Microwave Tempering of Shrimp with Susceptors

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(ABSTRACT)

Microwave tempering experiments were conducted on frozen blocks of shrimp (FSB) and the results were used to help determine if microwave tempering of FSB is an improved thawing method over the current, traditional method, water immersion. Results of the microwave tempering experiments were also used to help determine which microwave tempering method amongst those explored by this study is most effective.

Complete thawing of a FSB in a microwave oven was found to be impractical; however, using a combination of microwave tempering followed by water immersion can successfully thaw a FSB. After a microwave tempering experiment was conducted, the final stages of thawing were completed by using the traditional water immersion method. The amount of time to complete the thawing was recorded and is referred to as the additional thawing time. The amount of shrimp cooked during microwave tempering was also recorded and calculated as a percent. The additional thawing time and the percentage of shrimp cooked were used as criteria to compare microwave tempering experiments and also to compare microwave tempering experiments with the current method.

The first set of microwave tempering experiments explored the advantages of freezing a microwave susceptive material within the FSB before microwave tempering. FSBs with susceptors and FSBs without susceptors were tempered in a microwave oven. The FSBs were tempered in a 2450 MHz microwave oven at 255 W for 35 minutes and at 406 W for 22 minutes. The results showed that the addition of susceptors does improve the microwave tempering process. The percentage of cooked shrimp and the additional thawing time was less for FSBs with susceptors than for FSBs without susceptors. The susceptors seem to help distribute the microwave energy more evenly, which reduces runaway heating and in turn reduces the amount of shrimp cooked.

When compared to the current method, microwave tempering with susceptors reduced the total thawing time by 45% while microwave tempering without susceptors reduced the total thawing time by 43%. Both microwave tempering methods, with and without susceptors, are an improvement over the current method. The addition of susceptors does improve the microwave tempering process; however, the improvements are not significant enough to justify its recommendation.

The second set of microwave tempering experiments explored the advantages of pulse microwave tempering. During pulsed microwave tempering the microwave oven was set to a high power level and was turned ON for a period of time and then OFF for a period of time. The ON/OFF pattern was repeated throughout the microwave tempering process. Several pulsed tempering experiments were conducted at a microwave power level of 848 W and at a microwave power level of 993 W. The results showed that there is no significant advantage to using pulsed microwave energy during tempering as opposed to continuous, fixed microwave energy. The results showed that fixed microwave tempering is more effective than pulsed microwave tempering. The percentage of cooked shrimp was lower for fixed experiments than for pulsed experiments and the additional thawing time was slightly less for fixed experiments than for pulsed experiments.

A mathematical model was developed to help predict he temperature profiles of a FSB during microwave tempering. Experimental temperature data were collected at four locations within the FSB during microwave tempering by using four Luxtron Fluoroptic temperature probes and a Luxtron Fluoroptic thermometer. Overall, the temperatures predicted by the model were within 2 ^{o}C of the experimental temperatures. After the first 500 seconds or so of microwave tempering, the temperatures predicted by the model were consistently less than the experimental temperatures.

From this study it was determined that the most effective microwave tempering method, amongst those conducted in this study, of a 2.2 kg (5 lb) frozen block of shrimp was accomplished by setting the power output to 255 W and the microwave cooking (tempering) time to 35 minutes. As previously mentioned, the addition of susceptors does improve the process but the improvements are not significant enough to justify its recommendation. Pulse tempering is not an improved method over fixed tempering.

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Chapter 1

Introduction

As of 1995, the total world shrimp supply amounted to 2.64×10^9 kg (5.8 billion lb), which includes both farm raised and wild caught shrimp (Shang *et al.*, 1998). The amount of shrimp processed, domestic and international, has steadily increased since the 1960's. The world shrimp supply was 5.46×10^8 kg (1.2 billion lb) in 1969, 9.78×10^8 kg (2.2 billion lb) in 1979, 1.49×10^9 kg (3.3 billion lb) in 1989, and 2.64×10^6 kg (5.8 billion lb) in 1995 (Keithly *et al.*, 1993). This increasing trend of world shrimp production is expected to continue. Imports of shrimp to the USA have also increased since the 1960's and most of this increase occurred during the 1980's. Import shrimp amount was 1.2×10^8 kg (257 million lb) in 1979, 1.5×10^8 kg (336 million lb) in 1984, and 2.5×10^8 kg (538 million lb) in 1989 (Keithly *et al.*, 1993). A report by Keithly (1993) stated that the value of imported shrimp has also steadily increased since the 1960's. The value of imported shrimp in current prices increased from $1.61/kg ($0.73/lb) in 1969 to $6.34/kg ($2.88/lb) in 1989. The total value of shrimp imported by the USA was around $1.6 billion in 1989. This amount is expected to increase over the years since the amount of shrimp imported is expected to continue to increase and the value of imported shrimp is also expected to continue to increase.

The imported shrimp are frozen as raw whole shrimp in the form of blocks and stored on board fishing vessels at $-18\ ^{o}C$ (Olsen *et al*., 1990). Before any further processing of the shrimp can be made at the shrimp processing plant, the shrimp must be thawed. The thawing of frozen shrimp at the processing plant is performed by re-circulating freshwater over the blocks. The thawing process is often referred to as water immersion. After thawing, the shrimp are treated with various additives. At this point, depending on size and quality of the shrimp, the shrimp are packaged for sale, refrozen as individual shrimp and then packaged for sale, or cooked, refrozen as individual shrimp, and then packaged for sale.

The processing of shrimp at a shrimp plant is a time-consuming and expensive process. The majority of the processing time is spent on thawing the shrimp. The current water immersion thawing process takes 4-5 hours (Olsen *et al*., 1990). The length of the process is a concern of the shrimp plant for several reasons. One of these reasons is the fact that the long thawing process limits the ability of the shrimp plant to adjust purchase orders. Changes in purchase orders made by commercial companies to the shrimp plant must be made days in advance. Since the thawing process is a daylong process, the shrimp plant must process a shrimp order the day before the delivery date. Therefore, an increase to an order made on delivery day, or a rush order usually cannot be satisfied.

Attempted changes to shrimp purchase orders made on deliver day can cost the shrimp plant significant amounts of time and money. The inability of the shrimp plant to satisfy rush orders costs the industry since this inability can be viewed as possible revenue that is lost. A cancelled order or reduction in an order also hurts the shrimp industry. If an order is cancelled the day before or day of delivery, the shrimp for this order had most likely already been processed. The cancelled order leaves the plant with a large quantity of processed shrimp ready for delivery and sale. This shrimp must be placed back in storage, which takes time and occupies freezer space; furthermore, the time spent processing the order is wasted time, an additional cost to the plant.

The long thawing process also costs the plant because the thawing process produces wastewater. The shrimp industry produces large amounts of waste both as solid, heads and shells, and processing water with dissolved and particulate organic compounds. As previously mentioned, the thawing of shrimp is performed by re-circulating freshwater over the frozen blocks of shrimp (FSB). The majority of wastewater produced at a shrimp plant is attributed to the long thawing process. The disposing of this wastewater is a major concern from both an economic and environmental standpoint.

Improvements to the current thawing method can be made and a faster method that produces less wastewater is needed. Work done by Roberts *et al*. (1998) explored the possibility of using ohmic heat to thaw shrimp. Results from the study found that ohmic heat can be used to thaw FSBs. The ohmic heating of a FSB does not use any water and does not produce much wastewater. The results showed that the time for ohmic thawing was comparable to water immersion. The major concern of this method is runaway heating, which occurs because the electrical conductivity of thawed food is about two orders of magnitude greater than that of frozen food.

Microwave energy can be used to help thaw FSB. As with ohmic heating, the major concern of this method is runaway heating. It may be possible to control runaway heating during microwave tempering of a FSB by freezing a microwave susceptive material within the FSB.

Microwave susceptive materials are currently manufactured in the form of sheets. The sheets are known as microwave susceptor heater boards, microwave susceptors, or simply susceptors. The susceptors are currently used in the food industry to assist browning of foods during microwave heating and are used in microwave popcorn packages. The microwave susceptors are designed to absorb microwave energy at a much higher rate than foods.

The microwave susceptive material can theoretically be used to assist microwave tempering of a FSB. The material is frozen in some manner within the FSB. During microwave tempering, the susceptive material absorbs the majority of the microwave energy. The energy absorbed is converted to heat and transferred through conduction to the surrounding medium. The temperature of the surrounding medium rises and the shrimp is thawed. The susceptors will theoretically reduce or eliminate runaway heating by controlling the source of heat and limiting the amount of microwave energy directly absorbed by the FSB. The susceptors also provide an internal source of heat so that thawing is experienced throughout the FSB instead of from the surface to the interior.

Objectives

The goal of this study is to determine if the additions of microwave susceptors to frozen blocks of shrimp significantly improve the microwave tempering process. Several microwave tempering tests were conducted in this study. The following are the specific objectives of the microwave tempering tests and of this study.

1. Identify a microwave power output level and microwave tempering time that is most effective for the microwave tempering of frozen blocks of shrimp (FSB).
2. Determine if the addition of microwave susceptors to FSBs significantly improves the microwave tempering process.
3. Determine if microwave tempering is an improved method over the current water immersion method.
4. Investigate the possible advantages of pulsed microwave tempering. Determine if pulsed microwave tempering is an improved method over fixed microwave tempering.
5. Develop a mathematical model that can predict the temperature profile of a FSB during the microwave tempering process.

Chapter 2

Principles of Microwaves

and Microwave Heating

Overview

This chapter begins with a brief description of microwaves and microwave heating. Next, an explanation of how microwaves interact with a material and why this interaction causes an increase in the temperature of the material is provided. Of particular interest during this interaction is the amount of energy a material absorbs during microwave heating. This is known and calculated as the power absorbed and is related to the electrical properties of the material. A large portion of this chapter concentrates on power absorption and the related electrical properties.

The second portion of this chapter provides background and history on the thawing of foods with microwave and the art of microwave susceptors. The section explains why thawing foods is an important unit process in the food industry and the problems associated with thawing of foods. Next, past work done with microwave thawing is presented. The last section of this chapter contains a description of microwave susceptors.

The Theory of Microwaves and Microwave Heating

Frequency and wavelength

Wavelength or frequency classifies electromagnetic radiation. Microwaves represent the electromagnetic spectrum between frequencies of 300 MHz and 300 GHz. Usually microwaves are described as radio waves of very short wavelength. Microwaves are usually given in centimeters, while radio waves are in kilometers, television in meters and infrared in microns. The frequency of microwaves lies between the television frequencies and infrared. The relationship between wavelength and frequency is represented by the following equation:

$$? = c/f \qquad (2.1)$$

where

? = wavelength in free space (m)

c = speed of light (m/s)

f = microwave frequency (1/s)

Frequency is measured in Hertz (Hz) and is equivalent to cycles per second. Microwave use is regulated by government agencies because microwaves are used in radar navigation and communication equipment. The USA Federal Communications Commission (FCC) has set aside frequencies in the microwave range for industrial, scientific and medical apparatus. Most microwave ovens operate at either 915 MHz or 2450 MHz. Microwave ovens manufactured today for commercial and home usually operate at 2450 MHz. Some industrial microwave ovens operate at 915 MHz.

Absorb, transmit, and reflect

In many ways, microwaves are similar to visible light. Microwaves can be focused into beams, they can transmit through hollow tubes, and they can be reflected or absorbed by a material. Microwaves can also transmit through materials such as glass ceramics and plastics without any absorption or reflection. When a material absorbs microwaves, the microwave energy is converted to heat. Some materials reflect or transmit all microwaves, such as metals and plastics respectively; however, most materials transmit a certain percentage of microwaves, reflect a certain percentage of microwaves, and absorb the remaining percentage of microwaves. The microwave properties of a material determine the amount of microwaves absorbed, reflected, and/or transmitted.

Microwave heating

The absorption of microwaves by a material results in the microwaves giving up their energy to the material. This transfer of energy causes the temperature of the material to rise. The microwaves themselves do not heat up materials. The heat generation in a microwave field is caused by ionic polarization and dipole rotation of the water molecule.

The polar molecules in foods, such as water, interact with microwaves to produce heat. A molecule is described as polar if it has a positive and negative end. The polarity in a microwave field changes rapidly. A microwave oven operating at 2450 MHz produces a microwave field that changes polarity 2.45 billion times per second. Figure 1 shows how polar molecules in the presence of microwave field attempt to orient themselves according to the rapidly changing field (Decareau and Peterson, 1986). The rotation of the molecule leads to friction with surrounding medium and heat is generated. The rotation of the molecule also produces kinetic energy, which produces additional heat.

Ionic conduction is another important microwave heating mechanism. When an electrical field (i.e. microwave field) is applied to food solutions containing ions, the ions move at an accelerated pace due to their inherent charge. The ions collide and the collisions cause the conversion of kinetic energy of moving ions into thermal energy. A solution with higher concentration of ions will have more frequent collisions and therefore heat faster than a solution with lower concentration.

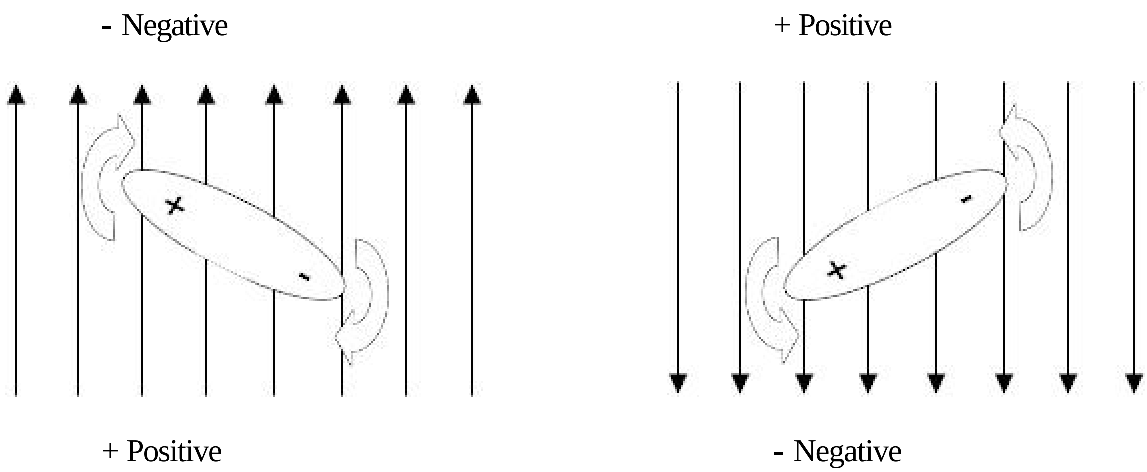


Figure 1. Movement of a dipole in an electrical field.

Power absorbed, dielectric properties and penetration depth

The amount of power absorbed by a material exposed to a microwave field is expressed by the following equation:

$$P = 55.61?10^{-14} E^2 f\ ?'tand \qquad (2.2)$$

where

P	= power dissipation (W/m^3)
E	= voltage gradient (V/m)
f	= frequency (1/s)
?'	= relative dielectric constant
tand	= the loss tangent

Equation 2.2 clearly show that the amount of power absorbed by a material exposed to a microwave field depends on the dielectric property, ?', of the material. There are two important dielectric properties, the relative dielectric constant, ?', and the relative dielectric loss, ?''. The relative dielectric constant expresses the true ability of the material to store electrical energy and the relative dielectric loss denotes the ability of the material to dissipate electrical energy. These properties provide a measure of a material's electrical insulating ability. Foods are very poor insulators and therefore absorb a large portion of electrical energy when placed in a microwave field, which results in instantaneous heating.

The dielectric properties are measurable quantities and the dielectric loss factor is equal to the product of two other measurable quantities: the dielectric constant, e', and the tangent loss, tand:

$$e'' = e' \tan d \tag{2.3}$$

The loss tangent provides an indication of how well a material can be penetrated by an electrical field and how it dissipates electrical energy as heat.

Over the past few decades research has been done on dielectric measurements of foods. Our basic understanding of dielectric properties in foods can be attributed to the work of Collie *et al.* (1948) and Hasted *et al.* (1948). Their work provides exact measurements of the debye parameter which is a major factor when determining food dielectric properties. Their work has also been a major building block in the development of predictive models for food dielectric behavior which are difficult to develop because dielectric properties of foods vary significantly with frequency, moisture content, temperature, salt content, and physical state.

As previously mentioned, the power absorbed by a material in a microwave field is strongly dependent on the dielectric properties of the material. The term penetration depth is often used when describing the amount of power absorbed by a material exposed to a microwave field. The penetration depth is a function of both dielectric properties and provides information that serves as a guideline for the heating efficiency of a material. The term penetration depth has over the years acquired three similar yet slightly different definitions.

Electrical field penetration depth

Equations that describe microwaves are often written in terms of the electrical field, E. The electrical field penetration depth is defined as the depth at which the electrical field has diminished to 1/e of its original value. This definition of penetration depth is used frequently by microwave engineers but rarely by food scientists or food engineers.

Half-power penetration depth

Half-power penetration depth is defined as the distance into a material microwaves must penetrate before the microwave power is reduced to one half its original value.

Power penetration depth

This is the most useful and commonly used definition of penetration depth. The heating of a product depends directly on the power available at any given position. The power at any point within an infinite slab is determined by the following equation:

$$P(z) / P_o = e^{-z/dp} \qquad (2.4)$$

where

P_o = incident power of microwave oven (W)

$P(z) / P_o$ = fraction of power remaining as a function of distance into the material

e = Napierian logarithm base, a mathematical constant

z = location within the material (m)

d_p = power penetration depth (m)

The power penetration depth is therefore defined as the depth at which the microwave power has decreased to 1/e or 36.8% of its original power. The power penetration depth of a material is a function of the microwave frequency and the dielectric properties of the material and is given by the following equation:

$$d_p = \frac{?_0\sqrt{2}}{2p}\left(e'\left[\sqrt{1+\left(\frac{e''}{e'}\right)^2}-1\right]\right)^{-\frac{1}{2}}$$

where

ε'' = relative dielectric loss

ε' = relative dielectric constant

λ_0 = wavelength of microwave (m)

Power output and speed of heating

The heating rate of a dielectric material is directly proportional to the power output of the microwave system. A high rate of heating is possible in a microwave field; however, most food applications require good control on how fast the foods are heated. If the foods are heated too fast, undesirable effects on the physical properties of the food may occur. Measuring the power output of a microwave is possible and is accomplished by following the procedure set by the International Microwave Power Institute. First heat a quantity of water, two liters, in the microwave oven for a period of time, 120 seconds, and note the temperature change. The following equation can then be used to calculate power output:

$$P = V\rho\Delta T c_p/\Delta t \qquad (2.6)$$

where

V = Volume of water = 2 liters = 1000 ml

ρ = density of water (g/ml)

ΔT = temperature difference (C^o)

c_p = specific heat of water (J/g-K)

Δt = change in time (s)

P = power output (W)

Most microwave ovens can operate at only one power level and thus one power output. This power level is the operating power level of the microwave oven and is also referred to as maximum power, high-power, or one hundred percent power. Since the microwave oven is not capable of operating at any power level besides the operating power level, the microwave oven applies pulsed heating to mimic the desired reduced power level. To operate at a percentage of the operating power level the microwave oven runs at maximum power for a period of time and then shuts off for a period of time. This ON/OFF cycle is repeated throughout the entire microwave-cooking process. The amount of time the microwave oven is turned ON and the amount of time it is turned OFF during each cycle is determined by the power setting of the microwave oven. At one hundred percent power setting, the microwave oven is ON one hundred percent of the time. At seventy-five percent power setting the microwave oven is ON for seventy-five percent of each cycle and OFF for the remainder of each cycle. The length of the cycle is different for different microwave ovens and can be as long as one minute and as short as a millisecond.

A microwave designed for use in the home has an ON/OFF cycle around sixty seconds long. These microwave ovens usually have the following power setting choices: High (˜100%), medium high (˜75%), medium (˜50%), and low (˜25%); therefore, a microwave oven of this type set at medium high-power level would operate for around 45 seconds and shut off for the next 15 seconds.

Commercial microwave ovens used in the food processing industry allow more flexibility in the power setting and can usually have power output adjusted to any percentage of maximum power output. The commercial microwave oven's ON/OFF cycle is much shorter than a microwave oven designed for use in the home. In fact, the pulsing between ON/OFF can be so rapid that multiple cycles can be completed in a second. Since the pulsing is so rapid, it can be assumed that this type of microwave oven is operating continuously at the selected power setting.

Thawing Foods with Microwave Energy

Introduction

The thawing of frozen foods is an important unit process in the food industry because the industry relies heavily on large quantities of food that have been preserved by freezing at harvest time for use throughout the year. The thermal conductivity of frozen foods is three times that of non-frozen foods. The most common thawing method is to apply heat to the surface of the frozen food and allow the heat to conduct to the interior. Since the heat is applied to the surface, it thus must travel through the surface to reach the interior. The surface thaws first and now has a lower thermal conductivity than the frozen interior and cannot transfer adequate heat to the interior without increasing the temperature of the thawing surface to undesirable levels. The result of this is long thawing cycles that are often characterized by unacceptable changes in product quality.

Early radio frequency thawing work

Using radio frequency energy was suggested as a solution to the thawing problem in the middle 1940's. The theory of radio frequency defrosting was discussed by Brown *et al.* (1947).

Martin (1945) discussed electronic defrosting of frozen fruit and Lund (1945) reported that radio frequency energy was being used commercially to defrost frozen eggs.

The work of Cathcart and Parker (1946) showed that frozen fruit and eggs could be thawed in minutes by radio frequencies. Some of the advantages of the new method were that only foods needed were defrosted, labor was reduced, and production was more flexible. It was also noted that it was not necessary to completely defrost the food products, but instead defrost to the point where it could be broken into smaller pieces.

The scientific work of radio frequency thawing was begun by Ede and Haddow who first reported on the electrical properties of foods at high frequency in 1951. They were the first to discover that these properties, in part, determine the amount of electrical energy absorbed by a food material. These electrical properties are known as the dielectric properties. It was at this time the term runaway heating was coined. During thawing with radio frequency, it was observed that portions of the food were overheated before the remainder had been thawed. This behavior was attributed to variations in electrical conductivity and thus dielectric properties within the food product.

Microwave thawing

Thawing foods with microwave energy is difficult because of the significant difference between electrical properties, dielectric properties of ice and water. Table 1 shows that ice has a low dielectric loss constant when compared to water (Schiffman, 1986).

Table 1. Dielectric properties of water and ice at 2450 MHz

	Relative Dielectric constant, e'	Relative Dielectric loss constant, e"	Loss Tangent, tand
Ice	3.2	0.0029	0.0009
Water (at 25°C)	78	12.48	0.16

Because of its low dielectric loss factor, ice is more transparent to microwaves than water and therefore water heats up much more rapidly when exposed to microwaves than ice. If the food product has portions frozen and unfrozen, then the product will experience runaway heating. To avoid this, all portions of the frozen food product should be maintained at a temperature just below the freezing point throughout microwave oven tempering process. This can be accomplished by using a low-power setting.

Bengstoson (1963) compared radio frequency thawing at 35 MHz and 2450 MHz. Although he found both frequencies showed satisfactory results, the thawing time was 20-30 minutes at 35 MHz for a 4-5 cm block of meat or fish compared to less than 3 minutes at 2450 MHz. Research by Decareau (1968) showed that beef chunks appear to thaw at the juncture between pieces at 2450 MHz and therefore large blocks can be easily separated after short exposure. Frozen seafoods (clam meat, scallops, shrimp, and flounder) were uniformly thawed to –2.2 to 1.2 °C by using microwave energy (Learson and Stone, 1969). The thawing allowed the seafood product to be easily separated.

The microwave thawing of frozen, raw, headless shrimp was noted as advantageous for many reasons (Learson and Stone, 1969); production control was improved; water usage was substantially reduced; ice requirements were reduced, since there was no temperature overshoot;

bacteriological quality control was improved and costs were lower than for air or water thawing. Microwave thawing of shrimp at 915 MHz was reported by Bezanson *et al.* in 1973.

There are several important factors to consider when designing a microwave thawing system. Decareau (1968) summarized these factors suggesting that the system should be designed in such way that the product goes directly from the freezer to the microwave. If the product remains in the ambient temperatures too long before microwave tempering, it is not possible to thaw the core because most of the energy is absorbed by the surface (Meisel, 1972). Decareau (1968) also recommended that thawing not be carried to completion in the microwave. The final portions of the thawing process should be completed under plant ambient temperature conditions or, where possible, in water as in case of shrimp.

Miesel (1972) first recognized that microwave penetration from the surface at 2450 MHz decreases rapidly as the product temperature approaches 0 ^{o}C. This makes it almost impossible to keep surface temperature of the product low and thaw the core of the product. In studies by Miesel on lamb and pork, he found that core temperatures higher than –3 ^{o}C were difficult to achieve without overheating the surface.

The work of Miesel (1972) and others brought on the idea of microwave tempering as opposed to microwave thawing. Microwave tempering is defined as raising the temperature of a frozen product from frozen storage temperature to temperature slightly below the product's freezing point. The penetration depth of microwave energy decreases as temperature of the frozen product increases. Wang and Goldblith (1976) collected data on the penetration depth of frozen beef at 2450 MHz and 915 MHz at several temperatures. Their work is summarized in Table 2.

Table 2. Penetration of microwave energy into frozen beef

Temperature (^{o}C)	Penetration (mm) 2450 MHz	Penetration (mm) 915 MHz
-40	300	600
-20	90	260
-10	20	90

Substantially less energy is required if the tempering is terminated at a lower temperature. The work of Wang and Goldblith (1976) showed that half as much energy is required to temper frozen beef from –17.7 ^{o}C to –4.4 ^{o}C, 62.8 J/g, than to temper it to –2.2 ^{o}C, 128.3 J/g.

Summary

The concept of using microwave energy to thaw foods was identified in the early 1950’s. Early work predicted that complete thawing with microwave was not practical; however, microwave tempering showed great potential. Microwave tempering rather than complete thawing makes sense because in most cases complete thawing is not necessary, is a waste of energy, affects quality, and increases processing time.

Microwave tempering has several advantages over most thawing processes. The microwave tempering process can handle large amounts of frozen product at small cost, has a high yield, and is accomplished in small spaces with no bacterial growth (Miesel, 1972).

Microwave Susceptors

Introduction

Microwave susceptors have been used in microwave packages to assist heating of microwave products since the early 1980’s. Their main use is to combat the lack of browning that occurs when foods are heated in a microwave oven. The surface of a food product heated in a microwave does not become hotter than the boiling temperature of water. For effective browning, temperatures of over 177 ^{o}C (350 ^{o}F) are required. A solution to this problem is to use an external source that can provide the temperature high enough for effective browning (Maynard *et al.* 1989).

The first type of external source used came out in the early 1980's and was called the browning dish. The dish was made of ceramic or glass and was coated with a thin layer of tin oxide. When exposed to microwaves, the oxide layer on the dish absorbs the energy and becomes extremely hot. In fact the temperature of the dish could be raised to as high as 204-260^{o}C (400-500 ^{o}F) (Turpin, 1989). As time passed, the browning dish lost popularity as the development of an inexpensive, disposable external-heating source that could be incorporated into each package was developed.

This inexpensive heater was created by depositing a thin film of metal on a plastic film of polyester and then laminating the metallized film to paperboard (Brastad 1980). The patent of Brastad (1981) includes the use of metallized film to convert microwave energy to heat. Aluminum with a thickness of around 10-20 angstroms was used initially. This aluminum film and paperboard combination became known as a susceptor heater board, a microwave susceptor, or simply a susceptor. A susceptor is defined by Winters *et al.* (1981) as a device for converting microwave energy to heat that in turn heats another product.

Theory of susceptors

A metallic sheet of very low resistivity (high conductivity) reflects virtually all microwaves. No energy is absorbed in the sheet, since all microwaves have been reflected. On the other hand, a sheet with extremely high resistivity (low conductivity) is essentially an insulator and nearly all microwaves are transmitted and none absorbed. Therefore, sheets of zero and infinity resistivity have zero power absorption and thus no heating.

The maximum possible amount of microwave energy absorbed by a sheet occurs at some value of resistivity between the two endpoints: zero and infinity (Anderson, 1988). The absorption of a susceptor as a function of resistivity can be calculated. Buffler (1991) presented the following simple equations for calculating the absorption of a susceptor as a function of resistivity:

$$P_r = \frac{1}{(1+2r)^2} \quad (2.7)$$

$$P_a = \frac{r}{(r+0.5)^2} \quad (2.8)$$

$$P_t = 1 - P_r - P_a \quad (2.9)$$

where

P_r = power reflected (W)

P_a = power absorbed (W)

P_t = power transmitted (W)

r = R/Z_o

R = resistivity of film (O)

Z_o = resistivity of free space, 377 O

According to the equation the maximum value of absorption occurs at a film resistivity of $Z_o/2$ = 188.5 O. This theoretical value agrees well with the experimental results of Lindstrom (1990).

Guidelines for microwave susceptors

Most susceptors are constructed by vacuum metallization where a thin film of metal is deposited on a PET substrate. The most common coating metal is aluminum; however, other metals such as chromium, tin oxide or even silver or gold can be employed (Brasted, 1980). Aluminum is preferred because it is inexpensive and readily available (Turpin, 1980). The thickness of the coating is correlated with the resistivity and thus the power absorbed. Brasted (1980) recommended a resistivity of the coating be 1-10 ohms/cm^2. Brasted, like Turpin, recommends thin coatings of aluminum applied by vacuum evaporation on a polyester substrate and states that metal coatings of 0.1 microns or less allow microwave energy to be transmitted to a considerable degree. The US patent by Brasted (1980) also mentions that the film can be supported by paperboard. Intimate contact of the film and the food are essential to success because of the low heat capacity of the film.

The US patent of Babitt (1992) states that the susceptor reaches the desired temperature within 5-10 seconds after exposure to the microwave field; furthermore, continued heating of the material occurs until maximum temperature is reached. The susceptor is designed in such a way that it becomes transparent to microwave energy after the maximum temperature is reached.

Limiting the maximum temperature and preventing runaway heating of the susceptor is important especially for susceptors laminated to paperboard. The problem is that if the paperboard temperature goes above 233 ^{o}C (451 ^{o}F) charring and burning can occur. To solve the problem the susceptor is designed in such a way that the continuous metal film breaks apart into "metal islands" as the plastic film expands when heated. This limits the heating and thus the temperature since the gaps between the metal have decreased the conductivity. Designing the susceptor film with a resistivity below the maximum absorbing point also solves the problem. By using these two "tricks of the trade" the susceptor film can be designed to reach a heating temperature anywhere between 121-233 ^{o}C (250-450 ^{o}F) almost immediately after exposure to microwave field and maintain this temperature throughout the microwave cooking process.

Chapter 3

Modeling the Heat Transfer of Foods

Overview

Presented in this chapter are the basic concepts important for proper modeling of the heat transfer of foods. The fundamental equations that govern heat transfer as well as a brief description of the equations are presented. Solving the equations using numerical methods and the advantages of numerical methods are discussed. This chapter also contains a brief description of past work done on modeling the heat transfer in foods during microwave cooking.

Of particular interest when modeling heat transfer of a material is the temperature distribution. An accurate model can provide the temperature distribution at any time during the heat transfer process by solving the fundamental heat transfer equations. Properties of the material such as density, specific heat, and thermal conductivity are included in the fundamental equations. For accurate modeling, the values of these properties must be known. For this reason, the values of density, specific heat, and thermal conductivity of shrimp as well as predicting equations used to estimate these properties are included in this chapter. The electrical properties of shrimp are also discussed and values are presented. The electrical properties are used to estimate the amount of power absorbed during microwave heating.

All knowledge necessary for development of the model has now been presented. A mathematical model that predicts the temperature distribution of a frozen block of shrimp (FSB) will now be presented. The last section of this chapter contains a detailed description of this model.

Fundamentals of modeling heat transfer

Modes of heat transfer

Modeling the heat transfer in food products is difficult. The first step is to become familiar with the fundamental equations that govern heat transfer. Heat transfer is energy in transit due to a temperature difference. There are three modes of heat transfer: conduction, convection, and radiation. Fourier's law defines one-dimensional conduction as follows:

$$q'' = -k \frac{dT}{dx} \tag{3.1}$$

where

q" = heat flow rate by conduction (W/m^2)

k = thermal conductivity of material (W/m-^{o}C)

dT/dx = temperature gradient (^{o}C/m)

The thermal conductivity, k, is a transport property and is a characteristic of the material which depends on temperature.

The next mode of heat transfer, convection, is due to conduction and bulk fluid motion. Convection occurs between a solid surface and a flowing fluid. Newton's law of cooling defines convection heat transfer as follows:

$$q'' = h(T_s - T_8) \tag{3.2}$$

where

q = heat flux normal to surface of solid (W/m^2)

h = heat transfer coefficient (W/m^2-^{o}C)

T_s = temperature at the surface of the solid (^{o}C)

T_8 = temperature of the fluid (^{o}C)

The flow property, h, depends on thermal properties, flow conditions, and geometry.

The last mode of heat transfer, radiation, is defined as energy emitted by matter at a finite temperature (Incropera, 1990). When modeling the heat transfer of food products this mode of heat transfer is insignificant and may be neglected. This is true for most processes that heat foods except for baking.

Heat conduction equation

The purpose of most food heat transfer models is to predict the temperature distribution within the food product during heating. The temperature distribution at any time during heating may be predicted by solving the heat conduction equation. The heat conduction equation is derived by using Fourier's law and applying the conservation of energy to a differential volume inside a solid. The following equation is a statement of the conservation of energy:

$$E_{st} = (E_{in} - E_{out}) + E_g \tag{3.3}$$

where

E_{st} = rate of energy storage at a time = t (J)

$E_{in} - E_{out}$ = net rate of energy entering the control volume by conduction (J)

E_g = rate of heat generation in the control volume at time = t (J)

Fourier's law is used to define the net rate of energy entering the control volume by conduction. The energy generation term, E_g, is defined by the following equation:

$$E_g = g\,dx\,dy\,dz \tag{3.4}$$

where

g = energy generation rate per volume (W/m^3)

The rate of increase of stored energy, E_{st}, is defined by the following equation.

$$E_{st} = ?c_p \frac{\partial T}{\partial t} dxdydz \tag{3.5}$$

where

? = density of material (kg/m^3)

c_p = specific heat of the material (J/kg-C^o)

The heat conduction equation is derived by substituting these conduction rates into the energy equation and then dividing by the differential volume, dxdydz. The temperature, T distribution as a function of position, x, y, and z and time, t can be calculated by solving the heat conduction equation. The complicated equation is difficult to solve but is simply a statement of the conservation of energy (Vick,1997).

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z} \right) + g = ?c_p \frac{\partial T}{\partial t} \tag{3.6}$$

The heat conduction equation presented uses a rectangular coordinate system. The equation has also been derived in cylindrical coordinates and spherical coordinates.

Numerical methods

As previously mentioned, the heat conduction equation can be difficult to solve. This is especially true for situations involving complicated geometry, nonlinear properties, and/or nonlinear boundary conditions. For these situations, numerical methods are employed.

Numerical methods are employed when modeling the heat transfer of food products. The most popular methods used are the finite difference method (FD) and the finite element method (FE). Numerical methods provide approximate solutions to the equation at a finite number of points (Vick, 1997).

Modeling heat transfer of foods during microwave cooking

Over the past several decades, numerous models describing the heat transfer in a food product during microwave cooking have been developed. Ohlsson and Bengtsson (1971) began the work on the modeling of the microwave heating process and used FD to solve the fundamental heat transfer equations. In 1995, Zhou *et al.* developed a three dimensional model using FE to predict temperature in food materials during microwave cooking.

Swami (1982) used FD to model microwave heating of cylindrical agar. Later that decade, a mathematical model was developed by Taoukis *et al.* (1987) to predict thawing time and temperature profiles of microwave thawed meat cylinders. Research by Mallikarjunan and Mittal (1994) used FE to model beef carcass chilling. The model included thermal properties as a function of temperature. The microwave cooking of shrimp was modeled by Malikarjunan *et al.* (1996) as a two dimensional cylindrical slab using FD.

Most of the models mentioned include the microwave energy as the heat generation term in the governing heat transfer equation and use some form of equation 2.5 to estimate the microwave power absorption by the food product. Equation 2.5 is a result of Lambert's law and is frequently used to estimate microwave power absorption of foods.

Properties of Shrimp

Thermal conductivity, specific heat and density

The thermal conductivity, specific heat, and density are all terms found in the heat conduction equation. The values of these properties must be known in order to solve the heat conduction equation and determine the temperature profile of the material during the heat transfer process.

Research by Mirsha in 1997 provided a density prediction model for shrimp and experimental data of the density of shrimp at various temperatures. These experimental data are summarized in Table 3.

Table 3. Density of shrimp at various temperatures

Temperature (°C)	Density (kg/m^3)
30	1065.24
20	1064.54
10	1064.48
-1	1065.05
-2	1034.61
-5	1019.70
-10	1010.95
-15	1006.78
-20	1003.28
-25	1000.61
-30	998.44

Bandyopadhyay *et al.* (1998) collected experimental data on the thermal conductivity and the specific heat of shrimp at various temperatures. They developed a theoretical model to predict the thermal conductivity of shrimp and used an empirical model based on the Schwartzberg's equation proposed by Succar and Hayakawa (1984) to predict the specific heat of shrimp. Summary of the experimental data and the values predicted by the models is shown in Table 4. Both models match well with the experimental results.

The following is the modified Schwartzberg equation:

$$C_{p,app} = C_1 \qquad T = T_o \qquad (3.7)$$

$$C_{p,app} = C_e + D/(T_o - T)^n \qquad T < T_o \qquad (3.8)$$

where

$C_{p,app}$ = apparent specific heat (J/kg-C^o)

C_e = constant whose value is listed in Table 5

C_1 = constant whose value is listed in Table 5

D = constant whose value is listed in Table 5

T = temperature of the shrimp (^{o}C)

T_o = freezing temperature of water (^{o}C)

Table 4. Experimental and predicted data of the thermal conductivity and specific heat of shrimp (Bandyopadhyay *et al.* 1998)

Temperature (^{o}C)	Thermal conductivity (W/m^{o}C)		Specific heat (kJ/kg^{o}C)	
	Experimental	Predicted by Theoretical model	Experimental	Predicted by empirical model
30	0.51	0.52	3.63	3.82
20	0.49	0.52	3.63	3.82
10	0.49	0.52	3.63	3.82
-1	0.50	0.52	203.18	207.95
-2	0.96	1.12	53.42	56.30
-5	1.27	1.48	9.9	10.11
-10	1.41	1.59	3.88	3.93
-15	1.49	1.64	2.80	2.82
-20	1.55	1.67	2.38	2.41
-25	1.58	1.68	2.20	2.27
-30	1.60	1.69	2.10	2.15

The values of the constants used by Bandyopadhyay *et al.* (1998) to predict the apparent specific heat of shrimp are listed in Table 5. Succar used these constants in 1989 to predict the specific heat of lean fish meat. Table 4 and Figure 2 clearly show that the specific heat varies substantially with temperature. Figure 2 shows that the specific heat increases dramatically near –1 ^oC, which is the freezing temperature of shrimp. This is due to the fact that a phase change is occurring within the shrimp as frozen water within the shrimp changes state to water.

Table 5. Values of constants used in equation 3.7 and 3.8

	m.c. (%)	C_e (kcal/kg-C^o)	n (-)	D (kcal-C^{on-1})/kg	C_1 (kcal/kg-C^o)
Fish meat lean	82	0.448	1.999	49.3	0.916
Fish meat lean	75	0.282	1.628	41.6	0.874

Table 5 clearly shows that the values of the constants are dependent on moisture content (m.c.). The shrimp samples used by Bandyopadhyay had a moisture content of 80.75%. He used simple interpolation to calculate the appropriate values of the constants used in equations 3.7 and 3.8.

As previously mentioned, Bandyopadhyay *et al.* (1998) suggested a model for predicting the thermal conductivity. They used equation 3.9 and the predicted values of thermal conductivity found by using equation 3.9 are listed in Table 4. The temperature dependence of the thermal conductivity term is shown graphically in Figure 3.

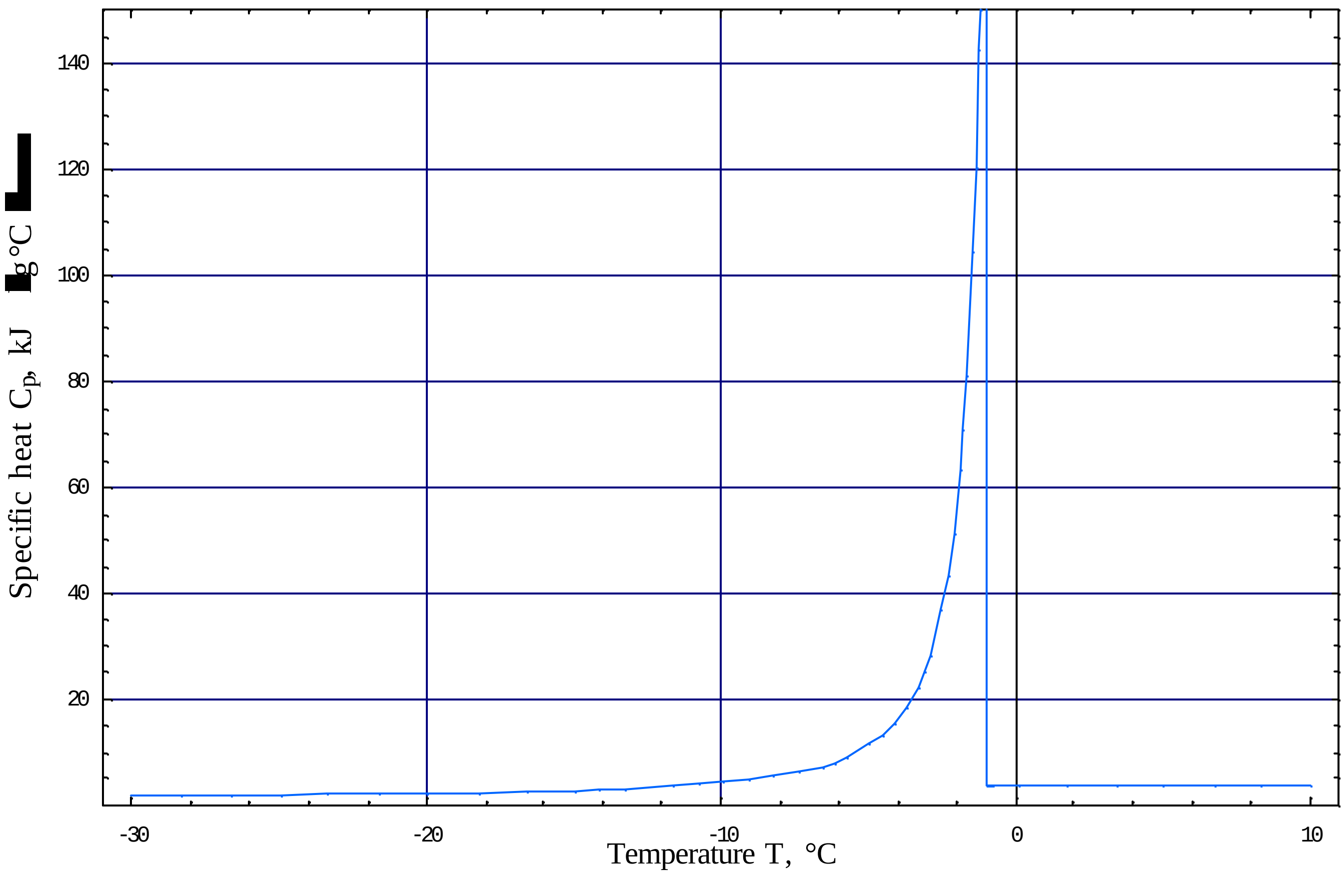


Figure 2. Specific Heat of Shrimp

Adopted from Bandyopadhyay *et al.* (1998)

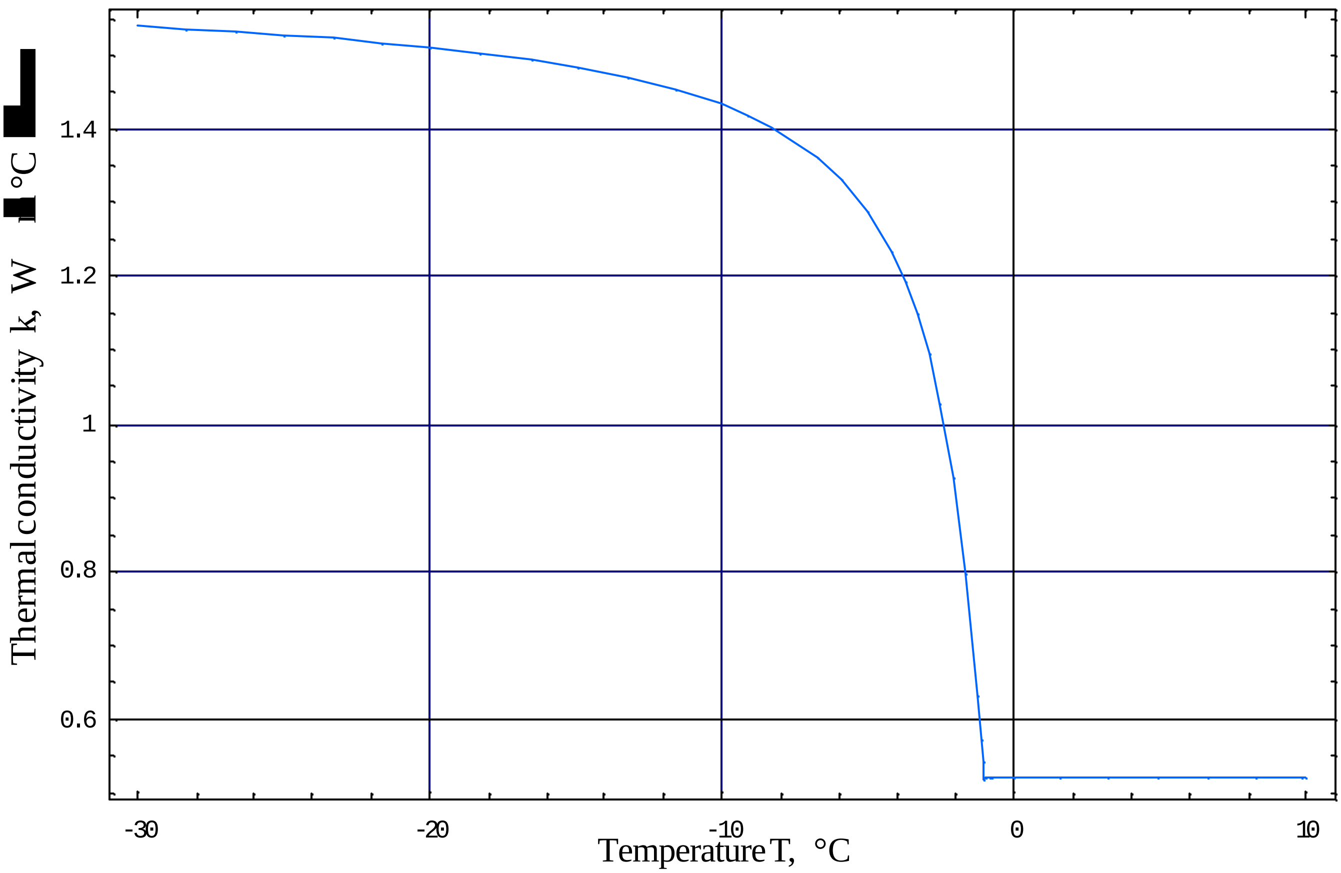


Figure 3. Thermal conductivity of shrimp

Adopted from Bandyopadhyay *et al.* (1998)

$$k = -1.35 + 0.271/(T_0 - T) + 4.645x_w + 0.5561/(T_0 - T)^2 - 2.39x_w/(T_0 - T) - 1.21x_w^2 \tag{3.9}$$

where

k = thermal conductivity of shrimp (W/m-^oC)

T = temperature of shrimp (^oC)

T_o = freezing temperature of water (^oC)

x_w = moisture content of shrimp

Dielectric properties

A model was developed by Mallikarjunan *et al.* (1999) to predict the dielectric properties of shrimp. The model equations depend on the temperature and moisture content of the shrimps and the frequency of the microwave oven.

$$e' = c_1 + c_2T \tag{3.10}$$

$$e' = (c_1 + c_2T)\left(\frac{T_o}{T}\right)^{aa} \tag{3.11}$$

$$e'' = c_3 + c_4T + c_5T^2 \tag{3.12}$$

$$e'' = (c_3 + c_4T + c_5T^2)\left(\frac{T_o}{T}\right)^{bb} \tag{3.13}$$

where

e' = dielectric constant

e'' = dielectric loss factor

T = temperature of the shrimp (^oC)

T_o = freezing temperature of shrimp (^oC)

C_1 = empirical parameter whose value is in Table 6

C_2 = empirical parameter whose value is in Table 6

aa = empirical parameter whose value is in Table 6

C_3 = empirical parameter whose value is in Table 6

C_4 = empirical parameter whose value is in Table 6

C_5 = empirical parameter whose value is in Table 6

bb = empirical parameter whose value is in Table 6

Table 6. Value of constants in equations 3.10, 3.11, 3.12, and 3.13

Frequency (MHz)	C_1	C_2	aa	C_3	C_4	C_5	bb
2450	58.82	-0.067	1.18	18.52	-0.1407	0.0012	1.55
915	64.54	-0.102	1.23	21.13	0.0055	0.0011	1.49

The values of the constants in equations 3.10, 3.11, 3.12, and 3.13 depend on the frequency of the microwave energy source. The freezing temperature of shrimp, T_o, is assumed to be –1 ^oC. If the temperature of the shrimp is greater than T_o, then the dielectric constant is calculated using equation 3.10 and the dielectric loss factor is calculated using equation 3.12. If the temperature of the shrimp is less than T_o, then the dielectric constant is calculated using equation 3.11 and the dielectric loss factor is calculated using equation 3.13.

The temperature dependence of the dielectric constant and the dielectric loss factor is shown graphically by Figure 4 and Figure 5. Chapter 2: *Microwave thawing* discussed the fact that the electrical properties of water are much greater than that of ice. This fact is the reason why water heats up much more rapidly when exposed to microwaves than ice. Figures 4 and 5 clearly show that the electrical properties of shrimp increase dramatically as the freezing point of shrimp is approached. This is logical since at this temperature ice within the shrimp is turning to water. The difference in the electrical properties of shrimp above and below freezing point explains why thawed portions of a FSB will heat much more rapidly than frozen portions.

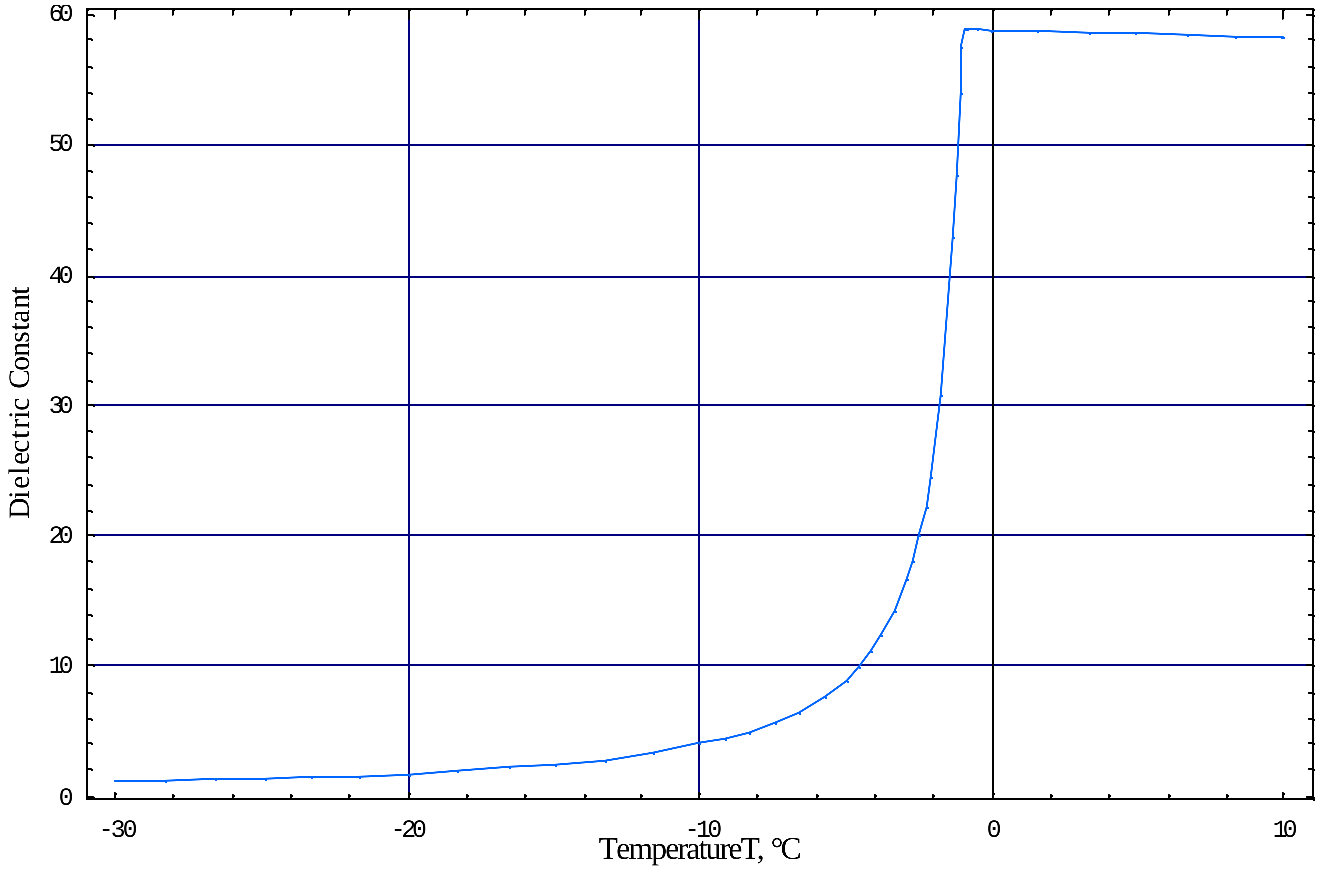


Figure 4. Dielectric constant of shrimp

Adopted from Mallikarjunan *et al*. (1999)

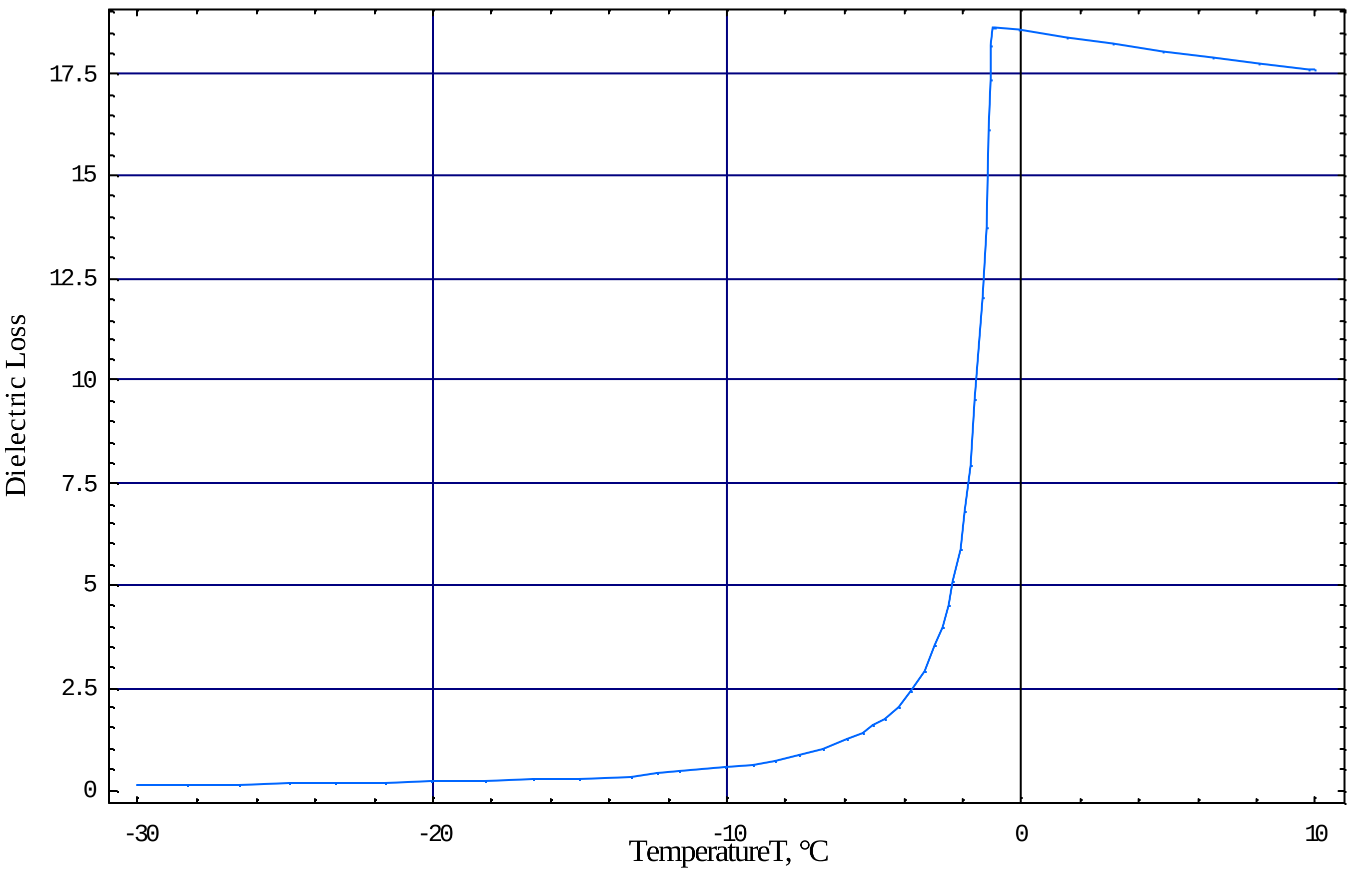


Figure 5. Dielectric loss of shrimp

Adopted from Mallikarjunan *et al*. (1999)

The Mathematical Model

Introduction

A two dimensional heat transfer model was developed to predict the temperature distribution of a frozen block of shrimp (FSB) during microwave heating. The finite difference method was used to solve the fundamental heat transfer equations and obtain the difference equations in the x-y plane. The difference equations were solved using the commercial software MATHEMATICA 3.0.1. Included in this section is a detailed description of the model. An electronic or hard copy of the model coding is available through Dr. C Gene Haugh, Virginia Tech or Matthew Schaefer, Penn State.

Assumptions

A schematic of the circumstances of which this model is intended to duplicate is shown in Figure 6. Figure 6 shows the experimental testing system, a FSB exposed to a microwave field with heat convection heat transfer boundary conditions at all four boundaries, $x = 0$, $x = L$, $y = 0$, and $y = H$. Also shown in Figure 6 are the microwaves that cause heat generation within the FSB. The model assumes the heat generation term varies only in the y-direction. The heat transfer in the z direction of the FSB is neglected. The rectangular coordinate system used by the model is shown in Figure 7. The bottom left corner of the rectangular FSB is taken as the origin, $x = 0$ and $y = 0$.

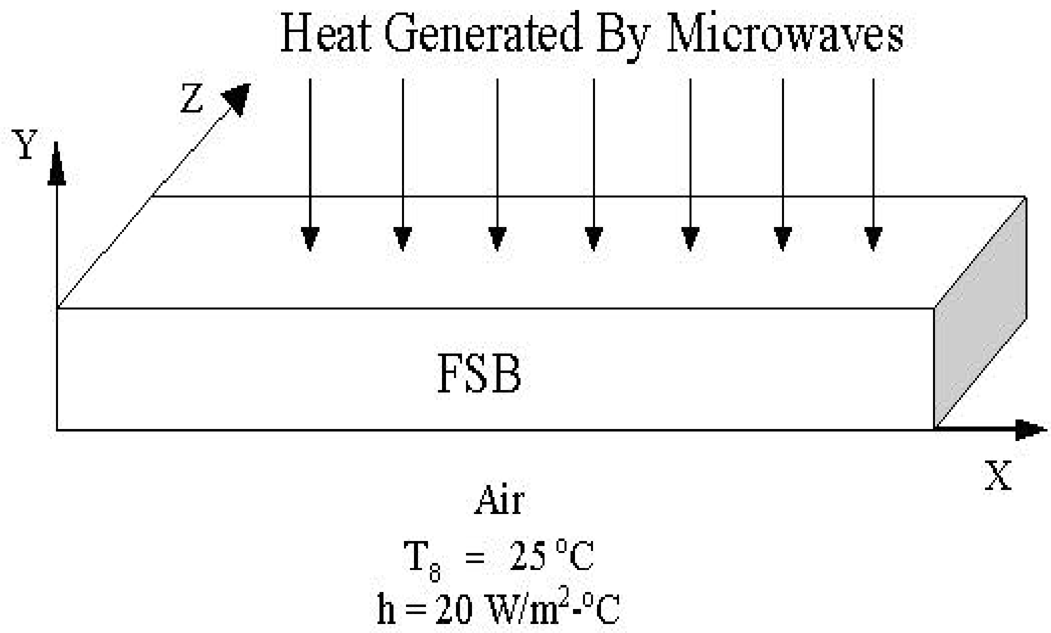


Figure 6. Schematic of a FSB during microwave tempering

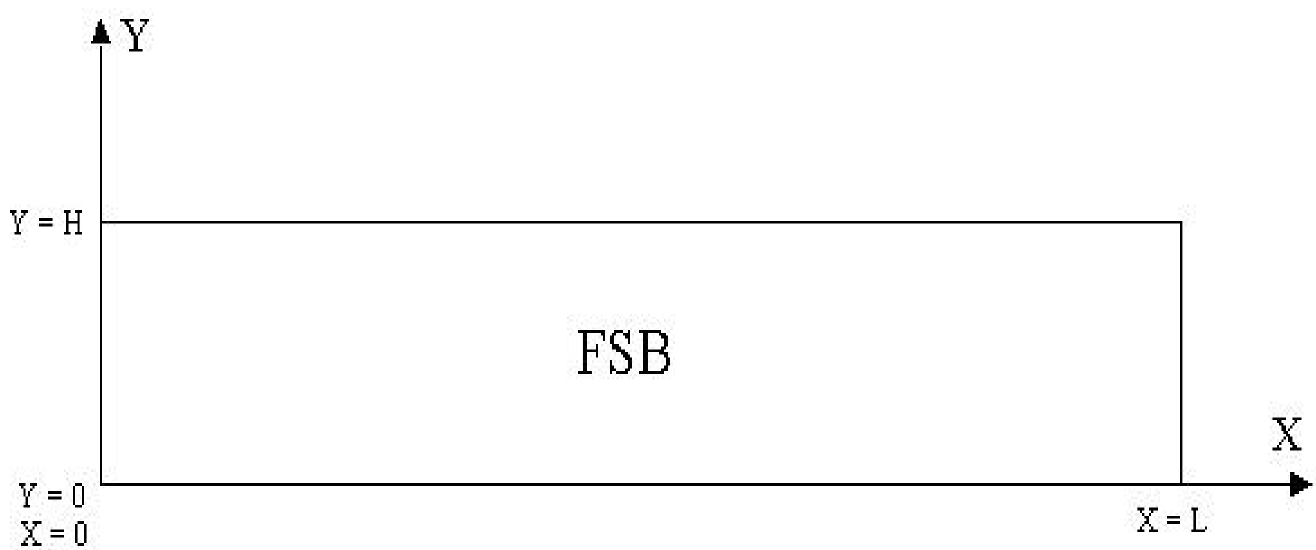


Figure 7. Coordinate system used by the mathematical model

The FSB is divided into a specified number of rectangular control volumes. The formulation of the control volumes is described in more detail later. For now it is important to understand that each control volume is distinguished with two integer numbers m,n. The integer m identifies the location of the control volume in the x-direction and the integer n identifies the location of the control volume in the y-direction.

The FSB is a combination of frozen shrimp and water; however it is assumed that the properties of the FSB are that of shrimp. As previously mentioned, Lambert's law is frequently used to estimate microwave power absorption by food. As previously mentioned, it is assumed that the microwave power absorption varies only in the y-direction. The model uses the following equation to calculate power absorption:

$$Sc_{m,n,p} = Q_o\left(\mathrm{Exp}\left[\frac{-(H - y_n)}{d_p}\right]\right) \tag{3.14}$$

where

d_p	= power penetration depth calculated by using equation 2.6 (m)
$Sc_{m,n,p}$	= heat generation or power absorbed due to microwave heating at location "m,n" and time p (W/m^3)
H	= height of the FSB (m)
y_n	= location in y-direction within FSB (m)
Q_o	= heat generation at the surface of the material (W/m^3)

The heat generation term is a function of penetration depth and therefore the amount of power absorbed by the FSB will vary in the y-direction. For example, the heat generation at the surface of the FSB will be significantly different than the heat generation at the midway point of the height of the FSB. The penetration depth is a function of the dielectric properties, which are a function of temperature; therefore, the penetration depth and thus the heat generation are also a function of temperature. Chapter 2: *Microwave thawing* explains that the penetration depth of microwave energy decreases as the temperature of the product increases. This makes it almost impossible to keep the surface temperature of the product low and thaw the core of the product. The decrease of penetration depth of a FSB as temperature increases is shown graphically by Figure 8. Figure 8 shows that the penetration of a FSB varies from 35.1 cm at –30 ^{o}C to 1.7 cm at –1 ^{o}C. As previously mentioned, the heat generation term, equation 3.14, represents the microwave power absorbed by the FSB during microwave tempering and is a function of temperature. Since the penetration depth varies significantly with temperature, it follows that the power absorbed will also vary significantly with temperature.

The temperature dependence of the heat generation or power absorbed is shown in Figure 9 and Figure 10. Figure 9 shows that the power absorbed near the surface of a FSB varies from around 110 kW/m^3 at –30 ^{o}C to 105 kW/m^3 at 0 ^{o}C. Figure 10 shows that the power absorbed at the core of a FSB varies from around 103 kW/m^3 at –30 ^{o}C to 24 kW/m^3 at 0 ^{o}C. The figures clearly show that the power absorbed by the FSB changes dramatically with temperature. As previously mentioned, the power absorbed varies significantly in the y-direction. This difference is shown in Figure 11, which is a plot of the graphs in Figure 9 and Figure 10. The powers absorbed at the surface and at the core are comparable at very low temperatures. At –30 ^{o}C, the power absorbed near the surface is 110 kW/m^3 and the power absorbed at the core is 103 kW/m^3. The difference between the power absorbed at the surface and at the core increases as the temperature approaches the thawing temperature of the FSB, -1 ^{o}C, with the largest difference occurring near the thawing temperature. At –20 ^{0}C, the power absorbed near the surface is still around 110 kW/m^{3} while the power absorbed at the core decreased to 100 kW/m^{3}. At –10 ^{0}C, the power absorbed near the surface is once again around 110 kW/m^{3} while the power absorbed at the core decreased to 92 kW/m^{3}. At –1 ^{o}C, the power absorbed near the surface decreased slightly to around 105 kW/m^{3} while the power absorbed at the core decreased to 23 kW/m^{3}.

The model developed predicts temperature profiles during microwave thawing or microwave tempering of a FSB. Obviously phase change, more specifically ice turning to water, will occur during the microwave thawing or tempering process. The energy required for this phase change is accounted for using a temperature dependent specific heat term. Unless the boundary conditions are changed by the user, the model assumes a convection boundary type exists at all four boundaries with an ambient temperature of 25 ^{o}C and a convection heat transfer coefficient value of 20 W/(m^{2}-C^{o}) (see Figure 6).

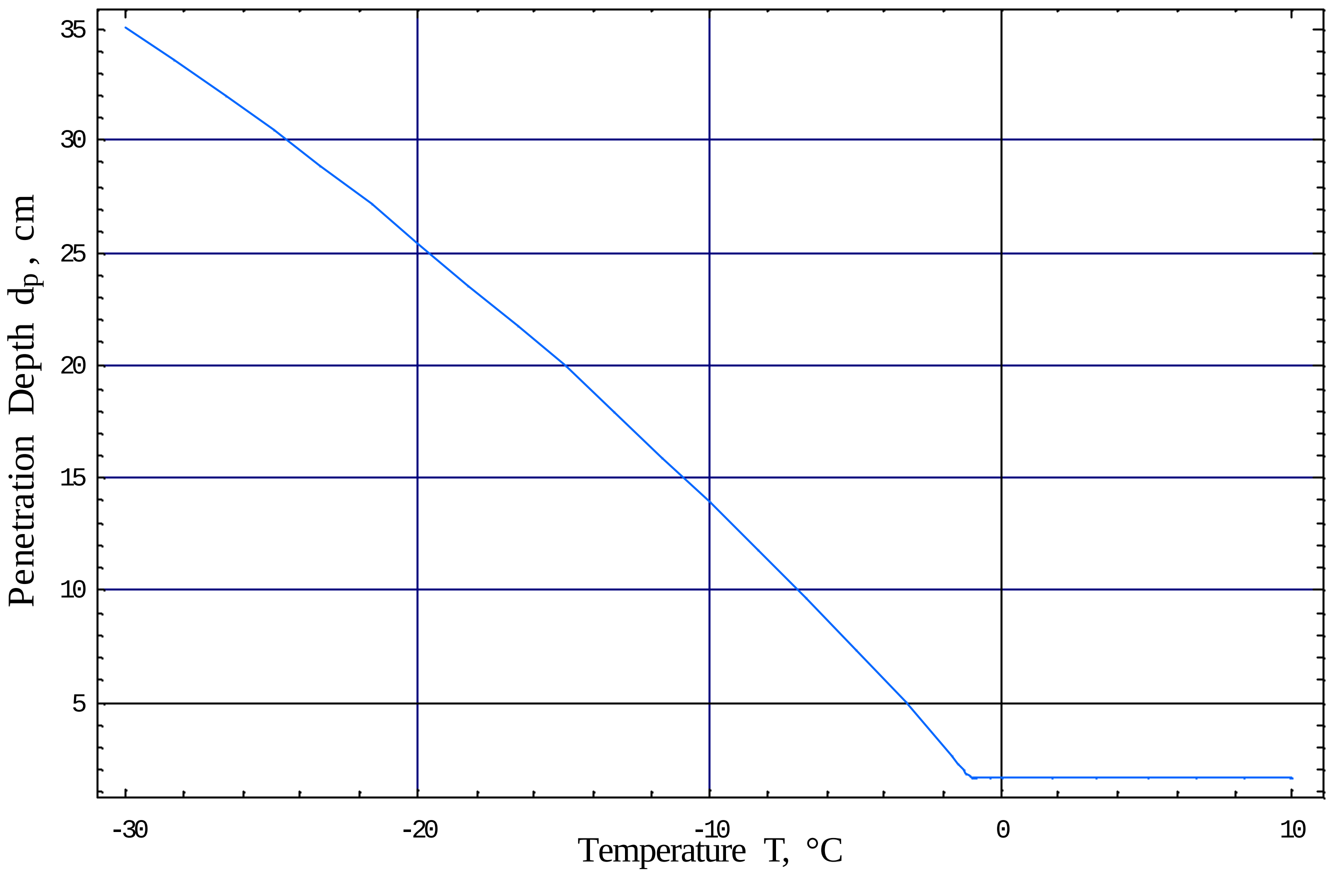


Figure 8. Penetration depth of a frozen block of shrimp (FSB)

Adopted from Mallikarjunan *et al*. (1999)

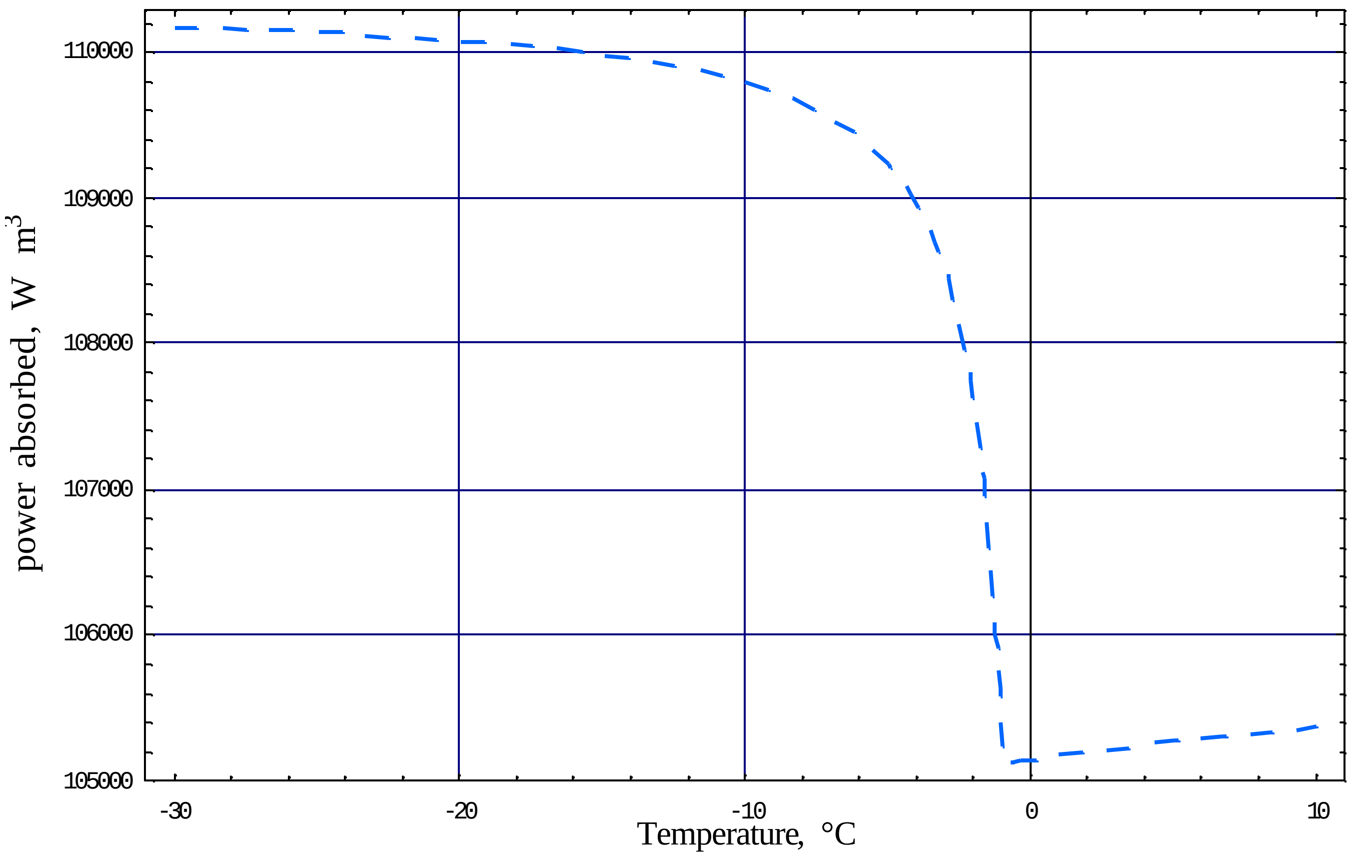


Figure 9. Power absorbed by a FSB just below the surface

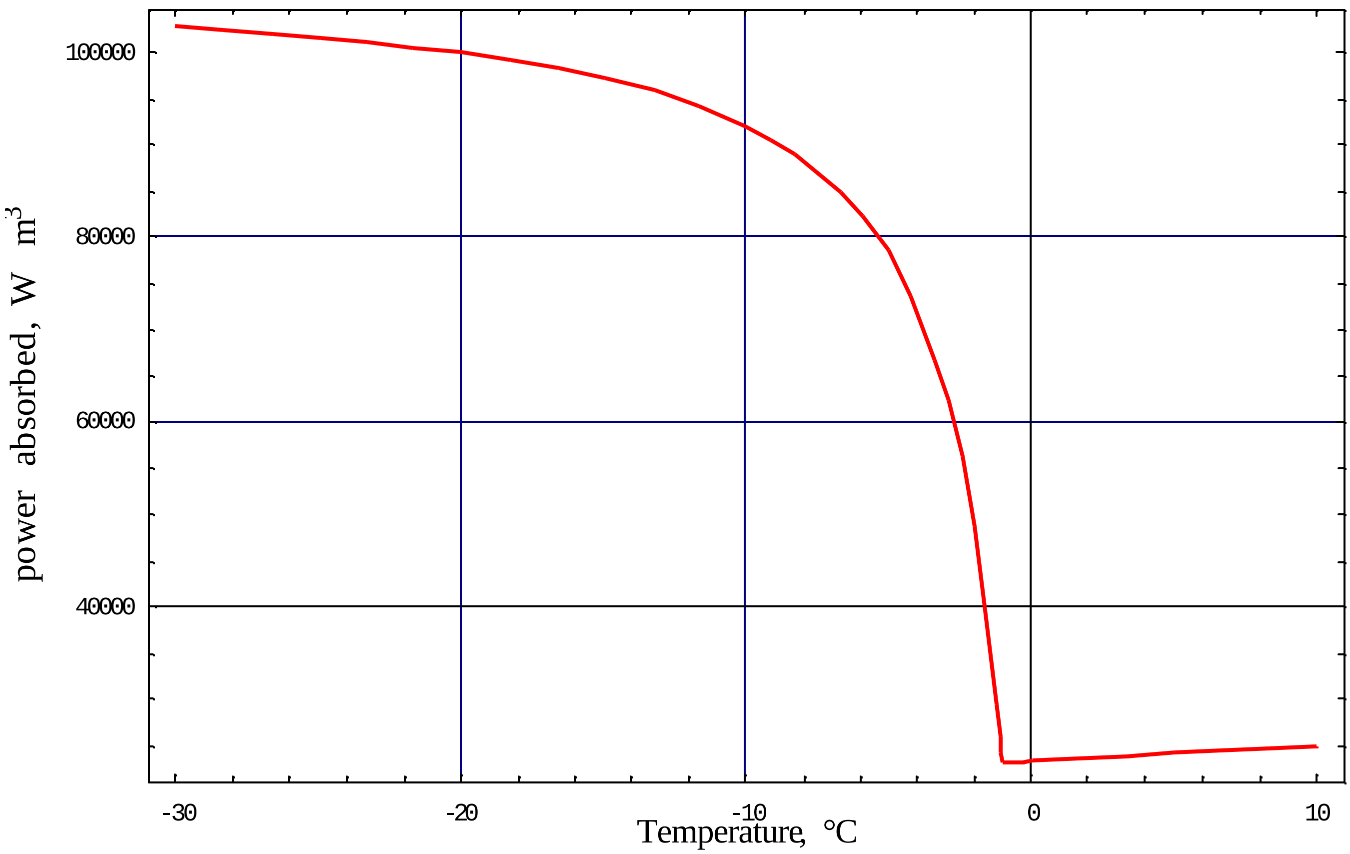


Figure 10. Power absorbed by a FSB at the core (y = H/2)

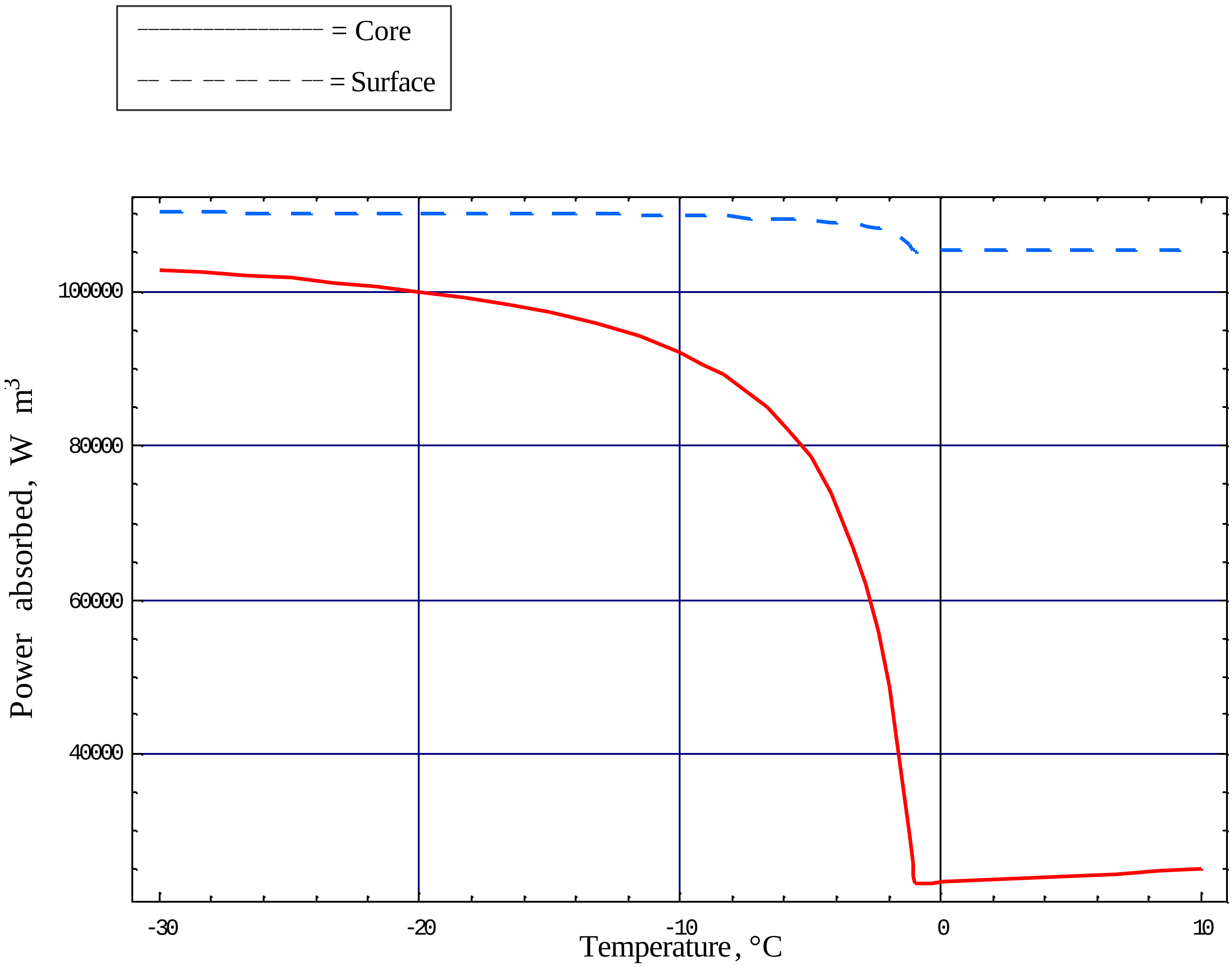


Figure 11. Power absorbed by a FSB at the surface and at the core

Finite difference method

The following section describes and derives the fundamental difference equations used by this model. The model considers two dimensional heat transfer with prescribed volumetric heat sources and boundary conditions. The following form of the heat conduction equation is used:

$$?C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K \frac{\partial T}{\partial y}\right) + S_c(x, y, t) - S_p(x, y, t)T \qquad (3.15)$$

The source term is divided into a portion independent of temperature and a portion proportional to temperature. The physical domain is broken into control volumes (CV's) for numerical analysis. Creating the CV's is known as control volume discretization and is shown in Figure 12. Figure 12 is constructed by first specifying the CV's and then placing a grid point in the center of each CV. A CV of zero thickness is then placed around each boundary. A typical control volume "m,n" from Figure 12 is shown in detail in Figure 13. The following is the notation used in Figures 12 and 13.

Notation

p	integer indicator of time
pp	total number of time steps
Δt_p	time step length (s)
m	integer indicator in x-direction for a typical CV
mm	total number of CV's in the x-direction

? x_m x-direction length of typical CV "m,n" (m)

x_m x-location of the center of typical CV "m,n" (m)

n integer indicator in y-direction for a typical CV

nn total number of CV's in the y-direction

? y_n y-direction length of typical CV "m,n" (m)

y_n y-location of the center of typical CV "m,n" (m)

E designates the east side face of the CV

W designates the west side face of the CV

N designates the north side face of the CV

S designates the south side face of the CV

$T_{m,n}$ temperature at the center of CV "m,n" (^oC)

? x_E distance between the center of CV "m,n" and its east neighbor "m+1,n" (m)

? x_W distance between the center of CV "m,n" and its west neighbor "m-1,n" (m)

? y_N distance between the center of CV "m,n" and its north neighbor "m,n+1" (m)

? y_S distance between the center of CV "m,n" and its south neighbor "m,n-1" (m)

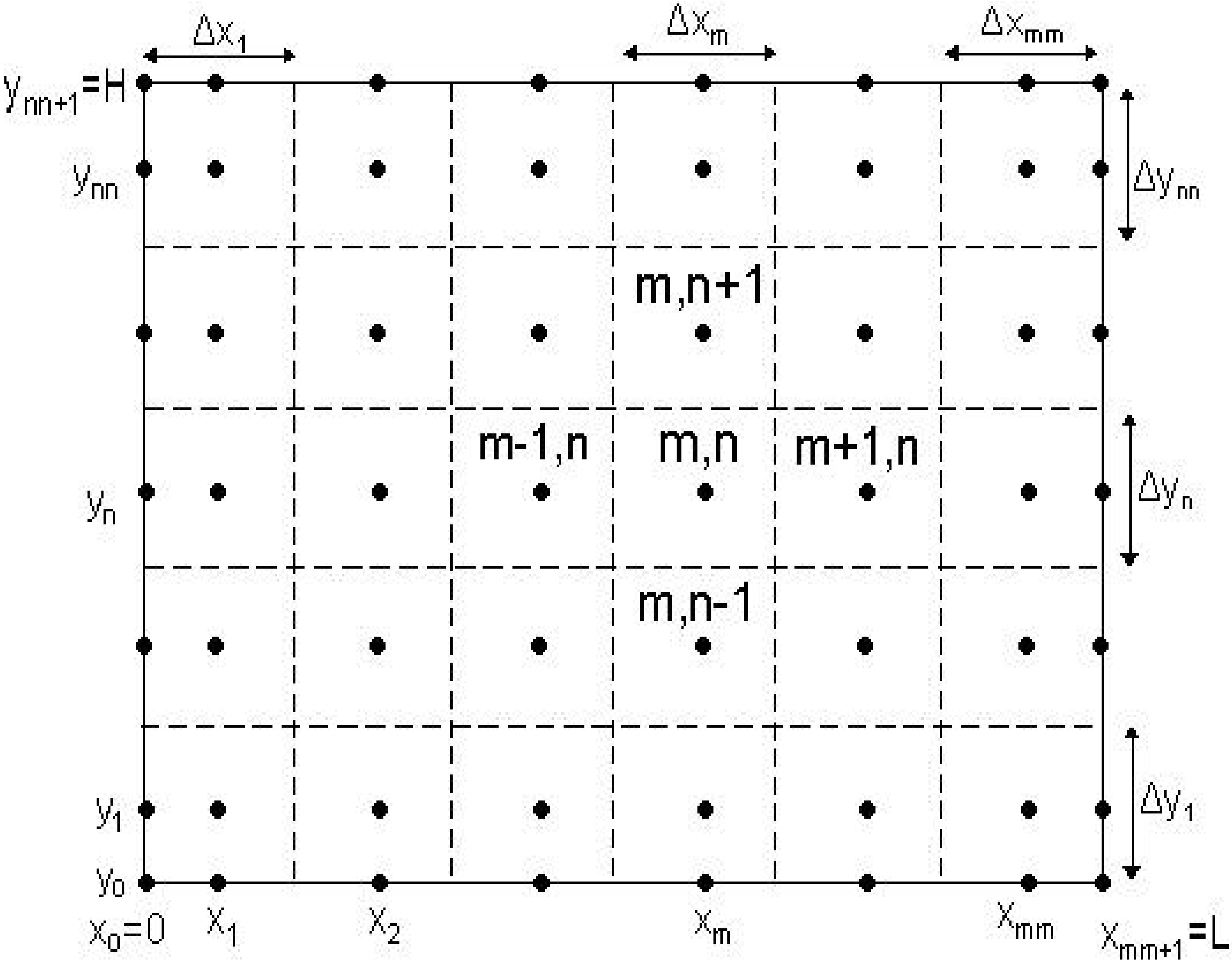


Figure 12. Control volume discretization (Vick, 1997)

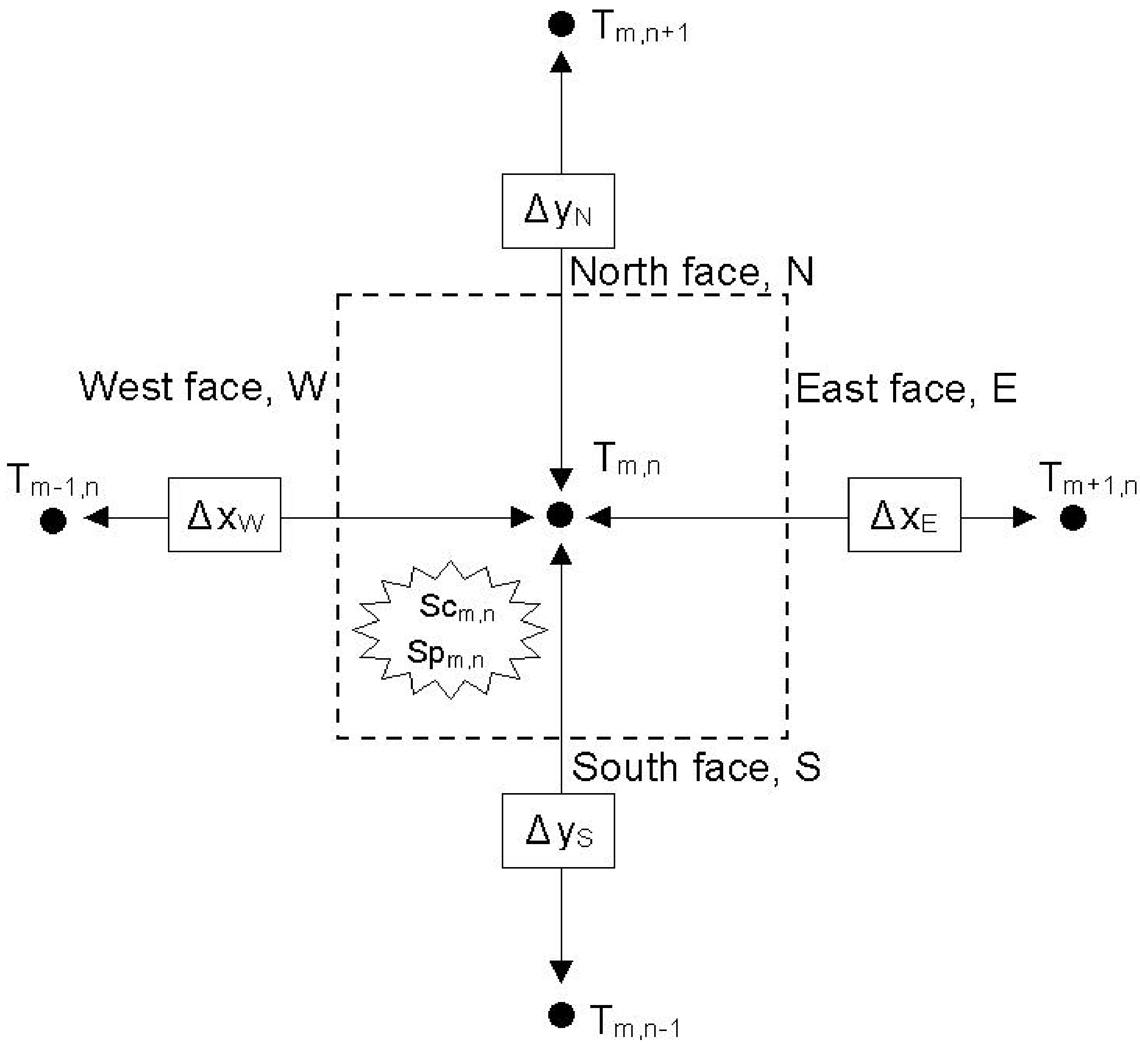


Figure 13. Typical control volume m,n (Vick, 1997)

The heat conduction equation is integrated over a typical control volume and time.

$$\int_{t_{p-1}}^{t_p}\int_S^N\int_W^E\left[\frac{\partial}{\partial x}\left(k\,\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial x}\left(k\,\frac{\partial T}{\partial x}\right)+S_c(x,\ y,\ t)-S_p(x,\ y,\ t)T-?C_p\,\frac{\partial T}{\partial t}\right]dxdydt\ =\ 0$$

Details of the integration are presented in Appendix A. After performing the integration, the solution is presented in the following form:

$$a_{m,n}T^p_{m,n}-aW_{m,n}T^p_{m-1,n}-aE_{m,n}T^p_{m+1,n}-aS_{m,n}T^p_{m,n-1}-aN_{m,n}T^p_{m,n+1}\ =\ b_{m,n} \tag{3.17}$$

where

$$aW_{m,n}\ =\ ?\,y_n\,\frac{k_W}{?\,x_W}\ =\ ?\,y_n\left(\frac{2k_{m-1,n}k_{m,n}}{?\,x_{m-1}k_{m,n}+?\,x_mk_{m-1,n}}\right)$$

$$aE_{m,n}\ =\ ?\,y_n\,\frac{k_E}{?\,x_E}\ =\ ?\,y_n\left(\frac{2k_{m+1,n}k_{m,n}}{?\,x_{m+1}k_{m,n}+?\,x_mk_{m+1,n}}\right)$$

$$aS_{m,n}\ =\ ?\,x_m\,\frac{k_S}{?\,y_S}\ =\ ?\,x_m\left(\frac{2k_{m,n-1}k_{m,n}}{?\,y_{n-1}k_{m,n}+?\,y_nk_{m,n-1}}\right)$$

$$aN_{m,n}\ =\ ?\,x_m\,\frac{k_n}{?\,y_n}\ =\ ?\,x_m\left(\frac{2k_{m,n+1}k_{m,n}}{?\,y_nk_{m,n=1}+?\,y_{n+1}k_{m,n}}\right)$$

$$aO_{m,n}\ =\ (?C_p)_{m,n}\,?\,x_m?\,y_n\,\frac{1}{?\,t_p}$$

$$a_{m,n}\ =\ aO_{m,n}+aW_{m,n}+aE_{m,n}+aS_{m,n}+aN_{m,n}+Sp^p_{m,n}?\,x_m?\,y_n$$

$$b_{m,n}\ =\ aO_{m,n}T^{p-1}_{m,n}+Sc^p_{m,n}?\,x_m?\,y_n$$

Boundary conditions

For this two-dimensional transient heat conduction model there are four boundary conditions, one at $x = x_o = 0$, one at $y = y_o = 0$, one at $x = x_{mm+1} = L$, and one at $y = y_{nn+1} = H$. The control volume discretization method used places a grid point on the boundary surrounded by a volume of zero thickness. This allows the boundary conditions to be used directly. At each boundary all but one neighbor coefficient in equation 3.17 is zero. The model can handle three types of boundary conditions, a constant heat flux, a constant temperature, or convection. As previously mentioned, convection heat transfer is assumed to be the boundary condition at each boundary. The values of the coefficients depend on the type of boundary condition. The user may change the boundary condition type; however, if the user chooses to change the boundary condition type the user must also enter the value of the heat flux or constant temperature. The notation used in Tables 7, 8, 9 and 10 is described in Appendix B.

Table 7. Coefficient values at x = 0 all coefficients zero except $aE_{0,n}$

Boundary Inputs	$aE_{0,n}$	$a_{0,n}$	$B_{0,n}$
T∞x0n , hx0n	$k^{P}_{1,n}/(\Delta x_1/2)$	$aE_{0,n}$ + hx0n	Hx0n × T∞x0n

Table 8. Coefficient values at x = L all coefficients zero except $aW_{mm+1,n}$

Boundary Inputs	$aW_{mm+1,n}$	$a_{mm+1,n}$	$b_{mm+1,n}$
T∞xLn , hxLn	$k^{P}_{mm,n}/(\Delta x_{mm}/2)$	$aW_{mm+1,n}$ + hxLn	hxLn × T∞xLn

Table 9. Coefficient values at y = 0 all coefficients zero except at $aN_{m,0}$

Boundary Inputs	$aN_{m,0}$	$a_{m,0}$	$B_{mm+1,n}$
T∞y0m , hy0m	$k^{p}_{m,1}/(\Delta y_1/2)$	$aN_{m,0}$ + hy0m	Hy0m × T∞y0m

Table 10. Coefficient values at y = 0 all coefficients zero except at $aS_{m,nn+1}$

Boundary Inputs	$aS_{m,nn+1}$	$a_{m,nn+1}$	$B_{mm+1,n}$
T∞yHm ,hyHm	$k^{p}_{m,nn}/(\Delta y_{nn}/2)$	$aS_{m,nn+1}$ + hyHm	HyHm × T∞yHm

A large number of simultaneous equations now exist and solving them can be difficult. Vick (1997) suggests the use of the line-by-line method. This method is a combination of the direct tridiagonal algorithm used to solve one-dimensional problems and the Gauss-Siedel method.

Model description

The following section is a detailed description of the two-dimensional heat transfer model used to predict the temperature profile in FSB during microwave heating.

User inputs

The model requires the user to input several values. The user enters the height, length and width of the frozen shrimp block (FSB) and also the initial temperature of the block. The freezing temperature of shrimp, Tshrimp, is assumed to be –1 ^{o}C. This value is used in the equations that are used to calculate the dielectric properties of the FSB. The user may change the value; however, it is not recommended.

The user next enters the total microwave cooking time, MCT, in seconds and chooses the time step, ?t. It is recommended that the time step be no greater than thirty seconds and no less than five seconds. The model was run using a thirty second time step, a ten second time step, a five second time step and a one second time step and the calculated temperature profiles were compared. The temperature profiles calculated when using a thirty second time step varied on average by only 0.04 ^{o}C from the temperature profiles calculated when using a one second time step; however, the computation time varied significantly. The computation time for a thirty seconds time step was 26 seconds while the computation time for a one second time step was 1051 seconds. Summary of the results used to determine the recommended time step length is listed in Table 11.

Table 11. Data used to determine appropriate time step length

Computation Time (s)	# of x CV's	# of y CV's	? t	Average Difference (^{o}C)
26	5	3	30	0.04
73	5	3	10	0.01
151	5	3	5	0.01
1051	5	3	1	--

After the time step is selected, the user enters the power level of the microwave oven. The model calculates the heat generation at the surface of the material by dividing this power level by the volume of the FSB. The user enters either 915 MHz or 2450 MHz as the operating frequency of the microwave oven. The model then chooses the appropriate constants for equations 3.10, 3.11, 3.12, and 3.13, which are used later to calculate the dielectric properties of the FSB. Finally, the moisture content of the FSB is entered. The moisture content entered must be less than or equal to 0.85 and greater than or equal to 0.75. If the user does not enter a value for the moisture content then the model assumes the moisture content is equal to 0.80.

Formulation of control volumes

Experiments were conducted that collected temperature data of a FSB during microwave tempering. Four temperature probes were placed at specific locations and the location of these probes is described in Chapter 4: *Sample Preparation*. All four probes are positioned to a depth of 2.54 cm (1 in.) and at the midway point of the width, 9.525 cm (3.75 in.). The positioning of the four probes varies only in the x-direction. One end of the FSB is taken as x = 0. Probe #1 is located at x = 4.445 cm (1.75 in.), probe #2 at x = 10.16 cm (4 in.), probe #3 at 16.51 cm (6.5 in.), and probe #4 at 22.225 cm (8.75 in.). The model constructs an x-grid and y-grid when formulating the control volumes. The x-grid and y-grid are constructed and the model is able to predict the temperature at the center of each control volume. The center of four of these control volumes is the location where a temperature probes was placed. This allows for a comparison between experimental data and temperature values predicted by the model. A recommended number of CV's in the x-grid and y-grid were determined in a similar manner as the recommended time step was determined. The results found that the y-grid should have at least five CV's and the x-grid at least ten CV's. Increasing the number of CV's in either direction from these recommended values does not significantly change the temperature profiles calculated by the model. Unless the user changes the grid size, the model constructs and uses a x-grid with ten CV's and a y-grid with five CV's.

Material properties

Since several of the material properties are dependent on temperature, the model calculates these properties at each time step by using the values found from at previous time step. The temperature dependent properties are thermal conductivity, specific heat, dielectric constant, and dielectric loss factor.

Microwave properties

The model contains a function, TempAverage, which calculates the average temperature of the FSB at each time step. The dielectric constant is calculated at each time step by using the function DielectricConstant, which uses either equation 3.10 or 3.11 to calculate the dielectric constant. The dielectric loss factor is also calculated at each time step by using the function DielectricLossFactor, which uses either equation 3.12 or 3.13. The DielectricConstant and DielectricLossFactor functions use the calculated average temperature as the value of the temperature of the shrimp. The dielectric properties vary with temperature and thus time; however, the model assumes that the dielectric properties do not vary with position. The penetration depth of the FSB is a function of the dielectric properties and therefore time. The model calculates the penetration depth at each time step by using the function PenetrationDepth, which uses equation 2.6.

Thermal conductivity

The thermal conductivity is calculated at each time step by using the function ThermalConductivity, which uses equation 3.9. The equation clearly shows that the thermal conductivity is dependent on temperature, which is dependent on position and time; therefore, the thermal conductivity is individually calculated not only at each time step but also at every grid point.

Specific heat

The specific heat is also dependent on temperature and thus position and time. The specific heat is calculated at each time step and at each location by using the function SpecificHeat, which is uses either equation 3.7 or 3.8. The model considers the fact that the constants in equations 3.7 and 3.8 depend on moisture content and calculates the appropriate constants to be used in the equations.

Density

The density of the shrimp is assumed by the model to be constant and equal to 1000 kg/m^3. The function DensitySpecificHeat is the product of the density and specific heat. The function calculates this product at each time step and location.

Boundary conditions and formulation of time steps

The next step of the model is to discretize time. The user has already entered the time step and total time. After these parameters were entered, the model calculated the total number of time steps, pmax. All information needed for the model to discretize time has been provided.

The model specifies the type of boundary condition, constant heat flux, constant temperature or convection at each boundary. A constant heat flux boundary is referred to as boundary condition type 1, a constant temperature is referred to as boundary condition type 2, and a convection boundary condition is referred to as boundary condition of type 3. By stating BCx0 = 3 this explains that the boundary condition at x = 0 is governed by convection. This notation is used at all four boundaries, i.e. BcyH = 1 explains that the boundary condition at y = H is governed by a constant temperature. The model assumes a type three boundary condition exists at all four boundaries. Furthermore, the value of the convection heat transfer coefficient at each boundary is assumed to be equal to 25 $W/(m^2\text{-}C^o)$ and the ambient temperature at each boundary is assumed to be equal to 23 ^oC. The model assumes these values are constant and do not vary with position or time.

The model is flexible and if the user desires he/she may change the value of the convection heat transfer coefficient or ambient temperature or even vary the value of the convection heat transfer coefficient or ambient temperature with position and/or time. The user may also enter a different type of boundary condition at any boundary. If the user decides to apply a different type of boundary condition then he/she must also enter the appropriate boundary condition inputs. The boundary condition inputs include the value of heat flux for boundary condition type 1, the value of constant temperature for boundary condition type 2, and of course the value of the heat transfer coefficient and the ambient temperature for boundary condition type 3.

Heat generation due to microwaves

The heat generation due to microwaves is dependent on position and the penetration depth. The penetration depth depends on the dielectric properties, which are dependent on temperature. Thus the heat generation is a function of position and time. The heat generation due to microwaves is calculated at each time step and position by using the function HeatGeneration, which uses equation 3.14. The source term, $Sp_{m,n,p}$ is assumed by this model to be equal to zero.

Calculate the coefficients in the finite difference equation

The model calculates the coefficients in equation 3.17 at each time step. The functions IteriorCoefficients1, InteriorCoefficients2, InteriorCoefficients3 and InteriorCoefficients4 are used by the model to calculate the values of $aW_{m,n}$, $aE_{m,n}$, $aS_{m,n}$ and $aN_{m,n}$. The value of these coefficients depend on the thermal conductivity, which may vary with position and time; for this reason, the model calculates the coefficients at each time step and each location except for the boundaries. The zero coefficients at the boundary are set equal to zero. The function InteriorCoefficients is used by the model to calculate the values of $aO_{m,n}$, $a_{m,n}$, and $b_{m,n}$. The value of these coefficients may also vary with position and time so the model calculates the coefficients at each time step and location except for the boundaries.

The coefficients at the boundaries are calculated by the functions CoefficientsAtx0, CoefficientsAty0, CoefficientsAtxL and CoefficientsAtyH. The function CoefficientsAtx0 calculates the non-zero coefficients $aE_{0,n}$, $a_{0,n}$ and $b_{0,n}$. The function CoefficientsAtxL calculates the non-zero coefficients $aW_{mm+1,n}$, $a_{mm+1,n}$ and $b_{mm+1,n}$. The function CoefficientsAty0 calculates the non-zero coefficients $aE_{m,0}$, $a_{m,0}$ and $b_{m,0}$. The function CoefficientsAtyH calculates the non-zero coefficients $aE_{m,nn+1}$, $a_{m,nn+1}$ and $b_{m,nn+1}$.

Solving finite difference equations

The function IterateForTemperatures calculates the temperature profiles by using the line-by-line method suggested by Vick (1997). The function works in the following manner. The function continues to calculate the temperatures as long as the initial *While* statement is satisfied. The *While* statement asks if a value known as RelativeChange is greater than RelativeChangeMax and if iterations_p is less than iterationsmax. The RelativeChange is initially set to a value equal to RelativeChangeMax + 1 and the iterations_p is initially set equal to zero. This ensures the *While* statement is satisfied and the ensuing *Do* statement that calculates temperatures will be initially activated. Next, the function stores the temperatures calculated at each location from the previous iteration and names them $\text{Told}_{m,n}$. Iterations_p is now equal to one more than it was before the *While* statement was satisfied.

The *Do* statement solves for the temperatures by using the line-by-line method. After the temperatures are calculated a value called AverageChange is calculated. The AverageChange is equal to the sum of the absolute difference between the temperature just calculated and the temperature calculated by the previous iteration at every location divided by the total number of grid points. The average temperature is also calculated and is called AverageTemp. The RelativeChange is equal to the AverageChange divided by the AverageTemp.

The user can set the convergence criteria. Otherwise, the value of RelativeChangeMax is set by the model to be equal to 10^{-4} and the value of iterationsMax is five. The model now sets the initial temperatures of the FSB at each location equal to the initial temperature entered by the user.

Solve for temperatures at each time step

The model has established all necessary functions to calculate temperature profile of the FSB at each time step. The functions are called upon at each time step in the following order: TempAverage, DielectricConstant, DielectricLossFactor, PenetrationDepth, HeatGeneration, ThermalConductivity, SpecificHeat, DensitySpecificHeat, InteriorCoefficients1, InteriorCoefficients2, InteriorCoefficients3, InteriorCoefficients4, InteriorCoefficients, CoefficientsAtx0, CoefficientsAtxL, CoefficientsAty0, CoefficientsAtyH and finally IterateForTemperatures. The corner temperatures are assigned as equal to the average of the temperatures of the north neighbor, east neighbor, south neighbor, and west neighbor, whichever two apply. The model is now ready to print the temperature profile of the FSB at each time step.

Chapter 4

Instrumentation and Experimental Procedure

Overview

This chapter describes in detail the microwave tempering experiments conducted by this study. In all eight different microwave tempering experiments were conducted on frozen blocks of shrimp (FSB). The microwave power levels used and microwave cooking times chosen for these experiments were based on observations made during preliminary experiments. Each different experiment was conducted three times.

The testing system

The FSB's were tempered in a microwave convection oven, model number LBM-1.2A/9276, designed and built by Cober Electronics. The microwave oven is capable of operating at any percentage of its operating power and has a very short (less than one second) ON/OFF cycle (see Chapter 1: *power output and speed of heating*). During microwave tempering, the temperature of the FSB was recorded at four locations within the FSB. The temperatures were recorded by using four Luxtron Fluoroptic temperature probes, model number SFF2, a Luxtron Fluroptic thermometer, model number 790, and a computer for data acquisition.

The FSB was placed in the microwave oven cavity on a stand. A schematic of the stand is shown in Figure 14. The stand was constructed out of Plexiglas, plastic screws and glue. During the microwave tempering, ice is thawed and water is produced. Preliminary experiments found that if this water is not removed from the microwave oven the water continues to heat and turns to steam. This steam does not temper the FSB but rather cooks the shrimp. Numerous 0.635-cm diameter holes were drilled through the base of the stand. The holes allowed any thawed ice produced during microwave tempering to drain into a funnel shown in Figure 15. The funnel drainage system was constructed from a regular Frisbee, a funnel, Teflon tubing, Duck tape and glue. The drainage system is placed under the stand and the Teflon tubing runs through a circular opening drilled through the bottom of the microwave oven cavity. The opening was 1.27 cm in diameter and was is located in the center of the base of the microwave oven.

A schematic of the microwave tempering testing system is shown in Figure 16. The figure shows a FSB in the Plexiglas stand, the drainage system placed beneath the stand, and the temperature probes connected to the thermometer.

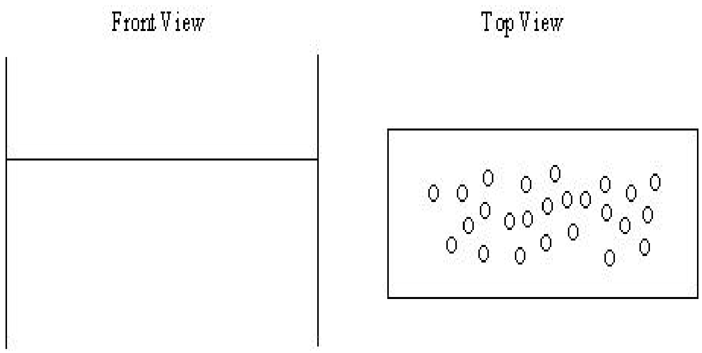


Figure 14. Schematic of the Plexiglas stand

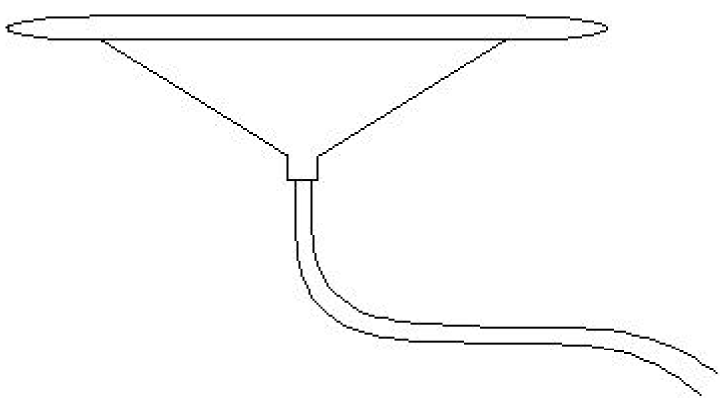


Figure 15. Schematic of the funnel drainage system

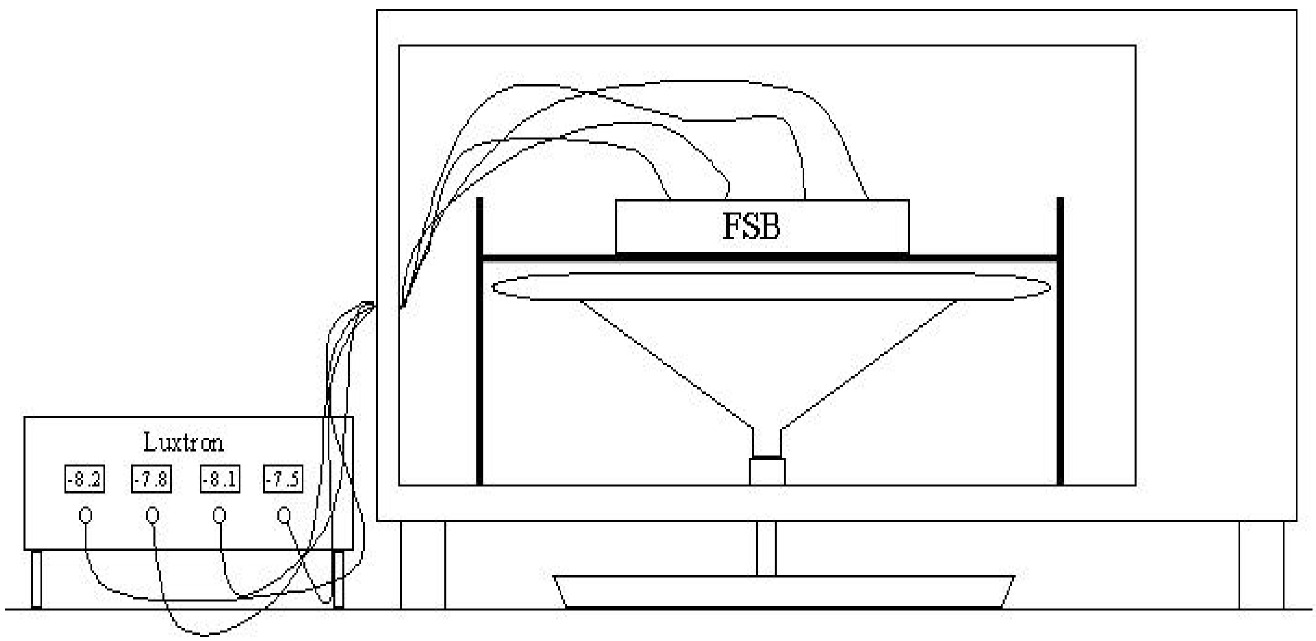


Figure 16. Schematic of microwave testing system

Acquiring the shrimp and microwave susceptors

A roll of microwave susceptor film laminated to paper was obtained from Phoenix Packaging, Maple Grove MN. Jeff Laney, National accounts manager at Phoenix Packaging, was kind enough to donate this roll of film to the Virginia Polytechnic and State University. The susceptor has a resistance of around 80 ohms/square and is made from aluminum at a thickness of around 20 angstroms. The aluminum is metallized to polyester film and then laminated to paperboard.

Ten blocks of frozen shrimp were obtained from Neptune Seafood inc., Norfolk VA and used during preliminary testing. Information obtained by the preliminary tests was used to help design the microwave tempering experiments. The shrimp from Neptune were sized at 31/35, had the shell on, and were headless. Shrimp sizes are expressed in counts per pound or per kilogram. For example, 31/35 means 31 to 35 shrimp per pound. Each block from Neptune had a net weight of 2 kg (4.4 lb).

After completion of the preliminary experiments, an additional 30 blocks of shrimp were purchased from Rich Sea Pack, St. Simon GA. Each block weighed 2.2 kg (5 lb). The shrimp were headless with shell off and sized at either 130/150 or 150/200. All thirty blocks were obtained from the same source; therefore, it is assumed that the properties of the shrimp used during each microwave tempering experiment are identical.

Sample preparation

The shape and size of the FSB, the location of the microwave susceptor, and the location of the temperature probes were identical for each experiment. This was accomplished with the help of two wooden boxes shown in Figure 17 and Figure 18. A 0.635 cm (0.25 in.) thick piece of oak plywood was used as the base of each box and pine boards with a width of 1.9 cm (0.75 in.) and a height of 8.9 cm (3.5 in.) were used for the front, back, and sides. The wooden boxes were identical in size, which ensured the length and width of each FSB formed was identical. As shown in Figure 17 and 18, the box forms a FSB with a length of 9.05 cm (7.5 in.) and a width of 26.67 cm (10.5 in.).

The FSB used during experiments were formed in the following manner. A FSB obtained from the Neptune Seafood or Rich Sea Pack was removed from a walk-in freezer maintained at -20 ^{o}C and placed in a large cylindrical container. The container was filled with cold water and the FSB was slowly thawed. Once the temperature of the block had reached a point in which the shrimp could be individually separated the water and shrimp in the container were poured into a large strainer.

While the FSB thawed, the wooden box was assembled. The base, front, back, and two sides of the wooden box were screwed to each other and to the base. To prevent leakage, Crisco was applied to all contact surfaces before the box was screwed together. Crisco was then applied with a brush to the inside surfaces. A piece of wax paper was placed on top of this layer of Crisco.

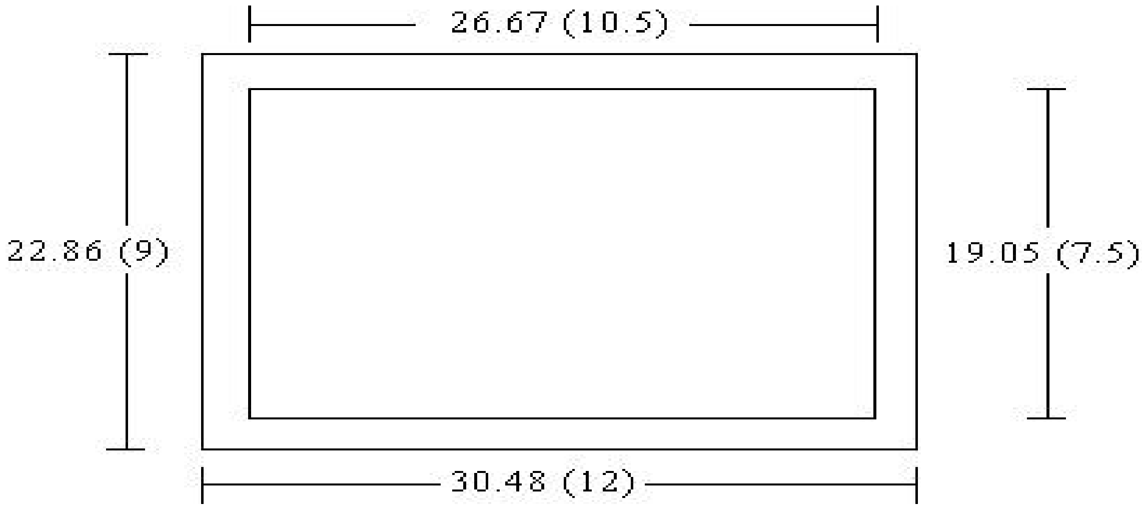


Figure 17. Top view of wooden box used to formulate a FSB without susceptors
Units for the dimensions are cm (in.)

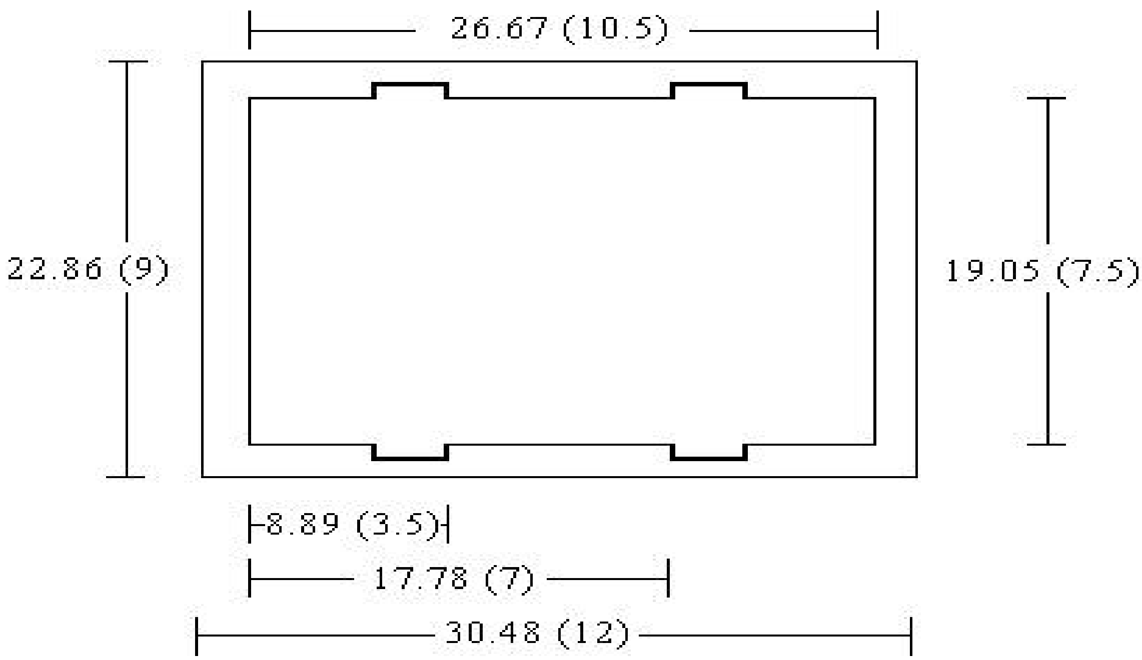


Figure 18. Top view of wooden box used to formulate a FSB with susceptors
Units for the dimensions are cm (in.)

For experiments conducted on a FSB with no microwave susceptive material, the wooden box preparation has at this point been completed. However, some of the experiments designed required the microwave susceptive material to be frozen within the FSB. For these experiments, the positioning of the microwave susceptive film was part of the wooden box preparation.

The paper-thin microwave susceptor sheets were cut into rectangles measuring 26.6 cm (8.5 in.) in length and 7.62 cm (3 in) in height. For reasons discussed later in Chapter 5, it was decided that the sheets would be frozen vertically within the FSB. The length of the FSB was 26.67 cm (10.5 in.) and a microwave susceptor sheet was positioned at 8.89 cm (3.5 in.) and 17.78 cm (7 in.). Positioning and securing of the sheets was a problem. The sheets were paper-thin and did not stand vertically on their own; furthermore, the sheets had to be positioned at exactly 8.89 cm (3.5 in.) and 17.78 cm (7 in.) for each experiment. This problem was solved by the following method. First a 0.635 cm (0.25 in.) deep and 2.54 cm (1 in.) wide rectangular cavity was carved into the inside front and back walls of the wooden box. The cavity extended from the bottom to the top of the box. In all, four rectangular cavities were carved. The cavities are shown in Figure 18.

One cavity was carved on the front wall in such a way that one side of this rectangular cavity was located at 8.89 cm (3.5 in.) and another cavity was carved so that one side of this rectangular cavity was located at a 17.78 cm (7 in). Identical cavities were then carved into the back wall. Rectangular wooden blocks 8.89 cm (3.5 in.) tall, one 2.54 cm (1 in.) wide and 0.635 cm (0.25 in.) deep were made and used to “plug” the cavities and hold the microwave susceptor sheets in position. The microwave susceptor sheet was placed vertically in the wooden box at either 8.89 cm (3.5 in.) or 17.78 cm (7 in.) and the ends of the sheet were placed into the cavity. A wooden block was then snugly placed into one of the cavities, trapping one end of the sheet. The sheet was pulled tight so that it stands vertical and the wooden block for the opposite side was inserted. Figure 19 shows a top view of the wooden box before the susceptor sheets are positioned in the box and Figure 20 shows a wooden box with microwave susceptor sheets. After the box was prepared, it was placed in a -20 ^{o}C freezer.

The wooden box was now ready to be filled with shrimp. The shrimp were removed from the strainer and placed gently, by hand, on top of the wax paper inside the frozen box. The shrimp were placed in such a way that the height of the entire block was equal. Ice water was then poured into the box and the entire box was covered with plastic wrap and placed inside the -20 ^{o}C freezer.

The original FSB was a combination of frozen shrimp and water. Preliminary experiments found that the block could contain anywhere from 200-600 ml of water. In order for the FSBs formed in this wooden box to be identical to a FSB processed at a seafood industry, this water must be taken into consideration. The water was accounted for by two factors. One, the shrimp was placed inside the box immediately after it was strained. Thus, this shrimp was wet and carried a significant amount of the water. Preliminary experiments and observations found that this did not account for all of the water and that adding 50 ml of water to each block was necessary. The shrimp blocks formed had an approximate height of 5.08 cm (2 in.)

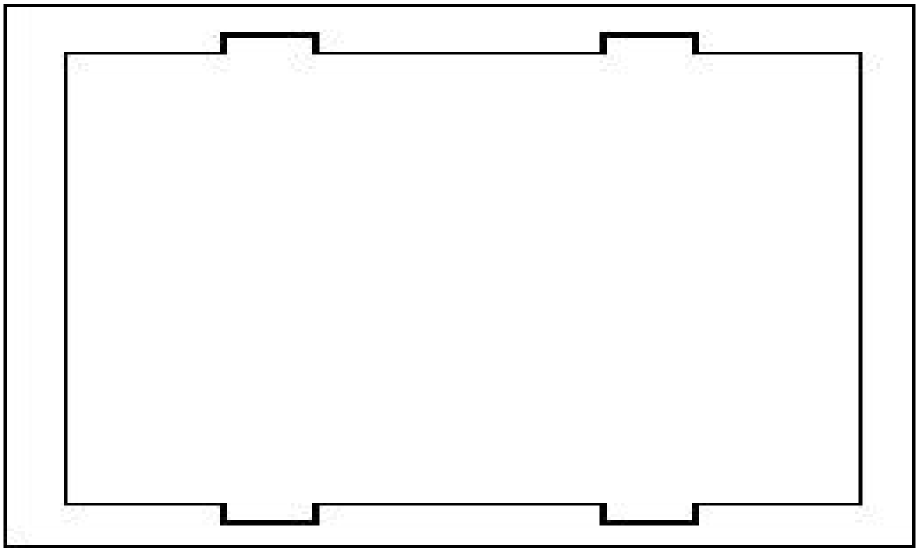


Figure 19. Top view of a wooden box before susceptors are positioned

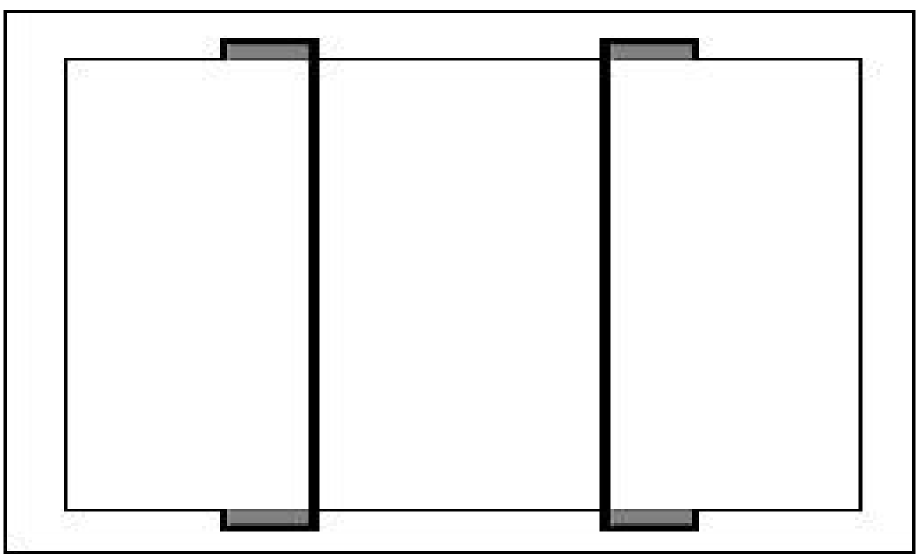
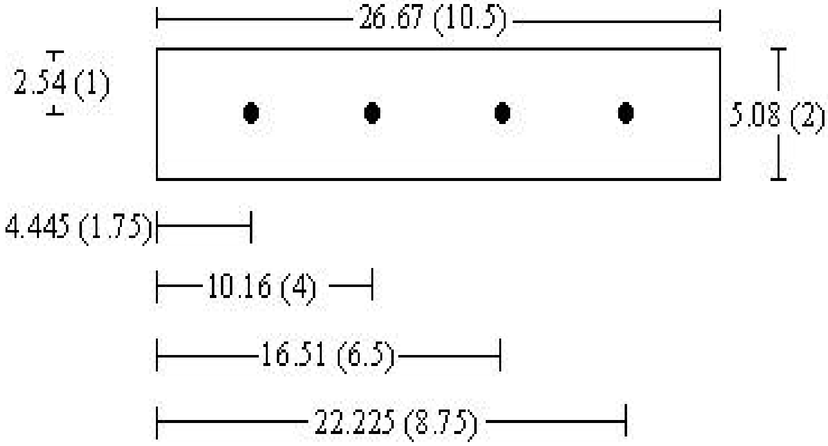


Figure 20. Top view of a wooden box after susceptors are positioned.

The wooden boxes constructed were assembled in five pieces and could be easily dismantled by removing the screws. The boxes were constructed in this manner because it is difficult to remove the FSB from the box without dismantling the box. A wooden box held together by screws no matter how tightly cannot hold water without leaking. Wet shrimp and water were to be placed inside the box and an obviously concern was water leaking out of the box during freezing process. Preliminary experiments helped determine the best method for ensuring no leakage would occur during freezing process. The combination of Crisco, wax paper and freezing the box solved the problem. Using a frozen box was essential; this helped speed the freezing process of the water and shrimp, thus giving less time and opportunity for leakage to occur.

The wooden box filled with the water and shrimp mixture was left inside the -20 ^{o}C freezer until the mixture formed into a solid. After phase change was accomplished, the box was removed from the freezer. As previously mentioned, the box forms a FSB that is 19.05 cm (7.5 in.) long and 26.67 cm (10.5 in.) wide. Four 0.3175-cm (0.125-in.) diameter holes were drilled into the FSB to a depth of 2.54 cm (1 in.) and at locations shown in Figure 21.

Front view



Top view

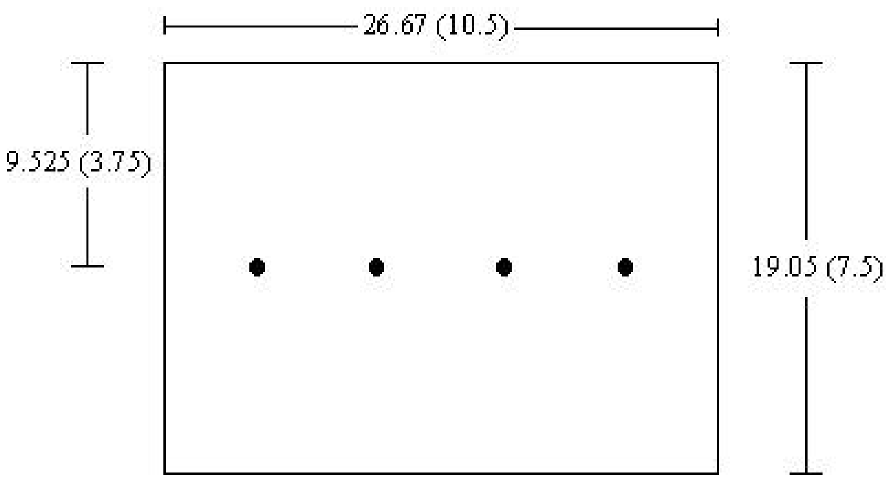


Figure 21. Location of temperatures probes
Units for the dimensions are cm (in.)

The holes were drilled precisely at these locations by the following procedure. A mark was made on the top of the 19.05 cm (7.5 in.) long left and right walls at exactly 9.53 cm (3.75 in.). The marks were made using a straight edge and a sharp knife. The markings were then emphasized with a marker. Similar markings where made on the top of the 30.48 cm (12 in.) long front and back walls at exactly 6.35 cm (2.5 in.), 12.07 cm (4.75 in.), 18.42 cm (7.25 in.), and 24.13 cm (9.5 in.). The markings are shown in Figure 22, which is a top view of a typical box. By using the markings, a piece of masking tape was placed from the left wall to the right wall at exactly 9.53 cm (3.75 in.). Similar strips of masking tape were placed from the front wall to the back wall at 6.35 cm (2.5 in.), 12.07 cm (4.75 in.), 18.42 cm (7.25 in.), and 24.13 cm (9.5 in.).

Figure 23 shows visually how the desired locations of the temperature probes are marked by the intersection of the masking tape. The desired locations were marked, the tape was removed and the holes were drilled. As previously mentioned, the holes were drilled to a depth of 2.54 cm (1 in.). A piece of tape was wrapped around the 0.3175-cm (0.125-in.) diameter drill bit at exactly 2.54 cm (1 in.). The tape prevented the drill bit from penetrating any deeper than 2.54 cm (1 in.).

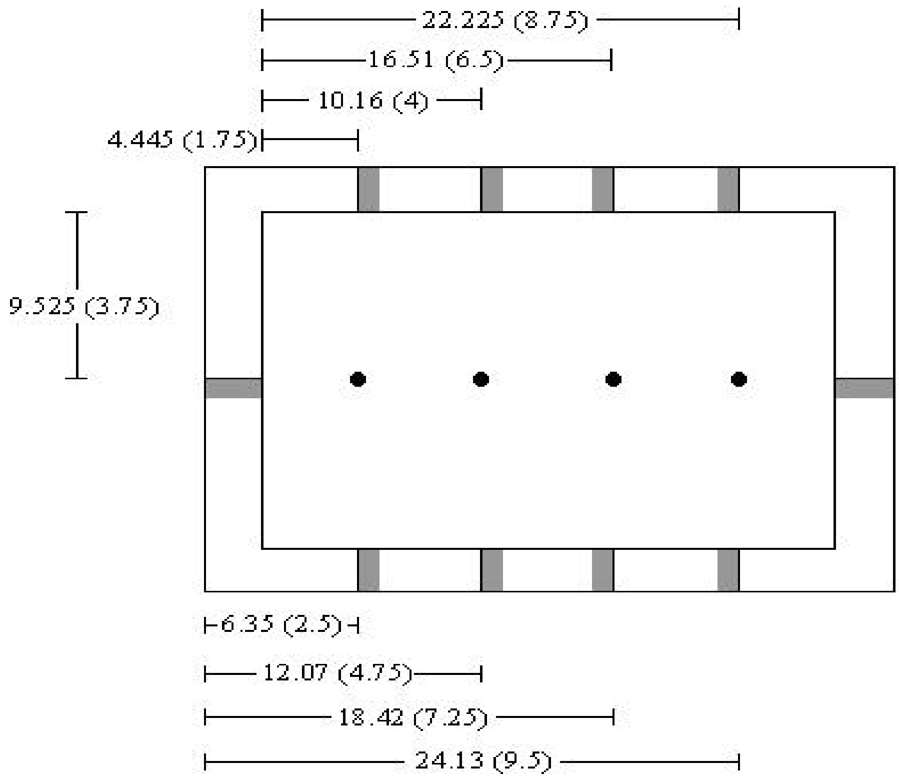


Figure 22. Top view of wooden box with markings used to accurately position temperature probes. Units for the dimensions are cm (in.).

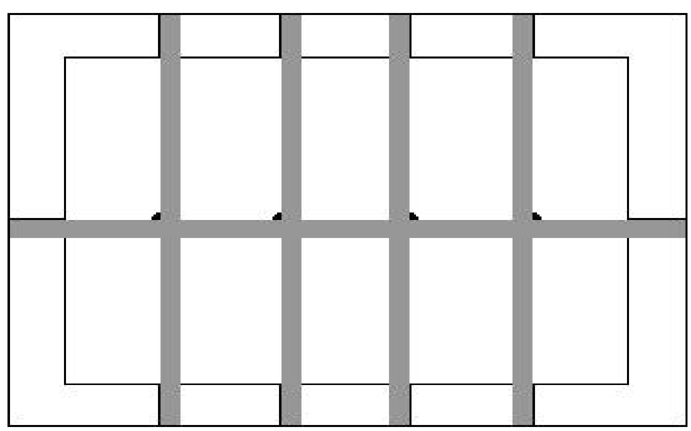


Figure 23. Top view of wooden box with intersection of masking tape used to accurately position temperature probes.

The shrimp and water has frozen into a FSB and the holes for the temperature probes have been drilled. Next, the wooden box was dismantled and the FSB was placed on a tray. The diameter of the temperature probes was between 0.229 cm (0.09 in.) and 0.279 cm (0. 11 in.), which is slightly smaller than the diameter of the holes. The probes were gently inserted into the holes. Since the diameter of the holes was larger than the diameter of the probes, a small gap existed. This gap was filled in with a mixture of shrimp and water that was kept in a 4 ^{o}C refrigerator. The mass of the FSB was recorded and the FSB was placed inside a freezer maintained at -40 ^{o}C. Preliminary experiments found that the FSB should be stored inside this freezer for a minimum of two hours before conducting the microwave tempering experiment.

Experimental testing

Next, the FSB was removed from the freezer and placed in the Plexiglas stand. The stand and FSB were then placed inside the microwave oven on top of the funnel drainage system and in the center of the microwave (Figure 16). The temperature probes were connected to the thermometer. The computer used for data acquisition was turned on and the data acquisition program, DiskSave, was initiated. The program was instructed to record temperature in degrees Celsius every second. The microwave oven cooking time and power level were set to the appropriate values. These values were determined by conducting numerous preliminary experiments.

A series of preliminary tests were conducted to help determine a microwave power level and cooking time that is most effective for tempering a FSB. The tests found that this power level is between 30% and 40%. Further testing found that a FSB stored at -40 ^{o}C can be significantly thawed with minimal cooking of shrimp by microwave cooking at 30% power level for 35 minutes.

The power output of the microwave oven was determined for the following power levels: 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30% and 20%. The method used for determining microwave power output is described in Chapter 2: *Power output and speed of heating* and the temperature data and calculations are in Appendix C. Table 12 is a summary of the microwave power outputs at each power level.

Table 12. Power output of microwave oven

Power level (%)	Power output (W)
100	993
90	885
80	848
70	794
60	639
50	550
40	406
30	255
20	101

A FSB tempered by this microwave oven at 255 W (30%) power level for 35 minutes is exposed to 535.5 kJ of microwave energy. In all eight different microwave tempering experiments were conducted by this study. Each type of experiment used approximately 535.5 kJ of microwave energy. For example, the microwave oven at 406 W (40%) power level has a higher power output, 406 W than at 255 W power level; therefore, the microwave cooking (tempering) time for 406 W power level is around 22 minutes. In 22 minutes at 406 W power level the FSB is exposed to 535.9 kJ during microwave tempering.

Microwave tempering at 255 W power level for 35 minutes and at 406 W power level for 22 minutes was conducted on FSB. The tests were conducted on a typical FSB without susceptors and a FSB with susceptors frozen within it in the manner previously described. A series of experiments that explored the effectiveness of pulsed heating (tempering) were also conducted. The pulse experiments were also based on using 535.5 kJ of energy and also on the previously determined microwave cooking times for 255 W and 406 W power levels. The pulse experiments used a high-power level, either 848 W (80%) or 993 W (100%), and were designed to mock the 255 W and 406 W power level experiments. For example, the 255 W power level test was mocked with pulsed heating at 406 W power level. To accomplish this, the microwave oven was turned ON for 18 seconds and then turned OFF for the next 42 seconds. This ON/OFF cycle was repeated until 35 minutes was reached. The 255 W power level test was also mocked with pulsed heating at 993 W power level and the 406 W power level test was mocked with pulsed heating at 848 W power level and 993 W power level. The ON/OFF cycle for each pulse experiment was 60 seconds and the microwave cooking time was 35 minutes for pulse experiments mocking 255 W power level and 22 minutes for experiments mocking 406 W power level. Calculations used to find microwave cooking times and total energy for the experiments are in Appendix D. The following is a detailed description of each experiment conducted.

1. Test: 255 W power level.

   Description: The FSB was tempered in the microwave oven at 255 W power level for 35 minutes. The FSB was exposed to approximately 535.5 kJ of energy during the microwave tempering process. The test was conducted three times.

2. Test: 255 W power level with susceptors.

   Description: The FSB with microwave susceptive material was tempered in the microwave oven at 255 W power level for 35 minutes. The FSB was exposed to approximately 535.5 kJ of energy during the microwave tempering process. The test was conducted three times.

3. Test: 255 W pulsed at 848 W power level.

   Description: The FSB was tempered in the microwave oven with pulse heating at 848 W power level for 35 minutes. During each minute of microwave tempering, the microwave oven was on at 848 W power level for 18 seconds and then turned off for the next 42 seconds. This cycle was repeated until 35 minutes was reached. The FSB was exposed to approximately 534.2 kJ of energy during the microwave tempering process. The test was conducted three times.

4. Test: 255 W pulsed at 993 W power level.

   Description: The FSB was tempered in the microwave oven with pulsed heating at 993 W power level for 35 minutes. During each minute of microwave tempering, the microwave oven was on at 993 W power level for 15 seconds and then turned off for the next 45 seconds. This cycle was repeated until 35 minutes was reached. The FSB was exposed to approximately 521.3 kJ of energy during the microwave tempering process. The test was conducted three times.

5. Test: 406 W power level.

   Description: The FSB was tempered in the microwave oven at 406 W power level for 35 minutes. The FSB was exposed to approximately 535.9 kJ of energy during the microwave tempering process. The test was conducted three times.

6. Test: 406 W power level with susceptors.

   Description: The FSB with microwave susceptive material was tempered in the microwave oven at 406 W power level for 35 minutes. The FSB was exposed to approximately 535.9 kJ of energy during the microwave tempering process. The test was conducted three times.

7. Test: 406 W pulsed at 848 power level.

   Description: The FSB was tempered in the microwave oven with pulsed heating at 848 W power level for 22 minutes. During each minute of microwave tempering, the microwave oven was on at 848 W power level for 30 seconds and then turned off for the next 30 seconds. This cycle was repeated until 22 minutes was reached. The FSB was exposed to approximately 541.0 kJ of energy during the microwave tempering process. The test was conducted three times.

8. Test: 406 W pulsed at 993 W power level.

Description: The FSB was tempered in the microwave oven with pulsed heating at 993 W power level for 22 minutes. During each minute of microwave tempering, the microwave oven was on at 993 W power level for 25 seconds and then turned off for the next 35 seconds. This cycle was repeated until 35 minutes was reached. The FSB was exposed to approximately 524.3 kJ of energy during the microwave tempering process. The test was conducted three times.

After the microwave cooking process was completed, the temperature probes were removed, the FSB was removed from the Plexiglas stand and the mass of the FSB was recorded. The microwave cooking processes described above did not thaw the FSB but instead tempered the FSB. The final stages of thawing were completed by using flowing water.

The FSB was placed in a rectangular plastic container that contained several 0.635 cm (0.25 in.) diameter holes on the side, back and front panels. Water at a temperature of approximately 29 ^{o}C and a flow rate of 1100 ml/s was used to complete the thawing process. The water was allowed to flow into the rectangular container at a specific location. The container would slowly fill with the thawing water. Every five minutes the shrimp that had become loose and separated form the block were removed. The block was also turned over and rotated 180^{o} every five minutes. This process was continued until the thawing was completed, that is, all the shrimp had separated into individual shrimp. The total time for this process was recorded and is called the additional thawing time.

As a basis of comparison, a FSB was completely thawed using only the thawing water method described above. This is the ninth and final experiment conducted. As before, this experiment was conducted three times.

At this point one of the nine tests had been completed and the FSB is thawed. After complete thawing, the shrimp were counted and the total number of shrimp in each block was recorded. Each shrimp was individually inspected to determine whether or not it had been cooked by microwave tempering process. The total number of cooked shrimp for each block was recorded.

The average volume occupied by 100 shrimp was determined for each block of shrimp by placing 100 shrimp in a graduated cylinder filled initially with 500 ml of water and recording the volume. The difference of the final volume and initial volume is the volume of the 100 shrimp. This measurement was performed three times using 100 different shrimp from the block for each measurement. The average of the three tests was taken as the volume occupied by 100 shrimp and the average volume occupied by a single shrimp was calculated for each block.

After the shrimp were counted and inspected, all of the thawed shrimp from the block were placed on a scale and the mass was recorded. Since the total number of shrimp and the mass of the shrimp are now known, the average mass of a single shrimp can be determined for each block. By knowing the mass and the volume of the shrimp, the average density of the shrimp in each block can be calculated.

The mass of the FSB was recorded before microwave tempering and after microwave tempering. During microwave tempering, water runs into the funnel drainage system and is directed into a rectangular tray located underneath the microwave oven. The difference of the mass before microwave cooking and after microwave cooking can be used to estimate the amount of water captured by funnel drainage system. This amount of water is an indication of the amount of ice thawed during microwave tempering. As previously mentioned, the weight of the shrimp is in each FSB is recorded; thus, the total amount of water in each block can be approximated by taking the difference of the initial mass of the FSB and the total mass of the shrimp in that FSB.

Chapter 5

Summary of Problem

and Formulation of Solution

Overview

Chapter one contains a brief discussion on the current thawing methods of shrimp used by the seafood industry. The problems associated with the current method are explained. These problems have prompted the industry to explore alternative thawing methods. This chapter contains a summary of the problems encountered by seafood industry when thawing shrimp and describes the proposed solution presented by this study.

Background

Microwave tempering of foods, in particular shrimp, has been successfully accomplished; however, the seafood industry has been reluctant to use microwave energy to temper shrimp mainly because the industry believes microwave tempering will significantly affect the quality of the shrimp. Quality of product is always important in the food industry but especially important when dealing with such a high priced product as shrimp.

The quality of shrimp is affected during microwave tempering when portions of the FSB are allowed to cook. Improper microwave tempering of a FSB produces a FSB with portions still frozen, portions thawed, and other portions cooked. The FSB is completely thawed in the microwave oven and the majority of the shrimp are still raw; however, a portion of the shrimp are cooked or partially cooked by the microwave tempering.

The FSBs processed for retail sale at a shrimp plant are first thawed. After the FSBs are thawed the shrimp are usually cooked and then refrozen as individual shrimp and packaged for sale. If the FSB is thawed by using the microwave thawing method described above, an obvious problem exists. The shrimp cooked during the microwave tempering process are cooked twice. This “twice cooking” may significantly affect the quality of these shrimp. To avoid this, the microwave tempering process should be designed in such a way that the amount of cooked shrimp is minimized.

The Problem associated with microwave thawing of shrimp

The main problem with microwave tempering of FSB is runaway heating, which is attributed to the difference in the electrical (dielectric) properties of ice and water (see Chapter 2: *Thawing foods with microwave energy*). This causes the above mentioned premature cooking which may result in undesirable changes in properties such as the texture, color, and/or taste of the shrimp. Nevertheless, microwave tempering has several advantages over most thawing processes. The microwave tempering process can handle large amounts of frozen product at small cost, has a high yield, and is accomplished in small spaces with no bacterial growth (Miesel, 1972). The only noteworthy drawback to microwave tempering is runaway heating.

The consequence of runaway heating is inflated when dealing with an expensive food product such as shrimp. Chapter 2 explains that to avoid runaway heating the frozen food product should be maintained at a temperature just below freezing point throughout the microwave tempering process. This can be accomplished by using a low-power setting.

If the temperature of a portion of the food product is allowed to rise above its freezing point, the temperature of this portion will rise much faster than the surrounding frozen portions and runaway heating will occur. Runaway heating is obviously related to temperature variation within the food product; therefore, by avoiding a large temperature variation within the food product during microwave tempering, runaway heating can be reduced and hopefully eliminated. At high-power levels, the product is exposed to high levels of microwave energy during short periods of time, often resulting in temperature differences within the product. A low-power setting reduces the chances of runaway heating since lower power settings produce less temperature variation within the product than high-power settings. It has been known for some time that a low-power setting should be used when thawing food products.

The proposed solution

Aside from using a low-power setting, other ideas on how to prevent runaway heating and control the sometimes erratic microwave energy have been proposed. One idea is to use some sort of microwave susceptive material to assist microwave-thawing process. The susceptive material is frozen in some manner within the food product. During microwave tempering, the majority of the microwave energy is absorbed by the susceptive material and not by the food product. The energy absorbed by the susceptive material is converted to heat and transferred through conduction to the surrounding medium. The temperature of the surrounding medium rises and the food product is thawed.

The microwave absorption capability of the microwave susceptive material must be substantially greater than that of frozen shrimp. Microwave susceptive materials have been used to assist the heating of microwave products since the early 1980's (see Chapter 2: Microwave Susceptors). A wide variety of these materials exist. The material absorbs microwave energy at an extremely high rate; some materials reach temperatures above 200 ^{o}C within seconds of exposure to a microwave field. Theoretically, this type of material can be used as described earlier to assist microwave tempering of frozen shrimp. The only thing left is to decide is how to spatially arrange the susceptive material within the FSB.

It was initially decided that the microwave susceptive material would be formulated into small spherical beads and the beads would be arranged throughout the shrimp block before freezing (Figure 24).

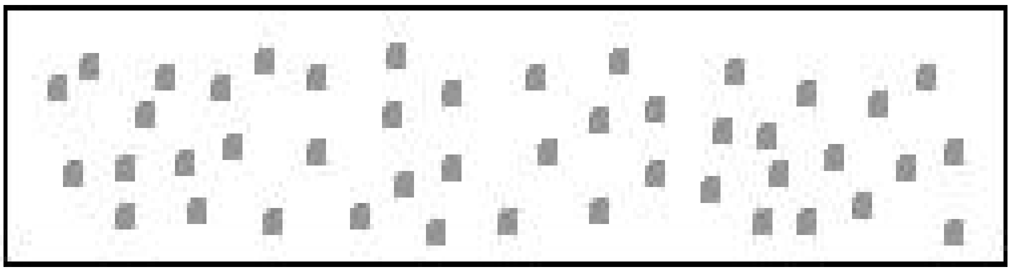


Figure 24. Front view of FSB with microwave susceptive beads

Arranging the beads in such a way that they are evenly distributed throughout the FSB is difficult if not impossible. The arrangement in theory has tremendous potential. The beads absorb microwave energy and provide heat sources throughout the FSB. The arrangement has not only solved the problem of runaway heating but also the major problem associated with thawing foods.

As explained in the introduction of Chapter 2: *Thawing foods with microwave energy*, the thermal conductivity of frozen foods is three times that of non-frozen foods. The most common thawing method is to in some way apply heat to the surface of the frozen food and allow the heat to conduct to the interior. Since the heat is applied to the surface, it must travel through the surface to reach the interior. The surface thaws first and now has a lower thermal conductivity than the frozen interior and therefore cannot transfer adequate heat to the interior without increasing the temperature of the thawing surface to undesirable levels. The result of this is long thawing cycles that are often characterized by unacceptable changes in quality. The addition of susceptive beads solves this problem by providing an internal source of heat. Thawing is experienced throughout the FSB as opposed to from the surface to the interior.

Arranging these beads in such a manner is difficult if not impossible. This is especially true since a large portion of shrimp processed are packaged and frozen overseas in third world countries. For the arrangement to work, the susceptive beads would be somehow arranged within the package before the shrimp are added. A package with beads suspended throughout it would be impractical and expensive.

A more practical arrangement of susceptors is needed. Instead of formulating the microwave susceptive material into beads the material is formulated into paper-thin sheets. These sheets are then frozen vertically within the FSB (Figure 25). This arrangement is much more practical than the arrangement involving beads. The shrimp are placed within a rectangular paperboard package and then frozen. Before the shrimp are placed in the package, one end of a susceptive sheet could somehow be fastened to the inside of one of the walls of the package and the other end fastened to the inside of the opposite wall.

Figure 25. Front view of FSB with microwave susceptor heater boards

The shrimp are added to this paperboard package with susceptors and the shrimp are then frozen into a FSB. The microwave susceptive material is not currently manufactured in the form of beads; however, the material is manufactured in the form of sheets and known as a microwave susceptor heater board, a microwave susceptor or simply a susceptor. The construction of this rectangular paperboard package with susceptor heater boards is much more feasible than a package with susceptive beads.

The rectangular paperboard package determines the size and shape of the FSB. The susceptor heater boards are arranged in some manner within the FSB. Numerous possibilities of this arrangement exist. As previously mentioned, it was decided that the susceptive sheets will stand vertically within the FSB. It was also decided that each FSB would contain a total of two susceptor heater boards. The sheets span widthwise across the FSB with one sheet located at one third of the length and the other at two thirds of the length (Figure 25).

The positioning of the sheets has visually separated the FSB into three sections identical in size and each one-third the size of the entire FSB. Chapter 2 explains that microwave thawing of shrimp is not practical; however, microwave tempering is practical. Successful thawing of FSB can be accomplished by microwave tempering followed by applying current thawing methods (water immersion). The objective of the microwave tempering is to complete as much of the thawing process as possible before using water immersion. This reduces the amount of time needed by the current method, which reduces water usage, cost, and processing time.

The decisions made regarding the arrangement of the susceptor heater boards hope to minimize the amount of time needed by the current thawing method. The susceptor heater boards will absorb the majority of microwave energy and distribute this energy to the surrounding frozen shrimp. The shrimp located close to the susceptor heater boards should thaw first. The FSB is now separated into three smaller partially thawed FSB.

By reducing the size of the FSB, the amount of time required by water immersion to complete the thawing process is also reduced. The susceptor heater boards not only assist the thawing process by separating the FSB into smaller pieces but also help prevent runaway heating. Finally, the temperature of the FSB is raised by the microwave tempering, which further reduces the amount of time required by water immersion.

Choosing the type of microwave susceptor

The "art" of microwave susceptors is briefly explained in Chapter 2: *Microwave Susceptors*. The susceptors properties, mainly the thickness and type of metal used, determine how the susceptive material will react when exposed to a microwave field. Specifically, the properties help determine how fast the temperature of the susceptive material will rise, to what temperature, and how long it can maintain at this temperature. The question this section hopes to answer is: Can the most effective type of susceptor to use for this microwave tempering of FSB application be identified, and if so is this material available?

The question is not easily answered. The microwave susceptor field is a fairly new area, beginning in the early 1980's. Information on different types of susceptors and their properties is not readily available. Research and work done in this area by individual corporations is kept within the company and not available to the public.

Many food corporations manufacture products that use microwave packages with a microwave susceptor. The most abundant product is the microwave popcorn package. A susceptive sheet is sandwiched between the paper packaging side of the package labeled "This Side Down". During microwave heating, the sheet heats up quickly to a very high temperature, 205-260 ^{o}C (400-500 ^{o}F), and the kernels resting on this sheet conduct this heat and eventually pop. The process continues until the bag is filled with popped kernels.

There is a temperature at which the popping of these kernels is most effective. Once this temperature is identified, the susceptive sheets are constructed in such way that they will reach this temperature and maintain it throughout the microwave cooking process. Each food corporation identifies what they believe is the most effective temperature and the susceptive sheets are designed according to these specifications. Even though a susceptor heater board is used for the same application, i.e. pop corn kernels, the susceptor heater board designed by one food corporation is slightly different than the susceptor heater board designed by a different food corporation.

The heater boards are used by the food industry for other applications, specifically browning of foods. Microwave susceptors are not currently used by the food industry for any other applications. A susceptor heater board designed to assist browning is slightly different than the microwave susceptor board designed for a microwave popcorn package.

Although the susceptor heater boards do differ, in general this difference is not significant. The two applications they are used for, browning and popping kernels require similar temperatures. Some boards designed may heat to the temperature more quickly or maintain the temperature more steadily but overall the susceptor heater boards available on the market today are essentially the same.

It is difficult to determine the most effective type of susceptor heater board to use for the microwave tempering of FSB. Logically, before spending the time on choosing or designing the best heater board for microwave tempering of shrimp, it should be determined whether or not the microwave tempering of shrimp is improved by the addition of a microwave susceptive material. Using this logic, it was decided that the microwave tempering experiments conducted would use microwave susceptor heater boards readily available in today's market; furthermore, assuming the difference between existing susceptor heater boards is not significant, any type of susceptor heater board can be used.

The focus of this study is to determine if the microwave tempering of FSB is significantly improved by the addition of a microwave heater board. If the process is significantly improved then the most effective type of susceptor should be identified. In the meantime, experiments are conducted with microwave susceptor heater boards available in today's market.

Location of temperature probes

During microwave tempering the temperature of the FSB was recorded every second. In all four temperature probes were available and the location of these probes is described in Chapter 4: *Sample Preparation*. All four probes are positioned to a depth of 2.54 cm (1 in.) and at the midway point of the width, 9.525 cm (3.75 in.). The positioning of the four probes varies only in the x-direction. One end of the FSB is taken as x = 0. Probe #1 is located at x = 4.445 cm (1.75 in.), probe #2 at x = 10.16 cm (4 in.), probe #3 at 16.51 cm (6.5 in.), and probe #4 at 22.225 cm (8.75 in.) (see Figure 21).

Using susceptive material theoretically will prevent runaway heating and thus the prematurely cooked shrimp; however, the concern of cooking shrimp is not eliminated by the addition of susceptors. The susceptor heats to a high enough temperature that the shrimp located close to the susceptor may be cooked. For this reason, the temperature of the shrimp located near susceptive heater boards is more closely monitored.

Two of the temperature probes are positioned so that for experiments conducted with susceptors probes #2 and #3 they are located only 1.27 cm (0.5 in.) from a susceptive heater board. Probe location was the same for all experiments. The temperature data collected is eventually compared to the temperature data predicted by the mathematical model.

Chapter 6

Results and Discussion

Overview

In this study, several microwave tempering experiments were conducted on frozen blocks of shrimp (FSB). During each microwave tempering experiments conducted, the FSB was exposed to approximately 530 kJ of microwave energy. In this chapter the results from the microwave tempering experiments are presented. The chapter begins by briefly describing the preliminary experiments and the criteria used for comparing microwave tempering experiments. The results from the microwave tempering experiments on FSB with susceptors and microwave tempering experiments on FSB without susceptors are compared. This comparison is used to determine whether or not microwave tempering process is significantly improved by the addition of susceptors.

Next, the microwave tempering experiments mentioned above are compared to the traditional current thawing method (water immersion). In this study the FSB were not completely thawed in the microwave oven; instead, the FSB was tempered by microwave energy and the final stages of thawing were completed by using a form of water immersion. A full description of the method used to complete the thawing can be found in Chapter 4: *Experimental Testing*. As a basis of comparison the method was used to thaw a FSB that was not tempered with microwave energy. This experiment is known as the control experiment.

The control experiment is used as a model of the traditional current thawing method. The results from microwave tempering experiments are compared to results from control experiments. This gives an indication of whether or not the use of microwave energy has significantly improved the thawing process.

The study's main goal was to determine whether or not the addition of susceptors significantly improves the microwave tempering of FSB and determine if the microwave tempering methods identified are a significant improvement over current thawing method. Although not the primary focus of this study, additional microwave tempering experiments were conducted. These microwave tempering experiments explored the advantage of using pulsed microwave heating as opposed to fixed microwave heating. The pulse heating microwave tempering experiments were compared to the fixed heating microwave tempering experiments. This comparison is used to determine whether or not microwave tempering process is significantly improved by using pulsed heating. The tests are ranked and the most effective microwave tempering method is identified. As before, the microwave pulse experiments are then compared to the control experiments.

The final section of this section is the model validation. A mathematical model was created to predict temperature of the FSB during microwave tempering. The temperature data predicted by the model is compared to the experimental data collected during testing.

Preliminary experiments

Chapter 4: *Experimental testing* explains that numerous preliminary experiments were conducted to help determine a microwave power level and cooking (tempering) time that is most effective for tempering shrimp. The microwave tempering experiments conducted in this study were based on these preliminary findings. A full description of the eight different microwave tempering experiments and the control experiment is found in Chapter 4: *Experimental Testing*.

Criteria for comparing experiments

The effectiveness of the microwave tempering experiments must somehow be measured. The effectiveness is measured by two factors: the thawing time after microwave tempering (additional thawing time) and the percentage of cooked shrimp. After microwave tempering, the thawing of the FSB is completed by using a thawing method similar to current methods used by shrimp industry. A full description of the method is found in Chapter 4: *Experimental testing*. The method submerges the FSB in water by continually filling a container with water. The amount of time to complete thawing is recorded and is referred to as the additional thawing time. The flow rate of the water during this method was measured and the amount of water used during this process was recorded. This amount of water is referred to as the additional thawing water amount.

With susceptors vs. without susceptors

FSBs were tempered in a microwave oven with susceptors and without susceptors at 255 W power level and 406 W power level. The FSB is exposed to approximately the same amount of energy, 530 kJ, during each microwave tempering experiment conducted. Differences between the values of the additional thawing water amount and the percentage of shrimp cooked may be attributed to whether or not the FSB contains susceptors but also may be attributed to whether the FSB was tempered at 255 W power level or 406 W power level. Furthermore, the additional thawing water amounts for FSBs with susceptors and without susceptors may differ significantly only for 255 W power level tests and not for 406 W power level tests or vice versa. When comparing the results, all of these possibilities must be considered.

All these possibilities are considered by statistically analyzing the data with a two factor ANOVA with replication test. The statistical test was run on the data collected by using EXCEL and the results are summarized in Table 13. A 95% confidence interval was used when comparing results of the tests; therefore, a p-value less than 0.05 indicates that values are significantly different.

Table 13. Effect of power level and susceptors

Treatment	DF	Mean value of additional thawing water amount (L)	Mean value of % of shrimp cooked	P-Value (additional thawing water)	P-Value (% of shrimp cooked)
Power	1				*
255 W		1512	1.4		
406 W		1531	5.3		
Susceptors	1			*	*
YES		1420	3.0		
NO		1618	3.7		
Power × Susceptors	1			*	
255 W YES		1458	1.1		
255 W NO		1565	1.7		
406 W YES		1392	4.9		
406 W NO		1671	5.7		

* mean values are significantly different (p-value<0.05)

Additional thawing water amount

The values of additional thawing water amount for tests conducted with susceptors was significantly less than the values of the additional thawing water amount for tests conducted without susceptors. The additional water amount for tests with susceptors was 1420 L while the additional water amount for tests without susceptors was 1618 L. The additional thawing water amounts for experiments conducted at 255 W power level and at 406 W power level do not vary significantly.

The interaction treatment, power $\times$ susceptors, is significant. The difference in the additional thawing water amount between experiments with susceptors and experiments without susceptors may only be significant at 255 W power level or only at 406 W power level. By referring to Table 13, it appears the additional thawing water amounts differ significantly at both 255 W power level and 406 W power level. The interaction p-value is less than 0.05 because the difference between the additional thawing water amounts amongst susceptors and non-susceptors is much greater at 406 W power level than at 255 W power level. At 255 W, the additional water amount for tests with susceptors was 1458 L while the additional water amount for tests without susceptors was 1565 L. At 406 W, the additional water amount for tests with susceptors was 1392 L while the additional water amount for tests without susceptors was 1671 L.

Percentage of shrimp cooked

As previously mentioned, the percentage of cooked shrimp is also used as a criteria for determining the effectiveness of the microwave tempering experiment. The percentage of shrimp cooked for FSBs with susceptors is significantly less than the percentage of cooked shrimp for FSBs without susceptors. The percentage of shrimp cooked during tests with susceptors was 3.0 while the percentage of shrimp cooked without susceptors was 3.7.

The percentage of shrimp cooked is significantly less at 255 W power level than at 406 W power level. At 255 W, the percentage of shrimp cooked was 1.4. At 406, the percentage of shrimp cooked was 5.3. The interaction treatment had no effect and from this it can be concluded that the difference between percentage of cooked shrimp for FSBs with susceptors and FSBs without susceptors is significant at both 255 W power level and 406 W power level.

At 255 W, the percentage of shrimp cooked during tests with susceptors was 1.1 while the percentage of shrimp cooked during tests without susceptors was 1.7. At 406 W, the percentage of shrimp cooked during tests with susceptors was 4.9 while the percentage of shrimp cooked during tests without susceptors was 5.7.

Summary

Less cooking of shrimp occurred during microwave tempering experiments with susceptors. This is due to the fact that the susceptive material absorbs microwave energy and distributes this energy to the interior. Significantly less shrimp were cooked at the 255 W power level than at the 406 W power level. There was no significant difference between thawing water amounts at 255 W power level and at 406 W power level; however, there was a significant difference between thawing water amounts of FSB with susceptors and FSB without susceptors. From these results it is concluded that the most effective microwave tempering method amongst those compared in this section is microwave tempering at 255 W power level for 35 minutes with susceptors. The next best method is microwave tempering at 255 W power level for 35 minutes without susceptors, followed by 406 W power level with susceptors, and finally 406 W power level without susceptors.

Microwave tempering vs. control experiment: part 1

The study has shown that a combination of microwave tempering and water immersion can successfully thaw a FSB. The next step of this study is to compare results from the microwave tempering experiments discussed in the previous section with the control experiment. Table 14 contains the thawing times and percentage of cooked shrimp for each type of microwave tempering experiment and the control experiment. Each experiment was conducted three times and listed in Table 14 is the mean value of the three tests.

Table 14. Comparing microwave tempering and control: part 1

Test Type	Additional thawing time (s)	% cooked Shrimp	Microwave Tempering time (s)	Total Thawing time (s)
255 W Susceptors: YES	1326a	1.1a	2100	3426a
255 W Susceptors: NO	1423b	1.7b	2100	3523a
406 W Susceptors: YES	1265a	4.9c	1320	2585b
406 Susceptors: NO	1519b	5.7d	1320	2839b
Control (current method)	--	0.0e	--	6180c

Mean values in a column not followed by the same letter are significantly different

The total thawing times of the experiments conducted with susceptors at 406 W power level and the experiments conducted without susceptors at 406 W power level were significantly less than the total thawing time of the control experiment. Using microwave tempering at 406 W power level with susceptors reduces process thawing time by 58%; Using microwave tempering at 406 W power level without susceptors reduces process thawing time by 54%. The process thawing time is substantially improved but the percentage of cooked shrimp at this power level is much too high. A percentage of cooked shrimp above 4% is considered high by this study and a percentage of cooked shrimp below 2% is considered low by this study. For these reasons, the microwave tempering of a FSB at 406 W power level is not recommended.

Using microwave tempering at 255 W power level without susceptors reduced thawing time by 45%. Using microwave tempering at 255 W power level with susceptors reduced thawing time by 43%. The percentage of cooked shrimp at 255 W power level was low. The use of susceptors has improved the thawing time as well as reduced the percentage of cooked shrimp, however, the improvements in this study are not nearly as substantial as expected.

The study has shown that microwave tempering of FSB combined with water immersion is a significant improvement over the current thawing method. Processing time can be significantly reduced with minimal cooking of shrimp. The study recommends microwave tempering for 35 minutes in a microwave oven with a power output around 250 W. The addition of susceptors will improve the process but the improvements are not substantial enough to outweigh the cost and difficulty of adding susceptors.

Fixed tempering vs. pulsed tempering

From this study, it is recommended that one use microwave tempering for 35 minutes in a microwave oven with a power output of around 250 W. The microwave oven is turned ON during the entire microwave tempering process. This type of continuous heating is referred to in this study as fixed heating. This study is also interested in the advantages of pulsed microwave tempering. Pulsed heating or pulsed microwave tempering is described in previous sections of this study. Pulsed microwave tempering consists of using a high-power level and turning the microwave ON and then OFF in cycles during the microwave tempering process.

The microwave tempering experiments using pulsed heating are described in Chapter 4: *Experimental Testing*. As before, the FSB is exposed to approximately the same amount of energy, 530 kJ, during each microwave tempering experiment conducted. For each power level, 255 W and 406 W, three categories of tests exist, those conducted without pulsed tempering (fixed), those conducted with pulsed tempering at 848 W power level (80%), and those conducted with pulsed tempering at 993 W power level (100%).

The results were compared by using a statistical test. Differences between the values of additional thawing water amount and the percentage of shrimp cooked may be attributed to whether or not pulsed tempering was used or whether the FSB was tempered under 255 W power level conditions or 406 W power level conditions. Furthermore, the additional thawing times for pulse experiments and fixed experiments may differ significantly only for 255 W power level conditions and not for 406 W power level conditions or vice versa. Once again a two factor ANOVA with replication statistical test was used to properly compare the data. The statistical test was run on the data collected by using EXCEL and the results are summarized in Table 15. A 95% confidence interval was used when comparing results of the tests; therefore, a p-value less than 0.05 indicates that values are significantly different.

Table 15. Effect of power level and pulse level

Treatment	DF	Mean value of additional thawing water amount (L)	Mean value of % of shrimp cooked	P-Value (additional thawing water)	P-Value (% of shrimp cooked)
Power	1				*
255 W		1565	4.3		
406 W		1617	8.0		
Pulse	1			*	*
Fixed		1618	3.7		
848 W		1673	6.3		
993 W		1656	8.4		
Power × Pulse	1			*	
255 W × Fixed		1565	1.7		
255 W × 848 W		1678	4.2		
255 W × 993 W		1655	7.0		
406 W × Fixed		1671	5.7		
406 W × 848 W		1667	8.4		
406 W × 993 W		1658	9.8		

* mean values are significantly different (p-value<0.05)

Additional thawing water amount

The additional thawing water amounts for experiments conducted at 255 W power level condition do not vary significantly from experiments conducted at 406 W power level conditions. The p-value for pulse level and for interaction is slightly less than 0.05. There is a significant difference between the additional thawing times of fixed experiments and pulse experiments; however, the interaction p-value indicates that this difference may only occur at either 255 W power level conditions or 406 W power level conditions.

Table 15 clearly shows that the additional thawing water amount for 406 W fixed, pulsed at 848, and pulsed at 993 W do not vary significantly. For 406 W fixed, the additional thawing water amount was 1671 L. For 406 W pulsed at 848 W, the additional thawing water amount was 1667 L. For 406 W pulsed at 993 W, the additional thawing water amount was 1658 L. On the other hand, at 255 W power level conditions the additional thawing water amounts for fixed is significantly less than the additional thawing water amounts for pulsed at 848 W and pulsed at 993 W. For fixed 255 W power level conditions, the additional thawing water amount was 1565 L. For 255 W pulsed at 848, the additional thawing water amount was 1678 L and for 255 W pulsed at 993, the additional thawing time was 1655 L.

Percentage of shrimp cooked

As previously mentioned, the percentage of cooked shrimp is also used as a criteria for determining the effectiveness of the microwave tempering experiment. The data were statistically analyzed in the same way that the additional thawing water amount data were analyzed.

FSBs tempered with fixed heat is significantly less than the percentage of cooked shrimp for FSBs tempered with pulsed heat. The percentage of shrimp cooked is significantly less at 255 W power level than at 406 W power level. The difference between percentage of cooked shrimp for FSBs tempered with fixed heat and FSBs tempered with pulsed heat is significant at both 255 W power level conditions and 406 W power level conditions. The percentage of shrimp cooked during fixed 255 W power level test was 1.7, which is significantly lower than at all other conditions. The percentage of cooked shrimp for 406 W fixed was 5.7, for 406 W pulsed at 848 W was 8.4, for 406 W pulsed at 993 W was 9.8, for 255 W pulsed at 848 was 4.2 and, for 406 W pulsed at 993 W was 7.0.

Summary

Percentages of cooked shrimp were much higher for pulse experiments than for fixed experiments at both 255 W power level conditions and 406 W power level conditions; furthermore, at 255 W power level conditions the additional thawing water amount for fixed experiments is less than that of pulse experiments. Additional thawing water amounts between fixed and pulse experiments do not vary significantly at 406 W power level conditions. Pulsed heating does not improve additional thawing water amount and more cooking of shrimp occurs when pulsed heating is used than when fixed heating is used. For these reasons, pulsed heating is not recommended as an improved method of microwave tempering.

Microwave tempering vs. control experiment: part 2

This section is intended to compare pulse microwave tempering experiments and the control experiments. The previous section determined that there is no significant advantage by using pulsed tempering. In fact, the best results occurred with fixed tempering at 255 W power level. Microwave tempering at 255 W power level was compared to control experiments in a previous section. Since it has been determined that pulsed tempering is not an improved method over fixed tempering, comparing pulsed tempering to the control experiment is unnecessary. The results of this section lead to the same recommendation as before, microwave tempering for 35 minutes in a microwave oven with a power output around 250 W.

Model validation

A mathematical model that predicts the temperature of FSB during microwave tempering was developed. The deviation between the experimental results and the results predicted by the model were calculated by using the following equation:

$$s = \sqrt{\frac{\sum_{i=1}^{n} \left(T_p - T_E\right)^2}{n}} \qquad (6.1)$$

where

σ = variance

T_p = temperature predicted by model (^oC)

T_E = Temperature observed during experimental testing

n = number of data points

The predicted data agreed well with the experimental data. The overall deviation was calculated by using equation 6.1. The temperature predictions were within 2 ^oC. The predicted data and the experimental data were plotted on the same graph and some examples of the graphs can be found in Appendix E. The predicted data are represented with a dashed line and the experimental data are represented with a solid line. It is clear from these graphs that the model matches well with experimental data during initial stages, up to around 500 s, of microwave tempering; however, the model does not match nearly as well in the latter stages of microwave tempering, especially near 0 ^oC, which is near the freezing temperature of the FSB.

The increased variance around this temperature is attributed to the fact that the specific heat equation used to predict the specific heat of the FSB was intended for predicting the specific heat of shrimp meat and not a shrimp and water combination such as a FSB. The specific heat of a FSB is less than the specific heat of pure shrimp and therefore the specific heat model over estimates the specific heat of the FSB. The differences in actual specific heat of the FSB and specific heat of pure shrimp are minor in beginning stages of microwave tempering but as 0 ^{o}C is approached the specific heat of the FSB increases dramatically. This increase is overpredicted by the specific heat model resulting in predicted temperatures that are less than the experimental temperatures.

Experimental data were collected at four locations within the FSB and in all eight different types of microwave tempering experiments were conducted. The overall variance between predicted and experimental results is around 2 ^{o}C. As previously mentioned, the model does not match as well during final stages of microwave tempering when the temperature approaches 0 ^{o}C. Therefore, in all likelihood the majority of the variance is attributed to differences in time and thus temperature.

The same model was used to predict the temperatures of each type of experiment. Some of the variance may be attributed to differences in type of test. In other words, the model may match satisfactorily for some types of experiments and not satisfactorily for other types. Experimental temperature data was collected at four different locations in the FSB. The probe location and positioning of the probes is thoroughly described in Chapter 4: *Sample preparation*. The probe locations were the same for each test conducted. Some of the variance may be attributed to probe locations meaning that the model may match better with experimental data at some probe locations than others. It is visually obvious from graphs in Appendix E that the majority of the variance is due to differences in time; however, further proof can be obtained by calculating the variance at each location and for each test. The calculated variances are listed in Table 16. The variances for each location and each test are around the same 2 ^{o}C as the overall variance. This is an additional indication that the majority of variance is due to differences in time.

Table 16. Variance between predicted and experimental results

	Variance (^{o}C)
Overall	1.96
Location#1	2.02
Location#2	2.08
Location #3	2.11
Location #4	1.82
255 W fixed Susceptors: YES	2.08
255 W fixed Susceptors: NO	1.70
255 W Pulsed at 848 W	2.03
255 W Pulsed at 993 W	1.96
406 W fixed Susceptors: YES	2.08
406 W Fixed Susceptors: NO	1.71
406 W Pulsed at 848 W	2.04
406 W Pulsed at 993 W	2.02

The model assumes the density of the FSB was 1000 kg/m^3. The density of the shrimp after thawing was found experimentally by the method described in Chapter 3: *Experimental testing*. The densities found experimentally were between 1010 kg/m^3 and 1070 kg/m^3 and matched well with the assumed value of density, 1000 kg/m^3.

Temperature distributions predicted by the model

The temperatures predicted by the model at the four locations were within 2 ^{o}C of the experimental temperatures. From this it can be assumed that the predicted temperatures at all other locations are also within 2 ^{o}C of experimental temperatures. The model can be used to analyze various temperature profiles of the FSB. Examples of some of these possibilities are illustrated by Figures B.1-B.11 found in Appendix B.

Chapter 7

Summary and Conclusions

Summary

Microwave tempering

The thawing of shrimp is an important unit process for the seafood industry. A large portion of the shrimp sold by seafood companies in the USA is imported in the form of frozen blocks. The frozen blocks of shrimp (FSB) are usually thawed by water immersion. After thawing, the shrimp are placed are tumbled and treated with salt solutions and coloring. The shrimp are then cooked, refrozen as individual shrimp, and packaged for sale. The thawing process is extremely time consuming, which limits the flexibility of the seafood industry to adjust purchasing orders; furthermore, the traditional water immersion method produces large amounts of wastewater and disposing of this water is a major expense. There is a demand for an alternative thawing method of shrimp that is faster and produces less wastewater than the traditional method.

In this study, microwave tempering techniques were investigated as an alternative thawing method of FSB. Preliminary experiments found that microwave tempering of a FSB followed by water immersion can successfully thaw a FSB. Complete thawing of a FSB with microwave energy is not practical because of “runaway heating”. Runaway heating occurs during microwave tempering because the electric conductivity of thawed foods is about two orders of magnitude greater than frozen foods. This study explored the possibility of freezing a microwave susceptive material within the FSB to help control or eliminate runaway heating. The study determined if the addition of such a material significantly improved the microwave tempering process.

Two microwave susceptive sheets were frozen vertically within a FSB. The FSBs tested were 26.67 cm (10.5 in.) long, 19.05 cm (7.5 in.) wide, and 5.08 cm (2 in.) high. The sheets were positioned widthwise across the FSB with one sheet positioned 8.89 cm (3.5 in.) from one end of the FSB and the other sheet positioned 8.89 cm (3.5 in.) from the other end of the FSB. The FSBs with susceptors and without susceptors were tempered in a microwave oven at 255 W for 35 minutes and at 406 W for 22 minutes. These combinations of power level and microwave tempering times were based on observations made during preliminary experiments. The final stages of the thawing process were completed by water immersion. The amount of time to complete thawing (additional thawing time) and the percentage of shrimp cooked during microwave tempering were recorded and used as criteria to compare microwave tempering experiments.

The experimental results indicated that around 2% fewer shrimp are cooked during microwave tempering of a FSB with susceptors than during microwave tempering of a FSB without susceptors; furthermore, the thawing time for FSBs with susceptors is 14% less than the thawing time for FSBs without susceptors. The results found the percentage of shrimp cooked at 406 W was 5.3 and that the percentage of shrimp cooked at 255 W was only 1.4. These results indicate that significantly more shrimp are cooked at 406 W than at 255 W. The susceptive material absorbs microwave energy and helps distribute this energy to the interior of the FSB. This helps control runaway heating and reduces the number of shrimp cooked during microwave tempering. The additional thawing time was less, 1290 s, for FSB with susceptors than for FSB without susceptors, 1470 s. This is an additional indication that the material helps distribute the microwave energy.

The microwave tempering followed by water immersion method (combined method) is a significant improvement over the water immersion method (control method). When compared to the control method, the thawing process time is reduced by 45% by using the combined method with susceptors and by 43% by using the combined method without susceptors. The thawing process time is reduced from 6180 s to 3426 by using the combined method with susceptors and from 6180 s to 3523 s by using the combined method without susceptors. Although the addition of susceptors seems to improve the microwave tempering this improvement is only significant when comparing microwave tempering methods. Both combined methods, with and without susceptors, are a significant improvement over the control method. When compared to the control method, the combined method with susceptors is only 2% more effective than the combined method without susceptors. The improvements are not significant enough to justify the use of susceptors during microwave tempering of FSB. The results from the combined method at 406 W were not considered since the percentage of shrimp cooked during microwave tempering was too high, around 5%.

The second set of microwave tempering tests explored the advantages of using pulsed heat as opposed to fixed heat to temper a FSB. The pulse microwave tempering experiments were based on observations made during preliminary testing. In all, four pulse experiments were conducted. During these pulse experiments, the FSB was tempered in a microwave oven for either 35 minutes or 22 minutes by turning the microwave oven ON and then OFF in cycles at a high-power level (848 W or 993 W). The FSB was exposed to approximately 535 kJ of energy during the pulsed tempering process. Results form the fixed experiments, the microwave tempering tests conducted earlier at 255 W and 406 W, were compared to results from the pulse experiments. As before, additional thawing time and percentage of cooked shrimp were used to compare microwave tempering experiments.

The results indicated that the use of pulsed heating during microwave tempering is not an improvement over fixed heating. The amount of shrimp cooked during the 255 W pulsed at 848 W tests, the 255 W pulsed at 993 W tests, the 406 W pulsed at 848 W tests, and the 406 W pulsed at 993 W tests were 4.2, 7.0, 8.4 and 9.8 respectively. The percentage of shrimp cooked during the fixed 255 W power level condition tests was 1.7 and the percentage of shrimp cooked during the fixed 406 W power level condition tests was 5.7. The amount of shrimp cooked during pulse experiments is greater than the amount of cooked shrimp during fixed experiments especially when compared to the fixed 255 W power level tests.

There is only a 2% difference between the additional thawing times (additional thawing water amount) of the tests conducted at 406 W power level and the tests conducted at 255 W power level. The additional thawing water amount of the tests conducted at 255 W was 1632 L while the additional thawing water amount of the tests conducted at 406 W was 1665 L. The additional thawing time was slightly less for the fixed experiments, 1470 s, than for pulse experiments, 1512 s.

Cost analysis

The purpose of this section is to determine whether or not using the combined method reduces costs. To do this, the operating cost of thawing the shrimp at a plant using the current thawing method is compared to the operating cost of thawing the shrimp at a plant using the combined method. In order to accomplish this comparison, several assumptions must be made and the assumptions are described throughout the analysis. The processing plant using the current method is referred to as the old plant and the processing plant using the combined method is referred to as the new plant. The operating costs of the plant are compared. The new plant uses less water and therefore has lower water costs and surcharges; however, the new plant must pay for additional electricity that is used during microwave tempering.

Shrimp amount

It is assumed that both the new and old plant process the same amount of shrimp as a typical shrimp processing plan, around 900 kg (2000 lb) of shrimp per 8 h. It is also assumed that the new and old plants operate for 5 days a week and for 2 weekend days a month. It is assumed that the plants are closed for two weeks a year due to holidays. Therefore, the new and old plants produce around 246,600 kg (543,000 lb) of shrimp per year.

$$900\,\frac{\text{kg}}{\text{day}}\left[\frac{5\text{ day}}{1\text{ week}}\right]\left[\frac{50\text{ week}}{1\text{ year}}\right] + 900\,\frac{\text{kg}}{\text{day}}\left[\frac{2\text{ day}}{1\text{ month}}\right]\left[\frac{12\text{ month}}{1\text{ year}}\right] = 246{,}600\,\frac{\text{kg}}{\text{year}}$$

Water amount

It is assumed the old plant uses the same amount of water as a typical shrimp processing plant, around 380,000 L (100,000 gal) to process 900 kg (2000 lb) of shrimp. Since the old plant processes 900 kg of shrimp per day then it follows that the old plant use 380,000 L of water per day. Sixty percent of this water is used to thaw shrimp. This assumption was based on thawing shrimp in vats and allowing 38 L/min (10 gal/min) of water to flow through 20 stations for 5 hours.

$$38\,\frac{\text{L}}{\text{min}}\left[20\text{ stations}\right]\left[\frac{60\text{ min}}{1\text{ h}}\right]\left[\frac{5\text{ h}}{1\text{ day}}\right] = 228{,}000\,\frac{\text{L}}{\text{day}}$$

$$\frac{228{,}000\ ^{\text{L}}\!/_{\text{day}}}{380{,}000\ ^{\text{L}}\!/_{\text{day}}} \times 100 = 60\%$$

As previously mentioned, the plants operate for five days a week, fifty weeks a year, and for two weekend days a month. The new plant uses approximately 62,472,000 L (16,503,000 gal) of water per year to thaw shrimp.

$$228{,}000\,\frac{\mathrm{L}}{\mathrm{day}}\left[\frac{5\ \mathrm{day}}{1\ \mathrm{week}}\right]\left[\frac{50\ \mathrm{week}}{1\ \mathrm{year}}\right] + 228{,}000\,\frac{\mathrm{L}}{\mathrm{day}}\left[\frac{2\ \mathrm{day}}{1\ \mathrm{month}}\right]\left[\frac{12\ \mathrm{month}}{1\ \mathrm{year}}\right] = 62{,}472{,}000\,\frac{\mathrm{L}}{\mathrm{year}}$$

The old plant uses the current method to thaw shrimp. Results from this study showed that by using microwave tempering the thawing water amount can be reduced by as much as 45%. This cost analysis assumes that using the combined method reduced thawing water amount by 40%. Therefore, the new plant uses approximately 37,483,200 L (9,900,000 gal) of water per year to thaw shrimp.

Operating costs

Using the combined method has reduced the thawing water amount; however, the new plant must pay for the additional energy used to operate the microwave oven. This study showed that successful microwave tempering of a 2.25 kg (5 lb) FSB can be accomplished by using a power level of 255 W for 35 minutes. From this it is assumed that the new plant uses 535.5 kJ of energy to thaw 2.25 kg (5 lb) of shrimp, which is equal to 238 kJ/kg. The amount of energy required per year can now be calculated and is equal to 5.9×10^{7} kJ.

$$238\,\frac{\text{kJ}}{\text{kg}}\left[\frac{900\,\text{kg}}{1\,\text{day}}\right]\left[\frac{5\,\text{day}}{1\,\text{week}}\right]\left[\frac{50\,\text{week}}{1\,\text{year}}\right] +$$

$$238\,\frac{\text{kJ}}{\text{kg}}\left[\frac{900\,\text{kg}}{1\,\text{day}}\right]\left[\frac{2\,\text{day}}{1\,\text{month}}\right]\left[\frac{12\,\text{month}}{1\,\text{year}}\right] = 58{,}690{,}800\,\frac{\text{kJ}}{\text{year}}$$

The energy is purchased by the new plant in the form of electric energy or electricity and then converted to microwave energy. Only a certain percent of the electric energy is converted to microwave energy and is referred to in this study as the overall microwave oven efficiency. The efficiency is assumed by this study to be 60%. This means the new plant must pay for 97,818,000 kJ/year of electric energy in order to provide the necessary 58,690,800 kJ/year of microwave energy. At an assumed rate of $0.07/kW-h, the total operating cost of the microwave oven is equal to $1,902/year.

$$97{,}818{,}000\,\frac{\text{kJ}}{\text{year}}\left[\frac{\$0.07}{1\,\text{kW}-\text{h}}\right]\left[\frac{1\,\text{kW}-\text{h}}{3600\,\text{kJ}}\right] = \$\,1{,}902/\,\text{year}$$

Cost of water and wastewater treatment

Both the new and old plants must pay for the water used to thaw shrimp. The following assumptions are made for each plant based on conversation with Robert Lane, 1999. The plant is billed on a monthly basis and the amount of water used is assumed to be the same each month. The plant is billed $1.20 per 100 ft^3 of water for the first 3000 ft^3 and $1.08 per 100 ft^3 for the remainder of water usage. The old plant uses 62,472,000 L/year (83,847 ft^3/month) and the new plant uses 37,483,200 L/year (110,308 ft^3/month). This means the old plant is charged $23,880/year ($1,990/month) and the new plant is charged $14,700/year ($1,230/month) for the water used to thaw the shrimp.

$$3000\,ft^3\left[\frac{\$1.20}{100\,ft^3}\right]+\left[183{,}847\,ft^3-3000\,ft^3\right]\left[\frac{\$1.08}{100\,ft^3}\right]=\$1{,}990\,/\,month$$

$$3000\,ft^3\left[\frac{\$1.20}{100\,ft^3}\right]+\left[110{,}308\,ft^3-3000\,ft^3\right]\left[\frac{\$1.08}{100\,ft^3}\right]=\$1{,}230\,/\,month$$

The new and old plant must also pay for disposing of the thawing water and since the thawing water amount is different for each plant then the cost of disposing the water will also be different. The assumptions made for the cost of disposing wastewater is again based on a conversation with Robert Lane. The plant must pay surcharges and the study assumes that there are a total of three surcharges, one based on BOD (biochemical oxygen demand), one on TSS (total suspended solids), and one on TP (total phosphates).

The BOD for the new and old plant is assumed to be 757 mg/L. The plants are charged for BOD above 250 mg/L and are charged $52 per 100 kg of BOD ($23.50 per 100 lb of BOD). The old plant is charged $16,470 per year for BOD and the new plant is charged $9,882 per year for BOD.

$$62{,}472{,}000\ \frac{\mathrm{L}}{\mathrm{year}}\left[757\ \frac{\mathrm{mg}}{\mathrm{L}} - 250\ \frac{\mathrm{mg}}{\mathrm{L}}\right]\left[\frac{1\ \mathrm{kg}}{10^6\ \mathrm{mg}}\right]\left[\frac{\$52}{100\ \mathrm{kg}}\right] = \$16{,}470 / \mathrm{year}$$

$$37{,}483{,}200\ \frac{\mathrm{L}}{\mathrm{year}}\left[757\ \frac{\mathrm{mg}}{\mathrm{L}} - 250\ \frac{\mathrm{mg}}{\mathrm{L}}\right]\left[\frac{1\ \mathrm{kg}}{10^6\ \mathrm{mg}}\right]\left[\frac{\$52}{100\ \mathrm{kg}}\right] = \$9{,}882 / \mathrm{year}$$

The TSS for both plants is assumed to be equal to 356 mg/L. The plants are charged for TSS above 250 mg/L and are charged $44 per 100 kg of TSS ($19.95 per 100 lb of TSS). The old plant is charged $2,913 per year for TSS and the new plant is charged $1,748 per year for TSS.

$$62{,}472{,}000\ \frac{\mathrm{L}}{\mathrm{year}}\left[356\ \frac{\mathrm{mg}}{\mathrm{L}} - 250\ \frac{\mathrm{mg}}{\mathrm{L}}\right]\left[\frac{1\ \mathrm{kg}}{10^6\ \mathrm{mg}}\right]\left[\frac{\$44}{100\ \mathrm{kg}}\right] = \$2{,}913 / \mathrm{year}$$

$$37{,}483{,}200\ \frac{\mathrm{L}}{\mathrm{year}}\left[356\ \frac{\mathrm{mg}}{\mathrm{L}} - 250\ \frac{\mathrm{mg}}{\mathrm{L}}\right]\left[\frac{1\ \mathrm{kg}}{10^6\ \mathrm{mg}}\right]\left[\frac{\$44}{100\ \mathrm{kg}}\right] = \$1{,}748 / \mathrm{year}$$

The TP for both plants is assumed to be equal to 14 mg/L. The plants are charged for TP above 6 mg/L and are charged $237 per 100 kg of TP ($107.6 per 100 lb of TP). The old plant is charged $1,184 per year for TP and the new plant is charged $711 per year for TP.

$$62{,}472{,}000\ \frac{L}{year}\left[14\ \frac{mg}{L} - 6\ \frac{mg}{L}\right]\left[\frac{1\ kg}{10^6\ mg}\right]\left[\frac{\$237}{100\ kg}\right] = \$1{,}184\,/\,year$$

$$37{,}483{,}200\ \frac{L}{year}\left[14\ \frac{mg}{L} - 6\ \frac{mg}{L}\right]\left[\frac{1\ kg}{10^6\ mg}\right]\left[\frac{\$237}{100\ kg}\right] = \$711\,/\,year$$

Overall cost of thawing

The overall cost of thawing the shrimp at the new plant (current method) and the old plant (combined method) is listed in Table 17. The table shows that the cost of thawing at the new plant is around $30,000, which is $15,000 less than the cost of thawing at the old plant.

Table 17. Cost of thawing

	Cost per year ($/year)	
Source	Old Plant (current method)	New Plant (combined method)
Additional electricity used to operate microwave oven	0	1,902
Water usage	23,880	14,700
BOD	16,470	9,882
TSS	2,913	1,748
TP	1,184	711
TOTAL	44,447	28,943

Mathematical model

A mathematical model was developed to help predict the temperature profile of a FSB during microwave tempering. The temperature profiles predicted by the model were within 2 ^{o}C of temperature data collected during microwave tempering experiments. Various plots of the temperature profile predicted by the model can be found in Appendix B. The plots illustrate how the temperature of the FSB varies with time as well as position in the x and y directions.

The model matched well with experimental data during the initial 500 s of microwave tempering. After that, the temperatures predicted by the model were consistently less than the experimental temperatures (see Appendix E). This differences is attributed to the fact that the model assumes the properties of the FSB are equal to properties of shrimp and therefore the model over estimates the value of specific heat of the FSB. The over estimation becomes more significant in the late stages of microwave tempering when the temperature of the FSB approaches the thawing temperature of shrimp because the value of specific heat of shrimp changes dramatically around this temperature.

The model is extremely flexible and allows the user to adjust numerous conditions of the microwave tempering process such as the size of the FSB, the microwave power level, and the microwave tempering time. The model can be used to help make suggestions and design microwave tempering experiments for future study. An accurate model can eliminate the need for preliminary testing, which saves time, money, and resources.

Conclusions

The following conclusions were made from the analysis of the experimental results in this study:

1. Microwave tempering of shrimp followed by water immersion is an improvement over the traditional water immersion method. The combined method saves time and reduces the amount of wastewater.
2. The most effective microwave tempering of a 2.2 kg (5 lb) frozen block of shrimp is accomplished by using a microwave oven with a power output around 250 W. The block should be tempered in the microwave oven for 35 minutes.
3. The addition of microwave susceptive sheets did improve the microwave tempering process but not significantly enough to justify its recommendation.
4. Use of pulsed microwaves in tempering is not an improved method over fixed microwaves.
5. The temperatures predicted by the model were within 2 ^{o}C of the experimental temperatures.

Recommendation for future study

Numerous possibilities and ideas for additional study in the area of microwave tempering of shrimp were discovered during this study. This study concluded that the improvements made by the use of susceptive material are insignificant. This conclusion holds true only for the type of susceptor and positioning of susceptor used in this study. Freezing the susceptive sheets horizontally instead of vertically within the FSB might make significant improvements in microwave tempering. Furthermore, the susceptive material could be formulated into small beads and these beads could be frozen throughout the FSB. The susceptive beads may significantly improve the microwave tempering process. This study recommends exploring the advantages of making these types of changes to the geometry and positioning of the susceptive material and identifying the most effective combination. The study also recommends conducting future studies that attempt to identify the most effective type of susceptive material to use during microwave tempering of shrimp.

This study used a 2450 MHz microwave oven to conduct microwave tempering experiments. The susceptive material available in today's market is designed for use at 2450 MHz. Microwave tempering is more effective with a microwave oven that operates at 915 MHz because the penetration depth at 915 MHz is larger than at 2450 MHz. The advantages of using 915 MHz to temper FSB should be explored. The addition of a microwave susceptive material that is more effective with 915 MHz microwaves may significantly improve the microwave tempering of FSBs.

The core temperature history of a FSB tempered at 2450 MHz and at 915 MHz was predicted by using mathematical model. The results were plotted on a graph (Figure 26). The solid line represents the core temperature of FSB tempered at 915 MHz and the dashed line represents the core temperature of FSB tempered at 2450 MHz. The graph shows that the use of 915 MHz is a possible improvement. This study also recommends exploring the advantages of using radio waves to thaw FSBs since the penetration depth of radio waves is even larger than microwaves at 915 MHz.

The mathematical model was also used to determine if theoretical addition of susceptive beads would improve microwave tempering. The mathematical model with susceptive beads assumed the beads absorb 75% of microwave energy. A plot of the core temperature history of a FSB with beads and the core temperature history of a FSB without beads are shown on the same graph (Figure 27). The solid line represents the FSB with beads and the dashed line represents the FSB without beads. According to the model response, the addition of beads has improved the microwave tempering process.

Improvements to the mathematical model can be made. The predicted temperatures are less than the experimental temperatures during later stages of microwave tempering as the temperature of the FSB approaches the temperature at which the ice turns to water. The energy required for this phase change is accounted for by a temperature dependent specific heat term. This energy could also be accounted for by using enthalpy formulation. The FSB is a mixture of water and shrimp. A more precise model would use property values in between the property values of shrimp and property values of water. This is possible by simply assigning a certain number of control volumes the properties of water and the others the properties of shrimp.

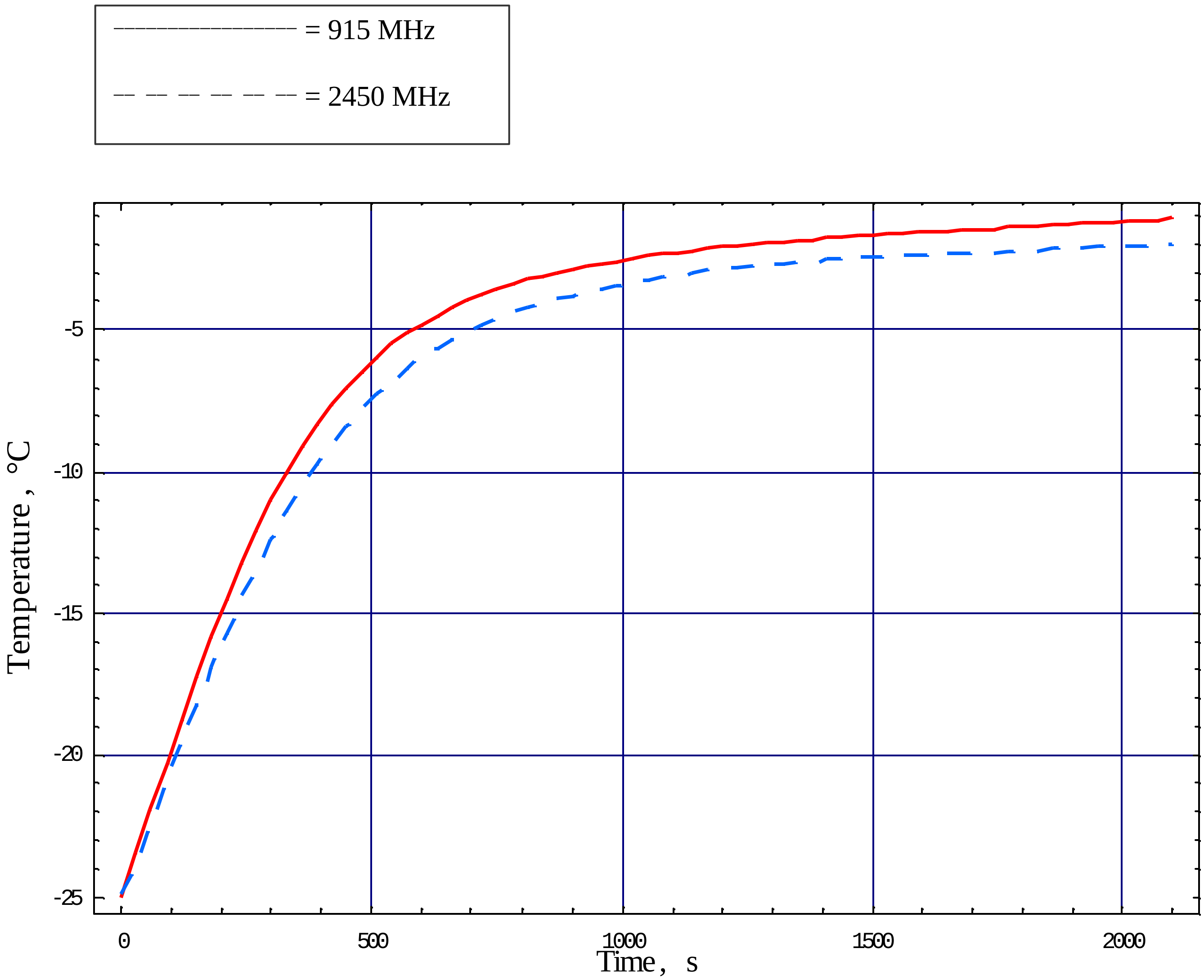


Figure 26. Core temperature history of a frozen block of shrimp during microwave tempering at 2540 MHz and 250 W and at 915 MHz and 250 W.

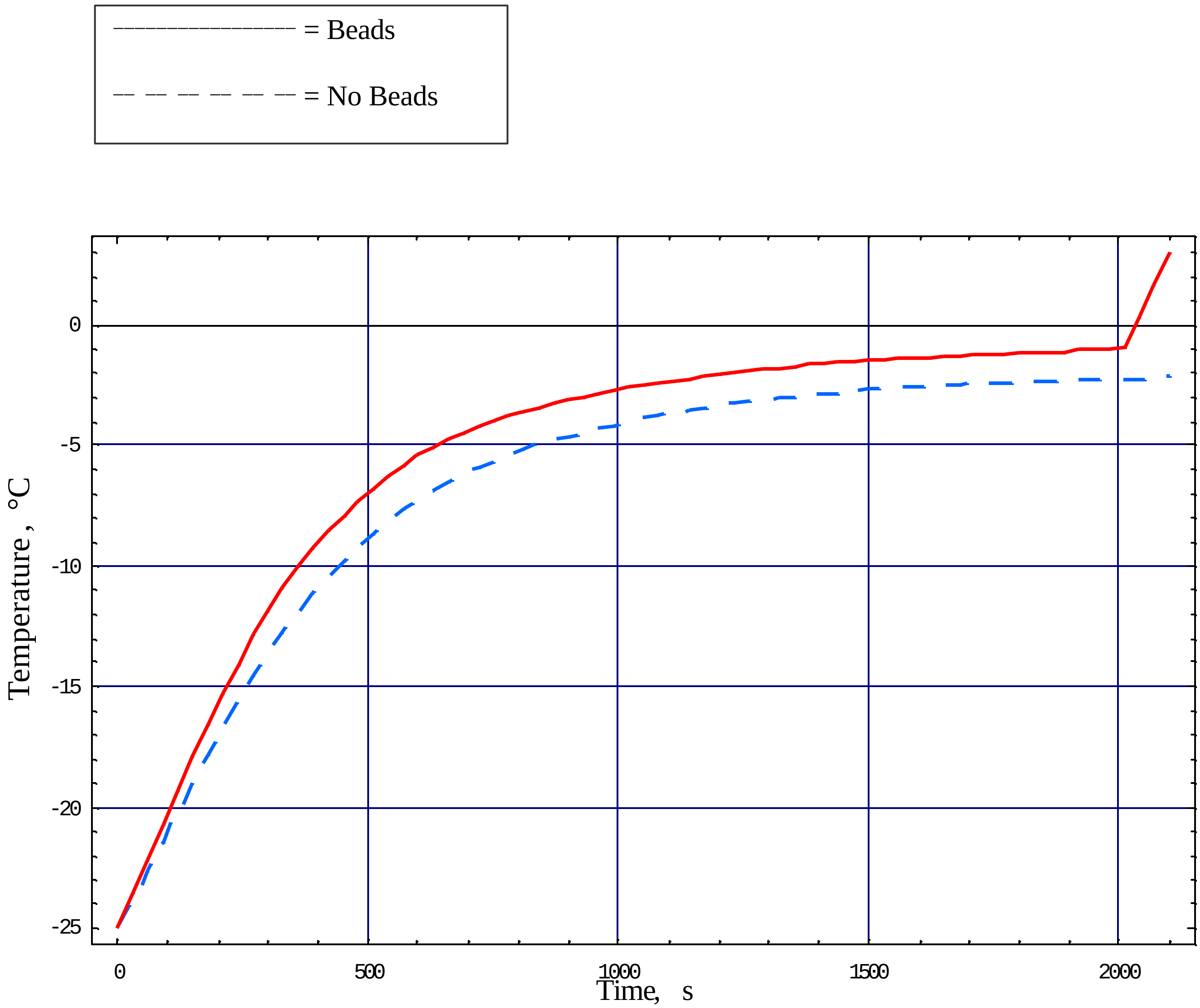


Figure 27. Core temperature history of a FSB during microwave tempering at 2450 MHz with susceptive beads and without susceptive beads.

References

Andreasen, M. 1988. New technologies to improve susceptor efficiencies in microwave packages. In *Proc. of the 31st Annual Technical Conference of the Society of Vacuum Coaters*, 133-138. San Francisco, CA

Babbitt, R.J. 1992. Microwave Food Package with Printed-On Susceptor. US Patent No. 5171594.

Bandyopadhyay, S., Karunkar, B. and Mishra, K. 1998. Specific Heat and Thermal Conductivity of Shrimp Meat. Journal of Food Engineering 37: 345-351.

Benzanson, A., Learson, R., and Teich, W. 1973. Defrosting shrimp with microwaves. Microwave Energy Appl. Newsl. 6(4): 3-8.

Bengtsson, N.E. 1963. Electronic defrosting of meat and fish at 35 and 2450 Mc. A laboratory comparison. Food Tech. 17(10): 92-100.

Brastad, W. A. 1980. Method and Material for Preparing Food to Achieve Microwave Browning. US Patent No. 4230924.

Brastad, W. A. 1981. Packaged Food Item and a method for achieving browning thereof. US Patent No. 4267420.

Brown, G.H., Hoyler, C.N., and Bierwirth, R.A. 1947. *Theory and Application of Radio-Frequency Heating.* New Jersey: Van Nostrand-Reinhold.

Buffler, C. 1991. A simple approach to the calculation of microwave absorption, transmission, and reflection of a microwave susceptor film. Microwave World 12(3): 5-7.

Cathcart, W.H., and Parker, J.J. 1946. Defrosting foods with high-frequency heat. Food Res. 11: 341-344.

Collie, C.H., Hasted, J.B., and Ritson, D.M. 1948. The dielectric properties of water and heavy water. Proc. R. Soc. London 60:140-160.

Decareau, R.V. 1968. High frequency thawing of foods. Microwave Energy Appl. Newsl. 1(2): 3-6,12.

Decareau, R.V. and Peterson, R.A. 1986. *Microwave Processing and Engineering.* Florida: VCH Publications.

Ede, A.J., and Haddow, R.R. 1951. The electrical properties of foods at high frequencies. Food Manufacturing 26(4): 156-160.

Hasted, J.B., Ritson, D.M., and Collie, C.H. 1948. Dielectric properties of ionic solutions. Parts 1 and 2. J. Chem. Phys. 16: 1-21.

Incropera, F.P. 1990. *Fundamentals of Heat and Mass Transfer.* New York: Jon Wiley and Sons.

Keithly, W.R., Roberts, K.J., Ward, J.M. 1993. Effects of shrimp aquaculture on U.S. market: an economic analysis. Aquaculture: models and economics. 125-156.

Lane, Robert. Personal communication, Blacksburg, VA, 14 December 1999.

Learson, R.J., and Stone, W.B. 1969. Microwave opening of oysters: some economic considerations. Microwave Energy Appl. Newsl. 2(5): 9-12.

Lindstrom, T. 1990. Evaluating the comparative performance of microwave susceptors. In *Proc. of Pack Alimentaire.* San Fransico, CA

Lund, A.A. 1945. Electronics makes a first beach-head in frozen food field. Food Material Equipment 5(9): 2.

Mallikarjunan, P. and Mittal, G.S. 1994. Heat and mass transfer during beef carcass chilling – modelling and simulation. Journal of Food Engineering 23: 277-292.

Mallikarjunan, P., Hung, Y-C., Brackett, R.E., and Hao, Y-Y. 1994. Modeling Heat and Mass Transfer and Microbial Inactivation Kinetics During Microwave Cooking of Chicken Breast. *Winter meeting sponsored by ASAE*. Atlanta, GA, 13-16 December.

Mallikarjunan, P, Hung, Y.-C., and Tanaka, F. 1999. Dielectric Properties of Shrimp Related to Microwave Frequencies: From Frozen to Cooked Stages. Accepted for publications in Journal of Food Process Engineering.

Martin, E.F. 1945. Electronic device defrosts frozen fruits. Ice Cream Field 45(5): 18-20.

Meisel, N. 1972. Tempering of meat by microwaves. Microwave Energy Appl. Newsl. 5(3): 3-7.

Mishra, S. K. 1997. A Density Prediction Model in Relationship to Shrimp Freezing Process. Journal of Food Science and Technology, 34 (4): 348-351.

Ohlsson, T., and Benggtsson, N. 1971. Microwave heating profiles in foods: a comparison between heating experiments and computer simulation. Microwave Energy Appl. Newsl. 4(6): 3-8.

Olsen, R.L., Johansen, A., Myrnes, B. 1990. Recovery of enzymes from shrimp waste. Process Biochemistry. 25(2): 67-68.

Roberts, J.S., Balaban, M.O., Zimmerman, R., Luzuriaga, D. 1998. Design and testing of a prototype ohmic thawing unit. Computers and Electronics in Agriculture. 19(2): 211-212.

Schiffman, R.F. 1986. Food product development for microwave processing. Food Tech. 40(6): 94-98.

Shang, Y.C., Leung, P., Ling, B.-H. 1998. Comparative economics of shrimp farming in Asia. Aquaculture. 164(1-4): 183-200.

Succar J., and Hayakawa, K. 1984. Parametric Analysis for Predicting Freezing Time of Infinitely Slab-Shaped Food. Journal of Food Science 49: 468-477.

Succar, J. 1989. Heat Transfer During Freezing and Thawing of Foods. In *Developmeants in Food Preservation- 5*, ed. S. Thorne, ch. 7, 253-304. New York: Elsevier Science Publishers LTD.

Swami, S. 1982. Microwave heating characteristics of simulated high moisture foods. MS Thesis, University of Massachusetts, Amherst, Massachusetts.

Taoukis, P., Davis, E.A., Davis, H.T., Gordon, J., and Talmon, Y. 1987. Mathematical modeling of microwave thawing by modified isotherm migration method. Journal of Food Science 52(2): 455-463.

Turpin, C.H., and Hoese, T.C. 1978. Microwave Heating Package and Method. US Patent No. 4190757.

Turpin, C. 1989. Browning and crisping: the functions, design and operation of susceptors. Microwave World 10 (6): 8-13.

Vick, B. 1997. ME 5304: Conduction Heat Transfer Class notes. The Virginia Polytechnic and State University, Blacksburg, Virginia.

Wang, D.I.C., and Goldblith, S.A. 1976. *Dielectric Properties of Foods*. Massachusetts: U.S. Army Natick Development Center.

Winters, W.C., Chang, H.-H., Anderson, G.R., Easter, R.A., and Sholl, J.J. 1981. Microwave Heating Package, Method and Susceptor Composition. US Patent No. 4283427.

Zhou, L, Puri, V.M., Amantheswaran, and Yeh, G. 1995. Finite Element Modeling of Heat and Mass Transfer in Food Materials During Microwave Heating – Model Development and Validation. Journal of Food Engineering 25: 509-529

Appendix A

Derivation of Finite Difference Equations

Notation

p integer indicator of time

pp total number of time steps

Δt_p time step length (s)

m integer indicator in x-direction for a typical CV

mm total number of CV's in the x-direction

? x_m x-direction length of typical CV "m,n" (m)

x_m x-location of the center of typical CV "m,n" (m)

n integer indicator in y-direction for a typical CV

nn total number of CV's in the y-direction

? y_n y-direction length of typical CV "m,n" (m)

y_n y-location of the center of typical CV "m,n" (m)

E designates the east side face of the CV

W designates the west side face of the CV

N designates the north side face of the CV

S designates the south side face of the CV

$T_{m,n}$ temperature at the center of CV “m,n” (^{o}C)

? x_E distance between the center of CV “m,n” and its east neighbor “m+1,n” (m)

? x_W distance between the center of CV “m,n” and its west neighbor “m-1,n” (m)

? y_N distance between the center of CV “m,n” and its north neighbor “m,n+1” (m)

? y_S distance between the center of CV “m,n” and its south neighbor “m,n-1” (m)

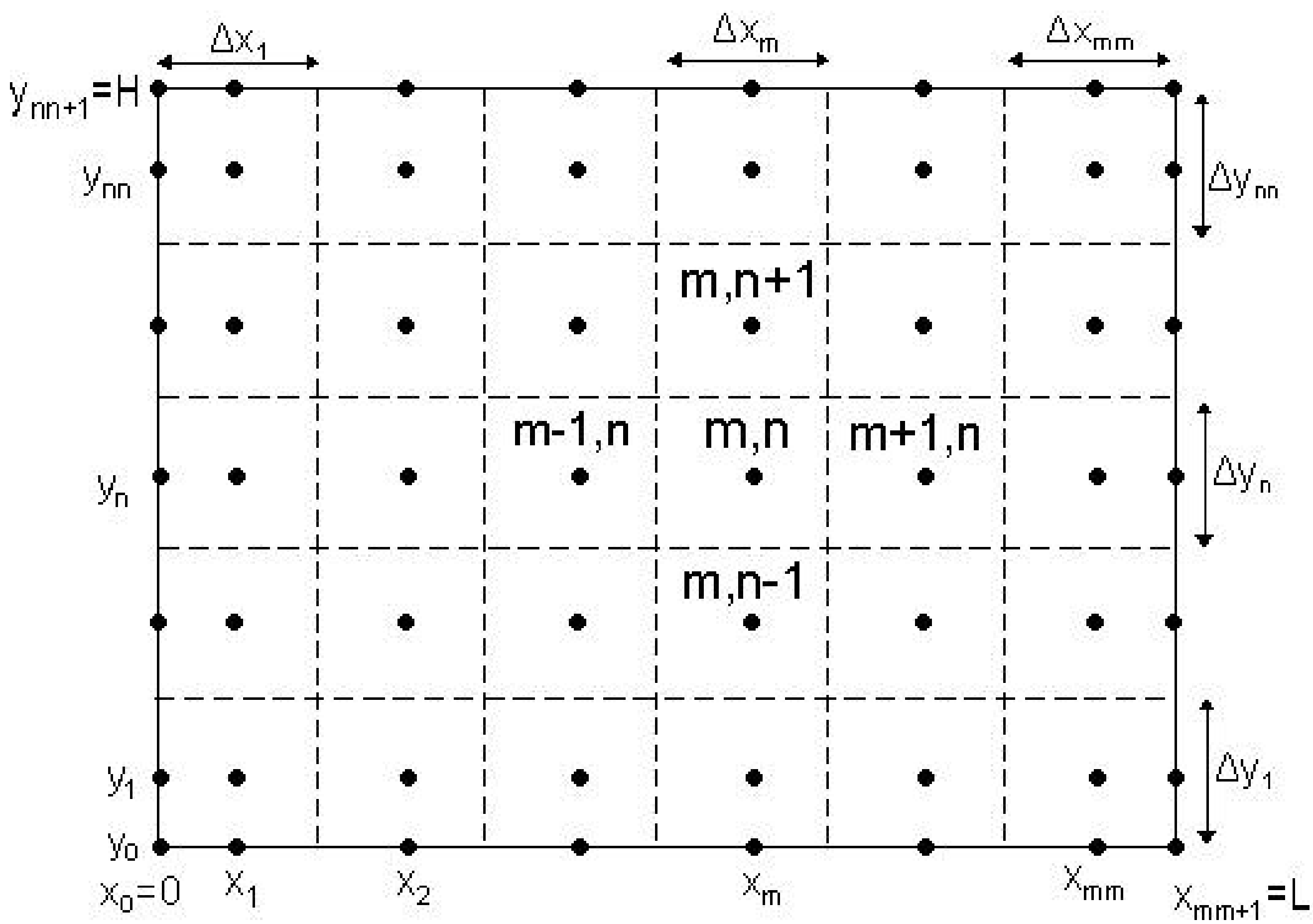


Figure 2. Control volume discretization (Vick, 1997)

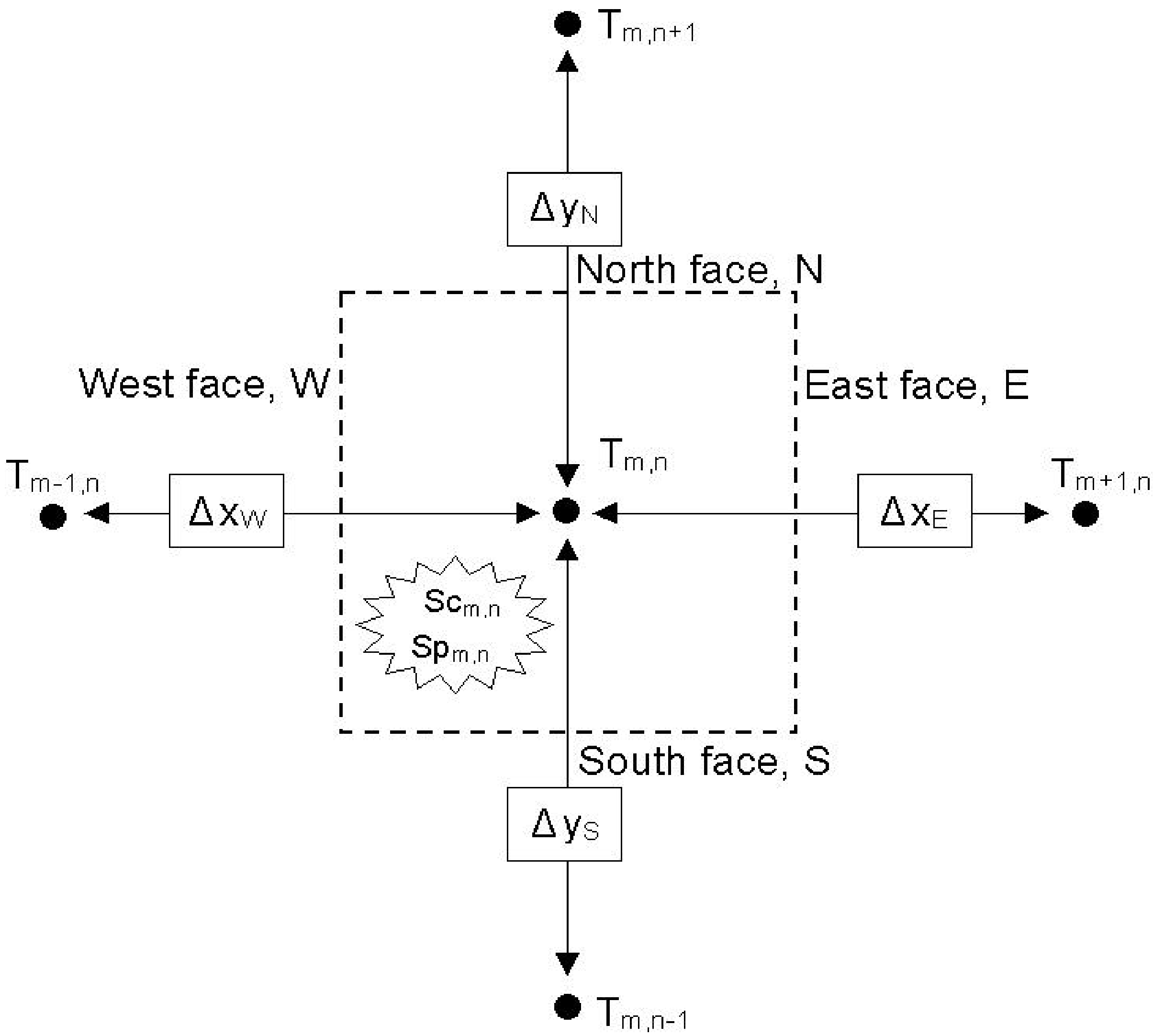


Figure 3. Typical control volume "m,n" (Vick, 1997)

$$\int_{t_{p-1}}^{t_p}\int_S^N\int_W^E\left[\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+S_c(x,t)-S_p(x,t)-?C_p\frac{\partial T}{\partial t}\right]dxdydt=0$$

Integrate the energy equation over a typical control volume "m,n" and over the time interval t_{p-1} and t_p. For convenience, the energy equation is divided into three terms before performing

$$\int_{t_{p-1}}^{t_p} T dt = T^p ?\, t_p$$

integration. The equation is integrated over time in a fully implicit manner, where the temperature over each time interval is evaluated at the end of each time interval. The temperature T^p is the temperature at time level t_p and represents the average temperature over the time interval $?t_p$ preceding time t_p.

Now perform integration of each term in the energy equation.

$$A = \int_{t_{p-1}}^{t_p}\int_S^N\int_W^E \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)dxdydt$$

$$A = \int_{t_{p-1}}^{t_p}\int_S^N\left[\left(k\frac{\partial T}{\partial x}\right)_E-\left(k\frac{\partial T}{\partial x}\right)_W\right]dydt$$

$$A = \int_{t_{p-1}}^{t_p}\int_S^N\left[k_E\left(\frac{T_{m+1,n}-T_{m,n}}{?x_E}\right)-k_W\left(\frac{T_{m,n}-T_{m-1,n}}{?x_W}\right)\right]dydt$$

$$A = \int_S^N\left[k_E\left(\frac{T^P_{m+1,n}-T^p_{m,n}}{?x_E}\right)-k_W\left(\frac{T^P_{m,n}-T^P_{m-1,n}}{?x_W}\right)\right]?t^P dy$$

$$A = \left[k_E\left(\frac{T^P_{m+1,n}-T^P_{m,n}}{?x_E}\right)-k_W\left(\frac{T^P_{m,n}-T^P_{m-1,n}}{?x_W}\right)\right]?t^P?y_n$$

$$B = \int_{t_{p-1}}^{t_p} \int_S^N \int_W^E \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) dxdydt$$

$$B = \int_{t_{p-1}}^{t_p} \int_W^E \left[\left(k \frac{\partial T}{\partial y} \right)_N - \left(k \frac{\partial T}{\partial y} \right)_S \right] dxdt$$

$$B = \int_{t_{p-1}}^{t_p} \int_W^E \left[k_N \left(\frac{T_{m,n+1} - T_{m,n}}{?y_N} \right) - k_S \left(\frac{T_{m,n} - T_{m,n-1}}{?y_S} \right) \right] dxdt$$

$$B = \int_W^E \left[k_N \left(\frac{T^P_{m+1,n} - T^P_{m,n}}{?y_N} \right) - k_S \left(\frac{T^P_{m,n} - T^P_{m-1,n}}{?y_S} \right) \right] ?t^P dx$$

$$B = \left[k_N \left(\frac{T^P_{m+1,n} - T^P_{m,n}}{?y_N} \right) - k_S \left(\frac{T^P_{m,n} - T^P_{m-1,n}}{?y_S} \right) \right] ?t^P ?y_n$$

$$C = \int_{t_{p-1}}^{t_p} \int_S^N \int_W^E \left[Sc_{m,n,p} - Sp_{m,n,p} T \right] dxdydt$$

$$C = \left[Sc_{m,n,p} - Sp_{m,n,p} T \right] ?x_m ?y_n ?t^P$$

$$D = \int_{t_{p-1}}^{t_p} \int_S^N \int_W^E \left[?Cp \frac{\partial T}{\partial t} \right] dxdydt$$

$$D = \int_S^N \int_W^E ?Cp \left[T^P - T^{P-1} \right] dxdy$$

$$D = ?Cp \left[T^P_{m,n} - T^{P-1}_{m,n} \right] ?x_m ?y_n$$

Substitute these terms, A, B, C and D, rearrange and divide through by $? t_p$.

$$? y_n\left(\frac{k_E}{? x_E}T^P_{m+1,n}\right)+ ? y_n\left(\frac{k_W}{? x_W}T^P_{m-1,n}\right)- ? y_n\left(\frac{k_E}{? x_E}T^P_{m,n}\right)- ? y_n\left(\frac{k_W}{? x_W}T^P_{m,n}\right)+$$

$$? x_m\left(\frac{k_N}{? y_N}T^P_{m,n+1}\right)+ ? x_m\left(\frac{k_S}{? y_S}T^P_{m,n-1}\right)- ? x_m\left(\frac{k_N}{? y_N}T^P_{m,n}\right)- ? x_m\left(\frac{k_N}{? y_N}T^P_{m,n}\right)+$$

$$Sc_{m,n,p}? x_m ? y_n - Sp_{m,n,p}T^P_{m,n}? x_m ? y_n - ?CpT^{P}_{m,n}? x_m ? y\frac{1}{? t_p} + ?CpT^{P-1}_{m,n}? x_m ? y\frac{1}{? t_p} = 0$$

Group terms and multiply through by –1.

$$T^P_{m,n}\left(?Cp?x_m ? y_n\frac{1}{? t_P} + ? y_n\frac{k_E}{? x_E} + ? y_n\frac{k_W}{? x_W} + ? x_m\frac{k_N}{? y_N} + ? x_m\frac{k_S}{? y_S} + Sp_{m,n,p}? x_m ? y_n\right)$$

$$- T^P_{m+1,n}\left(? y_n\frac{k_E}{? x_E}\right) - T^P_{m-1,n}\left(? y_n\frac{k_W}{? x_W}\right) - T^P_{m,n+1}\left(? x_m\frac{k_N}{? x_N}\right) - T^P_{m,n-1}\left(? x_m\frac{k_S}{? x_S}\right) =$$

$$Sc_{m,n,p}? x_m ? y_n + ?Cp?x_m ? y_n\frac{1}{? t_P}T^{p-1}_{m,n}$$

The solution is now presented in the following form:

$$a_{m,n}T^p_{m,n} - aW_{m,n}T^p_{m-1,n} - aE_{m,n}T^p_{m+1,n} - aS_{m,n}T^p_{m,n-1} - aN_{m,n}T^p_{m,n+1} = b_{m,n}$$

where

$$aW_{m,n} = ?\,y_n \frac{k_W}{?\,x_W} = ?\,y_n \left(\frac{2k_{m-1,n}k_{m,n}}{?\,x_{m-1}k_{m,n} + ?\,x_m k_{m-1,n}} \right)$$

$$aE_{m,n} = ?\,y_n \frac{k_E}{?\,x_E} = ?\,y_n \left(\frac{2k_{m+1,n}k_{m,n}}{?\,x_{m+1}k_{m,n} + ?\,x_m k_{m+1,n}} \right)$$

$$aS_{m,n} = ?\,x_m \frac{k_S}{?\,y_S} = ?\,x_m \left(\frac{2k_{m,n-1}k_{m,n}}{?\,y_{n-1}k_{m,n} + ?\,y_n k_{m,n-1}} \right)$$

$$aN_{m,n} = ?\,x_m \frac{k_n}{?\,y_n} = ?\,x_m \left(\frac{2k_{m,n+1}k_{m,n}}{?\,y_n k_{m,n=1} + ?\,y_{n+1}k_{m,n}} \right)$$

$$aO_{m,n} = (?C_p)_{m,n}\, ?\,x_m ?\,y_n \frac{1}{?\,t_p}$$

$$a_{m,n} = aO_{m,n} + aW_{m,n} + aE_{m,n} + aS_{m,n} + aN_{m,n} + Sp^p_{m,n}\, ?\,x_m ?\,y_n$$

$$b_{m,n} = aO_{m,n} T^{p-1}_{m,n} + Sc^p_{m,n}\, ?\,x_m ?\,y_n$$

The thermal conductivity, k could vary from one control volume to the next. The harmonic mean is used to calculate the thermal conductivity, k_E, k_W, k_S, and k_N, which represent the thermal conductivity at the interface of the control volumes.

Appendix B

Predicted Temperature Profiles

A mathematical heat transfer model was developed in MATHEMATICA 3.0.1 that predicts the temperature profiles of a frozen block of shrimp during microwave tempering. The temperatures predicted by the model are a function time and of position in the x-direction and y-direction. The model was run and numerous plots illustrating how the temperature varies during microwave tempering were produced. This appendix contains some of these plots.

The model was run under the following conditions. A time step of 30 seconds was used, the length was 26.67 cm (10.5 in.), the width was 19.05 cm (7.5 in.), and the height was 5.08 cm (2 in.). The FSB was divided into control volumes of equal size with 19 control volumes in the x-direction and 9 control volumes in the y-direction. The initial temperature of the FSB was -25 ^{o}C, the ambient temperature was 20 ^{o}C, and the convection heat transfer coefficient at all four boundaries was equal to 25 W/m^{2}-^{o}C. The moisture content was 0.80 and the density was 1000 kg/m^{3}.

Figure B.1 is a plot of temperature at midway point of the height, y = H/2, as a function of position in the x-direction. The figure contains three plots one at time = 450 s, one at time = 1050 s, and one at time = 1650 s. Figure B.2 is a plot of temperature at the midway point of the length, x = L/2, as a function of position in the y-direction. The figure also contains three plots one at time = 450 s, one at time = 1050 s, and one at time = 1650 s. Figures B.3-B.5 are three-dimensional graphs that illustrate the temperature distribution at time = 450 s, time = 1050 s, and time = 1650 s as a function of x and y position. Figures B.6-B.8 are three-dimensional graphs of the temperature distribution at y = H/2 as a function of x position and time. Figures B.9-B.11 are three-dimensional graphs of the temperature distribution at x = L/2 as a function of y position and time. Figures B.6 and B.9 show the temperature distribution during initial stages of microwave tempering, from time = 0 s until time = 300 s. Figures B.7 and B.10 show the temperature distribution during middle stages of microwave tempering, from time = 750 s until time = 1050 s. Figures B.8 and B.11 show the temperature distribution during initial stages of microwave tempering, from time = 1500 s until time = 1800 s.

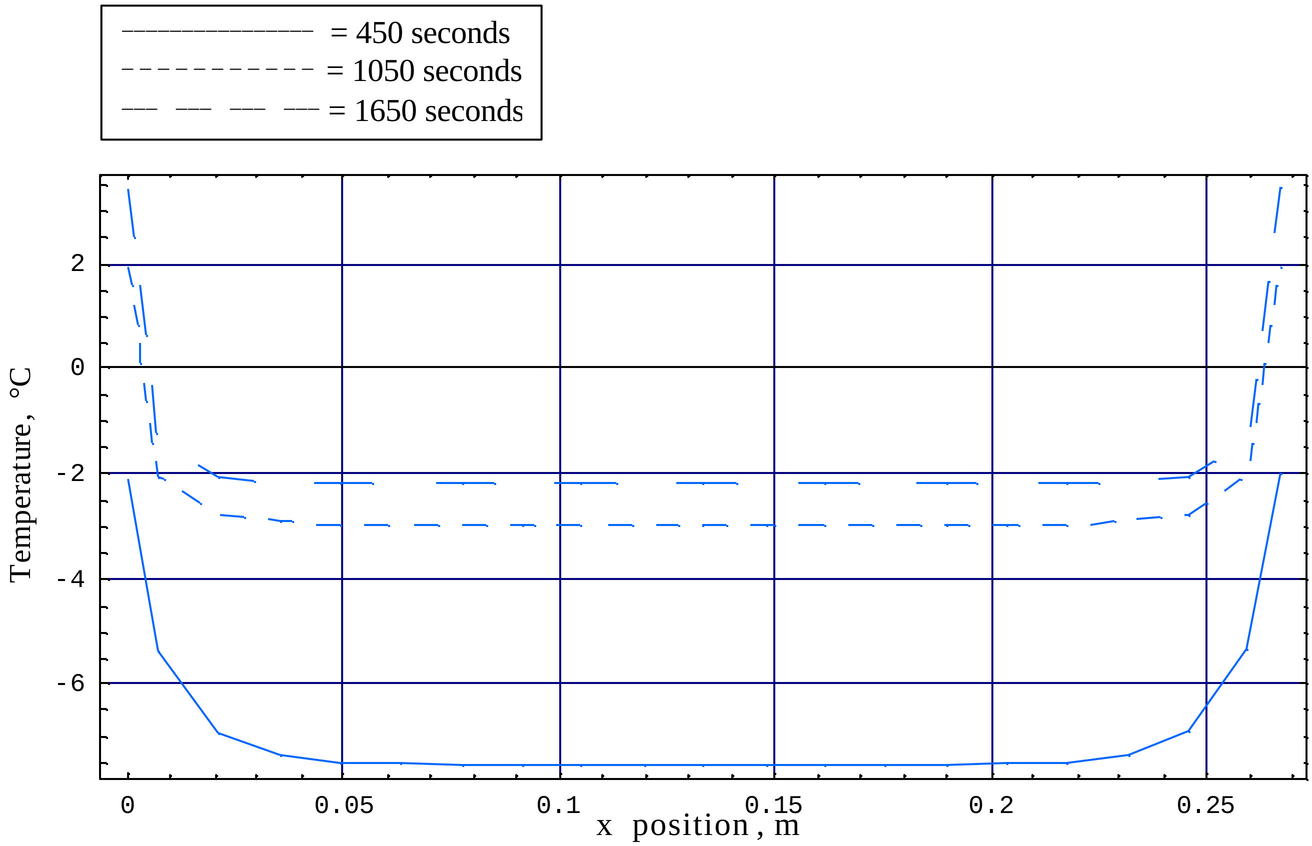


Figure B.1. Predicted temperature distribution as a function of position in x-direction, Y = H/2

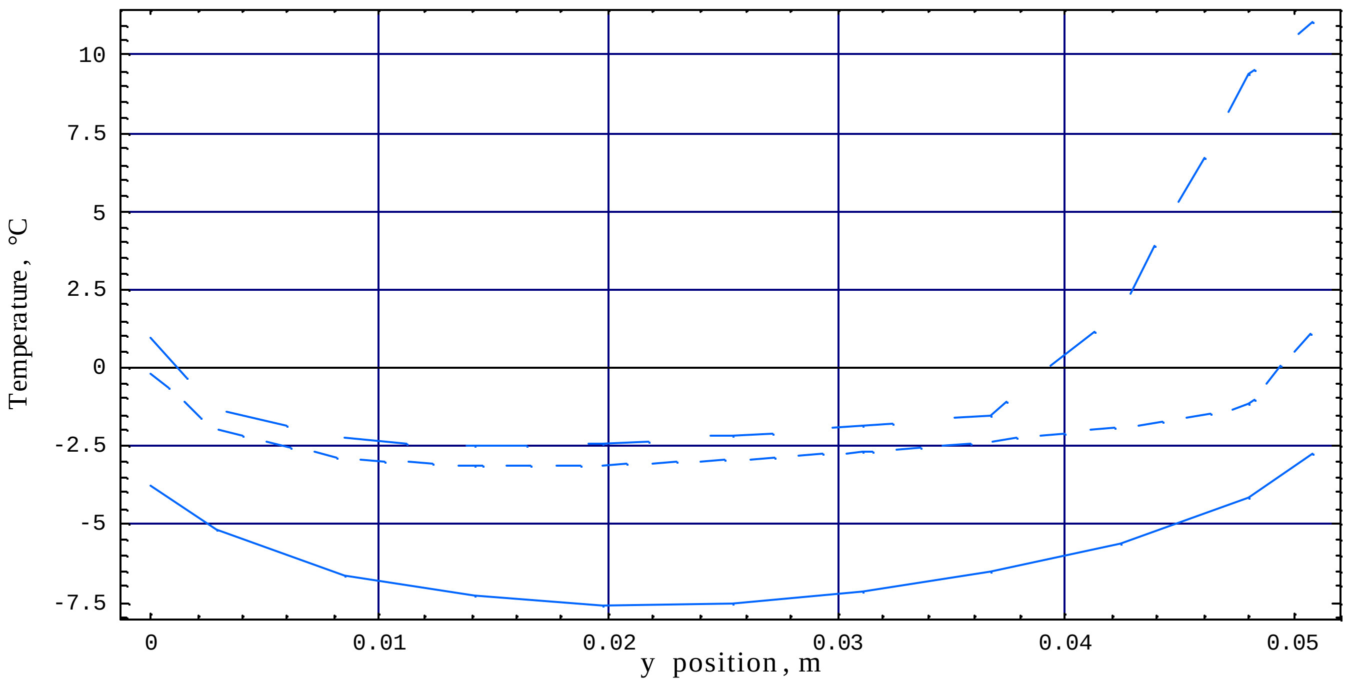


Figure B.2. Predicted temperature distribution as a function of position in y-direction, x = L/2

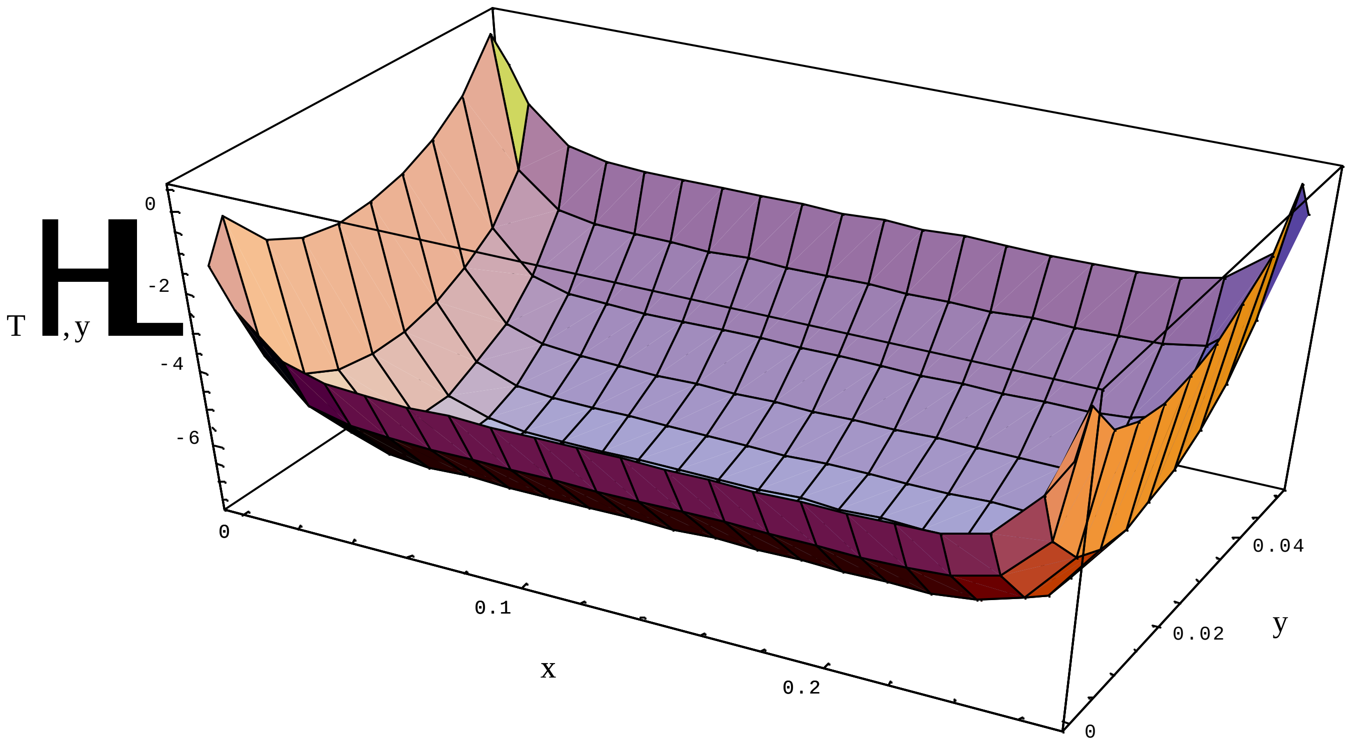


Figure B.3. Predicted temperature distribution of a FSB as a function of position, time = 450 s

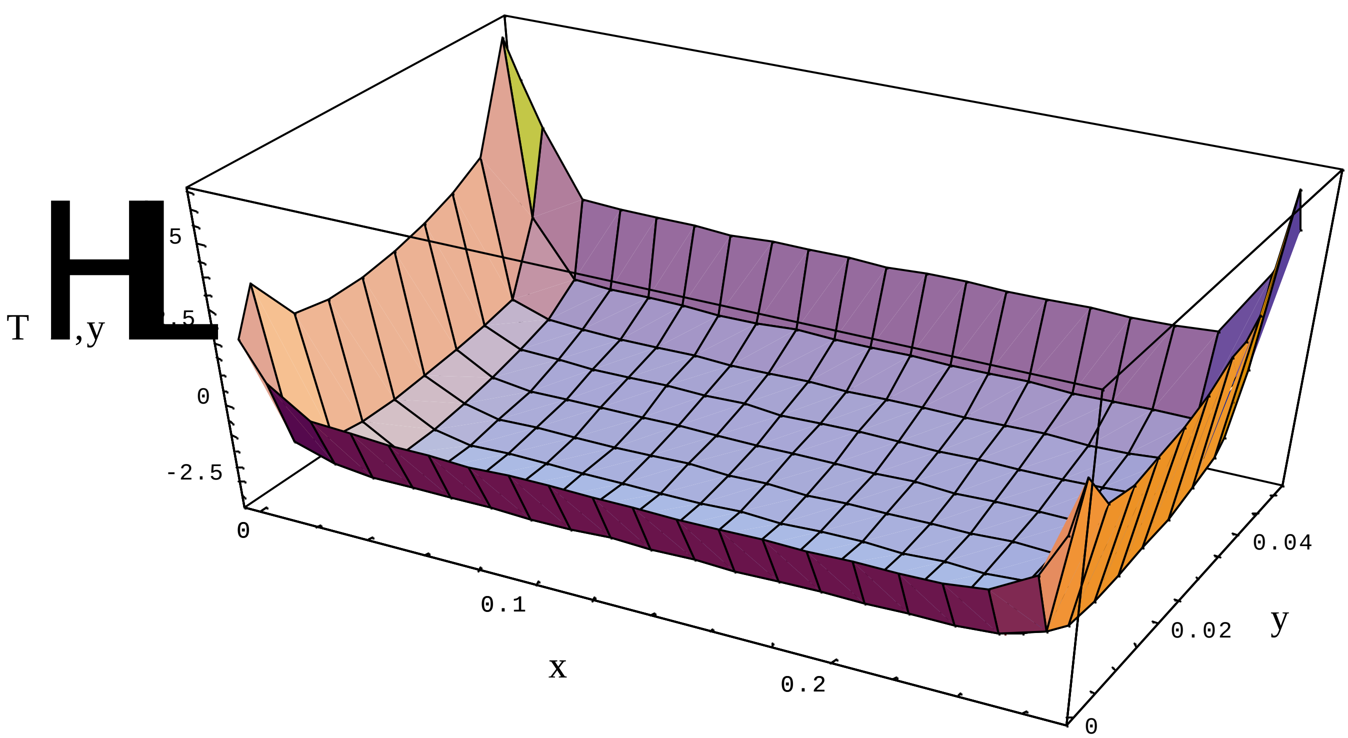


Figure B.4. Predicted temperature distribution of a FSB as a function of position, time = 1050 s

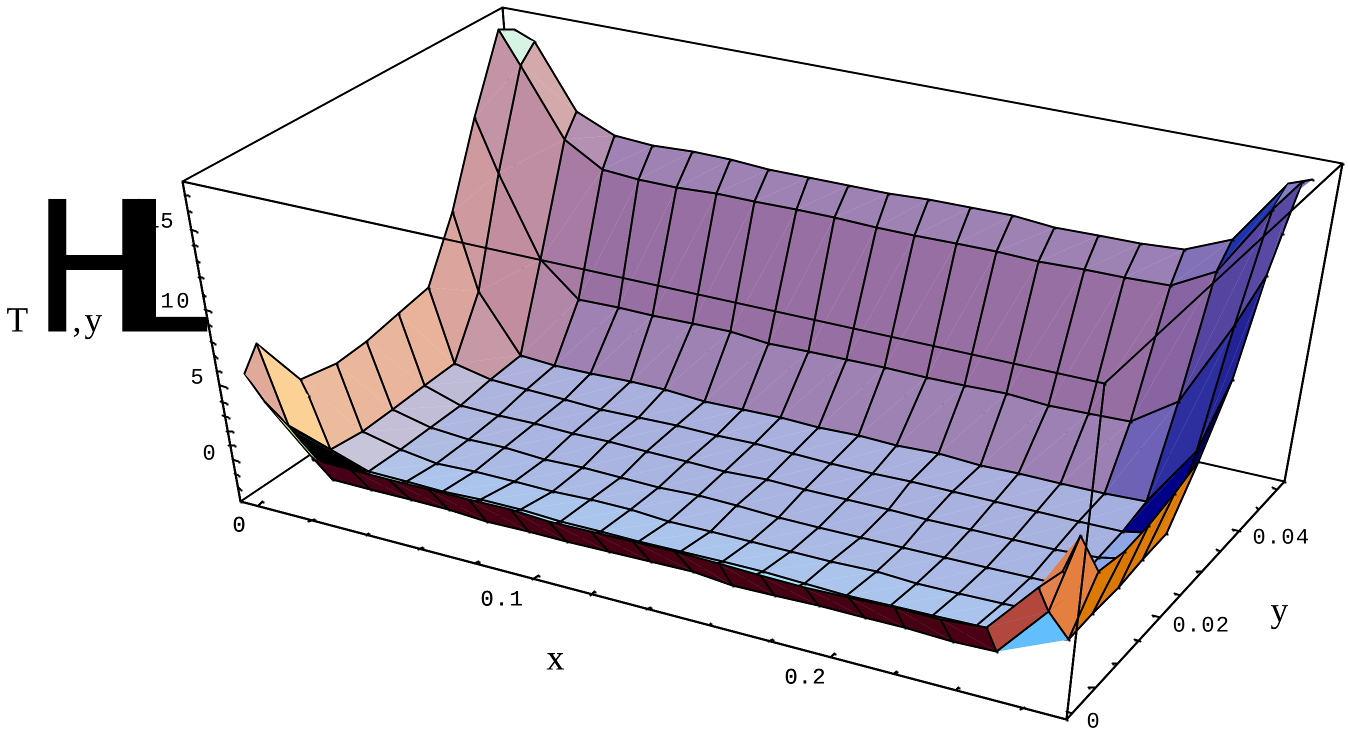


Figure B.5. Predicted temperature distribution of a FSB as a function of position, time = 1650 s

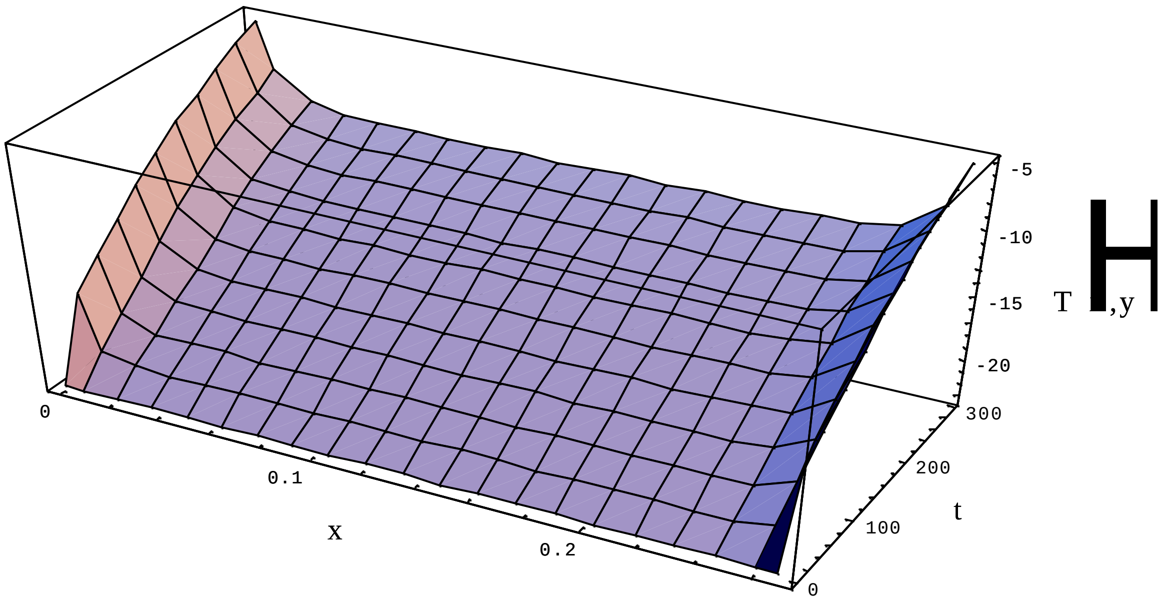


Figure B.6. Predicted temperature distribution of a FSB as a function of position in the x-direction from t = 0 seconds until t = 300 seconds. y = H/2.

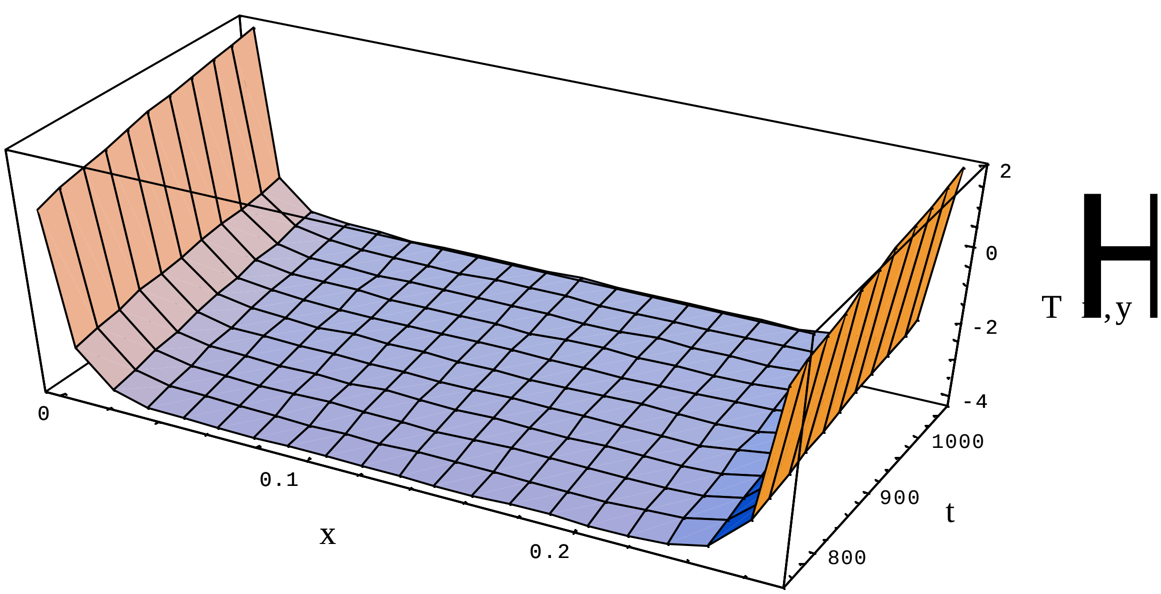


Figure B.7. Predicted temperature distribution of a FSB as a function of position in the x-direction from t = 750 seconds until t = 1050 seconds. y = H/2.

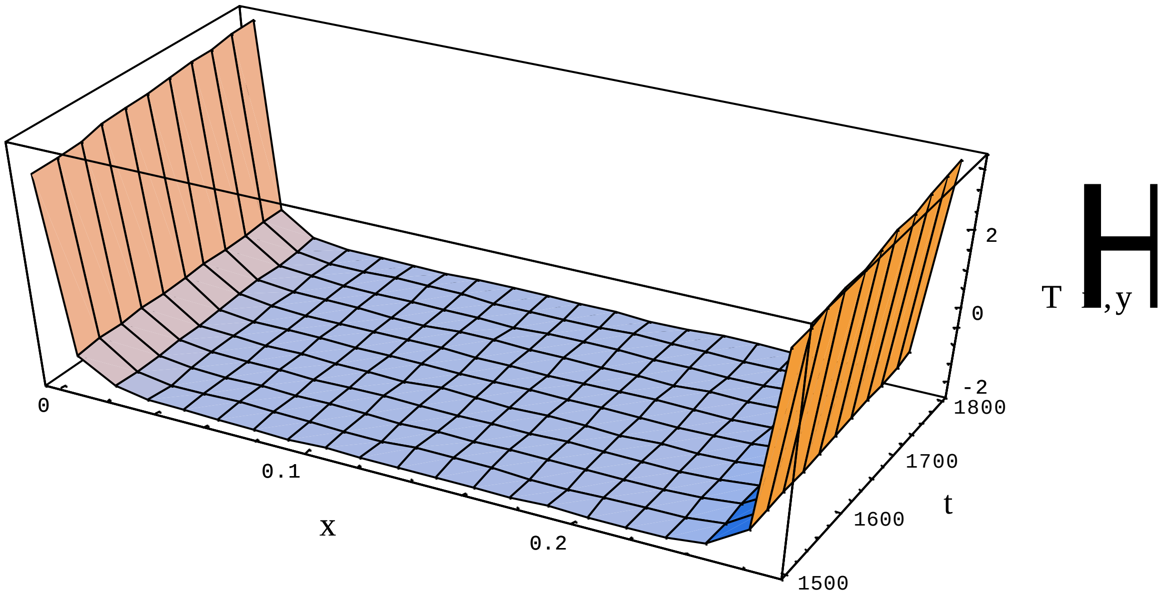


Figure B.8. Predicted temperature distribution of a FSB as a function of position in the x-direction from t = 1500 seconds until t = 1800 seconds. y = H/2.

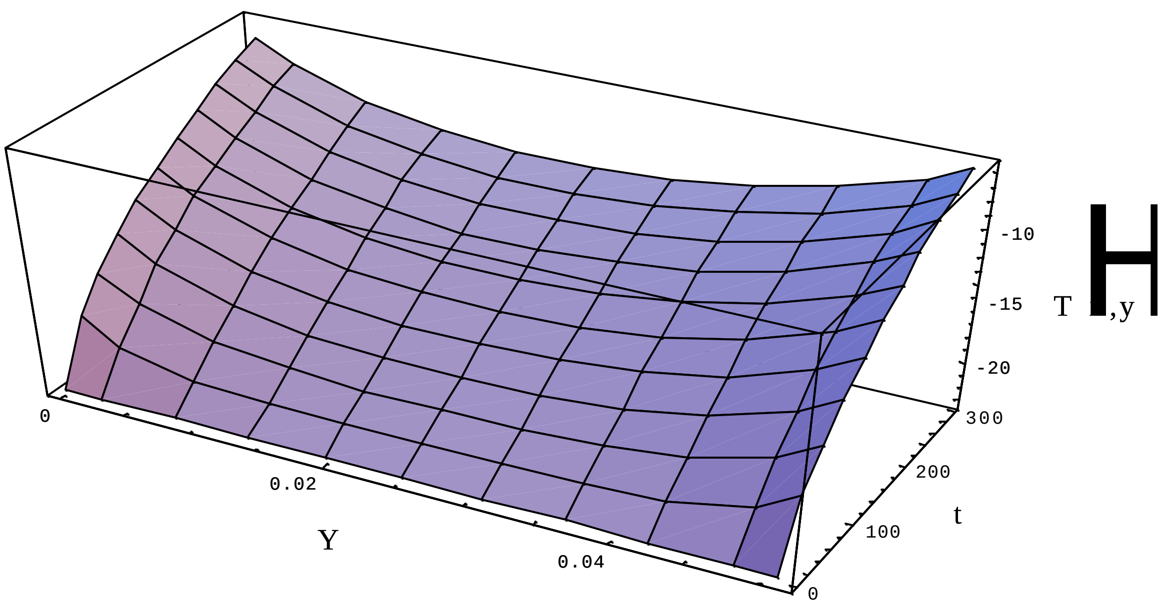


Figure B.9. Predicted temperature distribution of a FSB as a function of position in the y-direction from t = 0 seconds until t = 300 seconds. x = L/2.

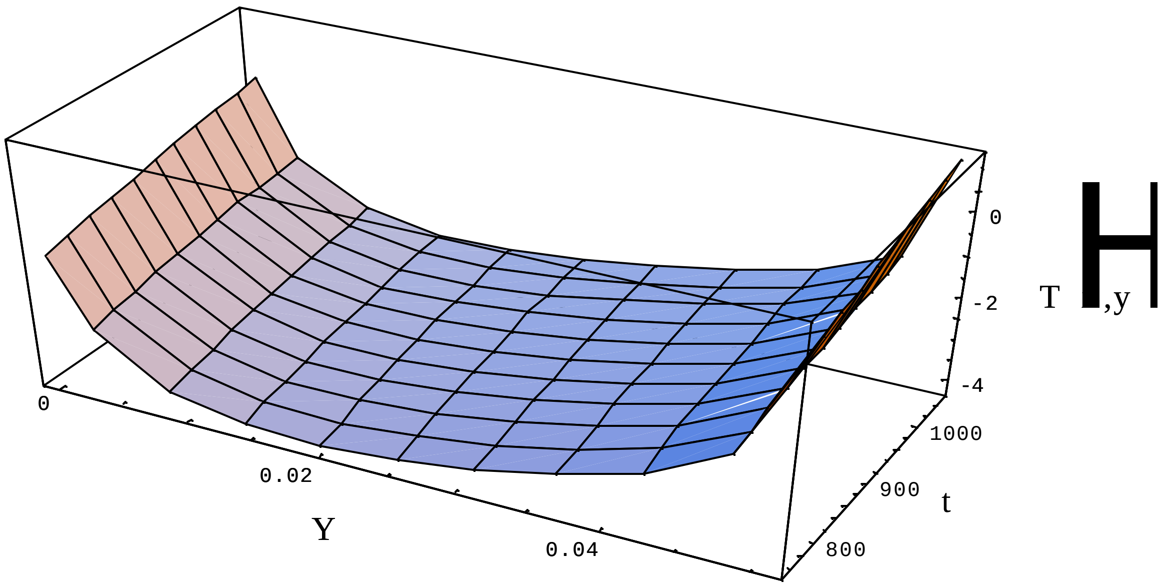


Figure B.10. Predicted temperature distribution of a FSB as a function of position in the y-direction from t = 750 seconds until t = 1050 seconds. x = L/2.

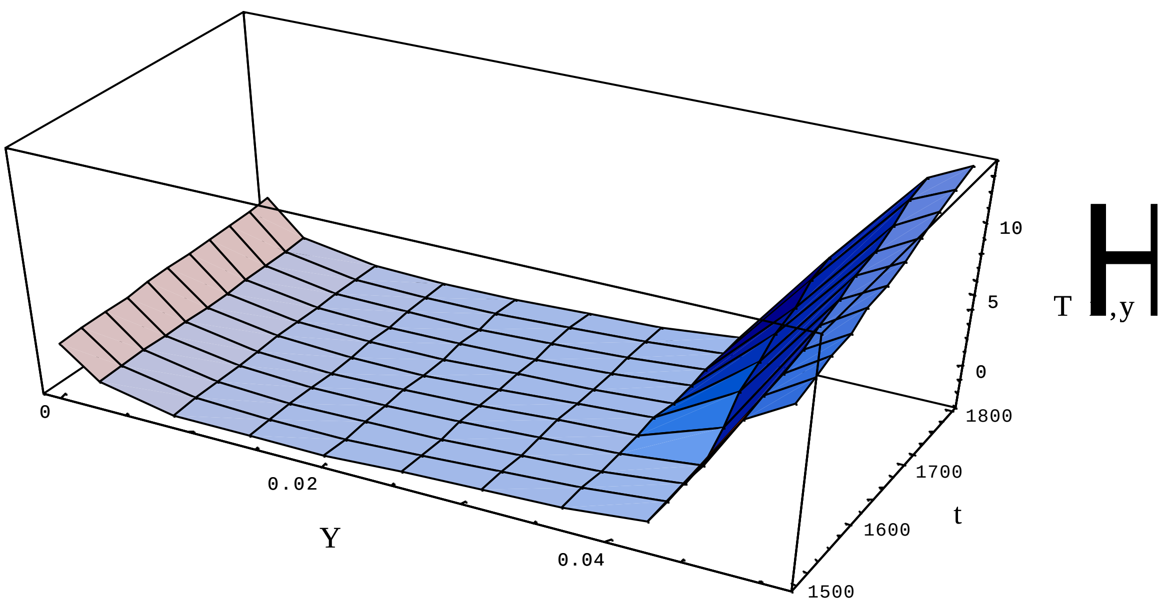


Figure B.11. Predicted temperature distribution of a FSB as a function of position in the y-direction from t = 1500 seconds until t = 1800 seconds. x = L/2.

Appendix C

Calculation of Power Output

Measuring the power output of a microwave is accomplished by following the procedure set by the International Microwave Power Institute. First, heat two liters of water in the microwave oven for 120 seconds and note the temperature change. Equation 2.6 can then be used to calculate power output. The density of water was assumed to be equal to 1 g/ml and the specific heat was assumed to be equal to 4.186 J/(g-K)

$$P = W\rho\Delta T c_p/\Delta t \qquad (2.6)$$

where

V = volume of water = 2 liters = 2000 ml

ρ = density of water (g/ml)

ΔT = temperature difference (C^o)

c_p = specific heat of water (J/g-K)

Δt = change in time (s)

P = power output (W)

Two temperature probes were used to record the temperature of the water during microwave cooking. Temperature probe #1 was placed near the bottom of the water level and probe #2 was placed near the top of the water level. The initial and final temperature of each probe was recorded and the average initial and final temperatures were then calculated. The difference of the average final and initial temperatures is the value of the temperature difference, ΔT in equation 2.6. For each power level, the power output was calculated three times and the average of the three calculations is taken to be the power output of the microwave oven for the power level in question. The data recorded and calculations performed are summarized in the following table:

Table C.1. Summary of power output calculations

Power level (%)	Initial Temperature (^{o}C)			Final Temperature (^{o}C)			Power (W)	Power (W)
	1	2	Avg.	1	2	Avg.	--	Avg.
100	24.94	24.80	24.87	36.82	40.73	38.78	970	993
100	25.22	24.98	25.10	37.09	42.41	39.75	1028	
100	25.22	24.98	25.10	36.45	41.89	39.17	982	
90	24.48	25.10	24.79	35.80	39.65	37.73	902	885
90	25.19	25.02	25.11	35.57	39.60	37.59	871	
90	24.93	24.95	24.94	35.47	39.69	37.58	882	
80	25.00	25.10	25.05	33.27	40.44	36.86	824	848
80	24.92	25.08	25.00	33.05	41.22	37.14	847	
80	24.85	24.89	24.87	33.79	41.03	37.41	875	
70	25.05	25.13	25.09	33.54	40.53	37.04	833	794
70	24.98	24.06	24.52	30.97	39.15	35.06	735	
70	24.89	24.81	24.85	33.79	39.25	36.52	814	
60	24.43	24.83	24.63	32.42	36.60	34.51	689	639
60	24.96	25.25	25.11	31.95	36.19	34.07	625	
60	24.97	24.91	24.94	32.27	34.91	33.59	603	
50	24.23	25.14	24.69	30.86	35.10	32.98	579	550
50	24.89	24.94	24.92	30.15	35.12	32.64	539	
50	25.00	25.03	25.02	31.22	34.10	32.66	533	

40	24.90	24.97	24.94	29.28	33.25	31.27	442	406
40	25.02	25.01	25.02	29.13	32.18	30.66	393	
40	24.98	25.08	25.03	29.35	31.65	30.50	382	
30	24.91	24.99	24.95	27.35	30.05	28.80	269	255
30	24.99	25.04	25.02	27.77	29.39	28.58	249	
30	24.90	24.84	24.87	27.74	29.11	28.43	248	
20	24.94	25.12	25.03	26.00	26.97	26.49	102	101
20	25.06	24.97	25.02	26.28	26.52	26.40	97	
20	24.84	24.95	24.90	26.22	26.57	26.40	105	

Appendix D

Calculation of Microwave Cooking Time

Preliminary microwave tempering experiments were conducted on frozen blocks of shrimp. The experiments found that the most favorable results occurred when the shrimp were tempered by a microwave oven with power output of 255 W for 2100 s (35 min). During this time the frozen block of shrimp was exposed to 535500 J of microwave energy. This amount of energy was used as a guide for all other experiments conducted.

The microwave used has a power output of 255 W when set at a power level of 255 W. The power output of the microwave oven for each power level was determined and those values are listed in Table 12 and the calculations of these values is described in Appendix C.

As previously mentioned, the microwave cooking time (MCT) for the 255 W power level tests was determined by the preliminary experiments and is 2100 s. The MCT was calculated for the 406 W power level experiments by dividing 535500 J by the power output of the microwave oven. This calculated MCT was then rounded to the nearest minute. The total energy for the particular experiment was calculated by multiplying this rounded value of MCT by the power output.

For the pulse experiments, an on/off cycle of 60 s was used. It was decided that the pulse experiments would have the same MCT as the experiment they wish to mimic; however, the microwave oven is not turned on for the entire MCT but rather for a portion of the MCT. The amount of time the microwave is turned on for during each cycle was calculated as a percentage. The percentage is found by dividing 535500 by the power output and the MCT. This percentage is then multiplied by 60 s to determine the amount of time the microwave is turned on for during each cycle. The time is rounded to the nearest second. As before the rounding affects the total energy. This new value of total energy for the particular experiment is calculated. The following are the calculations performed and a summary of the results is in Table D.1.

Notation

E	= amount of microwave energy produced by microwave oven during the microwave tempering experiment (J)
P	= power output of the microwave oven (W)
MCT	= microwave tempering time (minutes)
PCT	= percentage of on/off cycle of which microwave is turned on
On_t	= amount of time during each cycle of which the microwave oven is turned on (seconds)
$Cycle_t$	= total amount of time of each cycle = 60 seconds

1. Test: 255 W power level.

$$E = P \times MCT = 255\,W \times 35\,\text{minutes} \times \frac{60\,s}{1\,\text{minute}} = 535500\,J$$

2. Test: 406 W power level.

$$MCT = \frac{535500J}{P} = \frac{535500J}{406\,W} = 1318.9\,s = 22.0\,\text{minutes}$$

$$E = MCT \times P = 22\,\text{minutes} \times \frac{60\,s}{1\,\text{min}} \times 406\,W = 535920J$$

3. Test: 255 W pulsed at 848 W power level.

$$PCT = \frac{535500J}{P \times MCT} = \frac{535500J}{848\,W \times 2100\,s} = 0.301$$

$$On_t = PCT \times Cycle_t = 0.301 \times 60\,s = 18.0\,s$$

$$E = P \times MCT \times \frac{On_t}{Cycle_t} = 848\,W \times 2100\,s \times \frac{18\,s}{60\,s} = 534240\,J$$

4. Test: 255 W pulsed at 993 W power level.

$$PCT = \frac{535500J}{P \times MCT} = \frac{535500J}{993\,W \times 2100\,s} = 0.258$$

$$On_t = PCT \times Cycle_t = 0.258 \times 60\,s = 15.41\,s$$

$$E = P \times MCT \times \frac{On_t}{Cycle_t} = 993\,W \times 2100\,s \times \frac{15\,s}{60\,s} = 521325J$$

5. Test: 406 W pulsed at 848 W power level.

$$PCT = \frac{535500J}{P \times MCT} = \frac{535500J}{848\,W \times 1320\,s} = 0.478$$
$$On_t = PCT \times Cycle_t = 0.478 \times 60\,s = 28.7\,s$$
$$E = P \times MCT \times \frac{On_t}{Cycle_t} = 834\,W \times 1320\,s \times \frac{29\,s}{60\,s} = 541024J$$

6. Test: 406 W pulsed at 993 W power level.

$$PCT = \frac{598500J}{P \times MCT} = \frac{535500J}{993\,W \times 1320\,s} = 0.408$$
$$On_t = PCT \times Cycle_t = 0.409 \times 60\,s = 24.4\,s$$
$$E = P \times MCT \times \frac{On_t}{Cycle_t} = 993\,W \times 1320\,s \times \frac{24\,s}{60\,s} = 524304J$$

Table D.1. Summary of calculations

Test	P (W)	E (kJ)	MCT (min)	On_t (s)
255 W	255	535.5	35	--
406 W	406	535.9	22	--
255 W pulsed at 848 W	848	534.2	35	18
255 W pulsed at 993 W	993	521.3	35	15
406 W pulsed at 848 W	848	541.0	22	29
406 W pulsed at 993 W	993	524.3	22	24

Appendix E

Plots of Predicted Temperature History and Experimental Temperature History during Microwave Tempering of Shrimp

Eight different types of microwave tempering experiments were conducted on frozen blocks of shrimp (FSB). Temperature data were collected during each microwave tempering test conducted. The temperature data were collected at four locations within the frozen block of shrimp (FSB). This temperature data are referred to as the experimental temperatures. A mathematical model designed to predict the temperature of a FSB during microwave tempering was created. The temperature data produced by the model is referred to as the predicted temperature. For each type of microwave tempering test conducted, the resulting predicted and experimental temperatures obtained were plotted on the same graph. This appendix contains samples of these graphs. A dashed line represents the predicted temperatures and a solid line represents the experimental temperatures.

Figures E.1-E.2. Predicted and experimental temperature history during microwave tempering of FSB at 255 W power level

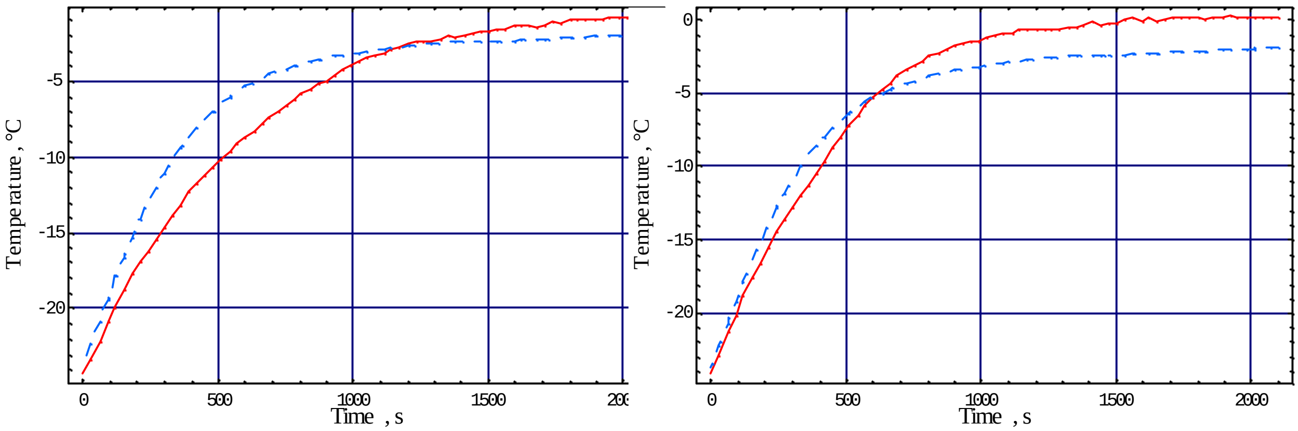


Figure E.1. Predicted and experimental temperatures at location #1 and #2

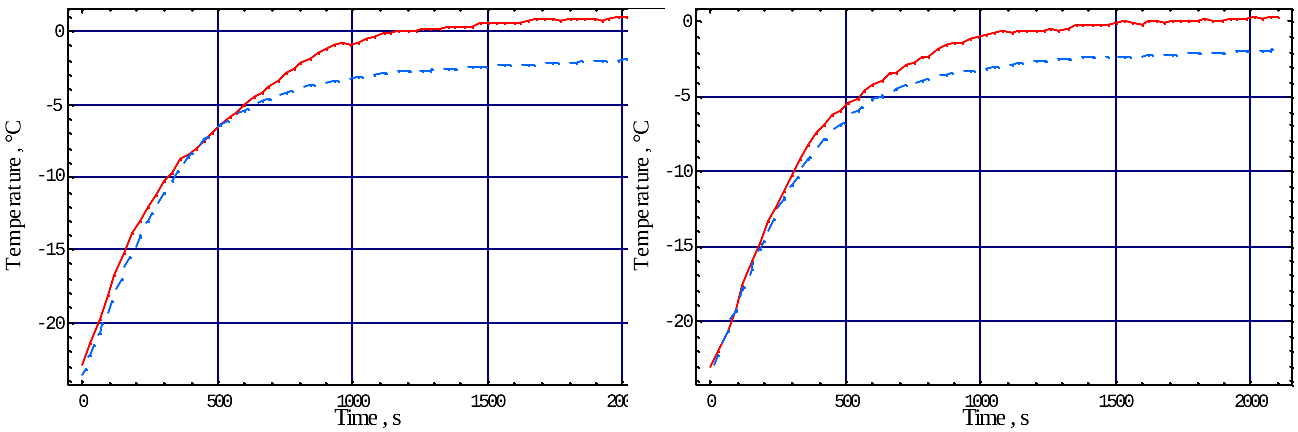


Figure E.2. Predicted and experimental temperatures at location #3 and #4

Figures E.3-E.4. Predicted and experimental temperature history during microwave tempering of FSB with pulse heat at 993 W power level (100 %) ON for 15 seconds and then OFF for 45 seconds for a total of 35 minutes

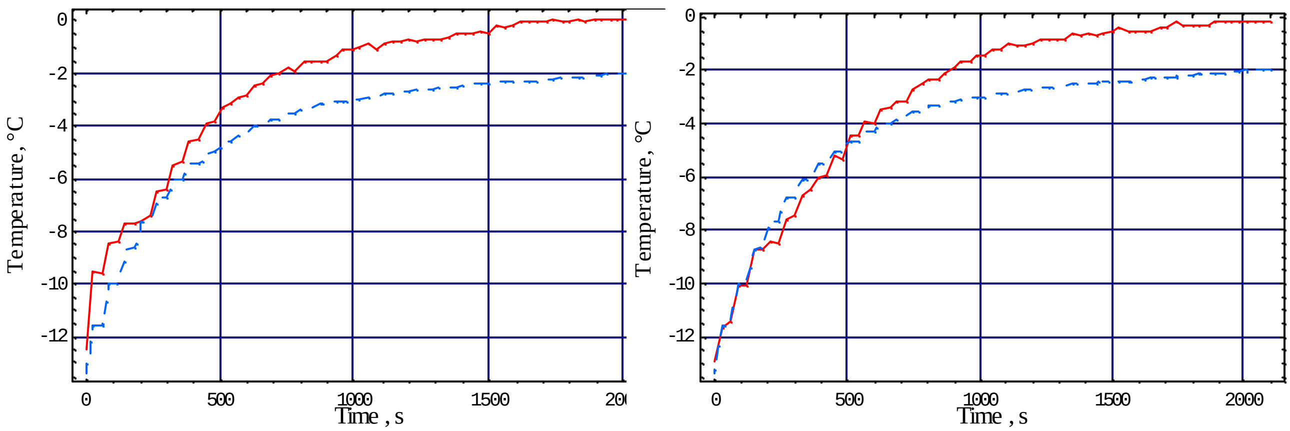


Figure E.3. Predicted and experimental temperatures at location #1 and #2

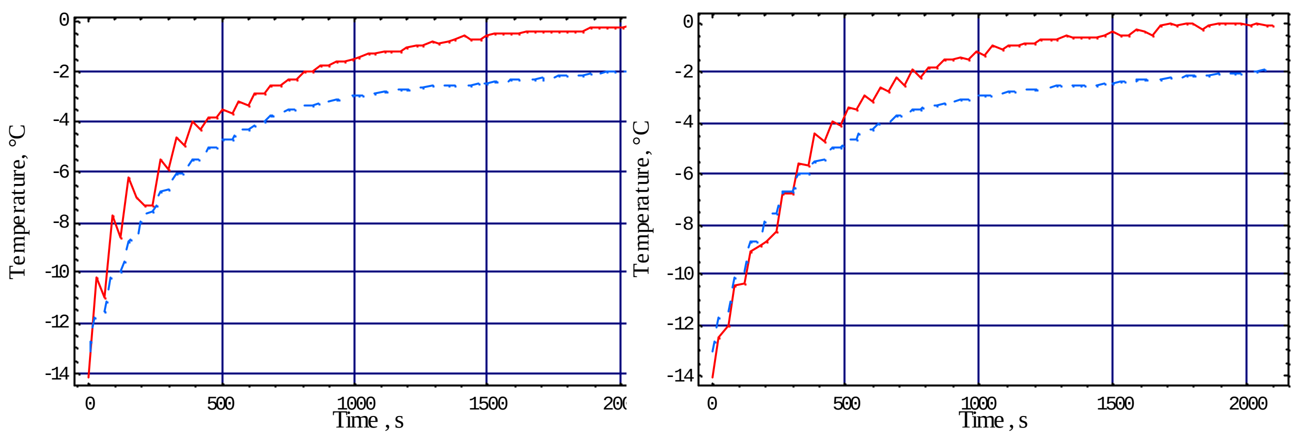


Figure E.4. Predicted and experimental temperatures at location #3 and #4

Figures E.5-E.6. Predicted and experimental temperature history during microwave tempering of FSB with susceptors at 406 W power level

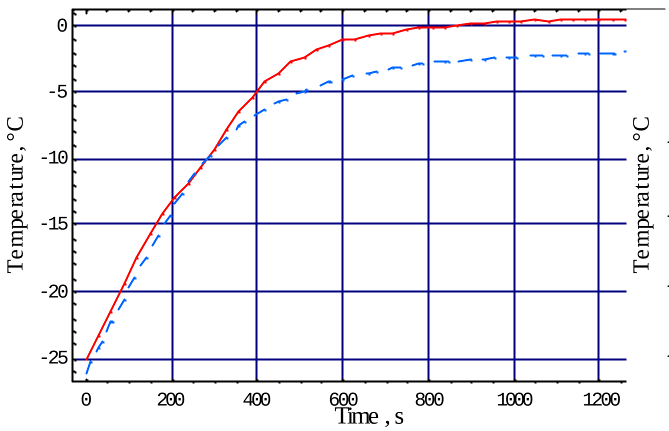


Figure E.5. Predicted and experimental temperatures at location #1 and #2

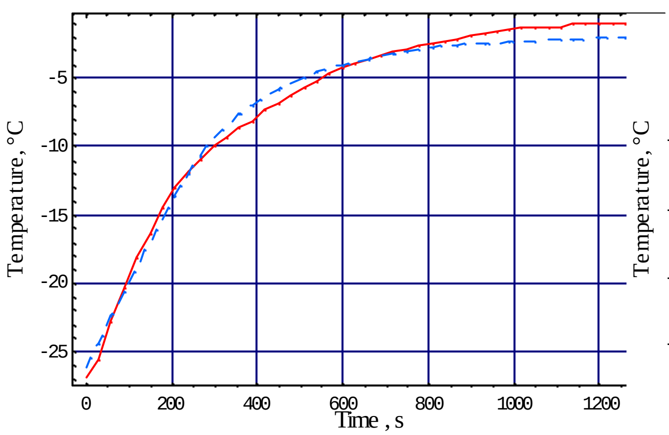


Figure E.6. Predicted and experimental temperatures at location #3 and #4

Figures E.7-E.8. Predicted and experimental temperature history during microwave tempering of FSB with pulse heat at 848 W power level (80 %) ON for 30 seconds and then OFF for 30 seconds for a total of 22 minutes

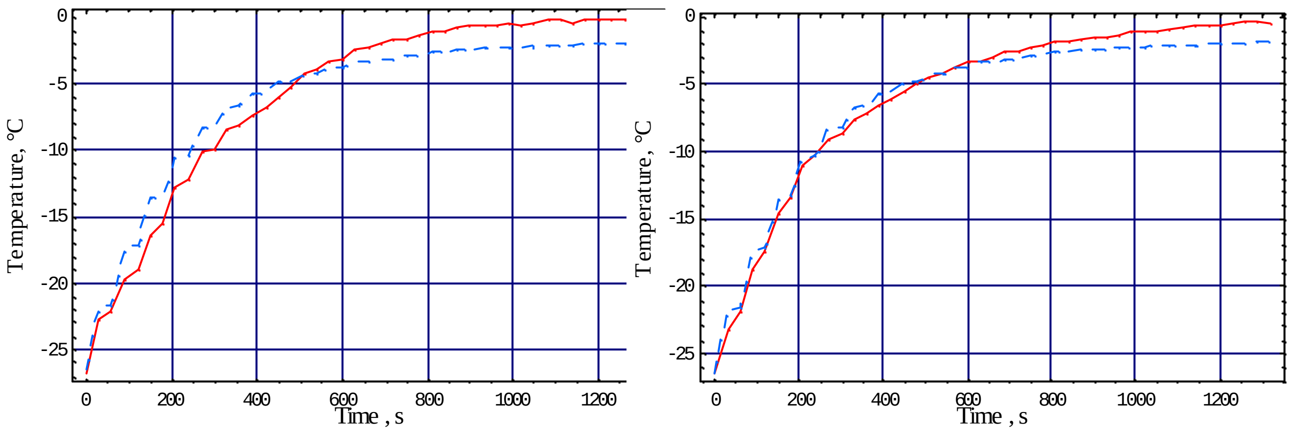


Figure E.7. Predicted and experimental temperatures at location #1 and #2

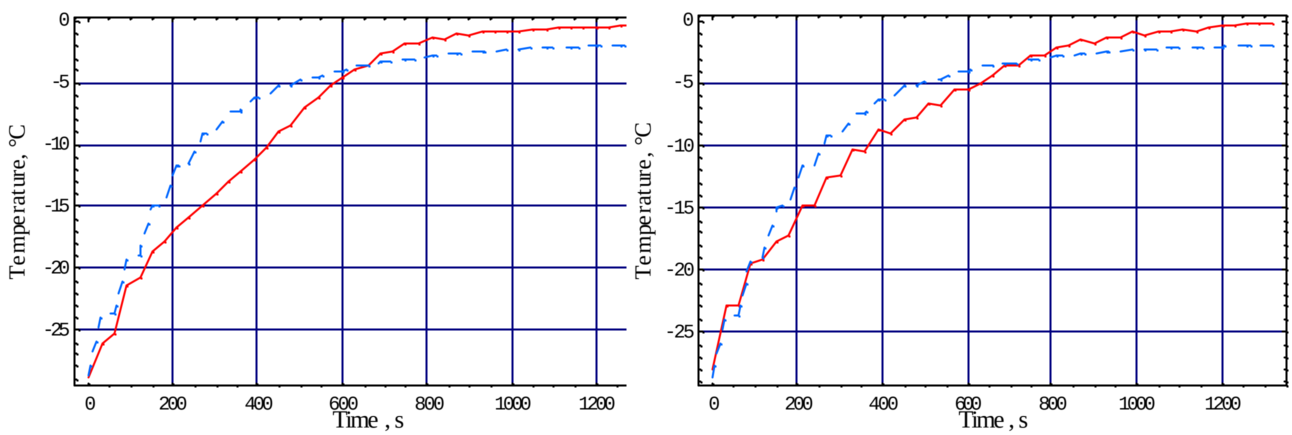


Figure E.8. Predicted and experimental temperatures at location #3 and #4

Vita

Matthew David Schaefer was born in LaGrange, IL on September 10, 1975. He graduated from Radnor High School located outside of Philadelphia, PA in May 1993. In the fall of 1993 he began studying at the Pennsylvania State University, State College, PA. He received his Bachelor of Science degree in Agricultural and Biological Engineering (Food Engineering) in May 1997. The following august he entered the Virginia Polytechnic Institute and State University, Blacksburg, VA to pursue a Master of Science degree. He worked as Teaching Assistant for 18 months and then worked on a SUCCEED project for 6 months. The SUCCEED project focused on improving engineering education in the Biological Systems Engineering department. He was also a member of the Alpha Epsilon honor society.

Matthew David Schaefer was a member of the Penn State Varsity soccer team and is also co-founder of the Penn State Club soccer team. He established the first club soccer team at Virginia Tech and served as both player and coach of this team. In their first official season, he guided the team to the Club Soccer National Tournament. During his time at Virginia Tech, he coached several youth traveling soccer teams. During the fall of 1998 he coached 15-year-old boys, during the spring of 1999 he coached 10-year-old boys, and then during the fall of 1999 he coached 17-year-old boys. He worked as a counselor for the Virginia Tech Gobbler Soccer camps during the summer of 1998 and 1999 and as a volunteer assistant coach for the Virginia Tech Varsity Soccer team during fall 1998 and fall 1999. By coaching youth soccer and working youth soccer camps, he was able to develop a solid relationship with the community of Blacksburg and their leaders.