ABSTRACT

CORONEL, PABLO. Continuous flow processing of foods using cylindrical applicator microwave systems operating at 915 MHz. (under the direction of Dr. K.P. Sandeep)

Microwave heating of foods is a proven and mature technology for household applications. However, industrial applications of microwave heating of food and biomaterials are scarce, due to the lack of suitable equipment and research on the subject. Aseptic processing and packaging of foods offers products of high quality with long shelf life. Aseptic processing of low thermal diffusivity and high viscosity food and bio products can lead to diminishing the quality of such products due to long exposures to high temperatures.

Industrial Microwave Systems (Morrisville, NC) invented a system that allows continuous flow microwave heating of foods in industrial scale, by focusing the microwave energy in a specially designed cavity. Food products can be pumped through a microwave transparent tube located in the focused area of the cavity and be heated with short time exposure to the microwave energy. Cooperation between Industrial Microwave System and North Carolina State University started this research.

This research evaluated the feasibility to use IMS microwave focused cylindrical applicators, operating at 915 MHz, for continuous flow aseptic processing of fluid food materials. In order to evaluate the feasibility of using continuous flow microwave heating system to process food products, a protocol to determine this feasibility was devised. Among other findings in this study the following are noteworthy; a method to
determine the temperature profile within a cross sectional area of the tube; a method to predict feasibility of a product to be processed by measuring its dielectric properties; and testing sequence to scale-up from bench-top to industrial scale operation were defined.

The findings of this work, and the methodologies developed can be of use to designers and processors alike to expand the use of this technology in the food and bio process industries.
CONTINUOUS FLOW PROCESSING OF FOODS USING CYLINDRICAL APPLICATOR MICROWAVE SYSTEMS OPERATING AT 915 MHZ

by

PABLO CORONEL

A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

FOOD SCIENCE

Raleigh 2005

APPROVED BY:

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Chair of the Advisory Committee
BIOGRAPHY

Pablo Coronel is the eldest son of Marcelo and Catalina Coronel, born and raised in Quito, Ecuador. Thanks to the rigorous and open education provided by his parents, he learned that science is the path to finding the most beautiful things in the universe. Pablo received his diploma in Chemical Engineering from the Escuela Politecnica Nacional, Quito, Ecuador, where he worked under the supervision of Prof. Bolivar Izurieta, and worked on a thesis in the field of Biotechnology with applications to the food industry.

After graduating from the university, he was hired by Sumitomo Corporation to work in the chemical products department, and then by Panificadora Moderna, the largest fresh bread bakery of Ecuador, as production engineer in the main plant, and took charge of the research & development department. He successfully graduated from the science and technology of baking courses, offered by the AIB in 1999. He was part of the team that designed a new plant for the production of extruded baby food based on soybean and cereals that is a part of the United Nations mother and infant feeding program (PANN 2000). The plant opened in June 2000.

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Pablo married Ana Katalina in June 17th, 2000 with whom he has two beautiful daughters, Rebeca and Amanda. Their love and support has driven him to improve every day and to finish this work.
ACKNOWLEDGEMENTS

Thanks are dedicated to my parents, Marcelo and Catalina for showing me that the universe is full of wonders awaiting to be discovered and opening my eyes to the great universe of science. Everything I accomplish is thanks to the curiosity and discipline my parents taught me.

This work could not have been accomplished without the wise advice of Dr. K.P. Sandeep, my academic advisor. His patience and wisdom helped me to finish this work and made my studies under his supervision enjoyable. His thoughtful scientific insight encouraged my interest in digging deeper into the knowledge of the basic principles under every aspect of this research.

Thanks to Dr. Josip Simunovic, senior researcher in this project. His friendship, daily encouragement, enthusiasm and knowledge have made me go through unopened doors and achieve what was thought impossible. I’ll always remember his favorite encouragement phrase “It’ll never work”.

The love of my wife Ana Katalina gave me the courage to work endless days and nights in the completion of this dissertation. Without her support and unconditional love, my body and mind couldn't accomplish the task. My wife, and my daughters Rebeca and Amanda have been the bright light at the end of the tunnel, giving me hope and reminding me that laughter helps heal the soul. Thanks go to these little angels for showing me that life is a lot more than just work. Thanks to them for coping with me during these hard times.
Thanks to the agencies and companies that have funded and made this project a reality, Industrial Microwave Systems, Center for Advanced Processing and Packaging Studies, Southeastern Dairy Foods Research Center, and United States Department of Agriculture.

Special thanks to Gary Cartwright and Jack Canady, for their help in the setup and operation of the equipment. No work could have been done without their effort and experience. Thanks to the Personnel of the NCSU Dairy Pilot Plant for their support and help day in and day out.

Thanks to all my friends that have helped in this project, without their support, advise and friendship I couldn’t have found the courage to advance: Koray Palazoglu, Stephen Sylvia, Qixin Zhong, Alex Riemann, Adam Tessneer, Jon Bell, Cristina Sabliov, Dorin Boldor, Brian Lloyd, Heather Stewart, Aswini Kumar, Prabhat Kumar, Andriana Vais, Yifat Yaniv, Shari Baxter, Melissa Funke, Ediz Batmaz, and to all the dungeon dwellers past and present.
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1. Introduction

Aseptic processing and packaging of foods provides a method to produce safe and high quality foods. While this method of preservation of foods has been known and applied to some food products, there is still need for improvement in rapid heating and cooling methods to improve the quality of the foods processed this way.

The use of microwaves for thermal treatment of fluid foods is an emerging technology in the food industry. Microwave heating promises rapid heating of food materials, which could be applied in aseptic processing and packaging. Research on this subject is underway in several institutions, but applications are still scarce. The lack of suitable equipment and the economics of the processing have been the main drawbacks of this technology.

Initial research in the use of continuous flow microwave heating was performed using household microwave ovens, through which a small diameter tube was inserted and food was pumped through the tube. These tests however had many drawbacks like the use of a small diameter tube, very small throughput, and the lack of controllability of the microwaves in the heating chamber. Household microwave ovens are designed using a box type heating cavity which adds complexity to the analysis of the electromagnetic distribution and absorption due to the presence of random modes inside the cavity. In order to overcome these problems a focused application cavity was required.

Industrial Microwave Systems (IMS), located in Morrisville, NC, invented a new method to apply microwaves to fluid food materials using a focused cylindrical applicator and were granted several patents for this invention. The microwaves are precisely focused in the material
being heated, improving the efficiency of the energy transfer. Cooperation between IMS and North Carolina State University allowed the use of their technology, and resulted in this study.

The main objective of this research was to evaluate the feasibility to use IMS microwave focused cylindrical applicators, operating at 915 MHz, for continuous flow aseptic processing of fluid food materials. In order to evaluate the feasibility of using continuous flow microwave heating system to process food products, a protocol to determine this feasibility was to be devised. This objective was separated into several smaller goals as follows; determining the temperature profile within a cross sectional area of the tube, predicting feasibility of a product to be processed by measuring its dielectric properties, and determining a testing sequence to scale-up from bench-top to industrial scale operation. The objectives were carried out as demonstrated in the following study.
2. Literature Review

2.1 Aseptic processing of foods

The ultimate goal of food processing is to provide safe foods with long shelf life that have the nutritional and quality attributes preserved as close to those of the fresh food as possible. Besides the requirement of high quality ingredients, processing has to be carried out in a manner that will preserve the quality attributes of the food materials, while minimizing the risk of microbial contamination. Food preservation processes including fermentation, salting, drying, and thermal processing have been used for many years. Thermal processing possesses a greater importance than the other methods due to the wide acceptance and utilization of this method to preserve foods around the world (Potter and Hotchkiss, 1995).

2.1.1 Thermal processing of foods

Thermal processing of foods is the most common method used to eliminate microorganisms in order to extend the shelf life of foods and avoid spoilage. Thermal processing relies on the use of heat to cook the food and eliminate microorganisms, and consists of one or a series of heat-hold-cool cycles. The product to be processed can be either packaged like in retort processing, or processed in bulk like in continuous flow processing. In the latter case, a packaging step follows the thermal processing. Heating the food has some benefits in the modification of its components for better digestibility, as well as inactivating enzymes that can cause browning and spoilage. However, if heating is carried out for a long time it can be
detrimental to quality, by destroying not only heat-sensitive components but also degrading proteins and producing non-enzymatic browning (Singh and Heldman, 2001).

The equipment used for thermal processing of foods includes retorts, plate-, shell and tube-, and scraped surface- heat exchangers, steam injection and infusion systems. Steam and hot water are the most common heat sources for thermal processing, used directly or indirectly on the food material, with the advantages of being widely available, relatively inexpensive, and well studied. Other alternative heat sources such as microwave, radio frequency, ohmic, and infrared heating are being studied for improved thermal processing of foods (Sing and Heldman, 2001).

There are several levels of thermal processing of foods with pasteurization, and sterilization being the two of the most widely used. Pasteurization refers to a process used to inactivate the microorganisms that may cause a public health concern, and at the same time extend the shelf life of the food products from an enzymatic and microbial point of view. Foods subject to pasteurization still contain microorganisms capable of growing and producing spoilage of foods, and usually require additional preservation processes such as refrigeration to lengthen their shelf life. A classic example of a pasteurized product is milk. Sterilization refers to a process in which the product is rendered free of microorganisms. However, rendering a food product completely free of microorganism is not practical because it would require large amounts of energy, and can result in an unacceptable product. Thus, a more practical level of destruction of microorganisms called commercial sterility has been defined for foods. Commercially sterile foods are those processed to a degree such that the product is free of pathogenic, spore, or toxin forming microorganisms, as well as microorganisms that can produce
spoilage under non refrigerated conditions. These foods have long shelf life (over 1 year) and can be stored without refrigeration (Potter and Hotchkiss, 1995).

Commercially sterile foods are widely available, in the form of canned foods. These foods are packaged in metallic cans, and after being packaged the cans are heated in autoclaves using steam until the “cold spot” of the can receives the necessary thermal treatment. The location of the cold spot in a can is a critical issue, and depending on the characteristics of the foods it can be located either in the geometrical center of the can if the heat transfer inside the food is mainly by conduction, or at two thirds of the height of the can if the heat transfer inside the food is mainly by convection. The thermo-physical properties of the material, such as thermal conductivity, viscosity, and specific heat will influence the way the heat is transferred within the food product. Stratification of temperature and high temperature differences between locations within the food can be found, which in turn lead to over processing of certain parts of the food, that can cause degradation of the food and render it unacceptable to the consumers. Size of can that can be processed using this method is limited, due to time and energy consumption considerations (Singh and Heldman, 2001).

Continuous flow processing promises an improvement in quality of the food, and economy of processing by providing uniformity in temperatures and avoiding over processing of the materials. Heat transfer within the food materials can be either direct or indirect. Tubular, plate, and scraped surface heat exchangers are used for indirect heat transfer processes, while steam injection and infusion are used for direct heat transfer processes. In order to achieve the correct degree of thermal treatment, the product needs to be exposed to a certain temperature for a period of time, defined by the degree of microbial inactivation required. In order to do so, a
certain length of tube (holding tube) is used to provide the necessary time for the inactivation of microorganisms. The food product is afterwards cooled and packaged in containers according to the shelf life expected or the customers requirements.

Temperatures used for these processes are higher and holding times are shorter than in canning, rendering a product with higher nutritional and sensorial qualities. Due to the convective heat transfer mechanisms occurring in these type of processes, the temperatures are more uniform than in canned foods, so the product is processed uniformly. In order to ensure that the food product has been sufficiently processed, the slowest heating point of the product has to be sufficiently processed. In the case of a homogeneous fluid, either in laminar or turbulent flow, the center of the tube is considered to be the critical point. If the food contains particulates, the center of the fastest moving particle and with the poorest thermal properties has to be considered the critical point. All efforts have to be made to insure that these critical spots have received the correct thermal processing (Sastry and Cornelius, 2002).

In order to define sufficient thermal processing of a food material, the inactivation of both microorganisms and food components must be studied. Thermal processing of foods affects the components of a food product, and it can have beneficial effects for components such as proteins that are easier to digest once denatured, starches that need to be gelled, and enzymes that need to be inactivated, or detrimental effects to thermolabile components such as of vitamins, antioxidants and some enzymes. Thus, the study of the kinetics of inactivation of both microorganisms and food components is necessary, in order to achieve a balance between microorganism reduction and nutrient retention.
2.1.1.1 Kinetics of microbial inactivation

The simplest and oldest way to thermally process foods is by packaging them in a metallic can and then increasing the temperature of the food product inside the can using steam until the number of microorganisms left is consistent with the degree of processing desired. In order to achieve the balance between time and temperature it is necessary to learn how the reduction of the number of microorganisms is achieved.

2.1.1.1.1 D and z values

Initial work on the destruction of microorganisms was carried out by Bigelow, Ball, Esty and others during the early part of the 20th century. Those studies showed that when microorganisms are subject to constant temperature, the number of surviving microorganisms decreased in a manner that followed first order kinetics, i.e., a straight line in a logarithmic plot. They observed that at constant temperature the decrease of the population (N) was dependent on the initial population (N₀), the time of exposure to such temperature (t), and the type of microorganism, denoted by a constant (k) specific of each microorganism. The kinetics of this destruction could be modeled into an Arrhenius-type model and the equation describing the destruction of microorganisms at constant temperature was written as follows:

\[ N = N_0 \ e^{-kt} \]  \hspace{1cm} [2.1.1]

In order to allow for simpler mathematics, equation 2.1.1 was transformed to allow the use of common logarithms, such that:

\[ N = N_0 \ 10^{-t/D} \]  \hspace{1cm} [2.1.2]
where D is the time required to decrease the microbial population by 90% or one logarithmic cycle, and is called the decimal reduction time or D value.

D value is a characteristic of the microorganism being studied. Further experiments showed that the D value for a given microorganism was dependent on the temperature at which the process was carried out. By testing the reduction of the same type of microorganism at different temperatures, they observed that the D value followed Arrhenius type kinetics such that:

\[ D = K e^{\frac{E_a}{RT}} \]  

[2.1.3]

where K is a constant and \( E_a \) is the activation energy for the destruction kinetics of a given microorganism. This equation was modified to use common logarithms and parameters that are simpler to measure, such as \( D_0 \) at a reference temperature \( (T_0) \), such that:

\[ D = D_0 10^{\frac{T-T_0}{z}} \]  

[2.1.4]

where \( z \) is called thermal resistance of the microorganism or z value.

z value is defined as the increase in temperature needed to change the value of D by one logarithmic cycle. The z value is dependent on temperature, but the changes within a reasonable range of temperatures are small, and it can be considered constant. For sterilization processes, the reference temperature is 121.1 °C (250 °F), and the reference microorganism has a z value of 10 °C (Jackson and Lamb, 1981; IFT, 2002).
2.1.1.1.2 Thermal death time and cook value

In order to evaluate the efficiency of a method to reduce the population of microorganisms, the complete thermal treatment must be evaluated and this is accomplished by an integration of the above mentioned parameters. The thermal death time (TDT) or F-value is calculated using the following equation:

\[
F_0 = \int_0^1 10^{\frac{T(t)-T_0}{z}} \, dt
\]  \[2.1.5\]

The subscript "0" is used to denote that the sterilization value has been normalized to a reference microorganism at a reference temperature (T_0). This method was proposed initially by Bigelow and others (1920) and has been used as a conservative approach to processing. The reference temperature used is 121.1 °C and the reference z value is that of *Clostridium Botulinum* (10 °C) at given reference temperature (Jackson and Lamb, 1981).

The destruction of nutrients, changes in texture, and elimination of enzymes follow similar kinetics to that of the destruction of microorganisms, but it has been proven that the z values for destruction of components of food products have to be reevaluated. Nutrient destruction in food products is calculated by using the equation introduced by Mansfield (1961), in which the thermal death time has been renamed as Cook value or C_0 value, and a redefined z_N value is used, as follows:

\[
C_0 = \int_0^1 10^{\frac{T(t)-T_0}{z_N}} \, dt
\]  \[2.1.6\]

for this value, the common reference parameters are T_0 = 100 °C and z_N = 33 °C (Jackson and Lamb, 1981).
The TDT method is used in industry, and it reflects a pseudo steady state model, which is based on canned foods in a constant temperature medium (steam), without agitation. However, continuous flow processing is not a steady state process. Therefore, modifications to the above-mentioned method are required in order to estimate the thermal effects in a more realistic manner. The heat-hold-cool cycle to which the products are exposed may last only a few seconds, and the heating and cooling are carried out in unsteady state. Therefore, additional considerations are necessary to estimate the microbial inactivation in these systems.

2.1.1.1.3 Considerations for continuous flow processing

In order to address the unsteady heat transfer, and subsequent thermal processing of food in continuous flow processes, where the changes in temperatures and flow parameters occur at very fast rates, it became necessary to revise the TDT methods. The standard TDT method is a conservative one, in which time and temperature are only taken into consideration in the holding tube, and come up and cool down times are neglected. However, when high temperatures are used, the heating and cooling of the products can have a large influence in the destruction of microorganisms as well as in changes in quality factors.

Swartzel (1982) proposed modifications to the traditional F₀ value thermal evaluation protocol to be suitable for continuous flow processing. A simulation of the processing conditions foods are subjected in continuous flow processing was modeled using non-isothermal reactors. However, this kind of reactor can only be used if the heat flux or the wall temperature is constantly changing and a method to accurately calculate the kinetic data in these reactors was presented by Swartzel (1984). This method is called the equivalent point method (EPM), and an
equivalent temperature \((T_E)\) and time \((t_E)\) are calculated to contrast canning to continuous flow processing, and it was demonstrated that these equivalent values were independent of activation energy, thus being valid for all the inactivation or cooking processes in the system. First, the thermal reduction relationships \((G\) value\) are calculated using equation 2.1.7 for each component of the food being tested. Then the equivalent point is found by finding the values of \(T_E\) and \(t_E\) that satisfy equation 2.1.8. \(T_E\) and \(t_E\) can be calculated by solving equations 2.1.7 and 2.1.8 for several activation energies. In other words, if logarithmic plots of the thermal reduction relationships versus reciprocal temperature are generated for several \(G\)\(-E_a\) pairs, the lines should intersect at a point that corresponds to the equivalent point.

\[
G = \int_0^t e^{\frac{E_a}{RT(1)}} \, dt \tag{2.1.7}
\]

\[
G = t_e e^{\frac{E_a}{RT_E}} \tag{2.1.8}
\]

Experimental verification of the EPM method showed that finding solutions of equation 2.1.8 was not trivial, and that some of the assumptions of the method had to be revised. The method was based on the existence of a unique intersection point of the different \(G\)\(-E_a\) curves, but this was not observed in experiments. Sadeghi and other (1986), Nunes and others (1991), Nunes and others (1993), and Maesmans and others (1994 and 1995) investigated this phenomena, and concluded that temperature acquisition and computational errors maybe responsible for the errors. Regression methods were proven to improve the accuracy of equivalent point estimation, with the weighted least squares regression favored by Nunes and others (1991). Maesmans and others (1995) showed that the EPM method was useful for
isothermal conditions, and Welt and others (1997) further extended the method and called it the Paired Equivalent Isothermal Exposure method (PEIE).

Kyereme and others (1999) investigated a procedure to improve the accuracy of the calculation of the equivalent point. It had been shown that \( t_E \) depends not only on the activation energies and \( G \) values of the different products, but also on \( T_{E_1} \). Thus, multiple intersection points may exist between different \( G-E_a \) lines for different products (1 and 2) as shown in the equation system 2.1.9.

\[
\begin{align*}
T_E &= \frac{E_{a2} - E_{a1}}{R \ln(G_1/G_2)} \quad [2.1.9a] \\
t_E &= G_1 e^{\frac{E_{a1}}{RT_E}} \quad [2.1.9b]
\end{align*}
\]

The equivalent \( F_0 \) and \( C_0 \) are calculated by plotting the intersection of characteristic curves. Characteristics curve are defined by plotting the solutions to the system of equations 2.1.9 on a \( \log(t_E) - T_E \) plot, which results in a line with slope of \(-1/z\). The tangent line is a plot of all the equivalent points. This method gives more accurate results and can be used to estimate the sterilization values in continuous flow processing of foods.

In summary, kinetics of microbial and nutrient inactivation are important to achieve safe and high quality products, continuous flow processing is the technology this study has been focused on, and especially aseptic processing.

**2.1.2 Aseptic processing and packaging**

Aseptic processing is a combination of continuous commercial sterilization of food products with packaging in an sterile environment. The packaging material has been separately
sterilized and the food product is filled into the package in a sterile environment. This method of processing and packaging provides food with very long shelf life (>2 years).

Aseptic processing of foods takes place at high temperatures and short holding times to assure microbial destruction, while retaining nutrients and sensorial qualities of the products. Typical process temperatures are between 120 and 150 °C with holding times between 5 and 90 s. Population of microorganisms is reduced very fast at high temperatures, and only short times of exposure are required. The undesirable changes in the food materials due to thermal treatment that result in changes in flavor, color, odor, reduction of nutrients, and denaturation of proteins are less likely to occur in the short times to which products are exposed during aseptic processing (Reuter, 1987).

The equipment used for aseptic processing differs in some aspects to the equipment used in other food processing, because of the unique requirements of this kind of processing. Besides of the specially designed packaging equipment, the heating and cooling stages of the processing need to be as short as possible.

The components of an aseptic processing system are: pump, flow controller, heating section, holding tube, cooling section, and packaging system (Singh and Heldman, 2001). Pumps used in aseptic processing can be either centrifugal or positive displacement types. Centrifugal pumps work well with low viscosity fluids, where high flow rates are required and pressure requirements are moderate. Positive displacement pumps are used for high viscosity products, or when an accurate flow rate or a high pressure drop must be overcome. Due to the back-pressure required to avoid flashing in aseptic processing, positive displacement pumps are preferred (Reuter, 1987).
The main concern with aseptic processing is to keep all of the components free of microbial contamination; product, processing and filling lines, surge tanks, packaging environment and materials. The system has to be presterilized prior to processing, which is achieved using hot water for the processing and filling lines, saturated steam for the surge tanks and scraped surface heat exchangers, and sterile air for the packaging environment. The packaging materials are sterilized in line using peroxides, or other chemicals together with sterile air.

The packaging equipment is the most significantly different component of an aseptic process line, when compared to a conventional canning process. The packaging material needs to be sterilized before it is formed, and a stream of sterile air is used to keep the whole environment microorganism free. Form-fill-seal machinery is preferred, such as carton and plastic, but bag-in-box fillers in which the bags are pre-sterilized using hot steam are used for high capacity filling (Reuter, 1987).

The main advantages of this technology when compared to canning are the possibility of continuous operation, flexibility of packaging options and sizes, smaller foot print, lower cost of packaging and greater quality and sensorial attributes due to the shorter heating time cycles the product is exposed to. The disadvantages include a high expenditure in equipment, the need for trained people, and the lack of mechanical stability that plastic and cardboard packaging posses (Singh and Heldman, 2001; Reuter, 1987).

Homogeneous food products, such as milk, cooking sauces, chicken broth, tomato paste, and fruit juices, are currently being processed using this technology. However, aseptic processing of low-acid foods and foods containing particulates are still not approved by the
FDA, and many concerns include not only the sufficient thermal treatment of the particles but also the possibility of having particles in contact with the seal portion of the packaging, preventing the formation of impervious seals. (Sastry and Cornelius, 2002).

Aseptic processing of foods is carried out in continuous flow and one of the requirements is the rapid heating and cooling of the food materials. Due to the FDA regulation, only the lethality accumulated in the holding tube can be accounted for the requirements of commercial sterility, but the heating and cooling sections may provide a significant lethality as well. This conservative lethality imposed by the law may be detrimental to the quality of the product. The high temperatures used in aseptic processing may destroy the nutrients of the food material to a greater extent than initially intended, if the exposure of the food to such high temperature is underestimated by a few seconds. For this purpose, specialty heat transfer equipment has been designed trying to maximize the heat transfer rates. Both indirect and direct heat exchangers have been improved and worked on. Yet the same limitations given by the thermophysical properties of the food materials are present. Steam infusion and steam injection have been proposed as rapid heating methods, but they have the disadvantage of introducing water into the product, which later needs to be flashed out (Reuter, 1987; Singh and Heldman, 2001).

Aseptic processing of foods relies on steam and hot water as heat transfer fluids, but several new technologies are also being investigated as alternative heat sources. Within those new technologies is microwave heating. The underlying principles and applications of this technology need to be analyzed in order to apply it to aseptic processing.
2.2 Introduction to microwaves

The electromagnetic spectrum includes waves with frequency that range from 300 to 300,000 MHz, corresponding to wavelengths of 0.001 to 1 m. These waves are called microwaves and are used for radar, telecommunications, television, and heating of food products (Ishii, 1995; Sadiku, 1995).

The use of microwaves to heat food products was discovered by Percy Spencer in 1946, while working on a military radar project for Raytheon corp. Spencer stopped for an instant in front of a microwave generator and noticed that a chocolate bar he had in his pocket had melted. Soon afterwards, Spencer began to experiment with some other food products and noticed that microwaves could be used to heat foods in a rapid and efficient manner. For this invention, Spencer was granted patent number 2,495,429 for a “method of treating foodstuffs” in 1950. Raytheon corp. began the production of commercial microwave ovens in 1947 under the name Radarange, although they were aimed for commercial use being 1.8 m tall and weighing over 300 kg. A smaller microwave oven, for use in homes and offices, was introduced in 1967 by Amana Corp. Since then, the microwave oven has become a ubiquitous appliance in the American lifestyle. While the microwave oven is a modern appliance, the underlying principles of heating using microwaves were discovered many years before, through the work of many scientists in the field of electromagnetics.

2.2.1 Electromagnetics

Electricity and magnetism are phenomena that have attracted the attention of scientists for millennia. The Greeks knew that amber could be charged by friction and attract small
quantities of straw, paper or hair by the 6th century B.C., but the knowledge of electromagnetism was stagnant for over two millennia. It was just at the turn of the 18th century that the industrial revolution sparked interest in the field again. The work of James Clerk Maxwell led to several inventions that allowed the practical usage of electromagnetism with the invention of the light bulb, the telegraph, and the telephone by the end of the 19th century. The presence of electromagnetic waves was acknowledged due to the work of Hertz (1857-1894) and led to the invention of the radio (1899), television (1927), and modern telecommunications. All these advancements and practical applications have made electromagnetics one of the branches of classical physics that has produced more comfort to the human race (Bernal, 1972).

The science of electromagnetics was born after the development of the Maxwell equations. The Maxwell equations laid the theoretical foundation for the development of the field of electromagnetics, but these equations were not universally accepted until Heinrich Hertz (1857-1894) successfully generated and detected radio waves (Rothwell and Cloud, 2001).

2.2.1.1 Maxwell’s Equations

James Clerk Maxwell (1831 – 1879) was a mathematician and is considered the father of electromagnetics. Maxwell made many contributions to science, but is remembered most by the contributions he made to the field of electromagnetics. Maxwell realized that the electric and magnetic phenomena were closely interrelated, and found a mathematical way to interrelate the work of Gauss, Ampere, Faraday, and others, which was presented in 1864 to the Royal Society. Both the electric and magnetic fields had been independently studied for years, and Maxwell
showed that both phenomena are coexistent and dependent on each other, creating the term "electromagnetism" and starting a whole new field of research (Rothwell and Cloud, 2001).

The Maxwell equations were originally postulated as a set of nine equations summarizing all known laws of electricity and magnetism at the time and added an extra term to make the set of equations consistent. Maxwell postulated the equations in a time before vectors were understood and he used many scalar quantities. Further developments in engineering mathematics have inspired changes in the way Maxwell’s equations are written by the use of time and space dependent vectors $\mathbf{E}(\mathbf{r},t)$. Both vector and tensor quantities are currently used to fulfill these equations making them more elegant and showing the simplicity of the underlying phenomena they propose. The nine original scalar equations were reduced to a set of four vectorial equations, by Minkowski (1908) and further developed by other authors. Minkowski’s contribution was to relegate all the equations that contained information relative to the properties of the materials to the constitutive relationships and use only the field equations using vector quantities. The equations in their final form, for time varying fields are shown in table 2.2.1 (Sadiku, 1995; Rothwell and Cloud, 2001).

Table 2.2.1. Generalized form of Maxwell’s equations

<table>
<thead>
<tr>
<th>Differential form</th>
<th>Integral form</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nabla \cdot \mathbf{D} = \rho_v$</td>
<td>$\int \mathbf{D} \cdot d\mathbf{S} = \int \rho_v , d\mathbf{v}$ Gauss’s law</td>
</tr>
<tr>
<td>$\nabla \cdot \mathbf{B} = 0$</td>
<td>$\int \mathbf{B} \cdot d\mathbf{S} = 0$</td>
</tr>
</tbody>
</table>
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \quad \int_{L} \mathbf{E} \cdot d\mathbf{l} = -\frac{\partial}{\partial t} \int_{S} [\mathbf{B} \cdot d\mathbf{S}] \]  
Faraday’s law

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad \quad \int_{L} \mathbf{H} \cdot d\mathbf{l} = \int_{S} \left( \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \right) \cdot d\mathbf{S} \]  
Ampere’s circuit law

In order to make the Maxwell equations provide a complete description of an electromagnetic field, a continuity equation is required:

\[ \nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \quad [2.2.1] \]

Four electromagnetic vector filed quantities are used by these equations and they are: \( \mathbf{E} \) the electric field intensity, \( \mathbf{H} \) the magnetic field intensity, \( \mathbf{B} \) the magnetic flux, and \( \mathbf{D} \) the electric displacements. In addition, the density flux vector \( \mathbf{J} \) and the scalar field charge density \( \rho \) are required to complete the description of the electromagnetic interactions. The constitutive relationships postulated in the Maxwell-Minkowski equations relate the alignment of the different fields inside a medium and can be used to classify materials as:

- **Isotropic**: field directions are aligned. Vectors are paired and depend on one another: \( \mathbf{D} \) to \( \mathbf{E} \), \( \mathbf{B} \) to \( \mathbf{H} \), and \( \mathbf{J} \) to \( \mathbf{E} \).

- **Anisotropic**: fields are not aligned, but the pairs are similar.

- **Biisotropic**: Fields are aligned. Vectors show dependence on more than one other vector: \( \mathbf{D} \) and \( \mathbf{B} \) depend on both \( \mathbf{E} \) and \( \mathbf{H} \).

- **Bianisotropic**: \( \mathbf{D} \) and \( \mathbf{H} \) depend on both \( \mathbf{E} \) and \( \mathbf{B} \), but there is no alignment of the fields.
The interdependency of the four fields needs to be resolved, as there are only two fundamental equations (the curl equations) and four unknowns. Categorization of the equations into fundamental and supplemental has been one of the approaches to this problem. Using this method, and taking into account physical arguments, the pair \((\mathbf{E}, \mathbf{H})\) is more fundamental for the analysis of electromagnetic waves. Interactions of the electric and magnetic field with the electronic structure of the molecules produce secondary effects that are described by the \((\mathbf{B}, \mathbf{D})\) pair. Moreover, the amount of energy that a field can transport is described by the Poynting vector, which is the cross product of \(\mathbf{E}\) and \(\mathbf{H}\) (Sadiku, 1995; Rothwell and Cloud, 2001; Shadowitz, 1975).

### 2.2.1.2 Poynting vector

In order to verify Maxwell’s equations, a link to measurable quantities was required. The most convenient way was to link the electromagnetic forces to a mechanical force using the Lorentz force equation. This equation supposes that a charge \((\rho \, dV)\) contained inside a small volume element \((dV)\), moves with velocity \(\mathbf{v}\) in an electromagnetic field. The force this charge experiences can be written as follows:

\[
d\mathbf{F} = \rho \, dV \, \mathbf{E} + \rho \, \mathbf{v} \, dV \times \mathbf{B} \tag{2.2.2}
\]

One of the consequences of this link with the Lorenz relation is that work can be done by the system, and transfer of momentum between the field and the charge is possible (Shadowitz, 1975). Therefore it became necessary to express mathematically these important links between electromagnetics and mechanics. These two quantities were postulated as \(S_{\text{em}}\) and \(g_{\text{em}}\) respectively and are used to describe the transmission of energy and momentum, as well as to...
explain the conversion of electromagnetic energy into mechanical energy and vice versa. These quantities are expressed as follows:

\[ S_{em} = E \times H \]  

[2.2.3a]

\[ g_{em} = D \times B \]  

[2.2.3b]

In the case of plane waves, the first relation is called the Poynting vector, and it represents the instantaneous power density vector for any electromagnetic field as shown in equation 2.2.4. The Poynting vector derives from the theorem proposed by John Henry Poynting and is written as a surface integral of the cross product of the electric and magnetic fields.

\[ \oint (E \times H) \cdot dS = -\frac{\partial}{\partial t} \int \left[ \frac{1}{2} \varepsilon E^2 + \frac{1}{2} \mu H^2 \right] dv - \int \sigma E^2 \ dv \]  

[2.2.4]

The first term on the right hand side is interpreted as the rate of decrease in energy stored in the electric and magnetic fields, and the second term is the power dissipated due to the conductivity of the medium (Ohmic dissipation) which is related to the conversion of electromagnetic energy into heat (Sadiku, 1995; Shadowitz, 1975; Reich and others, 1953).

The energy transported within the material depends on the values of \( E \) and \( H \) in each differential volume of the material, as well as on the properties of the material. Thus, the way the electromagnetic waves propagate inside materials needs to be understood.

### 2.2.1.3 Propagation of electromagnetic waves

Electromagnetic fields can take several characteristics depending on how they change with time. Static fields exhibit no variation with time. Therefore, a coupling of nearby sources or inductance effect should suffice to understand them, and can be described by circuit theory.
However, time changing fields exhibit wave-like behavior and are radiated away from the source. Time-varying sources produce waves, which travel as disturbances through a medium. The specific characteristic of waves, such as velocity, polarization and reflection depend on the medium through which it propagates. Also, the way the waves evolve in time depends on the characteristics of the medium. The wave can either be dispersed, absorbed or transmitted (Shadowitz, 1975; Sadiku, 1995).

Electromagnetic waves are a mean of transporting energy or information, and they have three main characteristics: they travel at finite speed; while traveling, they assume the properties of waves; and they radiate outwards from the source. In order to use equations to describe waves, they have to be modeled as functions of both space and time. Wave motion occurs when a disturbance at a source point at the initial time \( t = t_0 \) and \([0,0,0]\), is related to what happens at different times \( t > t_0 \) and \([x,y,z]\) in any point other than the source. Therefore, a wave equation for electromagnetic waves is a partial differential equation of second order in the form shown as follows:

\[
\nabla^2 \mathbf{E} - \mu \varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = -\frac{\rho_v}{\varepsilon}
\]  

\[2.2.5\]

Electromagnetic waves can be described using partial differential equations for the electric and the magnetic fields. In the simplest case of waves traveling uni-dimensionally in the z-direction, in a charge-free space \( (\rho_v = 0) \) the set of equations becomes what is known as Helmholtz equations.

\[
\frac{\partial^2 \mathbf{E}}{\partial t^2} - u^2 \frac{\partial^2 \mathbf{E}}{\partial z^2} = 0
\]  

\[2.2.6a\]
where $u$ is the velocity of the wave which is a function of the frequency of the wave, as well as its wavelength, as shown in equation 2.2.7. These Helmholtz equations have solutions for simple cases. In the case of equation 2.2.6a, for uni-dimensional propagation in free space, the solution can be written in the following form:

$$E = C_1 e^{j(\omega t - \beta z)} + C_2 e^{j(\omega t + \beta z)} = C_3 \cos(\omega t - \beta z) + j C_4 \sin(\omega t - \beta z)$$

[2.2.8]

where the constants $C_1$, $C_2$, $C_3$, and $C_4$ are real.

Analyzing the real form of the solution, it can be seen that it is in a cosine waveform, depending both on time and space. The constant ($C_3$) is called the Amplitude of the wave, $\omega$ is the angular velocity of the wave, and $\beta$ is called the phase constant or wave number (Sadiku, 1995; Shadowitz, 1975).

When waves propagate in a charge-free partially conducting medium ($\sigma \neq 0$), the wave equations become homogeneous Helmholtz type equations in which a propagation constant ($\gamma$) is added (Equation 2.2.9). These materials are called lossy dielectrics due to the loss of electromagnetic energy into heat. Figure 2.2.1 shows a typical wave penetration in a lossy dielectric.

$$\nabla^2 E - \gamma^2 \frac{\partial^2 E}{\partial t^2} = 0$$

[2.2.9]

where the propagation constant is defined according to the following equation:

$$\gamma^2 = j \omega \mu (\sigma + j \omega \varepsilon)$$

[2.2.9a]
Figure 2.2.1. Propagation of electromagnetic waves in a dielectric material

Since $\gamma$ is a complex quantity it can be written as shown in equation 2.2.10a. Where $\alpha$ is known as the attenuation constant and measures the spatial decay of the wave as it propagates (equation 2.2.10b). And $\beta$ is a measure of the phase shift per unit length and is called the phase constant or wave number (equation 2.2.10c). Both $\alpha$ and $\beta$ are dependent on the frequency of the wave, and the conductivity and permittivity of the material through which the wave propagates.

\[
\gamma = \alpha + j\beta \quad \text{[2.2.10a]}
\]

\[
\alpha = \omega \sqrt{\frac{\mu \epsilon}{2} \left[ 1 + \left( \frac{\sigma}{\omega \epsilon} \right)^2 \right] - 1} \quad \text{[2.2.10b]}
\]
\[
\beta = \omega \sqrt{\frac{\mu \varepsilon}{2} \left[ 1 + \left( \frac{\sigma}{\omega \varepsilon} \right)^2 \right] + 1}
\]  

where the propagation velocity and wavelength are dependent on \( \beta \) as follows:

\[
u = \frac{\omega}{\beta} \quad [2.2.11]
\]

\[
\lambda = \frac{2\pi}{\beta} \quad [2.2.12]
\]

One of the most interesting observations from the previous analysis is that the electric and magnetic fields \( E \) and \( H \) are out of phase. Which means that at any time, \( E \) leads \( H \) by an angle \( \theta/2 \), known as loss angle. This phase-shift of the fields is a result of the complex intrinsic impedance of the medium, and by analyzing the magnitude of the current density to the displacement current, the loss angle is defined as follows.

\[
\tan \theta = \frac{\sigma}{\omega \varepsilon} \quad [2.2.13]
\]

Due to the lossy nature of dielectric materials, the permittivity of such materials can also be written as a complex quantity. The tangent of the loss angle is equivalent to the ratio of the imaginary and the real part of complex permittivity, and is as follows:

\[
\varepsilon_c = \varepsilon \left[ 1 - j \frac{\sigma}{\omega \varepsilon} \right] = \varepsilon' - j\varepsilon'' \quad [2.2.14]
\]
This is called the complex dielectric constant and it is usually reported as a factor of the permittivity of free space. The real part relates to the capacity of the material to store electromagnetic energy and the imaginary part the losses of electromagnetic energy (Metaxas and Meredith, 1983; Sadiku, 1995; Shadowitz, 1975).

The propagation of electromagnetic waves in a lossless dielectric ($\sigma \ll \omega \varepsilon$) is similar to the propagation of electromagnetic waves in free space. In this case, $\alpha = 0$ so that there is no attenuation in the field energy and the loss tangent is 0, and $\mathbf{H}$ and $\mathbf{E}$ are in phase.

In a good conductor ($\sigma \ll \omega \varepsilon$), the loss tangent tends to infinity, and $\mathbf{E}$ and $\mathbf{H}$ will be out of phase by $45^\circ$. The electromagnetic wave loses energy very quickly generating what is called a skin effect. Both $\mathbf{E}$ and $\mathbf{H}$ will be attenuated by a factor $e^{-\alpha z}$. Penetration depth is defined as the depth where the wave amplitude becomes $1/e$ of the original. In the case of good conductors, the penetration depth ($\delta$) is defined as (Sadiku, 1995):

$$\delta = \frac{1}{\alpha} = \frac{1}{\sqrt{\pi f \mu \sigma}}$$  \[2.2.15\]

The penetration depth is an important parameter to analyze and describe the behavior of electromagnetic waves inside a material, but due to the finite dimensions of the material being processed in a microwave system, it becomes necessary to analyze the behavior of the waves when there are changes in the propagation medium.

### 2.2.1.4 Electromagnetic waves in interfaces

When plane waves meet a different medium, a portion of the wave will be reflected, and the other part transmitted. The proportion of reflected and transmitted wave depend on the
constitutive properties of the two materials ($\mu$, $\sigma$, $\varepsilon$) and on the angle of incidence of the waves.

The intrinsic impedance ($\eta$) of the medium is one of the parameters required to study this phenomena, and it is defined as:

$$\eta = \sqrt{\frac{j \omega \mu}{\sigma + j \omega \varepsilon}} = |\eta| \angle \frac{\theta}{2}$$  \[2.2.16\]

For perfect conductors, $\eta = 0$ while for perfect dielectrics, $\eta \rightarrow \infty$.

The loss tangent is related to the intrinsic impedance (Equation 2.2.16), and it can also be noticed from equation 2.2.16 that for any medium, the electric and magnetic fields are related by the intrinsic impedance such that:

$$H = \frac{E}{\eta}$$  \[2.2.17\]

At the interface of any two materials, the boundary conditions require that both $E$ and $H$ be continuous, so that the component of the fields that are tangential to the interface must follow a continuity equation of the form:

$$E_i + E_r = E_t$$  \[2.2.18a\]

$$H_i + H_r = H_t$$  \[2.2.18b\]

From this it can be shown that:

$$E_t = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2} E_i$$  \[2.2.19\]

and

$$H_r = \frac{2 \eta_2}{\eta_1 + \eta_2} E_i$$  \[2.2.20\]
Since part of the electromagnetic wave incident at an interface will be transmitted and some reflected, reflection (Γ) and transmission (τ) coefficients are defined. Both coefficients are dependent on the intrinsic impedance of the different mediums, and are dimensionless quantities, but can be complex numbers. The values of Γ range between 0 and 1.

\[
\Gamma = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2} \quad [2.2.21]
\]

\[
\tau = 1 + \Gamma = \frac{2\eta_2}{\eta_1 + \eta_2} \quad [2.2.22]
\]

When waves are enclosed within walls made of a conducting material and are allowed to reach steady state, a certain portion of the waves is reflected from the interface and a portion is transmitted. Thus, a standing wave is formed, in which the intensities of the electric and magnetic fields add and form a wave that apparently does not travel. The standing wave is a function of the reflection coefficient of the interface, and of the form of the incident and reflected waves. The ratio of the maximum to the minimum electric or magnetic field is called the standing wave ratio (s) and is defined as follows:

\[
s = \frac{|E_{\text{max}}|}{|E_{\text{min}}|} = \frac{|H_{\text{max}}|}{|H_{\text{min}}|} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad [2.2.23]
\]

From this definition, and given that s is easier to measure than E or H, or the reflection coefficient, an alternative method to calculate Γ has been derived as follows:

\[
|\Gamma| = \frac{s - 1}{s + 1} \quad [2.2.24]
\]
This is a more useful definition since the standing wave ratio is easier to measure than the reflection coefficient (Sadiku, 1995; Shadowitz, 1975; Rothwell and Cloud, 2001).

The electromagnetic concepts studied in this section, have been developed for communications and radar but they can be applied to food applications as well. The application and understanding of these concepts in industrial food application is necessary to improve the acceptance and of this technology in the industry.

2.3 Microwave heating of food

The use of microwaves to heat foods has become common in the American household. The microwave oven has become a common appliance in American kitchens, and it is commercially available in many variations, sizes, and powers. The frequency at which these microwave ovens operate has been regulated by the Federal Communication Commission due to the use of microwaves for communications, and radar. The allocated frequencies for industrial, medical, and household applications are 915 ± 13 MHz, 2450 ± 50 MHz, 5800 ± 75 MHz, and 24125 ± 125 MHz for industrial, scientific and medical applications (47CFR18.301, 2004). A frequency of 2450 MHz is used mostly in household microwave ovens, while 915 MHz is intended for industrial applications.

Conventional heating relies on heat transfer to the product from a hot or to a cold medium, either directly or indirectly. Direct heating occurs when a hot fluid (generally steam) is mixed with the product, while indirect heating takes place through the walls of a tube, plate, or vessel. The heating using microwaves has several characteristics that differentiate it from conventional heating, such as:
- Power can be turned on and off instantly
- It is very rapid
- It does not rely on contact with hot surfaces or a hot medium
- It is selective, i.e. different materials, or portions of the same food material having different properties will heat at different rates
- It is volumetric, thus theoretically more uniform than conventional heating

With all these considerations, Microwave heating is a promising technology for heating of food materials that are difficult to heat conventionally. However, observations show that microwave heating does not heat food uniformly. This lack of uniformity is due to several factors such as geometry of the microwave oven cavity, thermal and dielectric properties of the food, frequency used, etc. The development of microwave heating of foods has faced several challenges and setbacks over the years, mainly due to the observed lack of uniformity of heating of food materials. Thus, the mechanisms of heating of foods when exposed to a microwave field need to be investigated in more detail (Metaxas and Meredith, 1983; Datta and Anantheswaran, 2001).

2.3.1 Heating mechanisms of foods

It has been observed that dielectric materials heat when exposed to a microwave energy field. When a dielectric product is exposed to a microwave field, as explained in section 2.2.1.3, the rapidly changing field tries to polarize the charged molecules (ions, dipoles, and quadrupoles) present in the dielectric. However, the material cannot follow this rapid polarization and thus some of that energy is lost in the form of heat (Metaxas and Meredith, 1983). It is generally
accepted that water and ions (polar molecules) are the responsible for the ohmic loss of microwave energy within a food, as stated in equation 2.2.4 (Nelson and others, 1994). This statement maybe related to the mobility of ions, which in the absence of water, is very restricted.

The dielectric properties of the material, introduced in equation 2.2.12 are the properties that relate the ability of the food materials to be heated using microwaves. Food materials comprise a wide variety of dielectric properties, and it can be observed in compilations by Kent (1987), Funebo and Ohlsson (1999), Nelson (1991), and Nelson and others (1994). Due to this wide range of dielectric properties, it becomes very difficult to devise an apparatus or application that would be universal. Thus, many specific applications have been devised in the food industry.

2.3.2 Applications in the food industry

Applications of microwave heating in the food industry are slowly gaining acceptance. The applications that have initially succeeded in being adopted widely are shown in table 2.3.1.

It can be inferred in table 2.3.1 that most applications refer to solid foods, which can be conveyed by a belt. Applications for processing of fluid food material are pending, and require more research. Drozd and Joines (1999) invented a especially designed system that shows promise for processing of fluid materials, and is the one used in the experimental part of this research. These special heating systems, however, share the same components as the well known household microwave oven.
Table 2.3.1 Current applications of microwave heating in the food industry.

(Adapted from Datta and Anantheswaran, 2001)

<table>
<thead>
<tr>
<th>Product</th>
<th>Unit operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasta, onions, herbs</td>
<td>Drying</td>
</tr>
<tr>
<td>Bacon, meat patties, chicken, fish sticks</td>
<td>Cooking</td>
</tr>
<tr>
<td>Fruit juices</td>
<td>Vacuum drying</td>
</tr>
<tr>
<td>Frozen foods</td>
<td>Tempering</td>
</tr>
<tr>
<td>Surimi</td>
<td>Coagulation</td>
</tr>
</tbody>
</table>

2.3.3 Components of a microwave heating system

A microwave heating system, either batch or continuous, is composed of the following elements: Microwave source, directional coupler, waveguide, heating chamber, and control & safety elements. The microwave source can be a magnetron, a klystron type tube, or a solid state microwave generator. The waveguide is a conduit through which the microwaves are conducted to the heating chamber, where the food is placed and heated. The control elements include timers and power controllers, and safety elements are required to avoid the exposure of microwaves to the operators.

2.3.3.1 Magnetrons

Magnetrons are the most commonly used source of microwaves, due to their efficiency in converting electricity into microwave energy. The development on magnetrons can be traced
back to the development of radar equipment during World War II. A magnetron can be defined as a vacuum diode, made up of circular resonant cavities around a cathode immersed in a perpendicular magnetic field. The perpendicular magnetic field forces the electrons emitted by the cathode into a curved motion, which is very efficient in converting DC energy from the electrons into microwave energy. There are two types of magnetrons, pulsed and continuous wave magnetrons. Pulsed magnetrons are used in radar applications and have a very high peak power output for a very short time. Continuous wave magnetrons are the ones used in most heating application and have a continuous power output at the expense of peak output (Ishii, 1995).

The parts of a magnetron are: cathode, anode, and output. The cathode is usually a helix of tungsten that is heated to emit electrons by passing electric current through it. Once the electrons are emitted from the cathode and enter the chamber, some are attracted back to the cathode and generate what is called back-bombardment. Back bombardment increases the instantaneous output of the magnetron, and has to be controlled by controlling the temperature of the cathode. The anode is the most important piece of a magnetron; it is usually made of copper and consists of a series of resonant cavities placed around the cathode. The size and shape of these cavities determines the frequency of the microwaves produced by the magnetron. The different cavities have their vanes strapped alternately, so that the electrons are forced to follow a curved motion by following the alternate potential fields. The energy of the electrons is given up to the electromagnetic field before bombarding the anode, in the form of microwave energy that can be output to the waveguide. However the bombardment of electrons in the anode generates heat, that has to be removed to prevent overheating and burning, this is generally accomplished
by water cooling in industrial applications. The output of a magnetron is a mean to couple the energy from the magnetron to the waveguide, it consists of a loop in one of the resonant chambers or a coaxial conductor connected to a vane (Metaxas and Meredith, 1983; Ishii, 1995).

The power of a magnetron has to be varied and controlled in order to deliver power precisely and effectively. Several methods are available to control the output of the magnetron, which include:

- Pulsing the output of the magnetron is the method used in most household microwaves, in which the magnetron is turned on and off in intervals to control the average power delivered to the load. The pulse cycles can be in the 2-20 s range. This method is not compatible with continuous heating, as it will not expose the product to the microwaves uniformly but is used in household microwave ovens.

- Changing the Anode Current, it has been proved that the output power of a microwave is directly proportional to the anode current. However, there is a minimum voltage that needs to be applied to the anode, it is called Hartree voltage and is dependent on the magnetic field, anode radius, cathode radius, and the wavelength. Most power supplies are normalized to a certain voltage that will be higher than the Hartree voltage to avoid this pitfall.

- Adjusting the Magnetic Field, by adjusting the magnetic field inside the magnetron the power is varied. For a constant anode current and increasing magnetic field decreases the output power. (Ishii, 1995)
The conversion of electric energy into microwaves is very efficient, but some of this energy is spent as heat. The efficiency of a magnetron is thus defined by the amount of heat that must be removed. Current magnetrons operate with efficiencies ranging from 70 to 85% (Ishii, 1995).

The produced microwave energy inside the magnetron has to be conveyed to the product in the heating chamber. A method that delivers power from the microwave source to the heating chamber in a very efficient manner has been found in the use of waveguides.

2.3.3.2 Waveguides

While having electromagnetic waves in open space can be useful for broadcasting media, such as TV or radio, a method for propagating the waves in a more orderly manner is more appropriate for other applications. In order to transmit power or information efficiently, guided structures are used. These structures help to guide the electromagnetic waves from the source to the load in a direct manner; examples of these structures are transmission lines and waveguides (Sadiku, 1995).

Transmission lines consist of two or more parallel conductors that connect the source and the load. Typical transmission lines include coaxial cables, two wire lines, microstrips, and planar lines. Waveguides differ from transmission lines both in construction and functionality. Waveguides are hollow metallic conductors, through which the wave is delivered to the product to be heated. The geometry of the duct can be any arbitrary cross-section, but rectangular and circular are the most common, with dimensions standardized for the frequency of the microwaves (Sadiku, 1995; Cronin, 1995).
While transmission lines can only support transverse electromagnetic waves, waveguides can support many possible field configurations. Moreover, transmission lines can be used from DC to a certain frequency, while waveguides can only be used above a certain frequency acting as a high frequency filter. This characteristic makes them useful for high frequency electromagnetic waves, such as microwaves and radio frequency (Ishii, 1995; Sadiku, 1995; Cronin, 1995).

Rectangular waveguides are used more often in microwave heating, due to construction and wave transport considerations. In order to analyze what happens in a waveguide the following assumptions are made: the walls are made of perfect conductor \(\sigma \sim \infty\), the material in the inside is a perfect lossless dielectric \(\sigma = 0\), and no charges are found in the waveguide.

The coordinate system used has \(z\) as the direction of propagation of the wave, \(x\) and \(y\) as the dimensions of the waveguide. The resulting field equations are Helmholtz homogeneous differential equations in Cartesian coordinates, like the ones shown in equation 2.2.9, such that:

\[
\nabla^2 \mathbf{E} + \gamma^2 \mathbf{E} = 0 \quad \text{[2.3.1a]}
\]

\[
\nabla^2 \mathbf{H} + \gamma^2 \mathbf{H} = 0 \quad \text{[2.3.1a]}
\]

By using Cartesian coordinates \((x, y, z)\) the system of equations 2.3.1 lead to a system of 6 partial differential equations and 6 unknowns \((E_x, E_y, E_z, H_x, H_y, H_z)\). This system can be solved by separation of variables. The resulting equation for each field component is in the following form:

\[
\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} + \gamma^2 E_x = 0 \quad \text{[2.3.2]}
\]

In order to apply the separation of variables method, each component is regarded as:
\[ E_z = X(x)Y(y)Z(z) \]  \[\text{[2.3.3]}\]

After applying a separation constant and remembering that the wave propagates in the \( z \)-direction, equation 2.3.1 separates as:

\[
\begin{align*}
X'' + \gamma_x^2 X &= 0 \\
Y'' + \gamma_y^2 Y &= 0 \\
Z'' + \gamma_z^2 Z &= 0
\end{align*}
\[\text{[2.3.4]}\]

This results in electric and magnetic fields components in the following form:

\[
|E_z| = (A_x \cos k_x x + A_y \sin k_y y)(A_z \cos k_z z + A_y \sin k_y y)e^{-\gamma z} \tag{2.3.5}
\]

\[
|H_z| = (B_x \cos k_x x + B_y \sin k_y y)(B_z \cos k_z z + B_y \sin k_y y)e^{-\gamma z} \tag{2.3.6}
\]

The other field components can be deducted by remembering the cross product relationships in Maxwell’s equations and the resulting relationships are

\[
\begin{align*}
E_x &= -\gamma \frac{\omega \mu}{\epsilon \mu} \frac{\partial H_z}{\partial y} - j \frac{\partial}{\partial x} \\
E_y &= -\gamma \frac{\omega \mu}{\epsilon \mu} \frac{\partial H_z}{\partial x} - j \frac{\partial}{\partial y} \\
H_x &= -\gamma \frac{\omega \mu}{\epsilon \mu} \frac{\partial E_z}{\partial x} - j \frac{\partial}{\partial y} \\
H_y &= -\gamma \frac{\omega \mu}{\epsilon \mu} \frac{\partial E_z}{\partial y} - j \frac{\partial}{\partial x}
\end{align*}
\[\text{[2.3.7a-d]}\]

where \( h^2 = \gamma^2 + k^2 = k_x^2 + k_y^2 \)

From the equation set 2.3.7 it can be derived that several standing wave and field configurations are possible in waveguides. These configurations that satisfy the equation set are
called modes. These modes of the electric and magnetic fields have been classified in 4 categories as follows (Sadiku, 1995):

1. Transverse electromagnetic modes (TEM), both \( E \) and \( H \) fields are transverse to the propagation of the wave \([H_z = E_z = 0]\). But if this happens, all other components of the field vanish. Thus, TEM modes are not supported by rectangular waveguides.

2. Transverse electric modes (TE). \([E_z = 0]\). The remaining components of the electric field are transverse to the propagation of the wave, while the magnetic field is parallel to the propagation.

3. Transverse magnetic modes (TM). \([H_z = 0]\). The remaining components of the magnetic field are transverse to the propagation of the wave, while the electric field is parallel to the propagation of the wave.

4. Hybrid modes. \( E_z \neq 0 \) and \( H_z \neq 0 \). Neither the electric or magnetic field are transverse to the propagation of the wave.

The TE and TM modes are the preferred modes of propagation, because it is easier to control the fields into them. The propagation constant and phase velocity depend on the mode, and the definition of the constant \( h^2 \) is very important.

In the case of TE modes, when the electric field is transverse to the propagation of the waves \((E_z = 0)\), the field equations can be solved taking into account the boundary conditions, either in standard or alternative form as follows:
\[
\begin{align*}
\text{x} &= 0 \quad \mathbf{E}_y = 0 \quad \frac{\partial \mathbf{H}_z}{\partial x} = 0 \quad [2.3.8a] \\
\text{x} &= a \quad \mathbf{E}_y = 0 \quad \frac{\partial \mathbf{H}_z}{\partial x} = 0 \quad [2.3.8b] \\
\text{y} &= 0 \quad \mathbf{E}_x = 0 \quad \frac{\partial \mathbf{H}_z}{\partial y} = 0 \quad [2.3.8c] \\
\text{y} &= b \quad \mathbf{E}_x = 0 \quad \frac{\partial \mathbf{H}_z}{\partial y} = 0 \quad [2.3.8d]
\end{align*}
\]

The resulting components of the electromagnetic field are shown in equation set 2.3.9

and to satisfy the boundary conditions \(\cos (k_x x)\) and \(\sin (k_y y)\) have to be zero, thus \(k_x\) and \(k_y\) can be written as periodical functions of \(\pi/a\), affecting the way both \(h^2\) and \(\gamma\) are defined, as shown in the system of equations 2.3.10.

\[
\mathbf{E}_z = 0 \quad [2.3.9a]
\]

\[
\left| \mathbf{H}_z \right| = H_o \cos \left( \frac{m\pi}{a} x \right) \sin \left( \frac{n\pi}{b} y \right) e^{-\gamma z} \quad [2.3.9b]
\]

\[
\left| \mathbf{E}_x \right| = \frac{j\omega \mu}{\hbar^2} \left( \frac{n\pi}{b} \right) H_o \cos \left( \frac{m\pi}{a} x \right) \sin \left( \frac{n\pi}{b} y \right) e^{-\gamma z} \quad [2.3.9c]
\]

\[
\left| \mathbf{E}_y \right| = -\frac{j\omega \mu}{\hbar^2} \left( \frac{m\pi}{a} \right) H_o \sin \left( \frac{m\pi}{a} x \right) \cos \left( \frac{n\pi}{b} y \right) e^{-\gamma z} \quad [2.3.9d]
\]

\[
\left| \mathbf{H}_x \right| = \frac{\gamma}{\hbar^2} \left( \frac{m\pi}{a} \right) H_o \sin \left( \frac{m\pi}{a} x \right) \cos \left( \frac{n\pi}{b} y \right) e^{-\gamma z} \quad [2.3.9e]
\]

\[
\left| \mathbf{H}_y \right| = \frac{\gamma}{\hbar^2} \left( \frac{n\pi}{b} \right) H_o \cos \left( \frac{m\pi}{a} x \right) \sin \left( \frac{n\pi}{b} y \right) e^{-\gamma z} \quad [2.3.9f]
\]
m = 0, 1, 2,...  n = 0, 1, 2,...

m and n define the different standing wave patterns in the waveguide, and represent the half cycle variations in the x and y direction respectively. Note that if $m = n = 0$ all the fields components vanish and no propagation is possible. From equations 2.3.5 and 2.3.6 it can be observed that the definition of $\gamma^2$ depends on how $k_x$ and $k_y$ are defined, for propagation in waveguides these were defined as periodical functions. The propagation constant is also a function of $h$, and remembering that $k = \omega \sqrt{\varepsilon \mu}$ such that:

$$k_x = \frac{m \pi}{a} \quad \text{and} \quad k_y = \frac{n \pi}{b} \quad \quad [2.3.10a]$$

$$h^2 = k_x^2 + k_y^2 = \left( \frac{m \pi}{a} \right)^2 + \left( \frac{n \pi}{b} \right)^2 \quad \quad [2.3.10b]$$

$$\gamma^2 = \left( \frac{m \pi}{a} \right)^2 + \left( \frac{n \pi}{b} \right)^2 + \omega^2 \varepsilon \mu \quad \quad [2.3.10c]$$

Therefore the value of the propagation constant of the wave defines 3 cases of propagation within a waveguide as follow (Sadiku, 1995; Ishii 1995; Cronin, 1995):

1. $\gamma = 0$ In this case there is no propagation, so we have the cutoff frequency, that is defined as:

$$f_c = \frac{1}{2 \pi \sqrt{\varepsilon \mu}} \sqrt{\left( \frac{m \pi}{a} \right)^2 + \left( \frac{n \pi}{b} \right)^2} \quad \quad [2.3.11]$$

The cutoff frequency is the minimum frequency that can be transported through a rectangular waveguide of dimension $a$ and $b$. 
2. \( \gamma < 0 \) when the frequency is less than the cutoff. In this case the wave is evanescent and no propagation can occur.

3. \( \gamma > 0 \) when the frequency is greater than the cutoff. In this case the propagation is possible, and the phase constant is defined as

\[
\beta = \sqrt{k^2 - \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2}
\]  \[2.3.12\]

When the waveguide is filled with a lossless material (\( \mu, \varepsilon \)), the speed of light is defined as \( u = \frac{1}{\sqrt{\mu \varepsilon}} \) and in the case of air this is equal to c. Therefore, the cutoff frequency can be written as a function of the speed of propagation:

\[
f_c = \frac{u}{2} \sqrt{\left( \frac{m}{a} \right)^2 + \left( \frac{n}{b} \right)^2}
\]  \[2.3.13\]

The impedance of the waveguide can be defined based on the cutoff frequency of the waveguide, as well as the intrinsic impedance of the medium \( \eta' = \sqrt{\frac{\mu}{\varepsilon}} \). The effective impedance of a rectangular waveguide is a function of the frequencies as well, as follows:

\[
\eta_{TE} = \frac{\eta'}{\sqrt{1 - \left( \frac{f_c}{f} \right)^2}}
\]  \[2.3.14\]

Rectangular waveguides, when \( a > b \), operate preferentially in single mode. The modes with the lower cutoff frequency are TE10 and TE20 respectively and the dimensions of the waveguide are planned in such a way that the system operates between this cutoff frequencies. Standardized dimensions for rectangular waveguides are found in table 2.2.3. The dominant
mode is TE$_{10}$, in this mode the components of the fields that are not zero are $E_y$, $H_x$, and $H_z$ (Cronin, 1995).

The power that a waveguide can transmit in the z direction is given by a surface integration of the z-component of the Poynting vector and for the TE$_{10}$ mode it can be calculated as follows:

$$P = \int_a^b \int_{x=0}^{y=0} \mathbf{E} \times \mathbf{H} = \frac{H_0^2}{\eta} \left( \frac{\mu_0}{2\pi} \right)^2 a^3 b$$ \hspace{1cm} [2.3.15]

The material of the walls can cause losses of power in the transmitted microwaves, this occurs when the materials is less than a perfect conductor.

Table 2.3.2 Standardized dimensions for rectangular waveguides for use in microwave heating

(Adapted from Ishii, 1995)

<table>
<thead>
<tr>
<th>Frequency range (GHz)</th>
<th>Cutoff frequency (GHz)</th>
<th>Inside dimensions (*10$^{-3}$ m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32 – 0.49</td>
<td>0.256</td>
<td>584.2 , 292.1</td>
</tr>
<tr>
<td>0.75 – 1.12</td>
<td>0.605</td>
<td>247.65 , 123.83</td>
</tr>
<tr>
<td>0.96 – 1.45</td>
<td>0.766</td>
<td>195.58 , 97.79</td>
</tr>
<tr>
<td>1.70 – 2.60</td>
<td>1.372</td>
<td>109.22 , 54.61</td>
</tr>
<tr>
<td>2.20 – 3.30</td>
<td>1.736</td>
<td>86.36 , 43.18</td>
</tr>
</tbody>
</table>

The transmission of microwaves within a waveguide, generates a standing wave, but the application of a load changes the shape of the standing wave, and increases the reflection of the waves. The impedance of the load has to be matched to the impedance of the waveguide in order to maintain the standing wave ratio and maintain the reflection at a minimum.
2.3.3.3 Impedance matching

Impedance is defined as the total passive opposition offered to the flow of electric current. To maximize the transfer of power to the food material, and to keep the standing wave ratio and the reflection at a minimum in microwave heating, the impedance of both the waveguide and the product has to be matched (Bronwell and Beam, 1947).

Several techniques exist to match impedance, and the literature is abundant. One of such methods, also used in transmission lines, matches a load by using shorted sections of transmission line, called stubs. By changing the location and length of these stubs, the impedance of the load is matched. Techniques involving 1, 2, or 4 stubs can match any value of impedance (Ishii, 1995; Reich, 1953).

In the case of waveguides, the matching can be achieved by placing small rods of conductive material at a known distance from the load, these rods act in the same way as the stubs do in transmission lines. The length that these stubs are inserted into the waveguide determines the matching of the load in the cavity (Ishii, 1995).

Efficient transfer of the electromagnetic power to the product placed in the heating chamber is the ultimate goal of microwave heating. To achieve this purpose the design of the cavity, in which the microwaves will be applied to the load, is very important, in order to maximize the transfer of energy into the load. The most effective method is to use resonant cavities.
2.3.3.4 Resonant application cavities

When electromagnetic waves are confined into a cavity, a standing wave forms in a similar way as it does in waveguides. Depending on the geometry of the cavity and the way the waves are excited or introduced into it, the standing wave can have different modes. In household microwave ovens a cubic or rectangular cavity is used, in this type of cavities several modes form, mostly in a hard to control fashion, which later can cause the appearance of hot and cold spots where these modes are present (Datta and Anantheswaran, 2001).

Industrial and continuous flow applications require a more controllable way to apply microwaves, preferably in a single mode fashion. Circular and elliptical cylindrical cavities are cylindrical enclosures of conductive material with both ends closed or short-circuited. In these cavities a standing wave will develop and resonance will occur. The development of the standing wave will be greatly influenced by the way the waveguide and the resonant cavity are connected, as well as the dimensions of the cavity. Several modes can develop in cylindrical cavities, equation 2.3.14 shows the resonant wavelength in free space for a circular cylindrical cavity, where the factors $X_{lm}$ are the roots of the Bessel J and J' functions (Ishii, 1995).

\[ \lambda_o = \frac{2}{\sqrt{\left(\frac{2 \cdot X_{lm}}{\pi D}\right)^2 + \left(\frac{n}{L}\right)^2}} \]  

Cylindrical and elliptical application cavities have a preference for TM$_{010}$ modes, which means that a maximum mode will be concentrated in the z-axis of the cylinder. This can be
beneficial for controlling the penetration of microwaves, and improving the uniformity of heating since a tube can be located within such mode. Drozd and Joines (1999, 2001, 2002) made use of this concepts to patent the design of systems that can be used to heat fluids using microwave technology.

The design of the cavities must take into account also the behavior of the material when heated, and the changes in dielectric properties it may go through during heating. Therefore, the dielectric properties of food materials, its dependence on temperature and frequency have to be analyzed and understood.

2.4 Dielectric properties of Food materials

Food materials belong in the group of dielectric materials, which are materials that are not conductors, nor are they insulators. Electromagnetic waves propagate into dielectric materials but the amplitude of the waves decreases, and that energy that is lost by the waves is converted into heat inside the material, as shown in equation 2.2.9. Dielectric properties of food materials can be written as shown in equation 2.2.14, such that:

\[
\varepsilon_e = \varepsilon \left[ 1 - j \frac{\sigma}{\omega \varepsilon} \right] = \varepsilon' - j\varepsilon'' \tag{2.4.1}
\]

The complex permittivity of a dielectric material consists of two parts, a real and an imaginary part, which are generally expressed as factors of the permittivity of free space. The real part, called dielectric constant (\(\varepsilon'\)), relates to the amount of energy that is reflected or transmitted by the material and to the ability of the material to store electromagnetic energy. The imaginary part, called loss factor (\(\varepsilon''\)), to the ability of the material to lose the energy transmitted
into heat (Englender and Buffler, 1991). The conversion of the energy into heat, or ohmic heating is usually described as a function of frequency (f), electric field intensity and loss factor, as shown in the following equation (Metaxas and Meredith, 1983; Buffler, 1993):

\[ P = 2\pi f |E|^2 \varepsilon_0 \varepsilon'' \]  \[2.4.2\]

It is however, very difficult to predict the values of \( E \). The amount of energy absorbed by a food material need to be analyzed based on the value of the reflection and transition coefficients. The value of these coefficients can only be analyzed if the values of dielectric properties can be predicted as a function of temperature, frequency, and composition of the food.

The prediction of dielectric properties based on the composition of the food materials is a subject that has attracted attention. The classic approach to the dielectric behavior of liquids in an electromagnetic field comes from the work by Debye (1929). Debye analyzed the behavior of polar molecules in non-polar solvents as spheres suspended in a viscous liquid. From Debye’s work, equation 2.4.3 was derived, where \( \varepsilon_s \) and \( \varepsilon_\infty \) are the dielectric constants at D.C. and very high frequencies respectively, and \( \tau \) is the relaxation time of the system that control the amount of energy that is converted into heat (Metaxas and Meredith, 1983).

\[ \varepsilon = \varepsilon' - j \varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j \omega \tau} \]  \[2.4.3\]

The dielectric constant at very high frequencies is independent of frequency, and a transition should occur at the relaxation frequency (Equation 2.4.4). At this frequency the loss factor should have a maximum. In the case of pure water, the static dielectric constant has a value of approximately 80, while the high frequency dielectric constant has a value of 4.3, and the relaxation frequency is located in the vicinity of \( 10^{10} \) Hz (Ryynänen, 1995).
The relaxation time is dependent on the viscosity of the system, and has been modeled using the Stokes equation. This model has been used extensively, even though it is based on simple interactions. Hasted and others (1948) modified the above equation to account for losses due to conductivity of the material ($\sigma$) as shown in equation 2.4.4 which adjusts very well to aqueous solutions of ions, as observed by Stogryn (1971). Hill (1980) reviewed the behavior of dielectric materials, and concluded that a modified version like the Collie-Hasted-Ritson equation (1948) in which correction parameters are added is a very good model for such materials as follows:

\[ f_{\text{rel}} = \frac{1}{2\pi\tau} \]  

\[ \tau = \frac{2.4.4}{\tau} \]

Debye parameters are found in reference books for many solvents, but for food product some of these parameters have to be estimated or generated.

Composition is a very important factor in the dielectric behavior of any food material. However, foods have many complex components. Due to this complex nature of the components of a food material simple approaches like the Debye-Hasted equation are only valid for relatively simple food materials, such as milk, or apple juice (Mudgett and others, 1974, 1986). Several researchers have tried to correlate the composition of foods to its dielectric properties. Water content, salt concentration, protein, carbohydrate and fat contents have been used among other factors. Kudra and others (1991) analyzed the characteristics of milk constituents in microwave
heating. Funebo and Ohlsson (1999) made a prediction of the properties of fruits and vegetables as a function of temperature, bulk density, and water content. Their findings showed that other factors must be taken into account, and that the predictive equations failed to describe the products they targeted. Kent and others (2000, 2001) measured the dielectric properties of meat, poultry, and fish products, and tried to determine a method to detect the addition of water using dielectric properties. They were able to determine liquid uptake, salt content and protein, but had problems when more than one type of salt was added to the product.

Experimental data of dielectric properties is available in literature, with compilations like the ones by Kent (1987), Tinga and Nelson (1973), Nelson (1973), and Funebo and Ohlsson (1999). More data is required, especially in the frequencies of industrial interest, which have been neglected in favor of the more widespread frequencies of household interest. Thus, the measurement of these properties is very important to predict the heating characteristics of food materials.

2.4.1 Measurement of dielectric properties

Dielectric properties are measured using several methods, depending on the frequency of the electromagnetic field in which they need to be measured. Table 2.4.1 lists the available methods to measure dielectric properties (Hass, 1996; Agilent Technologies, 2003). The methods can generally be divided into two groups. Those for frequencies smaller than $10^8$ Hz are referred to as lumped circuit methods, while those for frequencies greater than $10^8$ Hz are called distributed circuit methods. The lumped circuit methods are designed to measure a cell capacitance and resistance which can be related to the dielectric properties of the sample. In
contrast distributed circuits are designed to measure an attenuation factor ($\alpha$), and a phase factor ($\beta$), which are directly related to dielectric properties.

Table 2.4.1 Methods to measure dielectric properties

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$ to $10^{-1}$</td>
<td>D.C. transient measurements</td>
</tr>
<tr>
<td>$10^{-2}$ to $10^{2}$</td>
<td>Ultra low frequency bridge</td>
</tr>
<tr>
<td>$10$ to $10^{7}$</td>
<td>Schering bridge and auto balancing bridge</td>
</tr>
<tr>
<td>$10^{5}$ to $10^{8}$</td>
<td>Resonance circuits</td>
</tr>
<tr>
<td>$10^{7}$ to $10^{10}$</td>
<td>Coaxial line</td>
</tr>
<tr>
<td>$10^{9}$ to $10^{12}$</td>
<td>Cavity resonator and waveguides</td>
</tr>
</tbody>
</table>

From the above mentioned methods, the coaxial line method is the one used more commonly to measure dielectric properties in the microwave frequency range. Stuchly (1980) recognized the utility of this method for biological substances, due to the small thickness of the sample required and the improvement of automated network analyzers and computational capabilities. The method consists on placing a probe in contact with the sample, the probe has an open coaxial core which transmits microwaves from the center conductor and an automated network analyzer measures the amount of such waves reflected. The standing wave ratio is measured and the network analyzer contains embedded software the calculates the dielectric properties. The precision of this method is slightly inferior to others, but the simplicity and efficiency of it makes it ideal for food and bio-materials (Engelder and Buffler, 1991).
Blackham and Pollard (1997) presented an improved method to calculate dielectric properties using the open ended coaxial probe methods. Boughriet and others (1999) showed that Blackham-Pollard’s equation was useful for measuring dielectric properties of liquids. Practical measurements are performed using an automated network analyzer, which is used in conjunction with software specially designed for that purpose. Agilent technologies (formerly Hewlett Packard) offer such packages, which integrate a probe, network analyzer and software.

Dielectric properties are dependent on the frequency in which they are measured, as seen from equation 2.4.1. Debye-Hasted models also suggest the existence of one or several critical or relaxation frequencies, at which there is a drastic change in dielectric properties, coinciding with the relaxation time as parameter. This has been observed experimentally, by Kaatze (1995). Each of the relaxation frequencies is named using a Greek letter, and change from compound to compound. Water presents a relaxation frequency in the vicinity of $10^{10}$ Hz. It has been observed, however, that the relaxation frequencies change after the addition of polar molecules and have to be measured experimentally for each material (Ryynänen, 1995).

Temperature is also a very important parameter on dielectric properties. Being dielectric properties the result of polarization of molecules, temperature affects the mobility of the molecules, changes molecules, as well as some macro characteristics of the food materials, such a gelation or protein denaturation, which all have an important effect on the dielectric properties.

2.4.2 Temperature dependence

Dielectric properties are a macroscopic effect of molecular interactions with the electromagnetic field, as stated in section 2.2.12. Temperature affects molecules by increasing
the internal vibration of their bonds, elongating such bonds, increasing the mobility of molecules and the internal energy in them (Van Wylen, 1994). Due to the changes in mobility of polar molecules dielectric properties have to be affected by temperature.

Stogryn (1971) observed that the dielectric constant of salt water decreased and the loss factor increased with an increase in temperature. This observation was supported with a decrease in relaxation time and a decrease in the static dielectric constant with an increase in temperature. These observations were explained by Hasted (1973) as results of the changes in internal energy and relaxation times of water with temperature. Since the main component responsible for microwave heating of foods is water, studies in aqueous dielectrics are relevant to food processing.

The dependence on temperature of the relaxation time has been recognized as the main responsible for the changes in dielectric properties with temperature (Runt and Fitzgerald, 1997). Dependence on temperature of relaxation time follows an Arrhenius-type kinetics, which should allow the prediction of properties using equations 2.4.4. However, the complexity of the food matrixes require experimental observations.

Available data of dielectric properties of food materials (Kent, 1987; Nelson, 1973; Tinga and Nelson, 1973) showed that most liquid products follow the behavior observed in water dielectrics. The dielectric properties of solid foods, were proposed to behave in a similar manner, being water the main responsible for dielectric heating. However, it has been observed that some solid foods showed a different behavior than aqueous solutions. Datta and others (1998) studied the dependence on temperature and composition of several food products, as a function of water, and ash fraction. Their results confirm that water and ash contents are not
enough to determine the dielectric properties of foods. It has been observed that foods containing hydrocolloids present differences in the dielectric properties behavior.

Hydrocolloids are polymers, and have two characteristics that affect dielectric properties, binding water, changing phase during heating. By binding water, the mobility of ions is restricted, thus the loss factor. During changes of phase dielectric properties undergo changes, which are noticeable and have been observed when studying the dielectric properties of starch solutions by Miller and others (1991), Ndife and others (1998), and Rozzi and Singh (2000). Before starch solutions reach the gelation point, the dielectric properties of these solutions are different to aqueous solutions containing the same solutes, loss tangent tends to be smaller in the starch solutions. But after the gelation point the dielectric properties become very similar to those of the solutions without starch.

The use of continuous flow microwaves heating systems in aseptic processing of food materials seems to be a promising technology. However, more knowledge is required on the interactions between foods and microwave energy in these systems. The following study tries to provide some knowledge in these areas by dealing with practical and theoretical matters.

Manuscript I presents a method to measure the temperature profiles at the exit of the heating chamber, using T-type thermocouples, and the results of applying such method to the heating of milk. Dielectric properties of selected products that maybe suitable for processing using continuous flow microwave heating are the subject of manuscript II. Matching of dielectric properties and preparation of the system and model foods is presented in Manuscript III, with emphasis in pre-sterilization of an aseptic system. Aseptic processing of a sample
product is presented in manuscript IV, for this research a method to determine the feasibility and scale-up of microwave processing was developed and tested successfully. Solutions to the microwave penetration were investigated in Manuscript V, certain criteria and methods are there presented in order to evaluate the feasibility to process any food and biomaterial in continuous flow microwave heating.
**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Width of waveguide (m)</td>
</tr>
<tr>
<td>B</td>
<td>Magnetic flux vector</td>
</tr>
<tr>
<td>b</td>
<td>Height of waveguide (m)</td>
</tr>
<tr>
<td>c</td>
<td>Speed of light (m/s)</td>
</tr>
<tr>
<td>C₀</td>
<td>Cooked value</td>
</tr>
<tr>
<td>cₚ</td>
<td>Specific heat at constant pressure (J/kg-K)</td>
</tr>
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<td>D</td>
<td>Electric displacement vector</td>
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<tr>
<td>D₀</td>
<td>Thermal death time (s)</td>
</tr>
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<td>Diameter (m)</td>
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<td>Activation Energy</td>
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<td>Sterilization value (s)</td>
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<tr>
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<td>Frequency (Hz)</td>
</tr>
<tr>
<td>fₙ</td>
<td>Cutoff frequency (Hz)</td>
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<tr>
<td>fₘ</td>
<td>Relaxation frequency</td>
</tr>
<tr>
<td>G</td>
<td>Thermal reduction relationship</td>
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<td>gₑₘ</td>
<td>Transmission of momentum (/m²)</td>
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<tr>
<td>H</td>
<td>Magnetic field vector</td>
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<tr>
<td>h</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Current (A)</td>
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ID Internal diameter (m)
J Electrical charge flux vector
j Complex constant \( \sqrt{-1} \)
k constant
L Length (m)
m number of modes in the x axis
n number of modes in the y axis
N Number of microorganisms

\[ N_{Re} = \text{Reynolds number} \frac{4}{\pi} \frac{m}{D \mu} \]

P Power (W)
\( \dot{q} \) Energy absorbed per unit time (W)
S Surface (m²)
\( S_{em} \) Transmission of energy (W/m²)
s Standing wave ratio
T Temperature (°C)
\( T_E \) Equivalent Temperature (°C)
t time (s)
t\(_E\) Equivalent time (s)
u Propagation velocity (m/s)
v velocity (m/s)
V volume (m³)
z Thermal resistance of microorganisms (°C)

**Greek letters**

\( \alpha \) Attenuation factor (\( m^{-1} \))

\( \beta \) Phase constant or wave number

\( \Gamma \) Reflection coefficient

\( \gamma \) Propagation constant

\( \delta \) Penetration depth (m)

\( \Delta T \) Temperature change (°C)

\( \varepsilon \) Permittivity (F/m)

\( \varepsilon_0 \) Permittivity of free space (8.85 \( \cdot 10^{-12} \) F/m)

\( \varepsilon' \) Dielectric constant relative to vacuum

\( \varepsilon'' \) Loss factor relative to vacuum

\( \lambda \) Wavelength (m)

\( \mu \) Magnetic …. (H/m)

\( \eta \) Intrinsic impedance

\( \theta \) Loss angle (rad)

\( \rho_v \) Charge density

\( \omega \) Angular velocity (Rad/s)

\( \sigma \) Conductivity (MHO)

\( \tau \) Transmission coefficient
### Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
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<tr>
<td>$E$</td>
<td>equivalent</td>
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<td>$in$</td>
<td>inlet</td>
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<tr>
<td>$out$</td>
<td>outlet</td>
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<tr>
<td>$rel$</td>
<td>relaxation</td>
</tr>
<tr>
<td>$s$</td>
<td>static</td>
</tr>
<tr>
<td>$\infty$</td>
<td>very high frequency</td>
</tr>
</tbody>
</table>
References


Buffler


Datta AK, Barringer S, Morgan MT. 1998 Effects of composition and temperature on dielectric properties of foods at 2450 and 27 MHz.


MANUSCRIPT I

Temperature profiles within milk after heating in a continuous flow tubular microwave system operating at 915 MHz

Paper No. FSR-02-43 of the Journal Series of the Department of Food Science, North Carolina State University, Raleigh, NC 27695-7624.

Abstract

Skim, 1% fat, 2% fat, 4% fat, and chocolate milks were heated in a specially designed continuous flow tubular microwave applicator operating at 915 MHz under laminar flow conditions. The nominal power used was 5 kW and the flow rates were 2.0 and 3.0 l/min. Temperature profiles at the exit of the applicator were measured using a thermocouple arrangement over the cross-sectional area of the tube. The results obtained show that the average increase in temperature of different types of milk was very similar to one another, being 42 °C at 2.0 l/min and 29 °C at 3.0 l/min. Recorded differences between the lowest and highest exit temperatures were 3.7 and 3.0 °C respectively. Maps of cross-sectional temperature distribution illustrate that slightly higher temperatures were achieved within product segments flowing close to the center of the tube.

Keywords: Continuous microwave heating, milk, temperature profile, dielectric properties
Introduction

Continuous flow microwave heating is a relatively new technology in the food industry, even though applications of microwave heating technology are highly evolved for household applications. Microwaves are a part of electromagnetic spectrum with a frequency between 300 MHz and 3 GHz and they are primarily used for communications and radar. It has been long known that microwaves can be used for heating of foods and small batch microwave oven units for household use are present in most kitchens in the U.S.A. Microwaves heat foods in a rapid and direct manner, providing volumetric heating of the food. In industrial applications, this could drastically reduce the come-up time needed to achieve the required process temperature, thereby reducing the total cumulative thermal treatment and better preserving the thermo-labile constituents of the foods such as aromas, vitamins, and pigments. The characteristic of instantaneous power-on and shut-off of microwave generators can help deliver energy very precisely into the food products (Metaxas and Meredith, 1983; Meredith, 1998).

Due to the volumetric heating characteristic of microwaves, i.e., heat is generated in the food as a result of the conversion of the electromagnetic energy, the cumulative heat treatment of the bulk of a product should be more uniform than in the case of conventional processing. In theory volumetric heating should minimize overcooking of the surface and undercooking of the center. This can be extremely beneficial for liquids, such as milk, in which fouling of the tubes occurs due to overheating of the product in contact with the tube wall (Kudra and others, 1991).
Continuous flow microwave heating of milk could be used as an alternative to tubular and plate heat exchangers in pasteurization. Milk heats faster than water when exposed to microwaves, with the proteins and ions present in milk being the major contributors to the heating effect. The fat and sugars present in milk have a less significant effect. Thus, milk with different fat contents can be heated with equal efficiency (Kudra and others, 1991). The effects of thermal treatment of milk in a continuous microwave system was studied by Lopez-Fandiño and others (1996) by studying the denaturation of $\beta$-lactoglobulin and the inactivation of alkaline phosphatase and lactoperoxidase using a modified 2450 MHz microwave oven. The results obtained were compared to those obtained in the heat treatment in a plate heat exchanger and it was found that the degree of inactivation caused by the heat treatment in both cases was similar. Villamiel and others (1996a, b, 1998) showed that microwave pasteurization of milk produced lower levels of denaturation of whey proteins than conventional thermal processes and that the denaturation of $\beta$-lactoglobulin was comparable between both processes. In addition, it also resulted in lower microbial counts and lower lactose isomerization. Valero and others (2000) studied the effect of microwave treatment of milk on the sensorial characteristics during storage. The results showed that the sensorial characteristics of milk treated by microwaves were comparable to those achieved by traditional heat treatments after 15 days of storage.
Research on heat treatment processes using microwaves has provided valuable insight on the dynamics of microwave heating coupled with the thermal and dielectric properties of foods and variation in the energy absorbed as a result of variations in properties of the processed materials (Datta and Anatheswaran, 2000; Zhang and Datta 2000a,b; Lau and others 1998).

One of the limitations of the implementation of microwave heating systems on an industrial scale has been the non-uniformity of temperature distribution caused by microwave heating (Mudgett, 1986). In order to address the issue of uniformity of heating of food products flowing through a cylindrical enclosure, Industrial Microwave Systems Inc. (IMS), located in Morrisville, NC, designed a cylindrical microwave applicator. This configuration was designed to focus the electrical field so that the material at the center would receive the highest amount of energy. The results of a mathematical simulation, run by the manufacturer, predicted a parabolic field distribution inside the tube for a fluid with dielectric properties like those of milk at 25 °C.

This design was implemented in order to achieve a nearly parabolic power distribution, with the maximum power at the center of the tube. For a fluid with a parabolic velocity profile (laminar flow of a Newtonian fluid), the parabolic energy field coupled with a parabolic velocity profile should result in every particle of the fluid receiving a nearly identical cumulative amount of thermal energy during their residence time in the applicator. The fastest moving particles (at the center) would receive higher power, but for a shorter period of time, while the slowest moving
particles (at the wall) would receive less power, but for a larger period of time. Resulting in uniform heating of the entire product. The predicted uniform temperature distribution in the heating section is important for the processing of viscous fluids, since achieving turbulent flow or mixing for viscous fluids can be difficult using conventional means.

In order to verify the uniform temperature distribution predicted by the manufacturer, research on the heating of milk in microwave cylindrical applicators is necessary. This study was thus undertaken with the objective of determining the temperature profiles of milk heated in a continuous flow microwave system, under laminar flow conditions.

**Materials and Methods**

Milk with different fat contents -- 0% (skim), 1% fat, 2% fat, 4% fat (Vitamin D) and chocolate milk (1.5% fat) -- were used as test fluids. The milk samples were provided by the dairy pilot plant at the Food Science department of NC State University. Milk was chosen as the test fluid because the design of the system was modeled by the manufacturer using the dielectric properties of milk.

Dielectric properties of milk were measured using an open end axial probe (HP85070B, Hewlett Packard, Palo Alto, CA) attached to a Network Analyzer (HP8753E, Hewlett Packard, Palo Alto, CA). The instrument was calibrated by measuring the properties of: air, short-circuit block, and water at 25°C. To maintain consistency in the readings, the instrument was turned on at least 3 hours before the
calibration and measurements were performed. Milk was heated in a water bath and its dielectric properties were measured at several temperatures in the range 10 to 90 °C, three measurements were done at each temperature and triplicate experiments were performed.

Penetration depth of microwaves in milk was first calculated to decide if the tube diameter chosen for these experiments was suitable. The formula used is the one presented by Datta and Anantheswaran (2000) and is as follows:

$$\delta = \frac{\lambda}{2 \pi} \frac{1}{\sqrt{2 \varepsilon' \left[1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right] - 1}}$$

Where $\lambda$ is the wavelength in free space, calculated as a function of the frequency of the microwaves ($f$) -- $\lambda = c / f$ -- with $c$ being the speed of light. For the case of 915 MHz microwaves, $\lambda = 0.328$ m.

The test fluids were pumped through the system with a positive displacement pump with a variable speed motor (Tri-Clover Rotary Pump, Model PRE3-1M, Ladish Co., Kenosha, WI) through stainless steel sanitary tubing with a nominal diameter of 1.5 inches. The fluids were heated using a microwave generator operating at 915 MHz and focusing the microwaves to a cylindrical applicator (Industrial Microwave Systems Inc. (IMS), Morrisville, NC). The temperatures at the inlet and outlet of the applicator were recorded using T type thermocouples and a datalogger (Model CR10X, Campbell Scientific Inc., Logan, UT). A schematic diagram of the experimental system setup is shown in Figure 1.
The cylindrical microwave applicator designed by IMS was used as the heating unit. It consisted of a 5 kW nominal generator, with a specially designed waveguide and an elliptical focusing structure that focused the microwaves to obtain a parabolic electric field distribution in the applicator. The applicator was a cylindrical PTFE (Polytetrafluoroethylene) tube with an outside diameter (O.D.) of 0.04572 m, an inside diameter (D) of 0.039 mm, and the length of the heating section of 0.124 m through which the fluid flowed and was heated. The plastic tube could be removed for easy cleaning or replacing. The system was equipped with a directional coupler from which a power meter (HP 34970A, Hewlett-Packard, Palo Alto, CA) read the power generated by the generator and the power reflected in the applicator. The automated control system of the microwave unit consisted of a personal computer and a program written in LabView (National Instruments Corp., Austin, TX).

To measure the exit temperature of the fluid, eight type T thermocouples ($\tau < 0.3$ s) were used in an assembly, located at the exit of the heating section, arranged as shown in Figure 2. Smart gaskets® (Rubber-Fab, Newton, NJ) were used to precisely locate three sections of 0.00317 m O.D. copper tube within the cross section of the tube. The copper tube sections had slots drilled to allow the precise radial location of thermocouples (Figure 2). By locating the assembly at the exit of the heating section, disturbances in the flow inside the applicator were minimized. In order to investigate the temperature profiles in the entire cross-sectional area at the exit of the tube, the described thermocouple assembly was first positioned in a
reference position facing the waveguide. The arrangement was rotated 90° and the experiments were repeated, rotating the assembly for each repetition until it returned to the reference position. In this way, the entire cross sectional area of the tube was investigated to obtain a radial temperature profile in 4 experiments. Three replicate runs of each set of experiments were performed.

The flow rates of milk were set at 2.0 or 3.0 l/min so as to have laminar flow conditions \( (N_{Re} = 550 \text{ and } 830 \text{ respectively}) \), measuring this by the time taken to fill a graduated cylinder with cold milk. Laminar flow was chosen to assure that the information on the temperature distribution in the cross-sectional area of the tube would be representative of the heating pattern and that convective heat transfer would be minimized. The nominal power of the generator was set at 5 kW and milk was recirculated through the system until temperature reached 100 °C.

The recorded energy absorbed by milk was compared to the heat per unit time required to raise the average temperature of milk by the same amount as microwaves did, using the following formula:

\[
\dot{q} = \text{Power} = \dot{m} c_p \Delta T
\]  

[2]

where the average thermophysical properties of milk used were: \( \rho = 1010 \text{ Kg/m}^3 \) and \( c_p = 3900 \text{ J/kg-K} \) (National Dairy Council, 2000). The efficiency of the microwave system was then calculated as the ratio of energy absorbed by milk to the energy delivered by the microwave source. Heat losses to the environment were neglected. This assumption would give us a more conservative approach in the exit
temperature close to the walls of the tube, where heat losses would occur in real situations.

**Results**

The dielectric properties of milk measured in this study and calculated penetration depths are summarized in Table 1. The penetration depth of microwaves was found to be greater than the radius of the tube (0.0195 m), thus making the diameter chosen initially feasible. The loss tangent of milk increased with temperature for all types of milk tested. Dielectric properties of all the types of milk tested were found to be in close proximity of one another. The values of the dielectric properties are similar to those presented by Mudgett and others (1974).

The system was run at a nominal power of 5 kW, for each type of milk. The magnetron was able to deliver more power than the nominal power. Thus, the resulting absorbed power varied from 5.21 kW to 6.28 kW for all types of milk tested. A comparison of the average outlet temperature and inlet temperature for flow rate of 2 L/min for an net absorbed power of 5.3 kW was conducted for 5 different types of milk; 4% fat (Vitamin D), 2% fat, 1% fat, skim, and chocolate milk (Figure 3). It was observed that no significant difference exist in the increase in temperature inside the applicator for the different types of milk tested in the temperature range studied. Similarity of the temperature increase for different types of milk is in accordance with the observation that the dielectric properties of different types of milk are similar to one another. Linear regression of the average outlet temperature as a function of the inlet temperature resulted in a line with a slope very close to 1.0 for
every kind of milk. A slope of 1.0 gave us an indication that the absorption of microwave energy was constant during the experiment. The results of these tests allowed us to use only skim milk in the subsequent experiments as these results can be applied to all types of milk under the conditions of these experiments.

Figure 4 presents the differences in average temperature for skim milk flowing at 2.0 and 3.0 L/min with a net absorbed power of 5.3 kW. The average increase in temperature between inlet and outlet when using a flow rate of 2.0 L/min was 42 °C and for a flow rate of 3.0 L/min 29 °C.

Temperature profiles at the exit of the applicator were measured at 32 radial positions using the thermocouple arrangement mentioned in materials and methods. Contour plots were created by interpolating the data to a 50 x 50 square mesh using Sigmaplot (SPSS Science, Chicago, IL) and assigning values of 0 to all the points outside the cross sectional area of the tubes, as shown in Figures 5a and 6a for 2.0 l/min, and 5b and 6b for 3.0 l/min, respectively.

The average temperature increase in the applicator, while heating skim milk at a flow rate of 2.0 l/min and a power of 5.3 kW is shown in Figure 5a and for 3.0 l/min and 5.3 kW in Figure 5b. The average temperature increase fell within a very narrow range from 39.0 to 42.8 °C with 41.9 °C being the average for 2.0 l/min. The average for 3.0 l/min was 29.1 °C with temperature increases ranging from 28.5 to 31.0 °C.

The outlet temperatures measured in these experiments show that the differences in temperatures in the cross-sectional area become smaller as the exit temperature increases (Figures 6a and 6b). This may be a result of a more uniform
absorption of energy in the applicator with increasing temperature as the dielectric properties of milk change, or an effect of convective and conductive heat transfer. Further research is required to analyze the effects of convection on the temperature profiles. The differences in temperature between the "hot" and "cold" spots varied for both flow rate and inlet temperature, with an average of 3.7 °C for the flow rate of 2.0 l/min and of 3.0 °C for 3.0 l/min. The location of the lower temperatures was found to be closer to the walls of the tube for every experiment performed. The “hot spot” (higher temperature point), in all the cases, was located in the vicinity of the center of the tube, closer to the wall facing the wave-guide. At higher flow rate, the difference in temperatures between the hot and cold spots is smaller due to a shorter residence time of the fluid in the applicator, and the effect of convective heat transfer within the cross-sectional area.

The ratio of absorbed power and incident power was 91.8 ± 0.4 % for all the experiments. A comparison of the microwave energy absorbed by milk, calculated based on the change in temperature to the net energy read from the directional coupler by the control system of the microwave applicator is shown in Figure 7. The energy required to increase the temperature of milk is not significantly different from the net microwave power recorded by the datalogger, with a larger difference observed when the inlet temperature was higher. These differences are mainly due to the changes in thermophysical properties of milk compared to the average properties used in this calculation.
Conclusions

The 915 MHz continuous flow cylindrical microwave applicator tested yield a relatively uniform temperature distribution for milk, in the cross-sectional area of the tube at the exit of the applicator. The increase in temperature in this experiment was of 42 °C for a flow rate of 2.0 l/min and of 29 °C for 3.0 l/min when the microwave generator as used at a net power of 5.7 kW. The study also showed a temperature distribution in which the hottest temperature is close to the center of the tube and the colder temperature is close to the walls of the tube. The designed thermocouple arrangement used in these experiments was an objective technique to measure the temperature distribution within milk in the cross-sectional area of the tube at the exit of the applicator. Further research using other food materials needs to be carried out to investigate a broader range of applications.
Acknowledgments:

Support for the research study undertaken here, resulting in the publication of Paper No. FSR-02-43 of the Journal Series of the Dept. of Food Science, NCSU, Raleigh, NC 27695-7624, from Industrial Microwave Systems is gratefully acknowledged.

The use of trade names in this publication does not imply endorsement by the North Carolina Agricultural Research Service of the products named nor criticism of similar ones not mentioned.
Nomenclature

c speed of light (m/s)
c_p Specific heat at constant pressure (J/kg-K)
D Internal diameter (m)
f Frequency (Hz)

\[
\text{NRe} \quad \text{Reynolds number} \quad \frac{4 \, \dot{m}}{\pi \, D \, \mu}
\]

\dot{m} Mass flow rate (kg/s)
P Power (W)
\dot{q} Energy absorbed per unit time (W)
T Temperature (C)

Greek letters

\[\delta\] Penetration depth (m)
\[\Delta T\] Temperature change (C)
\[\varepsilon'\] Dielectric constant relative to vacuum
\[\varepsilon''\] Loss factor relative to vacuum
\[\theta\] Loss angle (rad)
\[\lambda\] Wavelength (m)
\[\tau\] Response time of thermocouples (s)

Subscripts

in inlet
out outlet
References


Table 1. Dielectric properties and penetration depth for milk (at 915 MHz)

<table>
<thead>
<tr>
<th>Type of milk</th>
<th>T (°C)</th>
<th>ε'</th>
<th>ε''</th>
<th>tan θ</th>
<th>δ (m)</th>
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<tr>
<td>Skim Milk From the NC State Dairy Plant</td>
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<td>70.10</td>
<td>14.72</td>
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<td>0.03</td>
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<td>15.07</td>
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<td></td>
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<td>57.77</td>
<td>28.53</td>
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<td>Chocolate milk From the NC State Dairy Plant</td>
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<td>70</td>
<td>59.66</td>
<td>24.27</td>
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Figure 1. Schematic diagram of the experimental system

Figure 2: Schematic diagram of the experimental system
Figure 2. Thermocouple assembly

a) Thermocouple assembly

b) Positions relative to the main microwave beam
Figure 3. Mean outlet temperature of different types of milk as a function of inlet temperature
Figure 4. Mean outlet temperature of skim milk as a function of inlet temperature.
Figure 5a. Distribution of temperature increase at the exit of the tube for skim milk at 2.0 l/min
Figure 5b. Distribution of temperature increase at the exit of the tube for skim milk at 3.0 l/min
Figure 6a. Temperature distributions in the cross-sectional area at different inlet temperatures for skim milk at 2.0 l/min
Figure 6b. Temperature distributions in the cross-sectional area at different inlet temperatures for skim milk at 3.0 l/min
Figure 7. Incident, net, and calculated power for skim milk at 2.0 l/min.
MANUSCRIPT II

Dielectric properties of pumpable food materials at 915 MHz

Paper No. FSR-03-21 of the Journal Series of the Department of Food Science, North Carolina State University, Raleigh, NC 27695-7624.
Abstract

Dielectric properties of pumpable food materials having a potential to be processed using continuous flow microwave technology were measured at 915 MHz and in the temperature range of 10-90 °C. The products considered in this study were milk and dairy products ($\varepsilon'$: 70.0 to 57.8 and $\varepsilon''$: 14.7 to 26.3), ready to eat puddings ($\varepsilon'$: 69.4 to 52.1 and $\varepsilon''$: 17.2 to 23.8), soy beverages ($\varepsilon'$: 75.4 to 60.8 and $\varepsilon''$: 9.0 to 19.8), and avocado products ($\varepsilon'$: 51.6 to 39.0 and $\varepsilon''$: 17.7 to 67.5). Polynomial correlations were developed for dielectric properties as a function of temperature. The dielectric properties measured in this study are important parameters for designing a microwave system and for continuously processing food materials.

Keywords: Dielectric-properties, microwave-heating, pumpable foods
Introduction

Continuous flow microwave heating is one of the emerging technologies in the field of food processing. Two frequencies have been allocated by the Federal Communications Commission for microwave heating -- 915 MHz and 2,450 MHz. Household microwave ovens operate at 2,450 MHz, while industrial microwave systems in the U.S. generally operate at 915 MHz. The frequency of 915 MHz besides having a longer wavelength has a higher penetration depth (Datta and Anantheswaran, 2001). Continuous flow microwave heating relies on 915 MHz, because higher penetration depths translate to larger tube diameters that can be used. Research into tubular continuous flow microwave heating systems has been carried out at the department of Food Science of North Carolina State University, showing promise for thermal treatment of liquid and pumpable foods (Coronel and others, 2003).

Conversion of microwave energy into heat depends on the wavelength of the microwaves, and on the dielectric properties of the material being heated. Dielectric properties are the complex representation of the relative permittivity of a material as follows:

\[ \varepsilon_r = \varepsilon' - j\varepsilon'' \]  

[1]

and

\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} \]  

[2]

where \( \varepsilon' \) is the dielectric constant, \( \varepsilon'' \) the loss factor, and \( \delta \) the loss angle of the dielectric material. Dielectric constant represents the ability of the material to store electromagnetic energy and the loss factor represents the ability of the material to convert electromagnetic energy into heat by ionic conduction and relaxation mechanisms (Metaxas and Meredith, 1983). For materials with the same value of \( \varepsilon' \), materials with a higher value
of ε” would convert more energy into heat than materials with low value of ε”. However, the dielectric constant is also important because it directly affects the intensity of the electric field inside the material (Nelson, 1991).

Dielectric properties can be measured using several methods, with the open-ended coaxial probe method being the preferred technique for liquids and liquid-like materials (Boughriet and others, 1999). Dielectric properties of food materials are dependent on the frequency of the microwaves, composition of the food, and temperature. Variation of dielectric properties with temperature is a result of changes the product undergoes with temperature, such as increased mobility of the ions, changes in structure due to melting of fat, formation and break-down of gels, and denaturation of protein (Datta and Anantheswaran, 2001). It is very important to understand and be able to predict this dependency for designing industrial systems to be used in food processing as changes in dielectric properties will change the absorption of microwaves, and thus the heating rate of the product, as well as the uniformity of temperature distribution.

Dielectric properties have received a lot of attention over the last 20 years, coinciding with the increase in use of microwave ovens at home. However little data is available for industrial applications using a frequency of 915 MHz, despite the increased interest in microwave processing from a commercial standpoint and specially the use of continuous flow tubular microwave heating systems. Thus, the current study was undertaken to measure the dielectric properties of selected pumpable food products at 915 MHz for a range of temperatures from 10 to 90 °C. The food products were chosen based on their potential compatibility with continuous flow heating using microwaves.
Materials and methods

A list of the products tested in this study is presented in table 1. These products were chosen based on the possible use of continuous flow microwave systems in their processing. The products were purchased from a local supermarket, and were considered representative of the category of foods being analyzed.

Samples were homogenized (when needed) using a blender and heated in a water bath to attain the testing temperatures which was between 10 and 90 °C. The samples were taken out of the water bath and placed inside an insulation block while performing the experiments to measure the dielectrics. After the dielectric properties were measured, the temperature of the samples was measured again to ensure that it was within 2 °C of the desired temperature. Three measurements per sample and three repetitions were performed.

Dielectric properties of the samples were measured with a digital network analyzer (HP 8753C, Agilent Technologies, Palo Alto, CA) with an open-ended coaxial probe (HP 85070B, Agilent Technologies, Palo Alto, CA). The instrument was calibrated using the procedure recommended by the manufacturer (air, shorting block, and 25 °C water). A warm-up time of 3 hours was allowed before measurements were performed. The dielectric properties were recorded using a PC compatible computer equipped with a National Instruments GP-IB card (National Instruments, Austin, TX), using the HP 85070B v1.0 software provided with the dielectric test probe. The dielectric properties were measured at 300 frequencies (equally spaced) in the range of 850 to 1,050 MHz.

To verify the calibration of the instrument at different temperatures, the dielectric properties of distilled water were measured and the results were compared to the predictive
equation presented by Kaatze (1989). The error between the experimental and the published data was 1% at 20 °C and 3.7% at 90 °C.

The specific heat \( (c_p) \) of chocolate milk was measured using a Perkin Elmer differential scanning calorimeter model DSC 7 equipped with an intracooler II refrigeration unit (Perkin Elmer, Norwalk, CT). Sixty µL of product was pipetted into large volume stainless steel pans. Samples were scanned from 2 °C to 105 °C with isothermal steps at a heating rate of 2.5 °C/min. The 2-curve method built-in the manufacturer’s Pyris software (version 3.1) was used to calculate the \( c_p \) of the samples.

Results

The dielectric properties of the food products at 915 MHz measured using the network analyzer were collected and analyzed. The average values are presented in figures 1 - 5. Correlations of the dielectric properties of the products tested in this study as a function of temperature were developed and are tabulated in table 2. The correlations were developed using second order polynomials using Sigmaplot (SSPS Inc., Chicago, IL).

Values of dielectric constant for all of the products were lower than those of water (83.6 at 10 °C and 67 at 90 °C), and the loss factor values were higher than those of water (5.7 at 10 °C and 0.85 at 90 °C), calculated using the predictive equation developed by Kaatze (1989). In addition, a decrease in dielectric constant and an increase in loss factor with temperature were observed for all the products. These observations were similar to previous published data at various frequencies (Kent, 1987; Hasted, 1973).

a. Milk and dairy products
Dielectric properties of milk and dairy products were published in a previous article by the authors (Coronel and others, 2003). The dielectric properties of milk and dairy products at 915 MHz are presented in Figure 1. The dielectric properties of skim milk and 3.2% fat milk are very similar, with differences of less than 2% over the whole range of temperatures. This observation is consistent with the findings of Kudra and others (1991) regarding the small effect of fat content on the dielectric properties of milk. The value of the dielectric constant ranged from 70 to 57 and those of the loss factor from 14 to 28 at 10 and 90 °C respectively.

The results obtained in this study were consistent to the results obtained by Mudgett and others (1974), in which milk dielectric properties were measured at 1 GHz. In the study by Mudgett and others (1974), milk was prepared using its constituents and the results were compared to a 0.1M solution of NaCl using the Hasted-Debye equations. The values of the dielectric constant at 1 GHz were similar to the ones measured in this study. However, the values of the loss factor were noticeable larger than the ones measured in this study. This can be attributed either to the use of an aqueous solution to resemble milk compared to the use of real milk, or to the use of a standing wave method as compared to the conductivity method used by Mudgett and others (1974).

A special case was that of chocolate flavored milk (1.5% fat), which presented a deviation from the behavior of skim and 3.2% fat milk, as shown in figure 2. A depression in dielectric properties was observed at 30 °C with the values of $\varepsilon'$ changing from 65 to 23 and the values of $\varepsilon''$ changing from 16 to 5 for 20 and 30 °C respectively. Since this depression appeared in all the repetitions of the experiment, and in order to better understand the phenomenon observed, an experiment was conducted in which the temperature was slowly
increased in intervals of 2 °C between 20 and 40 °C. It was observed that the dielectric properties followed the same trend as skim milk in the 20-24 °C range, and from that temperature both $\varepsilon'$ and $\varepsilon''$ decreased. The minimum value of $\varepsilon'$ and $\varepsilon''$ occurred at 30 °C (23.75 and 5.84 respectively) and that the values of $\varepsilon'$ and $\varepsilon''$ returned to the trend found for skim milk at 40 °C. The specific heat was measured to observe if any phase changes occurred in this temperature range, which could affect the dielectric properties of the product. The specific heat data obtained using DSC is shown in figure 2. It was observed that a maxima of specific heat existed at 25 °C which coincides with the start of the depression in dielectric properties. Since the change in specific heat did not present a discontinuity, and it was small, a secondary change of phase in the product is most likely taking place. This can be attributed to changes in the gel structure of the stabilizer used to maintain the suspension of chocolate milk.

b. Soy beverages

The dielectric properties of soy beverages as a function of temperature are presented in figure 3. These followed the same general trend observed with dairy products, i.e. a decrease of the value of $\varepsilon'$ and an increase of the value of $\varepsilon''$ with an increase in temperature. Values of dielectric constant for the beverages tested were similar to those of milk, but the loss factor values were lower than those of skim milk. The lower loss factor can be a result of the different amounts and nature of solutes found in soy beverages as compared to those in skim milk.

The dielectric properties of these products were very similar to one another in the range tested with values of $\varepsilon'$ ranging from 73 to 61 and values of $\varepsilon''$ ranging from 9 to 14 for 10
and 90 °C respectively. However, 2% fat soy beverage exhibited a different behavior than the rest of the products in this group. The values of the loss factor were higher than the rest of soy beverages, being 11.2 and 20 for 10 and 90 °C respectively. This was attributed to the increased presence of emulsifiers in this beverage, added in order to keep the increased amount of fat in solution, which would increase the electrolyte concentration in the solution and thus the value of the loss factor.

c. Puddings

Dependence of dielectric properties of puddings on temperature is presented in figure 4. It was observed that all the puddings followed the same general trend of decrease in dielectric constant and increase in loss factor with temperature. The values of the dielectric constant were 64 and 52 for 10 and 90 °C respectively. However, the increase of $\varepsilon''$ with temperature was relatively smaller than the one presented by milk. The values of $\varepsilon''$ at 25 and 90 °C were of 17.2 and 22.7 respectively, which is a change of 38.6%. This can be attributed to the lack of mobility of the ions in the starch matrix as opposed to that in a liquid matrix.

Both cornstarch and tapioca puddings had dielectric properties similar to one another, while the fat-free pudding had a higher dielectric constant and higher loss factor than the other products from this group. Differences in dielectric properties between fat-free pudding and the other types of pudding tested could be a result of the different starch matrix as reported by Ndife and others (1998), or a result of the added water and salts as fat replacers in a similar manner to the results of Rozzi and Singh (2000).
d. Avocado products

Dielectric properties of avocado paste as a function of temperature are displayed in figure 5. The value of the dielectric constant of fresh-made avocado paste ranged from 51 to 39 and the values of the loss factor from 16 to 26 for 15 and 80 °C respectively. The values are similar to the ones of fresh avocado measured by Nelson and others (1994) at 23 °C. Values of the dielectric constant of both products followed a similar trend, with the values of the dielectric constant of fresh avocado being lower than those of the commercial avocado paste, at 70 and 80 °C. The loss factor of the commercial avocado paste was much higher than that of the fresh-made avocado paste and increased at a more rapid rate with temperature. The loss factor became larger than the dielectric constant between 30 and 40 °C. This could a result of the addition of one or more components to the commercial avocado paste, to improve flavor or color stability or to prevent the separation of the fat, which in turn would increase the ionic mobility and thus the loss factor.

e. Penetration depth

The penetration depth ($D_p$) of microwaves in a semi-infinite slab was calculated for several products, considered representative of each of the groups by using the formula provided in Datta (2001) and shown in equation 3.

$$D_p = \frac{c}{2\sqrt{2} \pi f} \sqrt{\varepsilon' \left[ 1 + \left( \frac{\varepsilon''}{\varepsilon'} \right)^2 \right] - 1}$$  \[3\]

The results of penetration depth calculations are shown in figure 6 as a function of temperature for the representative products of each group. It can be observed that the products with the higher loss factor have a smaller $D_p$. All products showed an inverse
dependence of $D_p$ on temperature, as expected from observing the behavior of the dielectric properties of the products tested.

While these data is for semi-infinite slabs, it can be inferred that a similar phenomena would occur with cylindrical tubes. Thus, the maximum diameter of the tubes at colder temperatures could be larger than that at higher temperatures. On the other hand, the decrease in the penetration depth is only an indication of how much of the energy input into the product would be converted into heat. Thus, a smaller $D_p$ is an indication of a more efficient conversion and can be used as a parameter to determine how feasible it is to process products in continuous flow tubular microwave heating systems.

**Conclusion:**

The dielectric properties of milk and dairy products, soy beverages, puddings and avocado products measured during this study serve as a step towards developing a comprehensive database of these properties at 915 MHz. The results showed that the dielectric properties of the selected food products followed a trend with decreasing dielectric constant and increasing loss factor. Chocolate milk presented a deviation from the behavior of the other dairy products, with a depression in the dielectric properties at 30 °C, by comparing this depression to specific heat data obtained by DSC, the depression was attributed to changes in the gels used as stabilizers. The results from this study will be very useful in designing continuous flow microwave systems to process the products analyzed.
Acknowledgments:

Support for the research study undertaken here, resulting in the publication of Paper No. FSR-03-21 of the Journal Series of the Dept. of Food Science, NCSU, Raleigh, NC 27695-7624, from Industrial Microwave Systems, and Center for Advanced Processing and Packaging Studies (CAPPS) is gratefully acknowledged.

The use of trade names in this publication does not imply endorsement by the North Carolina Agricultural Research Service of the products named nor criticism of similar ones not mentioned.
References:

Palo Alto, CA.


### Table 1. Products tested in this study

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>PRESENTATION</th>
<th>SOURCE</th>
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<tr>
<td>Skim milk</td>
<td>236 ml carton</td>
<td>NCSU Dairy Pilot plant</td>
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<td>4% fat milk</td>
<td>236 ml carton</td>
<td>NCSU Dairy Pilot plant</td>
</tr>
<tr>
<td>1.5% fat chocolate milk</td>
<td>236 ml carton</td>
<td>NCSU Dairy Pilot plant</td>
</tr>
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<td>Cornstarch pudding</td>
<td>4 x 99 g</td>
<td>Local Supermarket *</td>
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<tr>
<td>(Kraft Handy Snack ®)</td>
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<td></td>
</tr>
<tr>
<td>Tapioca pudding</td>
<td>4 x 99 g</td>
<td>Local Supermarket *</td>
</tr>
<tr>
<td>(Kraft Handy Snack ® Tapioca)</td>
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<td></td>
</tr>
<tr>
<td>Fat-free pudding</td>
<td>4 x 99 g</td>
<td>Local Supermarket *</td>
</tr>
<tr>
<td>(Kraft Handy Snack ® Fat free )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1% fat soy beverage</td>
<td>1 l aseptic package</td>
<td>Local Supermarket *</td>
</tr>
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<td>(WestSoy NonDairy 1% Fat Lite Soy Beverage)</td>
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</tr>
<tr>
<td>Fat-free soy beverage</td>
<td>1 l aseptic package</td>
<td>Local Supermarket *</td>
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<td>(WestSoy Plain Nonfat Soy Beverage)</td>
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<td>Lactose-free soy beverage</td>
<td>1 l aseptic package</td>
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<td>(WestSoy Vanilla Lactose Free Soy Beverage)</td>
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</tr>
<tr>
<td>2% fat soy beverage</td>
<td>1 l aseptic package</td>
<td>Local Supermarket *</td>
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<td>(WestSoy Non Dairy 2% fat Soy Beverage)</td>
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</tr>
<tr>
<td>Fresh-made avocado paste **</td>
<td>Puree made of fresh fruits</td>
<td>Calavo Growers</td>
</tr>
<tr>
<td>(From Haas Variety avocados)</td>
<td></td>
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</tr>
<tr>
<td>Commercial avocado paste **</td>
<td>2 kg aseptic package</td>
<td>Calavo Growers</td>
</tr>
<tr>
<td>(Pressure processed)</td>
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</table>

* Local Supermarket is one of the following: Harris Teeter (Matthews, NC) or Food Lion (Salisbury, NC)

** Samples homogenized before testing
Table 2. Correlations for dielectric properties as a function of temperature at 915 MHz

<table>
<thead>
<tr>
<th>Material</th>
<th>Correlation (T in °C)</th>
<th>R²</th>
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</thead>
<tbody>
<tr>
<td>Skim milk</td>
<td>ε' 70.705 – 0.092 T – 4.79 x 10⁻⁴ T²</td>
<td>0.95</td>
</tr>
<tr>
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<td>ε” 15.056 – 0.054 T + 2.28 x 10⁻³ T²</td>
<td>0.99</td>
</tr>
<tr>
<td>3.2% fat milk</td>
<td>ε' 71.746 – 0.142 T – 3.86 x 10⁻⁴ T²</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>ε” 15.795 – 0.060 T + 1.96 x 10⁻³ T²</td>
<td>0.96</td>
</tr>
<tr>
<td>Cornstarch pudding</td>
<td>ε' 63.287 – 0.018 T – 1.10 x 10⁻³ T²</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>ε” 18.319 – 0.067 T + 9.78 x 10⁻⁴ T²</td>
<td>0.93</td>
</tr>
<tr>
<td>Tapioca pudding</td>
<td>ε' 66.358 – 0.219 T + 7.07 x 10⁻⁴ T²</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>ε” 13.906 + 0.019 T + 1.87 x 10⁻⁴ T²</td>
<td>0.99</td>
</tr>
<tr>
<td>Fat-free pudding</td>
<td>ε' 70.350 – 0.069 T – 5.10 x 10⁻⁴ T²</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>ε” 16.746 + 0.126 T – 6.08 x 10⁻⁴ T²</td>
<td>0.92</td>
</tr>
<tr>
<td>1% fat soy beverage</td>
<td>ε' 74.279 – 0.131 T – 3.02 x 10⁻⁴ T²</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>ε” 7.835 + 0.069 T – 2.02 x 10⁻⁴ T²</td>
<td>0.97</td>
</tr>
<tr>
<td>Fat-free soy beverage</td>
<td>ε' 76.711 – 0.188 T + 9.08 x 10⁻⁴ T²</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>ε” 8.987 + 0.014 T + 5.1 x 10⁻⁴ T²</td>
<td>0.98</td>
</tr>
<tr>
<td>Lactose-free soy beverage</td>
<td>ε' 77.620 – 0.101 T – 8.88 x 10⁻⁴ T²</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>ε” 9.473 + 0.018 T + 3.32 x 10⁻⁴ T²</td>
<td>0.96</td>
</tr>
<tr>
<td>2% fat soy beverage</td>
<td>ε' 76.416 – 0.206 T – 2.10 x 10⁻⁴ T²</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>ε” 10.545 + 0.088 T + 1.98 x 10⁻⁴ T²</td>
<td>0.98</td>
</tr>
<tr>
<td>Fresh-made avocado paste</td>
<td>ε' 55.7 – 0.248 T + 3.38 x 10⁻⁴ T²</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>ε” 15.05 + 0.096 T + 4.64 x 10⁻⁴ T²</td>
<td>0.95</td>
</tr>
<tr>
<td>Commercial avocado paste</td>
<td>ε' 65.8 - 0.730 T + 6.11x 10⁻⁴ T²</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>ε” 32.8 - 0.389 + 8.31 x 10⁻⁴ T²</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Figure 1. Dielectric properties of milk and dairy products
Figure 2. Dielectric properties and specific heat of chocolate milk
Figure 3. Dielectric properties of soy beverages
Figure 4. Dielectric properties of puddings
Figure 5. Dielectric properties of avocado products
Figure 6. Penetration depth as a function of temperature for representative products from each group.
MANUSCRIPT III

Preparation of sterilization solutions for aseptic processing of foods in continuous flow microwave systems operating at 915 MHz

Paper no. FSR04-36 of the Journal Series of the Department of Food Science, NC State University, Raleigh, NC 27695-7624
Abstract

Model foods were prepared by matching the dielectric and flow properties of products to be processed using continuous flow microwave heating to those of solutions made of table salt, sugar, and CMC. Dielectric properties of solutions of table salt, table sugar, and CMC and mixtures of those solutes were measured and correlations were developed for dielectric properties as a function of concentration of solute and temperature. Sterilization solutions were prepared by matching the dielectric and rheological properties of food materials to those of aqueous solutions of salt, sugar, and CMC. Dielectric properties of milk and sweet potato puree were compared to the properties of salt-sugar-CMC mixtures and model solutions that closely matched the properties of each product were identified, experimental tests were conducted using these solutions. The heating of the solution was compared to the heating of product and the transition from sterilization solution to product was smooth from a temperature distribution stand-point. These model solutions can thus be used as sterilization solutions for aseptically processing products by microwave heating.

KEYWORDS: Microwave-heating, aseptic-processing, dielectric-properties, sterilization-solution
Introduction

Advanced and emerging thermal processing methods include pasteurization and sterilization using continuous flow microwave heating, in-package microwave processing, ohmic heating, radio frequency heating, and infrared heating as well as other techniques and combinations of traditional and advanced processing methods of heating and cooling.

Aseptic processing of foods requires that both the system and the packaging materials be free of microbiological contamination. A sterilization step should be carried out to assure that there is no contamination in the system before processing. When conventional heat exchangers are used, it is general practice in the industry to recirculate water heated to 125 °C or higher for a period of 30 minutes after the farthest point of the system has reached that temperature (Reuter, 1987).

However, this practice cannot be applied to continuous flow microwave systems because the food material to be processed absorbs microwave energy in a very different manner than does water, since the dielectric properties of the food materials and water are different. As a result, when the switch-over from pumping water to the product occurs, it could result in under- or over-heating. Under-heating can lead to loss of sterility, rendering the aseptic processing inadequate, while over-heating can potentially lead to runaway heating, flashing, or product deposition on the walls.

Therefore, a model solution that mimics the behavior of the food product to be processed by matching the dielectric and flow properties of the food product is required as a sterilization solution. This solution will be heated using microwave energy and recirculated through the system during sterilization. The matching of dielectric and flow properties is
very important to avoid over- or under- heating in the transition from sterilization solution to product.

This study deals with a method to prepare model solutions of liquid foods that can be used as sterilization solutions for aseptic processing of foods by continuous flow microwave heating, by matching the dielectric and flow properties of the solutions made with simple solutes to those of the food material to be processed.

Materials and methods

Dielectric properties of the solutions tested in this study were measured using a HP85070B dielectric probe and a HP8753C network analyzer (Agilent technologies, Palo Alto, CA), following the method described in Coronel and Others (2003) for a temperature range of 20-90 °C. Solutions of table salt (iodized NaCl), sugar, and CMC (Ticalose 6000, TIC gums, Belcamp, MD) were prepared with different amounts of each solute, as well as solutions containing binary and ternary mixtures of said solutes. The solutions were heated in an oil bath (Model RTE111, Neslab Instruments, Newington, NH) until the required temperature was attained. The samples were then placed in an insulating block and their dielectric properties were measured. Three repetitive measurements per sample were conducted in duplicate samples. The viscosity of different CMC solutions was measured using a viscometer (model DV-II, Brookfield Engineering, Middleboro, MA) following the method described by Vais and others (2002).

Matching of the dielectric properties was carried out by comparing the properties over the temperature range of both the product and the prepared solutions. A solution that closely mimics the dielectric and flow properties of the product was then prepared and tested
experimentally for temperature profile and discontinuities in the interface during the changeover from model solution to product. The experimental tests were carried out in a 5 kW continuous flow microwave system, operating at 915 MHz, as described in Coronel and others (2003). Temperatures at the inlet and exit of the heating section were monitored using a thermocouple arrangement similar to the one described by Coronel and others (2003).

Model solutions were matched for milk (Skim milk, NCSU Dairy processing plant, Raleigh, NC) and sweet potato puree (Bright Harvest Sweetpotato Company, Inc., Clarksville, AR). Tests in the 5 kW unit consisted of heating the model solution and comparing the temperature profile at the exit of the system to the temperature profile achieved when heating the food product. The temperature profiles were also monitored during the changeover from model solution to product. The temperatures at the exit of the heating section were measured to determine the temperature profiles of both the product and the model food solutions, as well as the effects of the transition from model solution to product.

Results and discussion

The dielectric properties of salt, sugar, and CMC solutions are shown in figures 1, 2, and 3 respectively. Dielectric properties of salt-sugar mixtures are shown in figures 4 and 5 and dielectric properties of salt-CMC solutions are shown in figure 6.

Dielectric properties of table salt solutions (figure 1) show a dependence on both temperature and salt concentration. The general trend was a decrease in $\varepsilon'$ and an increase in $\varepsilon''$ for an increase of temperature. This was consistent with the observations by Hasted (1973) and has been attributed to an increase in the mobility of the molecules with
temperature which makes the loss of energy more efficient. Salt concentration had a positive correlation with \( \varepsilon'' \), with the values of the loss factor increasing with an increase in salt content. This can be attributed to an increase in ionic concentration and thus increased polarization of the water molecules which leads to a better absorption of electromagnetic energy, as observed by Hasted (1973) and Kudra and others (1991). It can be observed that the values of the loss tangent \( (\tan \theta = \frac{\varepsilon''}{\varepsilon'}) \) became larger than 1 at salt concentrations of approximately 10 g/l.

Correlations were developed for both \( \varepsilon' \) (eq.1) and \( \varepsilon'' \) (eq. 2), as a function of C (concentration in g/l), and T (temperature °C) using a second order polynomial function, as follows.

\[
\varepsilon_{\text{Salt}}' = 90.38 - 0.33 C + 1.16 \times 10^{-3} C^2 \\
+ 1.43 \times 10^{-3} CT - 0.42 T - 1.73 \times 10^{-3} T^2 \\
r^2 = 0.96
\]  

\[
\varepsilon_{\text{Salt}}'' = 9.59 \times 10^{-8} + 2.83 C - 1.47 \times 10^{-2} C^2 \\
+ 4.46 \times 10^{-8} CT - 0.085 T - 2.08 \times 10^{-3} T^2 \\
r^2 = 0.94
\]

The dielectric properties of sugar solutions (figure 2) show dependence on both concentration (C) and temperature (T). The values of \( \varepsilon' \) were larger than the values of \( \varepsilon'' \) in the whole range of temperatures and concentrations tested, thus, the loss tangent was less than unity. Dependence of \( \varepsilon' \) on concentration and temperature had an inverse correlation. The dielectric constant (\( \varepsilon' \)) decreased with an increase in sugar concentration and with an increase in temperature as it was expected. However, the values of \( \varepsilon'' \) were relatively small when compared to the dielectric constant and showed dependence on concentration and temperature. The loss factor increased with increasing temperature but decreased with increasing concentration. This can be attributed to the lack of polarization generated by the
sucrose molecules and the binding of water to the sucrose molecules in a similar manner to that observed for starch suspensions by Rozzi and Singh (2000). Correlations for $\varepsilon'$ and $\varepsilon''$ using a second order polynomial are given by equations 3 and 4 respectively.

$$
\varepsilon'_{sugar} = 88.26 - 0.092C + 4.75 \times 10^{-4} C^2 \\
+ 1.79 \times 10^{-4} C T - 0.35 T - 6.8 \times 10^{-4} T^2 
$$

$$r^2 = 0.94 \quad [3]$$

$$
\varepsilon''_{sugar} = 6.48 + 0.031C - 3.33 \times 10^{-4} C^2 \\
+ 2.12 \times 10^{-4} C T - 0.09 T + 5.11 \times 10^{-4} T^2 
$$

$$r^2 = 0.81 \quad [4]$$

The dielectric properties of CMC solutions are shown in figure 3. The dielectric constant showed an inverse dependence on temperature and concentration, in a similar manner as sugar solution. A decrease of the value of $\varepsilon'$ with increasing temperature was observed, coinciding with the observations on the other products, as well as a decrease in the values of $\varepsilon'$ with increasing concentration. The values of the loss factor showed an increase with increasing temperature and a decrease with increasing concentration. These observation can be related to the water binding potential of CMC, by increasing the viscosity, the mobility of ions and dipoles is decreased, thus making the values of $\varepsilon''$ decrease. It was observed that between 60 and 70 °C, at all concentrations, a strong increase of the values of $\varepsilon''$ was observed. This anomaly was attributed to changes in the gel structure of the CMC between 60 and 70 °C, as observed in the thermorheological observations made by Owen and others (1992). They observed the formation of an elastic network (gelation) of dispersions of methyl cellulose between 54 and 67 °C, which coincides with the temperature range of this experiment.

Correlations for both $\varepsilon'$ and $\varepsilon''$ for the solutions of CMC were developed using a second order polynomial function and are given by equations 5 and 6 respectively.
Binary solutions of salt and sugar were analyzed and the dielectric properties of these solutions are shown in figures 4 and 5. Figure 4 shows the effect of temperature and concentration on the values of $\varepsilon'$. It can be observed that the values of $\varepsilon'$ decreased with an increase in temperature for all combinations of concentration. The values of $\varepsilon'$ increased with an increase in salt concentration, for constant sugar concentration, and showed no correlation to the concentration of sugar. The loss factor showed an increase with increasing temperature and increasing salt concentration. However, it is noticeable that for a given salt concentration, the loss factor decreased with an increase in sugar concentration (figure 5) coinciding with the observations made with sugar solutions regarding the binding of water to the sugar molecules. Correlations based on concentrations of salt and sugar, and temperature were developed for $\varepsilon'$ and $\varepsilon''$ and are given by equations 7 and 8 respectively.

$$
\varepsilon'_{\text{mix}} = 88.9 - 0.139 \, C_{\text{Salt}} + 0.070 \, C_{\text{Sugar}} - 0.023 \, C_{\text{Salt}}^2 - 1.65 \times 10^{-3} \, C_{\text{Sugar}}^2 + 1.55 \times 10^{-3} \, C_{\text{Salt}} \, C_{\text{Sugar}} - 0.456 \, T + 1.88 \times 10^{-3} \, T^2 \quad r^2 = 0.93 \tag{7}
$$

$$
\varepsilon''_{\text{mix}} = 0 + 4.25 \, C_{\text{Salt}} - 0.267 \, C_{\text{Sugar}} + 0.045 \, C_{\text{Salt}}^2 + 4.72 \times 10^{-3} \, C_{\text{Sugar}}^2 - 0.015 \, C_{\text{Salt}} \, C_{\text{Sugar}} - 0.22 \, T + 4.91 \times 10^{-3} \, T^2 \quad r^2 = 0.92 \tag{8}
$$

Dielectric properties of mixtures of CMC and salt are shown in figure 6. The values of the dielectric constant and loss factor followed the same trend as the trend observed for salt mixtures and did not show a significant change ($p > 0.95$) with an increase in concentration of CMC. Based on these results, salt-sugar-CMC solutions were not tested, as they would behave in a similar manner as salt-sugar solutions.
Based on the results discussed above, the dielectric properties of the product were matched to the properties of a salt-sugar solution. To match the properties of a given product, it is necessary to know its dielectric properties over the required temperature range. Since correlations have been developed for salt-sugar solutions and CMC does not have an effect on the dielectric properties of the solutions, the calculations can be performed using equations 7 and 8. The dielectric properties of the product were compared to those of salt and sugar combination solutions (equations 7 and 8), and by testing the goodness of fit to a given using a chi square test ($\chi^2$), a model food solution was prepared. The concentration of CMC was adjusted to match the rheological properties of the solution, following the correlation presented by Vais and others (2002).

Once the concentrations of salt and sugar had been established, validation tests were required to verify that the model solution adequately mimicked the properties of the food product. Verification tests were conducted in the 5 kW microwave unit. The model solution was recirculated through the system and it was followed by changeover to product. The temperature profiles of both solution and product were recorded and analyzed.

Based on the dielectric properties of milk measured by the authors in a previous study (Coronel and others, 2003), solution #1 was prepared with concentrations of 20 g/l of salt and 60 g/l of sugar. Figure 7 shows the temperatures at the exit of the system for solution #1 and milk during the changeover. The temperatures at the exit of the heating section of both solution #1 and milk were similar, with the difference between the highest and lowest temperature being less than 5 °C. However, it was observed that the model solution had a more uniform exit temperature distribution than the product. This was a result of using
simple components in the model solution (salt and sugar) as opposed to the variety and complexity of components in the actual food product.

Solution #2 was prepared to match the dielectric properties of sweet potato puree using 6 g/l salt and 20 g/l of sugar. Figure 8 shows the temperature at the exit of the heating section of solution #2 and the effect of changeover to sweet potato puree. The presence of an interface was observed, but it was small. This small interface is the result of the high viscosity of the sweet potato puree when compared to the aqueous solution of salt and sugar. The differences in temperature within the cross-section of sweet potato puree were very pronounced. Solution #2 presented differences between maximum and minimum temperatures of approximately 3 °C, while those for sweet potato puree were approximately 100 °C. However, the average temperatures were similar in both cases, which led us to repeat the experiment with the same concentrations of salt and sugar but adding 8 g/l of CMC to match the viscosity of the puree (solution #3). Solution #3 (Figure 9) mimicked the properties of the product better than solution #2. However, after the changeover, large temperature differences between maximum and minimum temperatures were still present in the product. In the cross-section of the solution #3, the difference between the minimum and maximum temperatures was approximately 25 °C, while for the product, those differences were again close to 100 °C. These differences between the sterilization solution and product were a result of the differences in the flow properties of the model solution compared to the sweet potato puree. The sweet potato puree had a higher viscosity over the whole temperature range, and together with the low flow rates used in the 5 kW unit, it led to large differences in temperatures within the cross-sectional area. However, the average temperature was similar for solution #3 and sweet potato puree, and hence solution #3 would
be acceptable in a case where the flow regime of the sweet potato would induce some mixing within the cross section or some mixing is induced by other means (such as by using static mixers).

**Conclusions**

A suitable model solution to be used as sterilization solution for aseptic processing of foods using continuous flow microwave heating can be prepared by matching the dielectric properties of a food material to the properties of model solutions made with simple ingredients such as salt, sugar, and CMC. The correlations presented in this study can be used for this purpose. These model solutions are cost effective and simple to prepare, making them ideal for use as sterilization solutions in industrial applications.


Acknowledgements

Support from Industrial Microwave Systems, the North Carolina Agricultural Research Center, and the Center for Advanced Processing and Packaging Studies (CAPPS) is gratefully acknowledged.

The use of trade names in this publication does not imply endorsement by the North Carolina State University of the products named nor criticism of similar ones not mentioned.
Figure 1. Dielectric properties of table salt solutions as a function of concentration and temperature
Figure 2. Dielectric properties of sugar solutions as a function of concentration and temperature
Figure 3. Dielectric properties of CMC solutions as a function of concentration and temperature
Figure 4. Dielectric constant of salt-sugar mixtures as a function of temperature
Figure 5. Loss factor of salt-sugar mixtures as a function of temperature
Figure 6. Dielectric properties of CMC-salt mixtures as a function of temperature
Figure 7. Time-temperature profile during sterilization (using solution #1) and processing of milk
Figure 8. Time-temperature profile during sterilization (using solution #2) and processing of sweet potato puree
Figure 9. Time-temperature profile during sterilization (using solution #3) and processing of sweet potato puree.
Manuscript IV

Aseptic processing of sweetpotato purees using a continuous flow microwave system

Paper no. FSR04-36 of the Journal Series of the Department of Food Science, NC State University, Raleigh, NC  27695-7624
ABSTRACT

Sweet Potato Purees (SPP) was aseptically processed using a continuous flow microwave system to obtain a shelf stable product. The dielectric properties of SPP were measured, and the dielectric constant and loss factor were within the range of the published values. Small-scale tests were conducted in a 5 kW unit to determine color changes and viscosity with different thermal treatments. The results of these tests showed that color values (L*, a*) and viscosity did not change significantly compared to the untreated control. Pilot scale tests were then conducted in a 60 kW unit, where the product was heated to 135 °C, and held at that temperature for 30 s. The pilot scale test produced a shelf stable product with no detectable microbial count during a 90 day-storage period at room temperature. This is the first report to the authors knowledge on aseptically packaged vegetable puree processed by a continuous flow microwave heating system.

Keywords: Sweetpotato, aseptic-processing, continuous-flow-microwave.
Introduction

The utilization of sweetpotatoes in the food industry often involves processing of the roots into purees that can be subsequently frozen or canned for the year-round availability of the produce. The sweetpotato purees (SPP) can be used as an ingredient in various products, including baby food, casseroles, puddings, pies, cakes, bread, restructured fries, patties, soups and beverages (Truong, 1992; Truong and others, 1995; Woolfe, 1992; Walter and others, 2001).

Preservation of SPP by freezing is a well-established method but the frozen puree requires considerable investment in frozen distribution and storage as well as a lengthy and poorly controlled defrosting treatment prior to use. Canned purees typically require excessive thermal treatment especially processed in institutional-size packages, provides poor utilization of storage space and presents a difficulty in handling, opening and dispensing of the product as well as disposing of the emptied packages. Due to the poor heat penetration characteristic of the purees, canned sweetpotatoes are retorted for over 2 hrs at 250 °F and the product quality within a can varies drastically from the can center to the wall edges where the product is severely over-processed with dark color and burnt flavor. The can size is therefore limited at can size number 10 and this size limitation is a major obstruction to the wider applications of canned sweetpotato purees in the food processing industry. Other thermal processing technologies such as scraped surface heat exchangers or flash sterilization treatment also has its limitation because of the low thermal diffusivity of SPP (Smith and others, 1982). Fasina and others (2003) reported that SPP has a thermal diffusivity in an order of $3 \times 10^{-7}$ m$^2$/s and a thermal conductivity of 0.54 W/m K. The low thermal diffusivity of SPP leads to very long periods of heating by
the conventional thermal processing methods to achieve the required sterilization levels, which in turn causes degradation of the nutrients in SPP and poor product quality.

Continuous flow microwave heating is one of the emerging technologies in food processing, offering fast and efficient heating. Heating of dairy products using this technology proved to be uniform in previous tests (Coronel and others, 2003). The heating of food products using microwaves is governed by the dielectric properties of the material. The dielectric properties of SPP, as reported by Fasina and others (2003), are in the range of products that have been identified as promising to be processed using continuous flow microwave heating systems (Coronel and others, 2004). Therefore, this study was undertaken to determine the technical feasibility of producing shelf stable SPP using continuous flow microwave heating systems operating at 915 MHz. To the best of our knowledge, this is the first report on an aseptically packaged and shelf-stable vegetable purees processed by a continuous flow microwave heating system.

**Materials and Methods**

**Preparation of sweet potato purees (SPP)**

Purees from Beauregard cultivar sweetpotatoes were prepared in the Fruit and Vegetable Pilot Plant, Department of Food science, NCSU, for testing in 5 kW microwave unit, and measurement of dielectric properties, color and viscosity. The roots were cured and stored at 13-16°C, 80-90% relative humidity, and the purees were prepared as previously described (Truong and others, 1994). Roots were washed, lye-peeled in boiling solution (104 °C) of 5.5% NaOH for 4 min, and thoroughly washed in a
rotary-reel sprayed washer to remove separated tissue and lye residue. Peeled roots were hand-trimmed and cut into 0.95 cm thick slices (Louis Allis Co. Slicer, Milwaukee, WI). The slices were steamed cooked for 20 min in a thermoscrew cooker (Rietz Manufacturing Co., Santa Rosa, CA) and comminuted in a hammer mill (Model D, Fitzpatrick Co., Chicago, IL) fitted with a 0.15 cm screen. The puree was filled into polyethylene bags, frozen and stored at -20 °C until used. For test runs in a 60 kW microwave unit, frozen sweetpotato purees from Beauregard cultivar were purchased from Bright Harvest Sweetpotato Company, Inc., Clarksville, AR.

Measurement of dielectric properties

An open coaxial dielectric probe HP 85070B (Agilent Technologies, Palo Alto, CA) and an automated network analyzer HP 8753C (Agilent Technologies, Palo Alto, CA) were used to measure the dielectric properties of the samples. The dielectric properties were measured in the 300 to 3000 MHz frequency range, with 541 intermediate frequencies. The system was calibrated using the calibration sequence following an instruction manual provided by the manufacturer. The samples were heated in a water bath (Model RTE111, Neslab Instruments Inc, Newington, NH) until the desired temperatures (10, 25, 45, 50, 60, 70, 75, and 95 °C) were attained and then taken out and placed in an insulating block to measure the dielectric properties. The temperature was measured again after the dielectric properties were measured to ensure that the temperature was within 2 °C of the set-point. Three repetitive measurements were performed for each duplicated samples.
Rheological tests

Constant rate measurement of sweetpotato puree viscosity as a function of shear rate was performed at 25 °C with a StressTech rheometer (Reologica Instruments AB, Lund, Sweden) using a cone and plate geometry (C40 4). Apparent viscosity was recorded as shear rates were ramped from 0.1 to 300 s\(^{-1}\). Two repeated measurements were performed on each of the duplicated samples.

Color analysis

Objective color of the samples were measured with a Hunter colorimeter (Hunter Associates Laboratory Inc., Reston, VA). Results were expressed as tri-stimulus values, L* (lightness, 0 for black, 100 for white), a* (-a* = greenness, + a* = redness), and b* (-b = blueness, +b = yellowness). The instrument (45°/0° geometry, D25 optical sensor) was calibrated against a standard white reference tile (L* = 92.75, a* = -0.76, b* = -0.07). The puree samples were filled into a 60 x 15 mm covered Petri dishes (Becton Dickinson Labware, Franklin Lakes, NJ). Six measurements were performed for each sample and average values were used in the analysis.

Tests in a 5 kW microwave unit

A continuous flow microwave-heating unit (Industrial Microwave Systems, Morrisville, NC) was used for processing SPP. The unit consisted of a 5 kW microwave generator operating at 915 MHz, a waveguide of rectangular cross-section, in which a directional coupler was attached, and a specially designed applicator. A tube of 1.5” nominal diameter (0.038 m ID) made of Polytetrafluoroethylene (PTFE or Teflon®) was
placed at the center of the applicator. The exposure region to the microwaves was 0.125 m long. The power delivered by the microwave generator and the power reflected back were measured using diodes located in the directional coupler and a software written in LabView (National Instruments Corp, Austin TX). This software also controls the amount of power the generator delivers to the product.

Ten liters of SPP were pumped using a positive displacement pump (Model MD012, Seepex GmbH+ Co, Bottrop, Germany) at a rate of 0.5 l/min. Temperatures at various radial locations were measured using a thermocouple arrangement described by Coronel and others (2003) and recorded using a datalogger (Keithley DAS-16, Keithley Metrabyte, MA). The power of the generator was adjusted using the control software to ensure that the product attained the required centerline temperature at the exit of the applicator. The product was then cooled in an ice-water bath and samples were taken for further analysis.

Test in the a 60 kW microwave unit

Based on the results obtained in the tests in the 5 kW, processing conditions were established for a test in a 60 kW continuous flow microwave-heating unit (Industrial Microwave Systems, Morrisville, NC) operating at 915 MHz. The power delivered from the generator was monitored using a control panel supplied by the manufacturer. The microwaves were delivered to the product by a waveguide of rectangular cross-section, which were split into two sections and geared toward two specially designed applicators, with a directional coupler in each as seen in Figure 1. A PTFE tube (0.038 m I.D.) was
placed at the center of each applicator and the exposure region was 0.2 m long in each applicator.

A positive displacement pump (Model A7000, Marlen Research Corp., Overland Park, KS) was used to pump the product through the system. Temperatures were measured at the inlet of the system, the inlet and exit of each applicator, and at the holding tube exit. Arrangements of the thermocouples were described by Coronel and others (2003). The temperatures were recorded in 4s intervals using a Datalogging system (HP 3497A, Hewlett Packard, Palo Alto CA). The temperature at the exit of the system was achieved by controlling the power generated by the microwave system.

The system was first sterilized using an aqueous solution of NaCl and sugar, which was heated to 130 °C and recirculated for 30 minutes. The product was heated to 135-145 °C, held for 30 s, rapidly cooled in a tubular heat exchanger, and then aseptically packaged in aluminum-polyethylene laminated bags (Scholle Corp, Chicago, IL) using a bag-in-box unit (Model PT.A.F., Astepo, Parma, Italy). The puree bags were stored at ambient temperature (22 °C) and two bags were randomly taken for microbiological analysis after 1, 15, and 90 days. Standard plate count assay was used to enumerate total aerobic bacteria in the sweetpotato puree samples. Fifty gram samples were aseptically transferred to sterile filter bags (Spiral Biotech, Bethesda, MD) containing 50 ml of sterile physiological saline solution (0.85% NaCl), and the bags were macerated with a Tekmar stomacher (Model TR5T, Tekmar Co., Cincinnati, OH) on a high speed for 160 s. Appropriate dilutions of the stomacher filtrate were made using sterile physiological saline solution and spread onto duplicate PCA agar plates using the Spiral Biotech Autoplate 4000 spiral plater (Bethesda, MD). The PCA plates were inoculated at 37 °C.
for 48 hrs for total aerobic bacterial counts. Sample dilutions were also spread onto plates of yeast/mold agar plates and inoculated for enumeration of yeast and mold colonies. Medium preparation was carried out following the standard procedures (Difco Laboratories, 1998).

**Results and Discussion**

**Dielectric properties**

The dielectric properties of the sweetpotato purees measured at 915 and 2450 MHz and temperatures of 10-95 °C are shown in Figure 2. The values for dielectric constant and loss factors were similar with those reported by Fasina and other (2003) for Beauregard sweetpotato puree, and they are within the ranges that have been reported for other food materials (Nelson and Datta and Anantheswaran, 2001). At 22 °C, the $\varepsilon'$ and $\varepsilon''$ values were 70.4 and 67.1 at 915 MHz, and 21.4 and 17.6 at 2450 MHz, respectively. Nelson and others (1994) reported an $\varepsilon'$ range of 47- 75 at 915 MHz and 45-73 at 2450 MHz, $\varepsilon''$ of 8-22 at 915 MHz and 10-18 at 2450 MHz for 24 common fresh fruits and vegetables at 23 °C. Sweetpotato was also included in these studies and the reported $\varepsilon'$ and $\varepsilon''$ values were about 20-25% lower than the results obtained in this study. The differences can be attributed to compositional, and moisture variations commonly observed in agricultural products. Sipahioglu and Barringer (2003) reported that variation in the contents of moisture, ash and high molecular weight carbohydrates affects the dielectric properties of various fruits and vegetables.
The obtained data fitted well using the predictive equations reported by Fasina and others (2003) for the dielectric constant and loss factor as a function of temperature (T) and frequency (f):

\[
\varepsilon' = 74.84 - 0.113 \, T - 0.00214 \, f \quad [1]
\]

\[
\varepsilon'' = 29.76 + 0.125 \, T - 0.0144 \, f - 8.60 \times 10^{-5} \, f \, T
\]
\[+ 4.11 \times 10^{-6} \, f^2 + 7.64 \times 10^{-4} \, T^2 \quad [2]
\]

As indicated by the dotted lines in Figure 2, the effect of temperature on the dielectric constant was similar for both 915 and 2450 MHz, \(\varepsilon'\) decreasing with an increase in temperature, with values of 71.5 at 10 °C and 60.8 at 95 °C for 915 MHz and 67.1 at 10 °C, 61.1 at 95 °C for 2450 MHz (Figure 2). The loss factor (\(\varepsilon''\)) followed an increased trend with increasing temperature, with values of 18.1 at 10 °C and 26.7 at 95 °C for 915 MHz. Elevated temperature reduced the puree viscosity resulted in increased in mobility of ions and higher electric conductivity (Herve and others, 1998). However, at 2450 MHz, \(\varepsilon''\) exhibited a decreased trend with increasing temperature with values of, 18.4 at 10 °C and 16.1 at 95 °C. Ohlsson (1989) attributed this phenomenon to the predominance of the dispersion resulting from dipole rotation of water molecules at 2450 MHz, and at high temperatures, fewer hydrogen bonds are formed and reformed, causing a decrease in \(\varepsilon''\) values.

The maximum operating diameter (MOD) of the tube to be used in the applicator was calculated using the method proposed by Coronel and others (2004) that involves a solution of the microwave energy penetration equation in cylindrical coordinates and a calculation of a theoretical temperature profile. MOD is defined as the largest diameter that can be used in continuous flow processing to obtain a theoretical uniform
temperature distribution across the cross-sectional area, and it is a function of dielectric properties at different temperatures. As shown in Figure 3, MOD decreases with temperature with values of 0.22 m at 10 °C and 0.12 m at 95 °C for 915 MHz. The increase in the loss factor with temperature makes the energy conversion into heat more effective, thus decreasing the penetration depth and hence, MOD.

Tests in a 5 kW microwave unit

The product was processed using the 5 kW microwave unit, keeping a constant holding time and changing the centerline exit temperature (temperature at the center of the tube at the exit of the heating section). The desired centerline exit temperatures were 110, 130, and 140 °C with an exposure time in the heating section of 17 s and a holding time of 90 s. The product was cooled rapidly in an ice-water bath and samples were taken for analysis of the rheological properties and color measurement.

Large temperature differences were observed between the walls and the center of the applicator tube. The differences between the maxima and minima were of 35, 40, and 43 °C for centerline exit temperatures of 110, 130, and 140 °C respectively with average exit temperatures of 80, 101, and 107 °C respectively. Figure 4 shows the interpolated temperature profiles in the cross section of the tube at the exit of the heating section for the exit temperatures of 110 and 130 °C. Interpolation of the temperature profile was carried out using the existing acquired temperatures into a 20x20 square mesh using SigmaPlot (Systat Software Inc., Point Richmond, CA). The simulated mesh was trimmed to resemble a round shape by eliminating all elements outside of the radius of the thermocouple assembly. It can be observed in Figure 4 that the maximum
temperature was achieved close to the center of the tube, and the minimum close to the walls. The temperature profile showed that the product close to the wall that faced the microwave generator had a higher temperature than the side opposite to the generator. This observation was consistent with that of Coronel and others (2003).

The rheological properties of the samples treated to different centerline exit temperatures are shown in Figure 5. All the samples exhibited shear-thinning behavior, i.e. lower apparent viscosity at higher shear rates. The rheological behavior was modeled using a Herschel-Bulkley model \( (\sigma = \sigma_0 + k \dot{\gamma}^n) \) (Steffe, 1996). The average values of the parameters were; yield stress \( \sigma_0 = 89.0 \pm 2.7 \) Pa, the consistency coefficient \( k = 18.78 \pm 1.76 \) Pa and the average flow behavior index \( n = 0.39 \pm 0.07 \). As indicated in Figure 5, the apparent viscosities of the different SPP samples were not significantly different between treatments (\( p \leq 0.05 \)).

Color measurements of the samples corresponding to different centerline exit temperatures are shown in Figure 6. There were no significant differences (\( p \geq 0.05 \)) in \( L^* \) (lightness) and \( a^* \) (redness) values between the control and the thermal treated samples. The \( b^* \) (yellowness) values of the thermal treated samples showed a significant increase (\( p \leq 0.05 \)) as compared to the control. However, there was no significant difference (\( p \leq 0.05 \)) in the values of \( b^* \) between the 130 and 140 °C treatments. The total change in color compared to the control, was calculated as

\[
\Delta E = \sqrt{\Delta L^* + \Delta a^* + \Delta b^*}
\]

and had values of 10, 20, and 20 for centerline exit temperatures of 110, 130, and 140 °C respectively.
Tests in the 60 kW microwave unit

With the information gathered from the tests on 5 kW microwave unit, the test runs using the 60 kW unit were carried out as a pilot plant experiment aiming to obtain a shelf-stable product. The flow rate was set to 4.0 l/min, and in order to obtain a shelf-stable product the centerline temperature at the exit of the holding tube should reach 135 °C with a holding time of 30 s ($F_0 = 30$ min). The power generated by the system was adjusted in order to achieve the required centerline exit temperature.

As observed in the 5 kW tests, the temperature differences between the centerline (135 °C) and the walls (70 °C) of the tube were large, as shown in Figure 7. Because of the high viscosity of the SPP no mixing occurred during the holding tube. Therefore, the product closer to the walls was the one that received the least thermal treatment with ($F_0 < 0.1$ min). However, the product was kept refrigerated and the visual observation indicated that there was no symptom of microbial growth after 30 days.

In order to minimize the non-uniformity in temperature within the product, static mixers were implemented at the exit of each of the microwave applicators of the system. The mixing at the exit of the heaters would diminish any temperature differences within the product at the exit of the heaters in order to improve the thermal treatment and in consequently the shelf life of the product. The second experiment was carried out with centerline exit temperature of 140 °C at the exit of the second heater, and a holding time of 30 s. The centerline temperature was increased in order to achieve a minimum temperature of 135 °C at the end of the holding tube.

Temperature profiles throughout the cross-sectional area were more uniform (Figure 8) which was attributable to the mixing effect of the static mixers on the flowing
purees. The temperature differences between center and wall were reduced from 48.4 to 20.1 °C after going through the first static mixer and from 37.6 to 11.7 °C after the second static mixer. At the inlet of the holding tube SPP had a temperature profile with a minimum temperature of 135 °C and a maximum of 146.7 °C, as shown in Figure 8, and so the fastest particle (at the center of the tube) received the least heat treatment. The fastest particle (center) received a thermal treatment equivalent to $F_o = 23$ min, which rendered a shelf stable product. Microbiological tests of the final product were performed in order to confirm the destruction of microorganisms. Microbiological test results on total plate count, molds and yeast showed no presence of microorganisms after 1, 15, and 90 days.

**Conclusions**

Aseptically packaged sweet potato puree was successfully produced using a continuous flow microwave heating system. The resulting product packed in flexible plastic containers had the color and apparent viscosity comparable to the untreated puree, and was shelf-stable. This process can be applied to several other vegetable and fruit purees. Further studies on the retention of nutrients by this processing method are necessary in order to establish advantages of the process.
Acknowledgments

Supports from Industrial Microwave Systems, NCSU Center for Advanced Processing and Aseptic Studies, North Carolina Sweetpotato Commission and USDA-Agricultural Research Services are gratefully acknowledged. The authors also thank Dr. Fred Breidt, Janet Hayes and Sue Hale of USDA-ARS Food Science Research Unit, NCSU, Raleigh for their technical expertise on microbial assays.

The use of trade names in this publication does not imply endorsement by the North Carolina State University of the products named nor criticism of similar ones not mentioned.
References


Nomenclature

ε’ Dielectric constant
ε” Loss factor
γ Shear rate (1/s)
σ Shear stress (Pa)
f Frequency (Hz)
F0 Lethality at 121 °C for a microorganism with z = 10 °C (min)
T Temperature (°C)

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Solution of the Helmholtz penetration equation for cylinders simulating a tubular microwave system operating at 915 MHz and a classification of food products based thereof

Paper No. FSR-05- of the Journal Series of the Department of Food Science, North Carolina State University, Raleigh, NC 27695-7624.
Abstract

In order to determine the feasibility of food materials to be processed using continuous flow microwave heating systems a method was developed. This method uses solutions to the Helmholtz equation in a cylindrical tube full with the food material. By combining these solutions with laminar flow profiles, the cross-sectional temperature profile of the food material can be modeled. Comparisons of real experiments and the results of the modeling show that this simple approach can be used to determine the feasibility of processing.

The present paper presents the most recent development in this feasibility testing methodology. This method uses solutions to the Helmholtz equation in a cylindrical tube filled with the food material. Availability of these solutions enables the modeling of theoretical cross-sectional temperature profiles within the flow-through, microwave transparent tubes by combining with the assumed laminar flow profiles. While this approach does not take into account the radial mixing and the concurrent thermal energy exchange among the various material segments within the flow profile; comparisons of thermal profiles obtained in real heating experiments with the results of this modeling approach indicate that this simple approach can be used as a valuable aid in the determination of feasibility of processing for a variety of examined foods and biomaterials.

KEYWORDS: Microwave-heating, Continuous-flow, Dielectric-properties,
Introduction

Continuous flow microwave heating has been recognized as an emerging technology for food processing, yet the applications in the industry are still scarce. One of the problems associated with this technology is the difficulty in predicting the temperature distribution at the exit of the system for the food to be processed. Computational numerical methods can be used, but they are time consuming and complex, requiring trained people using costly computers and software.

The objective of this research was to find a simple approach to the problem by coupling a solution of the microwave energy penetration (Helmholtz) equation with laminar flow profile to predict the temperature profile at the exit of a cylindrical continuous flow system. Parameters to determine the feasibility of processing food materials in a tubular continuous flow microwave system were to be generated. A classification of food materials according to the feasibility to be processed in continuous flow microwave systems would be proposed, by using the mentioned parameters.
Mathematical background

Penetration of electromagnetic energy into dielectric materials can be described by the Helmholtz equation, as shown in equation 1 (Sadiku, 1995). Since food materials can be considered to be non-magnetic and have no charges, the penetration equation (1) can be simplified to equation 2.

\[ \nabla^2 E - \mu \varepsilon \frac{\partial^2 E}{\partial t^2} = -\frac{\rho_v}{\varepsilon} \quad [1] \]

\[ \nabla^2 E - k^2 \frac{\partial^2 E}{\partial t^2} = 0 \quad [2] \]

where \( k \) is the propagation constant, and is a function of the dielectric properties of the material (\( \varepsilon' \) and \( \varepsilon'' \)), as shown in equation 3. Since \( k \) is a complex quantity, it can be defined using two parameters, \( \alpha \) and \( \beta \). \( \alpha \) is known as the attenuation constant and measures the spatial decay of the wave as it propagates. \( \beta \) is a measure of the phase shift per unit length and is called the phase constant or wave number (Sadiku, 1995). The angular velocity of the waves (\( \omega \)) is calculated knowing the frequency (\( f \)) of the waves

\[ k = \alpha + j\beta \]

\[ \alpha = \omega \sqrt{\frac{\mu_0 \varepsilon_0 \varepsilon'}{2} \left[ \sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1 \right]} \]

\[ \beta = \omega \sqrt{\frac{\mu_0 \varepsilon_0 \varepsilon'}{2} \left[ \sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1 \right]} \]

\[ \omega = 2 \pi f \quad [3] \]

The electromagnetic field distribution inside the cavity needs to be known in order to be used as a border condition to solve the differential equation. In the case of continuous flow microwave heating systems used at NC State University as described in Coronel and others (2003), a single mode resonant cavity is used, with a maximum of the
field in the center of the cavity. The mode is a TE_{011} mode, as illustrated in figure 1. (Ishii, 1995) Based on this field distribution, and considering that the tube that contains the food product is transparent to microwaves, it was assumed that the electromagnetic field was constant at the interface between the tube and the food product \( r = R, E = E_0 \).

**Figure 1.** Modes of propagation of electromagnetic waves in a cylindrical cavity

Generation of thermal energy inside food materials, considered non-magnetic is given in equation 4 (Datta and Anantheswaran, 2001). \( E \) is the magnitude of the electric field vector across the section of the food material and needs to be calculated by solving equation 2.

\[
Q = \frac{\varepsilon_0 \varepsilon'' |E|^2}{2} \quad [4]
\]

In order to calculate the cross-sectional temperature profile at the exit of the tube, the heat generation equation must be coupled with a flow profile equation, in order to account for residence time, considering laminar flow profile as a function of both the
average velocity and the radius, in the form shown in equation 5. The streamlines closer to the wall will have longer residence time (\( \tau \)), thus higher exposure to the microwave energy, while the streamlines closer to the center will receive the shortest exposure.

\[
\mathbf{u} = 2\pi[1 - r^2/R^2]
\]  

[5]

The combination of all above factors is necessary to predict the temperature profile of the food material at the exit of the microwave cavity.

**Solution of the Helmholtz equation**

To solve the Helmholtz second order differential equation, inside the cross sectional area of the tube, the following assumptions were made:

- Cylindrical geometry of the food product heated (r, \( \theta \), z)
- Constant dielectric properties of the material in the tube, so that polar coordinates could be used
- Symmetry relative to the \( \theta \) axis
- Constant electric field at the interface of tube and food material (r = R, E = E_0)
- Radial symmetry (r = 0, dE/dr = 0)

The resulting equation is simplified to equation 6, where E is a function of radius only.

\[
\frac{d^2E}{dr^2} + \frac{1}{r} \frac{dE}{dr} + k^2E = 0
\]

\[
r = 0 \quad \frac{dE}{dr} = 0
\]

\[
r = R \quad E = E_0
\]

[6]

Under the given assumptions, an analytical solution to equation 6 exists, and is given by equation 7.
By solving equation 7, distribution of the electric field is found across the cross-sectional area of the tube. Dielectric properties and radius of the tube will determine the penetration of the electric field and the absorption of microwave energy inside the tube. Examples of the penetration of the electric field are shown in figure 2, 3, 4, and 5. Power absorbed, and converted into heat, is found by plugging the solution of equation 7 into equation 4. Examples of the calculated power absorption distribution profiles are shown in figures 6, 7, 8, and 9.

In order to determine the temperature distribution in the cross-sectional area of the product both the generation of heat and the flow profile need to be accounted for. Numerical computations were performed using a finite difference FORTRAN program, considering isotropic materials with constant properties. To determine the temperature profiles at the exit of the tube, laminar flow profile was used to calculate a time residence for each streamline. Temperatures at the exit of the application zone for each streamline were calculated by integration of the net heat generated (equation 4) in each element for the residence time.

Results and discussion

The results of the calculations of the penetration of the electromagnetic field in a cylindrical food material with constant properties are shown in figures 2, 3, 4, and 5, and the absorbed power results are shown in figures 6, 7, 8, and 9. Both groups of figures present the dimensionless electric field value (E/E₀) or the dimensionless absorbed power (P*) as a function of both radius of the tube (r) and the dielectric properties (ε' or ε'').
In all the studied cases, the values of the electromagnetic field and absorbed power presented a maximum at the center of the cylinder (r=0), and an inflection point. These kind of radial distributions were expected from the use of Bessel J functions and a radial symmetry condition. Values and radial locations of the maxima, minima and inflection points changed according to the dielectric properties of the simulated materials. Values of the relative electric field and power absorption determine to what extent will the microwaves be absorbed and thus, converted into heat; and also give an indication of the expected temperature rise in each radial differential segment.

Figure 2 shows the calculated radial profiles of the relative electric field (E/E₀) within a material with ε’ = 40 as a function of ε’’ for a cylinder of 38mm I.D., and figure 6 shows spatial relative power distribution (P* = P/P₀) absorbed by the same material. The relative electrical field values showed an increase on the value of the maxima at r = 0 with a decrease on ε’’. At the lower values of ε’’, which correspond to a smaller loss tangent, the value of the maxima, minima and inflection point of the electrical field approach 1, indicating little absorption of microwaves thus little expected increase in temperature. The relative values of the maxima decreased with increasing ε’’ corresponding to a better absorption of microwaves with increasing loss factor. When the absorbed power is analyzed (figure 6), it can be observed that P* presents a maximum at r=0 that is higher than 1 at high values of ε’’ and decreases monotonically. Thus, a value of ε’’ can be defined as a "transition value", above which the value of the maxima of absorbed power is smaller than 1, thus a monotonic decrease of the absorbed power as a function of the radius is present for a value smaller than the "transition value" of ε’’. This transitional value of ε’’ can be helpful in understanding the interactions of the
electromagnetic field with the food materials of different properties, and will be used as a parameter in the classification of food products according to their feasibility to be heated with continuous flow microwave systems.

When $\varepsilon'$ is increased for constant $\varepsilon''$, as shown in figures 3 and 7, the relative value of the maximum at $r = 0$ increases as $\varepsilon'$ increases. It can be observed that a "transitional" value of $\varepsilon'$ is also present, above which there is a local minimum in the electrical field distribution. This observation is consistent with the one of figure number 2. An increase of $\varepsilon'$, which means a decrease of the loss tangent, translated into an increase of the relative minimum of the electric field at the center of the tube ($r=0$).

Location of the minima and the inflection points changed with changes in the value of the dielectric constant, being the minima and inflection points closer to $r=R$ at low values of $\varepsilon'$ and to $r=0$ at higher values of $\varepsilon'$.

The influence of the internal diameter of the tube transporting the food materials is shown in figures 4 and 8 for the electric field ($E/E_0$) and absorbed power ($P^*$) respectively. Tubes with small diameter cylinders, present ID similar to the penetration depth of microwave in a slab, and it can be observed in figure 4 that in these cases the electromagnetic field changes very little in the radial direction, and the absorbed power is nearly uniform across the radial direction as shown in figure 8. At larger diameters of the cylinder, the electromagnetic energy is absorbed mostly in the vicinities of the walls of the cylinder ($r=R$), following the penetration equations, in this case the power is absorbed more by the parts of the fluid closer to the walls of the cylinder. Several maxima and minima are encountered within the cross-section in larger diameter cylinders, due to the use of Bessel-type solutions in this study. Diameter is, thus, a parameter that needs to be
considered in the absorption of microwaves within a cylinder, and according to the
dielectric properties of the material a minimum and maximum diameters would yield
absorptions that allow a uniform increase in temperatures within the cross sectional areas.
The maximum operating diameter (MOD) is thus defined as the diameter in which \( E(R) = E(0) \). This MOD has been selected on the basis of having enough energy penetrating
through the center of the tube to achieve uniform heating across the cross-section of the
food materials.

Figures 5 and 9 illustrate the effect of loss tangent on the electromagnetic and
absorbed power radial distributions respectively. By keeping \( \tan \theta \) constant and changing
the values of \( \varepsilon' \) it was observed the existence of an "optimum" dielectric constant for
absorption of electromagnetic energy. This "optimum" value of \( \varepsilon' \) suggests that a certain
value of \( \varepsilon' \) would result in an absorption of energy that would relate to a temperature
distribution with a maxima at the center of the tube, but with a large difference between
the maximum and minimum.

The maxima of the absorption at \( r=0 \) were analyzed for combinations of \( \varepsilon' \) and \( \varepsilon'' \),
as shown in figure 10. In order to match the microwave absorption with laminar flow, a
maximum value of 2 between \( P^*(0) \) and \( P^*(\text{average}) \) was considered optimal. It can be
observed that at low values of the loss tangent (high values of \( \varepsilon' \) and low values of \( \varepsilon'' \)) the
maximum of the absorbed energy is relatively large at \( r=0 \); while at high values of the
loss tangent this value of the maximum of absorbed energy approached 0. It is therefore,
possible to determine if the product will be adaptable for microwave processing in
cylindrical heaters by relating the experimentally measured dielectric properties of a food
or bio material with the graph presented in figure 10. By identifying the values of the
relative maxima of absorption of microwaves, another parameter for the classification of food materials was generated.

All these criteria were used to provide a classification of food and biomaterials according to their feasibility to be processed in a continuous flow tubular microwave heating system.

Figure 11 shows a comparison of observed and calculated values of temperature at the exit of a 20s residence time cylindrical tube. The dielectric properties of the material simulated were those of skim milk at 20, 40, 60 and 80 °C. The simulated temperature profiles correlated to the observed values within a range of radius values of 0 to .01 m, outside this range the predicted temperature profile present lower temperatures than those observed. It can be observed that the simulated values follow a trend similar to that of the Bessel equations, with a maximum in the vicinity of the center of the tube and a minimum in the vicinity of the wall. However, the observed temperature profile for skim milk presented less variation in temperature between the edges and the center than the predicted. Thus, the approach used in this study, while it can be used as a first approach to the problem needs to be refined.

**Classifications of food and bio materials based on their feasibility to be processed using continuous flow microwave heating systems**

The analysis of the results presented above produced several parameters that could be investigated in order to determine how food and bio materials will behave in a continuous flow microwave heating system, from those the Maximum Operating
Diameter (MOD), and the location and value of the maxima of absorbed energy were chosen as parameters for classification.

A classification system based on the maximum operating diameter (MOD) is presented as follows. MOD is defined as the diameter in which the value of the electromagnetic field in the center is the same as in the interface between food material and tube, $E(0) = E(R)$. The use of MOD is based on having enough microwave energy absorbed through the cross-sectional area of the tube in order to have a radial temperature distribution profile that will allow the product to be sufficiently processed. Based on MOD food and bio materials can be classified into three categories as follows:

- Low loss tangent. $\tan \delta < 0.1$, MOD > 0.1 m
- Medium loss tangent. $0.1 < \tan \delta < 2$, $0.01 < \text{MOD} < 0.1$ m
- High loss tangent. $\tan \delta > 2$, MOD < 0.01 m

Analysis of the maxima of absorption of microwaves as a function of the dielectric properties of a food or bio material ($\varepsilon'$ and $\varepsilon''$), as presented in figure 10, showed that the dielectric properties of the material define the value of this relative maximum. From figure 10 it can also be observed that a cylinder of material with properties $\varepsilon'$ and $\varepsilon''$ could be classified by locating the dielectric properties in figure 10, or a similar figure generated for the diameter of the cylinder that would be needed, depending on the value of the maxima in the center. Food and bio materials can be classified in the following categories according to the suggested criteria:

- Non feasible: When the relative value of the maxima is larger than 8 or smaller than 0.25.
- Feasible with conditions: requiring mixing, changes in flow pattern, etc. When the relative value of the maxima is between 4 and 8 or 0.25 and 1.5.

- Feasible: When the relative value of the maxima is larger than 1.5 and smaller than 4.

It should be observed, however, that materials can move to different categories by changing the frequency of the microwave used to heat such materials, or the diameter of the cylinder that will be located inside the cavity. Dielectric properties and power absorption maps such as the one presented in figure 10 should be generated for each frequency of microwave energy to be used and for each diameter of tube to be used to transport and heat food and biomaterials.

Conclusions

The results from this study present a method to analyze the feasibility to process food and bio materials in continuous flow cylindrical microwave heating system. The parameters presented can be of great help for food processors and designers in order to improve processing sequences and determine whether extra steps are required to process food materials.

Comparison with experimental data is required to achieve a better understanding of the interactions between food and biomaterials with microwaves and to improve the model developed in this study.
Nomenclature:

E \quad \text{Electric field vector (volt/m)}

f \quad \text{Frequency (Hz)}

ID \quad \text{Internal diameter (m)}

J_i \quad \text{Bessel J function or order i}

k \quad \text{propagation constant}

P^* \quad \text{Dimensionless absorbed power}

Q \quad \text{Heat generated (W)}

r \quad \text{Radius (m)}

R \quad \text{Maximum radius in a cylinder (m)}

t \quad \text{time (s)}

u \quad \text{Velocity (m/s)}

\varepsilon \quad \text{Permittivity (Farad/m)}

\varepsilon' \quad \text{Relative dielectric constant}

\varepsilon'' \quad \text{Relative loss factor}

\mu \quad \text{Permeability (Henry/m)}

\rho_v \quad \text{Charge density per unit volume (Coulomb/m}^3\text{)}

\tau \quad \text{Residence time (s)}

\alpha \quad \text{Attenuation constant (1/m)}

\beta \quad \text{Phase constant (1/m)}

\omega \quad \text{Angular velocity (rad/s)}
References:


Figure 2. Penetration of microwave electrical field in a 38mm ID tube for materials with different dielectric properties (\( \varepsilon' = 40 \) and \( \varepsilon'' = 1 \) to 100).
Figure 3. Penetration of microwave electrical field in a 38mm ID tube for materials with different dielectric properties $\varepsilon' = 1$ to 100, $\varepsilon'' = 40$. 
Figure 4. Penetration of microwave electric field for 3 materials (a: $\varepsilon'=40$, $\varepsilon''=20$; b: $\varepsilon'=40$, $\varepsilon''=80$; c: $\varepsilon'=60$, $\varepsilon''=80$) in 4 different diameters (ID = 10, 38, 60 and 150 mm)
Figure 5: Penetration of microwave electrical field in a 38mm ID tube for materials with different dielectric properties

\(\varepsilon' = 1 \text{ to } 100 \text{ and } \tan \delta = 0.1, 0.5, 1.0 \text{ and } 2.0)\)
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Figure 11. Calculated temperature increase of product with dielectric properties of milk in a cylindrical tube of 39mm diameter, and residence time = 20s
3. Concluding Remarks

Continuous flow microwave heating is a technology that presents promise for aseptic processing of foods and biomaterials. The findings of this work, together with the methods and criteria developed can be of great help in further development of this technology for the food and bioprocess industries.

The feasibility of aseptic processing using continuous flow microwave heating was demonstrated by producing shelf stable sweet potato puree using this technology. The methodology defined to determine the feasibility and carry experiments out was proven.

The methodology used to determine feasibility and develop food products that maybe processed using continuous flow microwave systems was defined as follows:

- Measurement of dielectric properties
- Generation of theoretical penetration and temperature profiles
- Tests in 5kW unit
- Preparation of model solution used for sterilization of system
- Pilot scale run in 60 kW unit.

Other methods developed in this study allow the measurement of the temperature profile of the products at the exit of the heating system, using widely available type T thermocouples and a datalogging system. Data acquisition systems were developed to cope with the needs of this method.

Dielectric properties data was collected and a database generated for a wide range of products. Methods to measure dielectric properties at temperatures above the boiling point of water, which are of interest for aseptic processing of foods were developed.
Some practical problems were also solved, among those the preparation of model solutions using salt, sugar and gums that were used as sterilization solutions for aseptic processing of foods. Design of a microwave transparent tube that could deal with the temperatures and pressures used for aseptic processing was also developed in the course of this work and was proven useful in pilot scale runs.

Future work needed in the field of microwave processing of foods and biomaterials should include improvements in the mathematical modeling of the interactions between food materials and microwave energy, studies for processing of heterogeneous food and biomaterials, validation studies for regulatory agencies.

Among those the studies concerning the heating of heterogeneous and particulate materials should be prioritary, as there are not aseptic processed particulate foods in the market and microwave technology shows promise for these processing.