51	3.46
	2	3.67	3.67	3.67	3.70	3.64	3.64

Variety	Number	Specific Heat, kJ/kg•K					
		Temperature, °C					
		5	10	15	20	25	30
Tuna	3	3.53	3.52	3.53	3.55	3.50	3.45
	1	3.16	3.09	3.16	3.19	3.17	3.17
	2	3.41	3.41	3.41	3.41	3.42	3.41
	3	3.53	3.51	3.52	3.50	3.46	3.49

### C.12 Measured enthalpy data for all seafood

Temperature °C	Enthalpy kJ/kg		
	1	2	3
<b>Bluefish</b>			
-40	0	0	0
-35	11.302	10.416	11.156
-30	24.621	22.88	24.736
-25	43.403	40.145	42.977
-20	75.607	70.05	72.776
-15	179.21	186.63	169.27
-10	255.41	261.85	244.45
-5	282.76	287.42	276.98
0	303.3	306.01	297.5
5	320.85	322.71	314.63
10	337.77	339.1	331.25
15	355.08	355.46	347.69
20	372.37	371.81	364.16
25	389.81	388.28	380.84
30	407.73	404.79	397.83
<b>Croaker</b>			
-40	0	0	0
-35	10.771	11.209	11.08
-30	23.829	24.304	23.761
-25	41.724	41.684	40.735
-20	71.59	69.68	67.832
-15	175.37	179.06	166.94
-10	234.46	234.32	231.37
-5	258.95	256.86	255.61
0	277.1	275.7	274.16
5	293.05	293	291.01

Temperature °C	Enthalpy kJ/kg		
10	308.96	309.94	307.56
15	325.19	326.58	324.18
20	341.29	343.09	340.6
25	357.2	359.04	356.65
30	373.2	375.2	372.75
Salmon			
-40	0	0	0
-35	11.375	11.539	11.821
-30	25.198	25.478	26.083
-25	44.178	44.261	45.474
-20	76.739	76.364	78.722
-15	194.35	198.65	201.4
-10	246.68	264.56	263.43
-5	270.59	290.46	288.58
0	289.52	310.44	307.77
5	306.27	327.82	324.99
10	322.64	344.8	341.95
15	339.03	361.73	358.88
20	355.45	378.75	375.91
25	372.07	395.9	392.93
30	388.9	413.11	409.93
Seabass			
-40	0	0	0
-35	10.89	10.83	11.174
-30	23.505	23.964	24.463
-25	40.234	41.23	41.872
-20	67.291	69.505	70.377
-15	195.52	199.58	200.2
-10	286.61	292.45	287.84

Temperature °C	Enthalpy kJ/kg		
-5	315.88	321.99	318.38
0	338.31	344.62	340.58
5	357.47	363.7	359.08
10	375.38	381.5	376.7
15	393.3	399.27	394.48
20	411.15	417.13	412.29
25	429.2	435.18	430.26
30	447.24	453.21	448.14
Shrimp			
-40	0	0	0
-35	11.747	11.069	11.198
-30	25.463	24.445	24.574
-25	42.772	41.819	41.568
-20	72.201	70.523	69.721
-15	229.28	205.64	225.74
-10	323.47	300.36	313.05
-5	353.21	330.26	342.06
0	376.57	352.68	365.01
5	396.39	371.4	385.08
10	415.07	389.34	403.77
15	433.69	407.27	422.28
20	452.26	425.18	440.75
25	471.01	443.26	459.37
30	489.73	461.49	477.95
Mackerel			
-40	0	0	0
-35	11.127	11.035	11.096
-30	23.763	23.43	23.288
-25	40.292	39.188	39.3

Temperature °C	Enthalpy kJ/kg		
-20	66.069	63.513	64.019
-15	182.96	177.7	188.84
-10	263.63	278.7	266.98
-5	292.47	316.07	292.99
0	314.05	340.11	314.22
5	332.13	359.71	332.29
10	349.5	378.2	349.7
15	366.98	396.46	366.94
20	384.37	414.56	384.26
25	401.75	432.63	401.47
30	419.22	450.84	418.74
Spot			
-40	0	0	0
-35	11.686	10.496	11.617
-30	25.95	22.624	25.902
-25	45.216	38.738	44.998
-20	79.025	64.87	77.917
-15	206.91	200.43	207.65
-10	274.78	289.02	285.34
-5	300.65	316.54	311.42
0	321.63	338.65	332.85
5	339.73	357.7	351.33
10	356.8	375.56	369.02
15	373.99	393.2	386.62
20	391.26	410.97	404.26
25	408.55	428.76	422.1
30	426	446.68	439.98
Tilapia			
-40	0	0	0

Temperature °C		Enthalpy kJ/kg	
-35	11.19	11.45	11.573
-30	25.047	25.512	26.308
-25	43.547	44.725	46.617
-20	75.13	76.566	82.927
-15	207.99	179.38	208.38
-10	283.6	269.71	271.44
-5	309.73	303.39	298.14
0	330.2	326.15	319.09
5	348.15	344.48	337.2
10	365.59	362.06	354.57
15	383.04	379.51	371.96
20	400.45	397.11	389.38
25	417.95	414.64	406.75
30	435.34	432.36	424.21
Trout			
-40	0	0	0
-35	10.893	10.651	10.991
-30	23.57	22.735	23.764
-25	40.309	38.073	40.778
-20	66.828	61.913	69.305
-15	184.38	194.89	198.59
-10	274.86	295.77	275.29
-5	304.41	327.5	302.02
0	326.21	350.68	322.83
5	344.65	370.58	340.95
10	362.17	388.98	358.53
15	379.66	407.09	376.01
20	397.16	425.23	393.53
25	414.85	443.42	411.17

Temperature °C	Enthalpy kJ/kg		
30	432.83	461.82	428.97
Tuna			
-40	0	0	0
-35	13.267	12.654	12.682
-30	29.635	28.981	29.047
-25	53.328	51.959	52.12
-20	102.44	95.729	93.795
-15	182.46	227.99	213.24
-10	206.76	267.87	267.22
-5	225.6	290.44	291.39
0	242.12	309.83	311.48
5	257.75	327.31	329.24
10	273.5	344.31	346.55
15	289.42	361.29	363.92
20	305.29	378.28	381.26
25	321.11	395.33	398.71
30	336.92	412.55	416.36

**APPENDIX D**

**STATISTICAL ANALYSIS**

### D.1 SAS code to compute coefficients H0, H1, H3 for the temperature calibration

```
DATA ONE;INFILE THERMIST;INPUT TEMP R1 R2 R3;
```

```
T=1/(TEMP+273.15);
```

```
PROC NLIN;
```

```
PARMS B0 = 0.003 TO 0.003 BY 0.0001
```

```
B1 = 0.00020 TO 0.00030 BY 0.00001
```

```
B3 = -0.000001 TO 0.0000005 BY 0.0000001;
```

```
MODEL T = B0 + B1*LOG(R3) + B3*LOG(R3)**3;
```

```
DER.B0 = 1;
```

```
DER.B1 = LOG(R3);
```

```
DER.B3 = LOG(R3)**3;
```

```
OUTPUT OUT = larry PARMS = B0 B1 B3;
```

```
DATA TWO (KEEP = B0 B1 B3); SET LARRY;
```

```
IF _N_ = 2 THEN STOP;
```

```
FILE LARRY1;PUT B0 B1 B3;
```

```
/* */
```

```
'FI THERMIST DISK SUDHA DATA A1'
```

```
'FI LARRY1 DISK R3 DATA A1'
```

```
'SAS THER'
```

## D.2 SAS code to regress individual thermal conductivity and thermal diffusivity values with temperature

```
% macro accessit (filename, dataset);  
    proc access dbms=xls;  
        create work.&dataset.. access;  
        path=&filename;  
        getnames=yes;  
        assign=yes;  
        mixed=yes;  
        list all;  
        create work.&dataset..view;  
        select all;  
        run;  
  
%mend;  
  
%accessit ('a:allfish.xls',allfish);  
run;  
libname fish 'a:\';  
run;  
  
data fish1;  
set allfish;  
run;  
  
options ls=72;  
data cfish (keep= species_ m_conten fatconte conducti species temp rep fish);  
set fish1;  
run;
```

```
proc sort data=CFISH;  
by species species_ temp FISH;  
run;
```

```
PROC GLM DATA=CFISH;  
MODEL CONDUCTI = TEMP;  
by fish;  
run;
```

```
data dfish (keep= species_ m_conten fatconte conducti species temp rep fish);  
set fish1;  
run;
```

```
proc sort data=DFISH;  
by species species_ temp FISH;  
run;  
PROC GLM DATA=DFISH;  
MODEL CONDUCTI = TEMP;  
by fish;  
run;
```

```
QUIT;
```

### **D.3 SAS code to regress averaged thermal conductivity with moisture and fat content**

```
OPTIONS LS = 72;
TITLE 'MODEL';
DATA;
INPUT MOIST FAT COND DIFF;
CARDS;
<DATASET>
;
PROC PRINT;
PROC REG;
    MODEL COND = FAT MOIST;
    MODEL DIFF = FAT MOIST;
    MODEL COND = FAT;
    MODEL COND = MOIST;
    MODEL DIFF = FAT;
    MODEL DIFF = MOIST;
```

## D.5 SAS code to regress and correlate enthalpy with fat content and moisture content

```
OPTIONS LS = 72;
TITLE 'ENTH-T0 MODEL';
DATA;
INPUT ENTH MOIST FAT;
<DATASET>
;
PROC PRINT;
PROC REG;
    MODEL ENTH = FAT MOIST;
    MODEL ENTH = FAT;
    MODEL ENTH = MOIST;
PROC CORR;
    VAR ENTH MOIST FAT;
```

## VITA

Sudhaharini Radhakrishnan was born in Neyveli, Tamilnadu, India on November 11, 1972 to Radhakrishnan Nagamanickam and Selvalu Radhakrishnan. She graduated from St. Joseph of Cluny Higher Secondary School in March 1990, and in the same year she was admitted to Tamilnadu Agricultural University. In March 1995 she obtained a Bachelor of Engineering in Agriculture. She got married to Bala Dhandapani in March 1995 and, in August of the same year she was accepted as a graduate student to pursue a Master of Science at Virginia Tech in the Biological Systems Engineering Department. She will pursue her career as a research engineer in the Center for Food Safety and Quality Enhancement, University of Georgia.