ABSTRACT

BOLDOR, DORIN. Temperature Control of the Continuous Peanut Drying Process Using Microwave Technology. (Under the direction of Timothy H. Sanders and Kenneth R. Swartzel.)

The relationship between dielectric properties of peanuts (Arachis hypogaea L.), thermal and moisture distribution during continuous microwave drying, and automated control of the drying process was investigated. Dielectric properties (ε', ε'') of ground samples of peanut pods and kernels were measured for several densities, temperatures, and moisture contents, in the range of 300 to 3000 MHz. Dielectric mixture equations were used to correlate the dielectric properties with density. The coefficients of quadratic and linear dielectric mixture equations are tabulated for 915 and 2450 MHz, for different temperatures and moisture contents. The values of the dielectric constants (ε') and loss factors (ε'') of bulk peanut pods and kernels were determined by extrapolation of the first and second-order polynomials that relate ε' and ε'' with density. An equation that determines the dielectric properties of bulk peanut pods and kernels as a function of their temperature and moisture content was determined using multiple linear regression.

Peanut dielectric properties were used in transport phenomena equations previously developed for batch-type microwave drying. The equations were adapted to account for the spatial variation of the electric field inside a continuous microwave drying applicator. The theoretical equations developed, together with experimental methods, were used to determine the effect of microwave power level, initial moisture content and dielectric properties on the temperature profiles and the reduction in moisture content of peanuts.
The temperature profiles obtained from solution of these equations matched the experimental profiles determined using fiber optic temperature probes. The temperature profiles were determined to be dependent on both moisture content and microwave power level. Although the maximum temperature in the microwave applicator was a function of power level only, the rate at which that maximum was attained was a function of dielectric properties and moisture contents of the peanuts. An absolute theoretical determination of moisture content reduction during microwave drying was not possible due to the dependence of dielectric properties on the moisture content. When dielectric properties were assumed independent of moisture content, the theoretical estimations of moisture losses were always lower than the losses determined experimentally, although they were in the same range of values. The surface temperature distribution of the peanut bed measured using infrared pyrometry was well correlated with internal temperature profiles. Thermal imaging demonstrated that the temperature of the peanut bed surface at the exit of the microwave curing chamber was uniformly distributed.

The surface temperature determined as a function of power level was used to create a feedback control loop of the continuous microwave drying process of farmer stock peanuts of different varieties and various initial moisture contents. Process parameters were determined using process reaction curves and a PI (proportional, integral) controller was implemented in the software routine that controlled the microwave generator power level. The servo scenario (set point change) was simulated to determine the optimum tuning parameters of the PI controller. The potential for a combined feedback/feed forward control of the process based on complete surface temperature distribution measured with an infrared camera placed at the location of maximum surface temperature was evaluated.
This study quantifies the relationships between the various parameters that influence the continuous microwave drying process of peanuts. The results of this study may be used as a foundation for development of optimum process conditions in microwave drying of peanuts and other agricultural commodities, as well as for development of advanced process control methods in continuous microwave processing.
TEMPERATURE CONTROL OF THE CONTINUOUS PEANUT DRYING PROCESS USING MICROWAVE TECHNOLOGY

by

DORIN BOLDOR

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
BIOLOGICAL AND AGRICULTURAL ENGINEERING

Raleigh

2003

APPROVED BY:

[Signatures]

Co-chair of Advisory Committee - Co-chair of Advisory Committee
To my father
BIOGRAPHY

Dorin Boldor was born on February 6th, 1974, in Onesti, Romania. He received a Bachelor of Science degree in Mechanical Engineering in 1997, from Aurel Vlaicu University of Arad, Romania. During his undergraduate studies, Dorin Boldor was employed as a computer operator and computer programmer assistant with the Oil Unit Production and General Petro Service, in Arad, Romania. He was admitted to graduate school at University of Missouri – Columbia in 1998 to pursue a master’s program in Biological Engineering. In the summer of 1998 he transferred to North Carolina State University, where he received a dual Master of Science degree in Food Science and Biological and Agricultural Engineering in May 2000. Prior to admission to graduate school he played in the Romanian National Basketball League, for West Petrom Arad. He married Cristina Sabliov in July 2000, and they are expecting a baby girl in July 2003.
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INTRODUCTION

Justification of research

The annual production of peanuts in the United States of America has a field value of more than 1 billion dollars/year (USDA-NASS, 1999b). This figure does not include the existing stocks at farms that exceeds 50 million pounds. The United States is the third largest producer of peanuts in the world, with the first two countries being China and India (USDA-NASS, 1999a).

There are many factors that affect the yield and quality of peanut production. Cultural practices (climatic conditions, crop rotation, land preparation, variety selection, liming, fertilization and mineral nutrition, irrigation, weeds, insect and disease control during growing), maturity at harvesting, and harvesting, curing and storage methods all influence peanut production and quality (Henning et al., 1982). Of these factors, curing (or drying) is the most energy intensive process.

Drying is a processing step that reduces the moisture content of peanuts from 50% at digging to a moisture content safe for long term storage (8-10%). Drying is performed in two steps. First, peanuts are dried in the field in inverted windrows to 20% moisture content. The second step is artificial drying in wagons from 20% to 10-11% in about 18-24 hours. After artificial drying, peanuts are moved to storage facilities where they continue to lose some moisture during the storage period.
Artificial drying is an energy intensive process and therefore expensive in terms of electrical energy consumed by fans and in terms of fuel consumption for heating the air. A goal of the peanut industry is to reduce energy requirements during drying through use of different methods. Recently developed "green grading" procedure which allow for mixing of different lots before curing are conducing to continuous flow drying procedures. The reduction in handling will be cost efficient and reduce damage to peanuts.

Current methods used to reduce the cost of artificial drying concentrate on improving energy efficiency of wagon drying methods. This study is focused on application of a new technology for reduction of energy consumption: the use of microwave energy in a continuous drying applicator. Microwave energy is more efficiently converted into heat when compared with conventional convective drying (Metaxa and Meredith, 1983). Very fast drying rates can be easily achieved which reduces the drying time and thus energy use.

In conventional artificial drying, the driving forces are the temperature and moisture gradient created by heated air blowing through the deep bed of peanuts. The heated air creates a drying front that moves upward through the peanut bed as the drying process progresses (Young et al., 1982). At the pod level, on the outer shell of the pods, heated air creates a front at which the water is heated, vaporized and removed. As drying progresses, this drying front moves inward toward the center of the peanut pod. As the front gets closer to the center of the pod the drying rate decreases as water vapor must diffuse through the peanut in order to be removed from the pod.

In microwave drying, the oscillating electric field causes polar molecules to rotate and charged ions to oscillate. This ionic and molecular movement leads to intermolecular friction causing rapid heating.
The heating takes place volumetrically, and water is heated and vaporized within the whole volume of the peanut pod. The rapidly formed water vapor creates a large pressure gradient that is the driving force in microwave drying.

The energy transfer between the microwave field and material is a function of the dielectric properties of the material. Due to the inherent nature of microwaves, in conventional microwave ovens, the multiple reflections of the oven walls create standing electric field patterns. These standing waves lead to heating non-uniformities that are commonly encountered in microwave units and therefore limit the adoption of the technology to a few applications such as tempering of frozen meats. New microwave system designs such as traveling wave applicators create a uniform electric field distribution. A material with uniform dielectric properties running on a conveyor belt at the center of the applicator is exposed to the constant electric field and is uniformly heated.

This study focused on understanding the fundamentals of heating and drying mechanisms of peanuts undergoing continuous microwave drying. There has been little research on continuous microwave drying of peanuts, thus there is a lack of knowledge pertaining to thermal and moisture distribution in peanuts during continuous microwave drying. The influence of dielectric properties on the temperature distribution and moisture reduction in peanuts is not well understood. This study addressed these fundamental issues of continuous microwave drying, as well as a practical application of methods to control the microwave drying process.

The study is structured in three major parts. The first part deals with the dielectric properties of shelled and in-shell peanuts and the dependence of dielectric properties on moisture content and temperature.
The second part covers the theoretical foundation of heat and mass transfer during continuous microwave drying, as well as the experimental work performed to validate the mathematical developments. In this second part, the interpretation of the temperature distributions and moisture reduction data, as related to dielectric properties and initial moisture content of peanuts, and relationship between the internal temperature and the surface temperature of peanut bed are also presented. In the third part relationship between the surface and internal temperature was used to create an effective feedback control algorithm that maintains the temperature at a desired level.

The information and technology created in the study of theoretical and practical aspects of continuous microwave drying can be applied to a large number of agricultural commodities. This information may lead to significant improvements in the drying methods currently used in processing of agricultural products.
Objectives

Research objectives were:

- to determine the dielectric properties of peanuts at microwave frequencies and the relationship to temperature and moisture content.

- to determine the influence of peanut dielectric properties and initial moisture content on internal and surface temperature distributions and moisture reduction during continuous microwave drying.

- to develop the relationship between the internal and surface temperature distribution in peanut pods during microwave drying and use the relationship to create a feedback control mechanism that maintains the surface temperature at a desired level.
REFERENCES


Manuscript 1. Dielectric Properties of In-Shell and Shelled Peanuts at Microwave Frequencies

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ABSTRACT

Dielectric properties ($\varepsilon'$, $\varepsilon''$) of ground samples of peanut (*Arachis hypogaea* L.) pods and kernels were measured for several densities, temperatures, and moisture contents, in the range of 300 to 3000 MHz. Dielectric mixture equations were used to correlate the dielectric properties with density. The coefficients of quadratic and linear dielectric mixture equations are tabulated for 915 and 2450 MHz, for different temperatures and moisture contents. The values of the dielectric constants ($\varepsilon'$) and loss factors ($\varepsilon''$) of bulk peanut pods and kernels were determined by extrapolation of the first and second-order polynomials that relate $\varepsilon'$ and $\varepsilon''$ with density. An equation that determines the dielectric properties of bulk peanut pods and kernels as a function of their temperature and moisture content was determined using multiple linear regression.

Keywords: *Arachis hypogaea* L., dielectric properties, peanuts, microwave
INTRODUCTION

Dielectric properties ($\varepsilon', \varepsilon''$) of materials characterize their interaction (transmittance, absorbance, and reflection) with electric fields, and implicitly with electromagnetic waves, including those in the microwave region. Dielectric theory and dielectric properties of materials have been studied in detail for many years (von Hippel, 1954; Birks, 1967) and a comprehensive review has been recently published (Neelakanta, 1995). Dielectric properties also characterize the ability of the material to dissipate electromagnetic energy as heat (Nelson, 1992) according to:

$$P = \sigma E^2 = 2 \pi f \varepsilon_0 \varepsilon'' E^2$$  \[1.1\]

Microwave drying and roasting are two major agricultural related processing applications in which the knowledge of the dielectric properties of various agricultural commodities is important. Many commodities have their dielectric properties compiled in extensive studies (Nelson, 1973; ASAE, 2000b).

Whitney and Porterfield (1967) measured the dielectric properties of Starr peanuts at frequencies up to 50 MHz. While some of their results are similar to those reported by other researchers, their analysis has been criticized for large errors in high moisture peanuts and methods used in measurement (Nelson, 1973). Also the dielectric properties in the microwave region (300 – 3000 MHz) may differ significantly from those at lower frequencies. The purpose of this study was to determine the effect of temperature and moisture content on the dielectric properties of peanuts in the microwave region of the electromagnetic spectrum (300 – 3000 MHz).
For biological materials (non ferromagnetic) the dielectric properties of interest are the
dielectric constant ($\varepsilon'$) and the dielectric loss ($\varepsilon''$), which relate to the complex permittivity $\varepsilon$
through the relationship (Nelson, 1978):

$$\varepsilon = \varepsilon' - j \varepsilon''$$  \[1.2\]

Where $\varepsilon'$ and $\varepsilon''$ are relative to the permittivity of free space (vacuum) $\varepsilon_0$.

Free air has a similar permittivity to a vacuum (no loss and the same storage ability),
therefore it can be approximated as:

$$\varepsilon_{\text{air}} = 1 - j \ 0$$ \[1.3\]

Two other properties of interest in microwave processing of biological materials are
conductivity ($\sigma$) and loss tangent ($\tan \delta$):

$$\sigma = \omega \varepsilon_0 \varepsilon''$$ \[1.4\]

$$\tan \delta = \varepsilon''/\varepsilon'$$ \[1.5\]

The permittivity of materials varies with frequency (von Hippel, 1954; Lawrence et al.,
1990; Neelakanta, 1995), and for pure polar materials it can be expressed using Debye’s
equation (von Hippel, 1954):

$$\varepsilon = \varepsilon'_\infty + \frac{\varepsilon'_s - \varepsilon'_\infty}{1 + j \omega \tau}$$ ; \quad $$\varepsilon' = \varepsilon'_\infty' + \frac{\varepsilon'_s' - \varepsilon'_\infty'}{1 + \omega^2 \tau^2}$$ ; \quad $$\varepsilon'' = \frac{(\varepsilon'_s' - \varepsilon'_\infty') \omega \tau}{1 + \omega^2 \tau^2}$$ \[1.6\]

For non-pure polar materials an extension of Debye’s equation (Cole-Cole equation) is
used (Nelson, 1973):

$$\varepsilon = \varepsilon'_\infty + \frac{\varepsilon'_s - \varepsilon'_\infty}{1 + (j \omega \tau)^{1-a}} ;$$ \[1.7\]
The general equations presented so far cannot be used in evaluating the dielectric constant and dielectric loss of peanuts as they are not pure polar materials, they have multiple layers (in the case of in-shell peanuts) and they form a heterogeneous mix with the air that surrounds them.

**Dielectric properties of heterogeneous mixtures**

In microwave processing, the influence of the dielectric properties depends on the amount of mass interacting with the electromagnetic field. Therefore, given that the total volume is constrained by the microwave cavity, the density (mass/unit volume) will have an effect on dielectric properties. This is especially notable with particulate dielectrics such as pulverized or granular materials (Nelson, 1983; Nelson, 1992). The influence of bulk density on dielectric properties has been studied in detail and equations have been developed that can be applied to heterogeneous mixtures (van Beek, 1967; Tinga and Voss, 1973).

\[
\varepsilon_{\text{mix}} = 1 + \frac{1}{3} v_2 \sum_i \frac{\varepsilon_i - 1}{1 + A_i (\varepsilon_i - 1)}; \quad \text{if } v_2 < 0.1 \quad [1.8]
\]

\[
\varepsilon_{\text{mix}} = 1 + \frac{1}{3} v_2 \sum_i \frac{\bar{\varepsilon}_i (\varepsilon_i - 1)}{\bar{\varepsilon}_i + A_i (\varepsilon_i - \bar{\varepsilon}_i)}; \quad \text{for any } v_2 \quad [1.9]
\]

Where for prolate spheroids:

\[
A_i = \frac{-1}{\left(\frac{a_i}{b_i}\right)^2 - 1} + \frac{a_i}{b_i} \ln \left[ \frac{a_i}{b_i} + \left(\frac{a_i}{b_i}\right)^2 - 1 \right]^{1/2}; \quad A_i \in [0, 1] \quad [1.10]
\]
An alternative approach for determining the dielectric properties of particulate and pulverized materials has been developed throughout the years. It is based on the observation that the dielectric constant and dielectric loss for granular and pulverized samples depend on density according to the following formulas (Nelson, 1983; Nelson et al., 1991; Nelson, 1992):

$$\varepsilon' = 1 + A_1 \rho + A_2 \rho^2$$  \[1.11\]

$$\left(\varepsilon'\right)^{1/2} = m_1 \rho + 1$$  \[1.12\]

$$\left(\varepsilon'\right)^{1/3} = m_3 \rho + 1$$  \[1.13\]

$$\varepsilon'' = B_1 \rho + B_2 \rho^2$$  \[1.14\]

$$\left(\varepsilon'' + \epsilon\right)^{1/2} = m_2 \rho + \left(\epsilon\right)^{1/2}$$  \[1.15\]

where:

$$\epsilon = \frac{B_1^2}{4B_2}$$  \[1.16\]

These equations are similar with the complex refractive index mixture equation [1.17] (Kraszewski, 1977; Nelson et al., 1991) and the Landau and Lifshitz, Looyenga equation [1.18] (van Beek, 1967)

$$\sqrt{\varepsilon_{\text{mix}}} = v_1 \sqrt{\varepsilon_1} + v_2 \sqrt{\varepsilon_2}; \quad v_1 = 1 - v_2;$$  \[1.17\]

$$\varepsilon_{\text{mix}}^{1/3} = v_1 \varepsilon_1^{1/3} + v_2 \varepsilon_2^{1/3}; \quad v_1 = 1 - v_2;$$  \[1.18\]

Equations [1.11] to [1.18] were successfully used to determine the dielectric properties of pecans (Nelson, 1981; Lawrence et al., 1992), wheat (Nelson, 1984; Lawrence et al., 1990), rice (You and Nelson, 1988), and fish meal (Kent, 1977). The present study of dielectric properties of peanuts is based on the theoretical developments presented above.
MATERIALS AND METHODS

Field dried peanuts were shipped from USDA – ARS National Peanut Research Laboratory in Dawson, Georgia in August 2002 to North Carolina State University. They were separated into 4 different samples. The first sample was stored in a cooler at 8°C, while the others were dried on an air blower in three stages, to reach a total of four different moisture contents. The moisture content of each sample was determined according to ASAE Standards (ASAE, 2000a). Each sample was subsequently divided into two separate samples, out of which one was shelled in order to determine the dielectric properties of both in-shell and shelled peanuts. In addition to bulk moisture content of the samples, the moisture content of each sample undergoing dielectric properties measurements was measured by collecting a small sample after the dielectric measurement.

The peanut samples were sealed in quarter size plastic bags and left to equilibrate their moisture content for 24 hours in refrigerator at 4°C. After equilibration the bags were removed from the refrigerator and left to equilibrate at room temperature for 4 hours (23°C).

In-shell and shelled peanuts were grounded using a Waring Blendor Model 702B (Waring Product Corp., New York, NY) and the ground product size separated using a 3.35 mm U.S. Standard Sieve (Dual Manufacturing Co., Chicago, ILL). Ground samples were placed in 250 ml sealed mason jars at four different densities (Nelson and You, 1989). The smallest particle density was achieved by pouring the sample as loose as possible. The higher particle densities were obtained by tapping and pressing the sample in the jar with three different weights (1870, 4570 and 16935 g). Measurements for all four densities were performed at 23°C (room temperature), 30, 40 and 50 °C respectively.
For temperatures above room temperature, the jars were held in water baths for a few hours, until an extra jar with temperature sensor at the geometric center filled at the highest density was determined to be at thermal equilibrium with the water bath.

Dielectric properties were measured with a HP Network Analyzer 8753C (Hewlett-Packard, Palo Alto, CA) using the open-ended coaxial probe method adapted from Nelson and Bartley (2000) and Engelder and Buffler (1991), in a 361 point frequency sweep from 300 MHz to 3 GHz. The network analyzer was controlled by Hewlett-Packard 85070B dielectric kit software (Hewlett-Packard, Palo Alto, CA) and calibrated using the 3-point method (short-circuit, air and water at 25°C).

The least square method (Milton and Arnold, 1995) was used in Matlab (The Mathworks, Inc., Natick, MA) to determine the coefficients of regression ($A_1, A_2, B_1, B_2, m_1, m_2, m_3, e$) and coefficients of determination ($r^2$) for $\varepsilon'$ and $\varepsilon''$ as a function of density for all 361 points in the frequency sweep. The method was used for both first-order and second-order polynomials according to equations [1.11] - [1.16] as described by Nelson (1984).

Dielectric properties of in-shell and shelled peanuts at nominal bulk density for all moisture contents and temperatures tested were determined afterward using dielectric mixture equations [1.11] to [1.15] in Microsoft Excel XP (Microsoft Corp., Redmond, WA). The equations that relate the dielectric properties of peanut pods and kernels to their moisture content and absolute temperature were obtained by performing multiple linear regression on the logarithmic transforms of the data:

$$
\log (\varepsilon') (\text{or} \log \varepsilon'') = c_1 \log (10) + c_2* \log (T(K)) + c_3 \log (mc) \tag{[1.19]}
$$

$$
\Rightarrow \quad \varepsilon' (\text{or} \varepsilon'') = 10^{c_1} T^{c_2} mc^{c_3} \tag{[1.20]}
$$
RESULTS AND DISCUSSION

The FCC regulates the use of frequencies of the electromagnetic spectrum in the US, and the two frequencies reserved for food uses are 915 MHz and 2.45 GHz. Most of the results presented here are at these two frequencies.

The dielectric properties of ground pods and kernels as a function of density are displayed in Figures 1.1 and 1.2. The density dependence of the dielectric properties ($\varepsilon'$ and $\varepsilon''$) of ground peanuts is similar to those obtained for other agricultural commodities (Nelson and You, 1989). As the density increases, the dielectric properties increase for both ground kernels and ground pods. The dependence was determined using equations [1.11] to [1.17] with very good results. In general the quadratic equations [1.11] and [1.14] give better estimates of the dielectric properties ($r^2 > 0.9$) than linear equation [1.12], [1.13] and [1.15] respectively. The coefficients for quadratic and linear predictive equations ([1.11] to [1.16]) as a function of density for peanuts at various temperatures and moisture contents are presented in Tables 1.1 through 1.4.

Two notable exceptions occur for the dielectric loss of ground pods (18% mc and 50°C) and kernels (33% mc and 50°C). While the quadratic equation [1.14] shows a very good dependence of bulk density ($r^2 > 0.9$), the linear estimations using equation [1.15] becomes unusable ($e<0$, therefore $e^{1/2}$ is a complex number). In general, the dielectric mixture equations proved to be more accurate for temperatures below 50°C and lower moisture contents. Similar effect was observed in high moisture dough ($>26\%$) by Kim et al. (1998) due to increased water mobility resulting in decreased ionic conductivity.
Since deviations from the equation [1.14] are noticed even in lower moisture peanuts, the authors hypothesize that in addition to increased water mobility, oil extraction from peanuts also has a previously unaccounted effect on the density dependence of dielectric properties. The extraction of oil is caused by a combination of the grinding process, the pressure applied to create a high density mixture, and the higher temperatures. Ground peanuts change from a heterogeneous mixture of solids and air to a mixture of solids, oil, and air, and the linear dielectric mixture equations [1.11] – [1.16] do not accurately represent the system. In this case the quadratic equations [1.11] and [1.14] prove to be valuable tools in estimating the dielectric properties of peanuts at high temperatures and moisture content.

Dielectric properties of Georgia Green peanut kernels as a function of frequency at 23°C and all four moisture contents are presented in Figure 1.3. While the dielectric properties decrease with frequency, they increase as the moisture content increases up to 33%, and afterward decrease at 39% mc. This effect was previously noticed in potatoes and explained by Mudgett (1995) by a dilution of dissolved salts by the extra free water. The dielectric mixture theory equations [1.11] to [1.16] were used subsequently to determine the dielectric properties of bulk peanuts at different moisture contents and densities (Figures 1.4 and 1.5).

In the lower moisture region (18-23%), both temperature and moisture content seem to affect the dielectric constant and dielectric loss of peanuts. In the higher moisture region (23-33%), the temperature effect becomes insignificant when compared to the effect of moisture content. Therefore, for dielectric heating of peanuts in the high moisture content, the rate of heating (Eqn. [1.1]) will be mainly affected by the moisture content, with the temperature range studied not affecting the dielectric loss of the peanuts.
The authors assume that at temperatures above those studied in this paper, the dielectric loss of peanuts will increase significantly according to the microwave thermal runaway effect (Rosenthal, 1992).

The multiple linear regression performed on the logarithmic transforms of the data (equations [1.19] and [1.20]) gives the following relationship of the dielectric properties of the peanuts with their moisture content and temperature:

**Kernels at 915 MHz:**

\[ \varepsilon' = 10^{2.6840} \times T(K)^{-0.5262} \times m^{0.8870} \quad r^2 = 0.83 \quad [1.21] \]

\[ \varepsilon'' = 10^{5.5882} \times T(K)^{-1.8323} \times m^{1.3083} \quad r^2 = 0.84 \quad [1.22] \]

**Kernels at 2450 MHz:**

\[ \varepsilon' = 10^{2.1730} \times T(K)^{-0.3401} \times m^{0.8562} \quad r^2 = 0.85 \quad [1.23] \]

\[ \varepsilon'' = 10^{7.8072} \times T(K)^{-2.7511} \times m^{1.3483} \quad r^2 = 0.86 \quad [1.24] \]

**Pods at 915 MHz:**

\[ \varepsilon' = 10^{0.7776} \times T(K)^{0.2299} \times m^{1.2642} \quad r^2 = 0.93 \quad [1.25] \]

\[ \varepsilon'' = 10^{3.1577} \times T(K)^{-0.7181} \times m^{2.4603} \quad r^2 = 0.93 \quad [1.26] \]

**Pods at 2450 MHZ:**

\[ \varepsilon' = 10^{0.5638} \times T(K)^{0.2843} \times m^{1.1614} \quad r^2 = 0.94 \quad [1.27] \]

\[ \varepsilon'' = 10^{6.4954} \times T(K)^{-2.0955} \times m^{2.5433} \quad r^2 = 0.95 \quad [1.28] \]
CONCLUSIONS

Peanut dielectric properties were determined using methods previously applied to wheat, corn and other agricultural commodities. Dielectric theory mixture equations were found to provide good estimates of the dielectric loss and the dielectric constant as a function of density, and they proved to be very useful in determining the dielectric properties of bulk peanuts in the microwave region of the electromagnetic spectrum. Data for dielectric properties of peanut pods and kernels was provided for a range of moisture contents and temperatures at microwave frequencies used in food processing (915 and 2450 MHz). The dependence on temperature was found to be more significant at lower moisture contents. At higher moisture contents, the significance of temperature effects on $\varepsilon'$ and $\varepsilon''$ was reduced by the high dependence on moisture content of dielectric properties. The dielectric properties of peanuts obtained using equations [1.21] to [1.28] are similar to those presented in literature (Nelson, 1973), with certain variations due to different moisture contents and frequencies used.
LIST OF SYMBOLS

\( a_i, b_i \) – major and minor axis of the prolate spheroids; m

\( A_1 \) – depolarizing factor

\( A_1, A_2 \) – regression coefficients of dielectric constant quadratic equations

\( B_1, B_2 \) – regression coefficients of dielectric loss quadratic equations

\( c_1, c_2, c_3 \) – coefficients of regression equation

\( e \) – regression constant

E – electric field; V/m

\( f \) – frequency; Hz

\( j \) – \((-1)^{1/2}\)

\( m_1, m_2, m_3 \) – regression coefficients for linear equations

\( m_c \) – moisture content dry basis; %

P – power absorbed per unit volume; W/m³

\( \tan \delta \) – loss tangent (\( \tan \delta = \varepsilon''/\varepsilon' = \sigma/\omega\varepsilon_0\varepsilon' \))

T – absolute temperature; K

\( v_1 \) – volume fraction of the continuous phase (air)

\( v_2 \) – volume fraction of the dispersed phase (solid)

\( \alpha \) – spread of relaxation times; \( \alpha \in [0,1] \)

\( \delta \) – phase of a complex number

\( \varepsilon \) – relative complex permittivity or relative complex dielectric constant

\( \varepsilon_0 \) – dielectric constant of the vacuum = \( 8.854 \times 10^{-12} \) Far/m

\( \varepsilon_1 \) – relative dielectric constant of the continuous phase (air)

\( \varepsilon_2 \) – relative dielectric constant of the dispersed phase (solids)

\( \varepsilon_{\text{mix}} \) – relative dielectric constant of a mixture

\( \varepsilon_{\infty} \) – relative dielectric constant as \( \omega \) goes to infinity

\( \bar{\varepsilon}_i \) – mean value permittivity around a spheroid particle

\( \varepsilon' \) – relative electric constant or storage factor

\( \varepsilon_s' \) – relative static dielectric constant (at \( \omega = 0 \))

\( \varepsilon'' \) – relative dielectric loss or loss factor

\( \sigma \) – conductivity; siemen/m

\( \tau \) – relaxation time for a polar molecule; sec

\( \omega \) – angular frequency;
REFERENCES

ASAE Standards. 2000a. Moisture Measurement – Peanuts. ASAE S410.1 DEC97. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA

ASAE Standards. 2000b. Dielectric Properties of Grain and Seed. ASAE D293.2 DEC99. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA

Birks, J.B. 1967. Progress in Dielectrics. CRC Press, Cleveland, OH.


Table 1.1. Values for coefficients and $r^2$ of the quadratic and linear regressions at 915 MHz for kernels

<table>
<thead>
<tr>
<th>MC (%)</th>
<th>(\rho ) (kg/m$^3$)</th>
<th>18% (628 kg/m$^3$)</th>
<th>23% (654.6 kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(c' = A_2 \rho^2 + A_1 \rho + 1)</td>
<td>(c'' = m_3 \rho + 1)</td>
<td>(c'' = m_3 \rho + 1)</td>
</tr>
<tr>
<td></td>
<td>(e' = A_2 \rho^2 + A_1 \rho + 1)</td>
<td>(e'' = B_2 \rho^2 + B_1 \rho)</td>
<td>(e'' + e = m_2 \rho^{1/2})</td>
</tr>
<tr>
<td></td>
<td>(e' = A_2 \rho^2 + A_1 \rho + 1)</td>
<td>(e'' = B_2 \rho^2 + B_1 \rho)</td>
<td>(e'' + e = m_2 \rho^{1/2})</td>
</tr>
</tbody>
</table>

Table 1.2. Values for coefficients and $r^2$ of the quadratic and linear regressions at 915 MHz for pods

<table>
<thead>
<tr>
<th>MC (%)</th>
<th>(\rho ) (kg/m$^3$)</th>
<th>18% (715.1 kg/m$^3$)</th>
<th>23% (751.3 kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(c' = A_2 \rho^2 + A_1 \rho + 1)</td>
<td>(c'' = m_3 \rho + 1)</td>
<td>(c'' = m_3 \rho + 1)</td>
</tr>
<tr>
<td></td>
<td>(e' = A_2 \rho^2 + A_1 \rho + 1)</td>
<td>(e'' = B_2 \rho^2 + B_1 \rho)</td>
<td>(e'' + e = m_2 \rho^{1/2})</td>
</tr>
</tbody>
</table>
### Table 1.3. Values for coefficients and $r^2$ of the quadratic and linear regressions at 2450 MHz for kernels

<table>
<thead>
<tr>
<th>MC (%)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>Temp (°C)</th>
<th>18% (628 kg/m$^3$)</th>
<th>23% (654.6 kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>$\varepsilon'$ = $A_3\rho^2 + A_2\rho + A_1$</td>
<td>$A_2$</td>
<td>8.384E-6</td>
<td>6.937E-6</td>
<td>6.663E-6</td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
<td>5.930E-4</td>
<td>2.079E-3</td>
<td>2.129E-3</td>
</tr>
<tr>
<td></td>
<td>$A_0$</td>
<td>0.949</td>
<td>0.843</td>
<td>0.763</td>
</tr>
<tr>
<td>$\varepsilon'^{1/2}$ = $m_0\rho + m_1$</td>
<td>$m_1$</td>
<td>1.939E-3</td>
<td>2.027E-3</td>
<td>1.991E-3</td>
</tr>
<tr>
<td></td>
<td>$m_0$</td>
<td>0.878</td>
<td>0.810</td>
<td>0.731</td>
</tr>
<tr>
<td>$\varepsilon'^{1/3}$ = $m_0\rho + m_1$</td>
<td>$m_1$</td>
<td>1.094E-3</td>
<td>1.137E-3</td>
<td>1.118E-3</td>
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<td></td>
<td>$m_0$</td>
<td>0.899</td>
<td>0.833</td>
<td>0.751</td>
</tr>
<tr>
<td>$\varepsilon'' = B_3\rho^2 + B_2\rho$</td>
<td>$B_2$</td>
<td>3.220E-6</td>
<td>2.720E-6</td>
<td>3.051E-6</td>
</tr>
<tr>
<td></td>
<td>$B_1$</td>
<td>-4.960E-4</td>
<td>-2.990E-4</td>
<td>-5.570E-4</td>
</tr>
<tr>
<td></td>
<td>$B_0$</td>
<td>0.988</td>
<td>0.882</td>
<td>0.765</td>
</tr>
</tbody>
</table>

### Table 1.4. Values for coefficients and $r^2$ of the quadratic and linear regressions at 2450 MHz for pods

<table>
<thead>
<tr>
<th>MC (%)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>Temp (°C)</th>
<th>18% (332 kg/m$^3$)</th>
<th>23% (336.6 kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>$\varepsilon'$ = $A_3\rho^2 + A_2\rho + A_1$</td>
<td>$A_2$</td>
<td>1.502E-5</td>
<td>1.540E-5</td>
<td>7.286E-6</td>
</tr>
<tr>
<td></td>
<td>$A_1$</td>
<td>-2.199E-3</td>
<td>-2.961E-3</td>
<td>1.743E-3</td>
</tr>
<tr>
<td></td>
<td>$A_0$</td>
<td>0.935</td>
<td>0.973</td>
<td>0.890</td>
</tr>
<tr>
<td>$\varepsilon'^{1/2}$ = $m_0\rho + m_1$</td>
<td>$m_1$</td>
<td>2.801E-3</td>
<td>3.019E-3</td>
<td>2.873E-3</td>
</tr>
<tr>
<td></td>
<td>$m_0$</td>
<td>0.917</td>
<td>0.969</td>
<td>0.956</td>
</tr>
<tr>
<td>$\varepsilon'^{1/3}$ = $m_0\rho + m_1$</td>
<td>$m_1$</td>
<td>1.470E-3</td>
<td>1.569E-3</td>
<td>1.510E-3</td>
</tr>
<tr>
<td></td>
<td>$m_0$</td>
<td>0.935</td>
<td>0.973</td>
<td>0.890</td>
</tr>
<tr>
<td>$\varepsilon'' = B_3\rho^2 + B_2\rho$</td>
<td>$B_2$</td>
<td>4.677E-6</td>
<td>5.228E-6</td>
<td>2.019E-6</td>
</tr>
<tr>
<td></td>
<td>$B_1$</td>
<td>1.840E-4</td>
<td>9.100E-5</td>
<td>2.324E-3</td>
</tr>
<tr>
<td></td>
<td>$B_0$</td>
<td>0.930</td>
<td>0.943</td>
<td>0.941</td>
</tr>
<tr>
<td>$(\varepsilon'^{+e})^{1/2}$ = $m_0\rho + e^{1/2}$</td>
<td>$e$</td>
<td>1.800E-3</td>
<td>3.940E-4</td>
<td>6.687E-1</td>
</tr>
<tr>
<td></td>
<td>$m_0$</td>
<td>2.144E-3</td>
<td>2.290E-3</td>
<td>1.417E-3</td>
</tr>
<tr>
<td></td>
<td>$e$</td>
<td>0.935</td>
<td>0.933</td>
<td>0.948</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Figure 1.1   Density dependence of peanut kernels dielectric properties at 18% mc and 30°C at 915 MHz. a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$).

Figure 1.2   Density dependence of peanut pods dielectric properties at 23% mc and 30°C at 2450 MHz. a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$)

Figure 1.3   Dielectric properties of peanut pods at several moisture contents as a function of frequency at 23°C. a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$)

Figure 1.4   Temperature and moisture dependence of dielectric properties of peanut kernels based on the quadratic equations [1.12] and [1.15]. a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$).

Figure 1.5   Temperature and moisture dependence of dielectric properties of peanut pods based on the linear equations [1.13] and [1.16]. a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$).
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Figure 1.3. Dielectric properties of peanut pods at several moisture contents as a function of frequency at 23°C. a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$)
Figure 1.4. Temperature and moisture dependence of dielectric properties of peanut kernels based on the quadratic equations [1.12] and [1.15].
a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$).
Figure 1.5. Temperature and moisture dependence of dielectric properties of peanut pods based on the linear equations [1.13] and [1.16].

a. Dielectric constant ($\varepsilon'$); b. Dielectric loss ($\varepsilon''$).
Manuscript 2. Thermal Profiles and Moisture Loss during Continuous Microwave Drying of Peanuts

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ABSTRACT

The use of microwave energy in a planar applicator for continuous drying of farmer stock (in-shell, uncured) peanuts (*Arachis hypogaea* L.) was investigated. Transport phenomena equations previously developed for batch-type microwave drying were successfully adapted to account for the spatial variation of the electric field inside the applicator. The theoretical equations developed, together with experimental methods, were used to determine the effect of microwave power level, initial moisture content and dielectric properties on the temperature profiles and the reduction in moisture content of peanuts. The temperature profiles obtained from solution of these equations matched the experimental profiles determined using fiber optic temperature probes inserted into drying peanut pods. The temperature profiles were determined to be dependent on both moisture content and microwave power level. Although the maximum temperature in the microwave applicator was a function of power level only, the rate at which that maximum was attained was a function of dielectric properties and moisture contents of the peanuts. An absolute theoretical determination of moisture content reduction during microwave drying was not possible due to the dependence of dielectric properties on the moisture content. When dielectric properties were assumed independent of moisture content, the theoretical estimations of moisture losses were always lower than the losses determined experimentally, although they were in the same range of values. The surface temperature distribution of the peanut bed measured using infrared pyrometry was well correlated with internal temperature profiles. Thermal imaging demonstrated that the temperature of the peanut bed surface at the exit of the microwave curing chamber was uniformly distributed.
This study quantifies the relationships between the various parameters that influence the continuous microwave drying process of peanuts. The results may be used as a foundation for development of optimum process conditions in microwave drying of peanuts and other agricultural commodities.

Keywords: *Arachis hypogaea* L., peanuts, drying, microwave, continuous, moisture loss, temperature, distribution, thermal treatment
INTRODUCTION

Peanut drying reduces the moisture content of harvested peanuts to a level at which the quality is maintained (Young et al., 1982). Curing, or drying, is generally performed in two stages: field curing in inverted windrows to 20-25% moisture content and drying in wagons or bins to about 10% moisture content (Baldwin et al., 1990). Field curing is a natural process and the factors that affect it have been studied and described extensively by other researchers (Young et al., 1982).

Wagon or bin drying is a process in which water is removed from farmer stock peanuts (field dried peanuts at 20-25% mc) through moisture and temperature gradients created by air flowing through the mass of peanuts. Moisture movement during air drying of thin-layer peanut pods was studied and described by Whitaker and Young (1972a). Moisture flux is determined by the thermal and physical properties of the peanuts and psychometric properties of the air (Suter et al., 1975; Whitaker and Young, 1972b; Young et al., 1982). In practice, drying is performed in deep beds, where air is forced upwards through the peanuts. A drying zone is created in the lower portions of the bed and moves upward through the bed of peanuts as the process evolves. Requirements for air flow in terms of volume, temperature and relative humidity, in wagon drying, combined with the drying time (about 18-24 hours), make drying in wagons an energy intensive process. A large number of studies have been conducted to determine ways to increase the energy efficiency in air drying of peanuts (Troeger, 1982; Blankenship and Chew, 1978; Rogers and Brusewitz, 1977; Chai and Young, 1995). Past studies have frequently focused on the use of high temperatures and on methods of reducing the amount of running time for fans (Baker et al., 1993; Blankenship and Chew, 1979; Butts, 1996).
Little research has studied the use of alternative methods for energy input, such as microwave or radio frequency energy. The microwave region of the electromagnetic spectrum has long been used in a variety of industrial applications, ranging from telecommunication to dielectric heating of foods and other materials. Due to the large number of applications available, the FCC regulates the use of the frequency bands of the electromagnetic spectrum, and the two microwave frequencies reserved for dielectric heating in the United States are 915 and 2450 MHz. The mechanism of dielectric heating has been thoroughly analyzed and described in many studies (von Hippel, 1954; Rosenthal, 1992; Clark et al., 1997; Schiffmann, 1997).

The heating of a dielectric in the presence of an electromagnetic field is based on intermolecular friction that arises via ionic conduction and dipolar rotation (White, 1973; Schiffmann, 1997). Charged ions present in the dielectric material move according to the direction of the electric field component of the electromagnetic wave. At the same time, polar molecules try to align themselves in the position of minimum energy, parallel with the electric field. The rapid oscillation of the electric field in the electromagnetic wave causes the charged ions to move back and forth at high speed, and the polar molecules to rotate rapidly. This molecular motion generates heat through friction with the surrounding molecules and ions (Figures 2.1 and 2.2, Zhong, 2001).

The potential for ionic conduction and dipole rotation of materials is expressed by the imaginary part of the relative complex permittivity (relative dielectric loss) (Nelson, 1973; Boldor et al., 2003):

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

[2.1]
The real part of the complex permittivity is represented by the dielectric constant ($\varepsilon'$) and represents the property that characterizes the ability of material to store and transmit electromagnetic energy. The power dissipated in dielectric heating is proportional to the frequency, dielectric properties and the electric field distribution according to formula (Nelson, 1973; Metaxa and Meredith, 1983):

$$\Delta P = \sigma E^2 = 2 \pi f \varepsilon_0 \varepsilon'' E^2$$  \[2.2\]

Microwave heating has been used in the past to reduce the moisture content of various fruits and vegetables such as bananas (Maskan, 2000), apples, mushrooms and strawberries (Funebo and Ohlsson, 1999; Funebo et al., 2000; Erle and Schubert, 2001), carrots (Prabhanjan et al., 1995; Sanga et al., 2000), corn (Shivhare et al., 1991; Beke et al., 1995; Beke et al., 1997), potatoes (Bouraoui et al., 1994; Sanga et al., 2000), and broad bean (Ptasznik et al., 1990). Blanching of endive and spinach (Ponne et al., 1994), corn (Boyes et al., 1997), and peanuts (Rausch, 2002) as well as studies performed to investigate the shelf life and roast quality of microwave blanched peanuts (Katz, 2002) are other examples of utilization of microwave energy in processing of foods and agricultural commodities. Most of these studies were performed on static samples that were not characteristic of an industrial environment typified by continuous processing. Except for Rausch (2002) and Katz (2002) the research indicated above was based on modification of multimode cavity microwave ovens used in the home. Modifications were performed to allow air flow and temperature and mass measurement. An inherent problem in the use of multimode cavity ovens is non-uniform heating due to standing wave patterns created by the electric field (Rosenthal, 1992).

Another drawback is that the multimode cavity home oven frequency (2450 MHz) yields a shorter wavelength than the 915 MHz frequency found in industrial applications.
The oscillating electric field for the 2450 MHz system results in less penetration according to (Stuchly and Hamid, 1972; Metaxa and Meredith, 1983; Griffiths, 1999):

$$E = E_0 e^{-\alpha z};$$

[2.3]

Where:

$$\alpha = 2\pi f \left( \frac{\mu_0 \mu' \varepsilon_\varepsilon_0}{2} \right)^{0.5} \sqrt{1 + \left( \frac{\varepsilon''}{\varepsilon'} \right)^2} - 1$$

[2.4]

Theoretical models for temperature and moisture distribution during microwave drying of materials, including foods was studied in detail (Lu et al., 1999; Khraisheh et al., 1997; Ramaswamy and Pillet-Will, 1992; Wei et al., 1985; Ni and Datta, 1999; Lyons et al., 1972). Other empirical methods were developed to model moisture loss during microwave drying (Khraisheh et al., 1995; Khraisheh et al., 2000). However, most of these models were also developed for multimode batch-type processing applications and at the higher frequency of 2450 MHz.

Previous studies on continuous microwave processing in a TE$_{10}$ (transverse electric) mode traveling wave applicator concentrated on the effect of power level and the belt speed on blanching, roast quality and storage stability of peanuts (Rausch, 2002; Katz, 2002). A semi-continuous microwave dehydration process for apple and mushrooms was developed to compare conventional and microwave assisted drying in a transverse magnetic mode applicator (Funebo and Ohlsson, 1999).

The TE$_{10}$ traveling mode applicators for drying are widely used in the wood and paper industries (Metaxa and Meredith, 1983; Jones, 1975; Jones, 1986). In a TE$_{10}$ waveguide at the center of any transversal section perpendicular on the main axis the distribution of the electric field is relatively uniform (Figure 2.3).
Dielectric material placed at the center of the waveguide, running parallel with the electrical field, will be heated uniformly by the electric field.

The typical temperature profile in microwave drying of materials is shown in Figure 2.4 (Metaxa and Meredith, 1983; Lyons et al., 1972). Three distinct regions can be observed on the temperature profile. The first one is the initial heat-up region, when the temperature increases to the wet bulb temperature of the liquid that is being removed. The second one is the constant temperature drying region, where most of the liquid is being vaporized within the sample and removed through pressure gradients. The third region occurs after most of the liquid has been removed and the temperature increases without any liquid being removed. For all practical purposes, any microwave drying process should stop at the end of the constant temperature drying region, unless there is a requirement to heat the material after is dried.

This study focused on the temperature distribution and potential for moisture removal of farmer stock peanuts (25 to 45% mc dry basis) in a continuous TE_{10} traveling wave applicator using microwaves at 915 MHz.
Mathematical development

The fundamental theories of heat and mass transfer during conventional microwave heating were adapted to the continuous process to account for the unique distribution of the electric field along the waveguide. While in the conventional ovens the electric field creates a standing pattern, in traveling wave applicators the electric field is constant in the transversal section of the waveguide (Figure 2.3). Along the longitudinal axis of the waveguide, the electric field decreases exponentially as a function of distance (Eqn. [2.3], Figure 2.5), and the conversion between the time and distance coordinates is performed through the conveyor belt speed according to:

\[ \dot{z} = v_z \dot{t} \]  

[2.5]

The attenuation constant in this case has to be adjusted for the presence of the dielectric traveling on the conveyor belt in the center of the applicator according to the formula (Metaxa and Meredith, 1983):

\[ \alpha = 17.37 \pi e'' \frac{w}{a} \frac{\lambda_e}{\lambda_0^2} \text{ dB/m} \]  

[2.6]

At the working frequency of 915 MHz and for the waveguide dimension of 247.5 x 123.8 mm the attenuation constant becomes:

\[ \alpha = 894 \text{ w} e'' \text{ ; dB/m} \]  

[2.7]

The governing equation for the transport phenomena assuming negligible convective and radiating losses during microwave drying is (Metaxa and Meredith, 1983; Lu et al., 1999):

\[ \frac{\partial T}{\partial t} = \alpha_T \nabla^2 T + \frac{e_e}{C_p} L_h \frac{\partial M}{\partial t} + \frac{\Delta P}{pC_p} \]  

[2.8]
The coupling between heat and mass transfer phenomena described by Eqn. [2.8] makes analytical solution extremely difficult. However, we can use the unique properties of the traveling wave applicators and a few assumptions to simplify the equation by dividing the waveguide into the three regions. The third region, of heating up without drying is not considered for this study and the microwave drying process is considered to stop at or toward the end of the second region (Figure 2.4). The influence of the radiative and convective losses is treated separately.

Region I. Initial heat-up

Assumptions:

- In the initial heat-up region, the material heats without any significant moisture loss:

\[ \frac{\partial M_i}{\partial t} = 0 \]  \hspace{1cm} [2.9]

- Microwave heating is volumetric; no temperature gradient within the sample:

\[ \nabla T = 0 \]  \hspace{1cm} [2.10]

The partial differential Eqn. [2.8] is now a first order differential equation and after changing the coordinates from time to distance (Eqn. [2.5]) becomes:

\[ \frac{dT}{dz} = \frac{\Delta P}{\nu_s \rho C_p} \]  \hspace{1cm} [2.11]

To determine the temperature profile of the material undergoing microwave processing in a traveling wave applicator, knowledge of the power absorbed over a certain region of the applicator is required. The absorbed power is dependent on the electric field distribution in that respective region according to Eqn. [2.2]:

\[ \Delta P = 2 \pi f \varepsilon_0 \varepsilon'' E_{\text{rms}}^2(z) \]  \hspace{1cm} [2.12]
Where:

\[ E_{\text{rms}} = E_{0\text{rms}} e^{-\alpha z} \]  \[2.13\]

Total power input to the system is:

\[ P_{\text{in}} = A_{\text{wg}} I \]  \[2.14\]

Where:

\[ I = \varepsilon_0 E_{0\text{rms}}^2 \]  \[2.15\]

Substituting Eqn. [2.13], [2.14], and [2.15] into [2.12] the power loss at distance \( z \) is:

\[ \Delta P = \frac{2\pi f \varepsilon'' P_{\text{in}} e^{-2\alpha z}}{A_{\text{wg}} c} \]  \[2.16\]

After substitution and separation of variables in Eqn. [2.11]:

\[ dT = \frac{2\pi f \varepsilon'' P_{\text{in}} e^{-2\alpha z}}{v \rho C_p A_{\text{wg}} c} dz \]  \[2.17\]

Assuming that the density \( \rho \), specific heat \( C_p \) and dielectric loss \( \varepsilon'' \) do not change as a function of temperature (Boldor et al., 2003; Metaxa and Meredith, 1983), Eqn. [2.17] can be solved through integration:

\[ \int_{T_0}^{T_z} dT = \frac{2\pi f \varepsilon'' P_{\text{in}}}{v \rho C_p A_{\text{wg}} c} \int_0^z e^{-2\alpha z} dz \]  \[2.18\]

After integration:

\[ T_z = T_0 + \frac{\pi f \varepsilon'' P_{\text{in}}}{v \rho C_p A_{\text{wg}} c} (1 - e^{-2\alpha z}) \]  \[2.19\]

In this region of the microwave applicator the temperature will depend mainly on the input power level and the belt speed. The temperature follows a first order curve and will increase at a rate depending on the value of the attenuation constant \( \alpha \).
Region II. Drying at constant temperature.

For the second region of the microwave drying process, the simplification of the Eqn. [2.8] was made using the following assumptions:

- Drying takes place at constant temperature:
  \[
  \frac{\partial T}{\partial t} = 0 \quad [2.20]
  \]

- Microwave heating is volumetric therefore:
  \[
  \nabla T = 0 \quad [2.21]
  \]

- All moisture that is being removed leaves the system in vapor form:
  \[
  \varepsilon_v = 1; \quad M_i = M \quad [2.22]
  \]

Equation 8 then becomes:

\[
\frac{dM}{dz} = -\frac{\Delta P}{v_x \rho L_h} \quad [2.23]
\]

Substitution of the power dissipated over the region (Eqn. [2.16]) and separation of variables yields:

\[
dM = -\frac{2\pi \int \varepsilon'' P_{in}}{v_x \rho L_h A_{wg} c} e^{-2a z} dz \quad [2.24]
\]

Equation [2.24] can be solved in two different ways. The first one assumes that the dielectric loss \(\varepsilon''\) and density \(\rho\) are independent of the moisture content \(M\), and the solution is found through simple integration:

\[
\int_{M_i}^{M} dM = -\frac{2\pi \int \varepsilon'' P_{in}}{v_x \rho L_h A_{wg} c} \int_{z_i}^{z} e^{-2a z} dz \quad [2.25]
\]

After integration:
\[
M_z = M_0 - \frac{\pi f \varepsilon'' P_{in}}{v_z \rho L_h A_{wg} \alpha} (e^{-2a z_i} - e^{-2a z})
\]

[2.26]

Equation [2.26] can be used to obtain an approximation of the moisture distribution during drying, but most of the time the dielectric loss \(\varepsilon''\) is a linear function of the moisture content (Boldor et al., 2003; Metaxa and Meredith, 1983):

\[
\varepsilon'' = \varepsilon_0'' + k_1 M
\]

[2.27]

In this case, assuming that the density \(\rho\) and the attenuation constant \(\alpha\) do not change significantly with the moisture content, Eqn. [2.24] becomes:

\[
\frac{1}{\varepsilon''} \frac{dM}{dM} = -\frac{2\pi f P_{in}}{v_z \rho L_h A_{wg} c} e^{-2a z} \int dz
\]

[2.28]

Integrating over a constant distance \((z_2 - z_1)\):

\[
\int_{M_i}^{M_f} \frac{1}{\varepsilon_0'' + k_1 M} dM = -\frac{2\pi f P_{in}}{v_z \rho L_h A_{wg} c} \int_{z_i}^{z_f} e^{-2a z} \int dz
\]

[2.29]

After integration (Metaxa and Meredith, 1983):

\[
\ln(k_1 M + \varepsilon_0'') \bigg|_{M_i}^{M_f} = \frac{k_1 \pi f P_{in}}{v_z \rho L_h A_{wg} \alpha c} (e^{-2a z_2} - e^{-2a z_1}) = k_2 = \text{constant}
\]

[2.30]

And:

\[
\frac{k_1 M_f + \varepsilon_0''}{k_1 M_i + \varepsilon_0''} = k_3
\]

[2.31]

Equation [2.31] provides information on the moisture leveling effect of the microwave drying. Assuming that at a certain power level and belt speed the moisture content of a material is reduced from 25% to 15%. Assume a dielectric constant varying with the moisture content according to:

\[
\varepsilon'' = 0.2 + 8 M
\]

[2.32]
To find the final moisture content for a 20% initial moisture content, in Eqn. [2.31]:

\[
\frac{8 \times 0.15 + 0.2}{8 \times 0.25 + 0.2} = k_3 = \frac{8x + 0.2}{8 \times 0.2 + 0.2}
\]  

[2.33]

The final moisture content will be:

\[x = 0.118 = 11.8\%\]  

[2.34]

For a difference in initial moisture contents of 5%, the difference in final moisture contents is only 3.2%. In reality, most of the time the higher moisture content material will also have higher dielectric loss, which will determine a higher attenuation constant (Eqn. [2.7]). The higher attenuation constant will determine a faster arrival at the constant drying temperature (Eqn. [2.19]), and therefore a longer time in the applicator, further reducing the differences between the two final moisture contents.
MATERIALS AND METHODS

Field dried peanuts (Runner and Virginia type) at moisture contents ranging from 25 to 45% were used in this study. Samples were shipped from USDA-ARS Peanut National Laboratory in Dawson, Georgia to the Department of Food Science at North Carolina State University during the months of September - November of 2002.

The microwave curing chamber (Industrial Microwave Systems, Morrisville, NC) was a traveling wave applicator composed of a conveyor belt running at the geometrical center along the axis of an aluminum waveguide \( (v_z = 8.4 \text{ mm/s}) \). The microwaves were generated by a 5 kW microwave generator (Industrial Microwave Systems, Morrisville, NC) and transported to the curing chamber through aluminum waveguides (Figure 2.6). The curing chamber was outfitted with an electric fan and an electric heater to assist the microwave drying process. The heater was set to maintain an ambient temperature of 25°C in the chamber. The microwave generator was controlled through a data acquisition and control unit (HP34970A, Agilent, Palo Alto, CA) and a software routine written in LabView (National Instruments Corp., Austin, TX). The data acquisition unit and the software monitored and recorded the power output, reflected power and power at the exit of the microwave curing chamber through power diodes (JWF 50D-030+, JFW Industries, Inc., Indianapolis, IN).

All temperature measurements during microwave curing were performed using fiber optic probes and remote infrared temperature measurement (Mullin and Bows, 1993; Goedeken et al., 1991).
The fiber optic probes (FOT-L/10M, Fiso Technologies, Inc., Quebec, Canada) were connected to a multi-channel fiber-optic signal conditioner (Model UMI 4, Fiso Technologies, Quebec, Canada) remotely controlled by FISOCommander software (FISO Technologies, Quebec, Canada) installed on a laptop computer (Dell Inspiron 8500, Dell Computer Corp., Round Rock, TX). The surface temperature of the peanut bed (3 cm thick) was monitored with infrared thermocouples (model OS36-T, OMEGA Engineering, Inc., Stamford, CN) placed at various distances along the waveguide as shown in Table 2.1 and Figure 2.7. The surface temperatures were monitored and recorded using the same software routine that was used to control the generator and to record the power levels.

A Thermovision Alert N infrared camera (FLIR Systems AB, Danderyd, Sweden) was placed at the exit of the microwave curing chamber to monitor the spatial distribution of the peanut bed surface temperature. The camera was controlled by Thermovision Remote software (FLIR Systems AB, Danderyd, Sweden) installed on a laptop computer (Samsung SensPro 520, Samsung, Ridgefield Park, NJ).

Data collection was started simultaneously for all three systems (fiber optic probes, infrared thermocouples and infrared camera) in order to match the temperature measured with the fiber optic probes with the surface temperatures of the peanut bed as measured by the infrared thermocouples and the infrared camera.

Data was collected based on two experimental designs. The first re-used the same samples (both Runner and Virginia type peanuts) in three consecutive passes at two power levels (1.2 and 2 kW) to simulate a three stage microwave curing chamber.
For one sample of Runner type peanuts with an initial moisture content of 29%, the fiber optic probes were mounted such that both the internal temperature of the seed and the temperature at the pod surface were monitored while in the microwave curing chamber. For the other samples, one Runner type (25% initial mc) and one Virginia type (46% initial mc), only the internal seed temperatures were monitored with fiber optic probes in the microwave curing chamber.

The second experimental design used Runner type peanuts to study the effect of six power levels (0.3, 0.6, 0.9, 1.2, 1.5, and 2 kW) and four initial moisture contents (33, 20, 14, and 11%) on seed temperatures, heating rates and moisture content. The initial moisture contents were obtained through conventional drying on air blowers.

The power levels denoted in this paper were set points on the control panel of the software routine. Due to the non-linearity of the data acquisition and control unit, the nominal power levels (or the power output) of the generator were always smaller than the set points. The reflected power was caused by the change of impedance of the waveguide where the microwaves entered the planar applicator as shown in Figure 2.8 (Stuchly and Hamid, 1972; Griffiths, 1999). Although the impedance mismatch was minimized through the special design of the waveguide connector, the reflected power was considered lost and was not considered for calculations.

The internal temperature measurements were performed on 8 to 12 peanut pods in two replicates. The fiber optic probes were placed in pods in previously drilled holes and spread to cover the whole width of the conveyor belt (Figure 2.9).
For each set of data the temperature profiles along the waveguides were determined by averaging all the measurements from the two replicates for the fiber optic probes measurements (internal temperatures) and the infrared thermocouple measurements (surface temperatures). Bulk moisture content of the samples and single seed moisture contents of the peanuts that had mounted fiber optic probes on them were determined using the ASAE standard (ASAE, 2000).

All temperature and moisture content data, with the exception of the infrared images, was processed using Microsoft Excel 97 (Microsoft Corp, Redmond, WA). The data on the spatial distribution of temperatures in the temperature images acquired with the infrared camera was processed with the Thermacam Researcher software package (FLIR Systems AB, Danderyd, Sweden). The analytical solutions to Eqn. [2.17] and [2.26] were implemented using Microsoft Excel 97.
RESULTS AND DISCUSSION

Simulated results

The temperature profiles obtained from equation [2.19] at 6 different power levels, with the parameters estimated for peanuts at 22% moisture content (Table 2.2) are shown in Figure 2.10. The dielectric loss and bulk density were estimated based on measurements at different moisture contents and temperatures (Boldor et al., 2003). The solutions to equations [2.17] and [2.24] do not account for the losses that occur due to convection and radiation, which can be expressed as (Metaxa and Meredith, 1983; Roussy and Pearce, 1995):

\[ q_{\text{conv}} = h A (T - T_{\text{inf}}) \quad \text{[2.35]} \]
\[ q_{\text{rad}} = \sigma T^4 \varepsilon_i A (T^4 - T_0^4) \quad \text{[2.36]} \]

An estimation of these loses at a power level of 2 kW with the parameters given in Table 2.3 is shown in Figure 2.11. These two types of losses manifest themselves throughout the microwave drying process. A third type of energy loss occurs during the drying stage of the process (region II) through evaporative cooling. When all these energy losses are accounted for, the temperature profiles presented in Figure 2.10 would change; in the first region the temperature would reach the equilibrium faster and below the plateau resulting from equation [2.19] and on the second region the temperature would decrease due to cooling effects.

Moisture losses estimated from Eqn. [2.26] are shown in Figure 2.12, based on the parameters represented in Table 2.4. Equation [2.24] assumes that all moisture is lost in vapor form, thus losses due to filtrational flow are not considered (Metaxa and Meredith, 1983; Roussy and Pearce, 1995). Therefore, moisture loss estimated by Eqn. [2.26] is likely higher than reported.
**Experimental results**

An example of temperature distribution as measured with fiber optic probes for 21% mc Runner type peanuts exposed to microwave power at 1.2 kW is shown in Figure 2.13. The temperature profiles are fairly close with the exception of probe one, which had a higher temperature profile than the others. This behavior was consistent with the location the peanut pods on the right-most side of the conveyor belt throughout all the experimental runs (right-edge effect). These peanuts were very close to the waveguide right wall. The parameter with the most influence on the maximum temperature was the magnitude of the electric field (Eqn. [2.19]). The high temperatures recorded for peanuts on the right-most side of the conveyor belt may be explained through abnormally high electric fields along the right wall of the waveguide.

Theoretically, a rectangular waveguide creates a uniform electric field in any cross-sectional area perpendicular on the direction of propagation or the main axis of the waveguide (Figure 2.3). But the existing microwave curing chamber was equipped with side panels on the right side (Figure 2.14) covering openings in the waveguide that are used for cleaning purposes. These openings form a discontinuity on the inside of the waveguide wall, thus generating multiple reflections of the electromagnetic waves. This leads to significant increases in the electric field values along the right wall. This increase in electric field value leads to higher temperatures as determined by Eqn. [2.19].
Experimental design 1.

The internal temperature profiles in the microwave curing chambers for the consecutive passes of Virginia and Runner type peanuts at power levels of 1.2 and 2 kW are shown in Figures 2.15 to 2.18. There was not a significant difference in the temperature profiles between the three consecutive passes (different moisture contents) at the same power level. This behavior is consistent with the Eqn. [2.19] which states that the equilibrium temperature is dependent only on the belt speed, power level, and the dielectric loss of the material. With the assumption that the dielectric loss of the material does not change significantly with temperature, the contribution of the attenuating factor $\alpha$ to the magnitude of the temperature change in Eqn. [2.19] can be considered constant.

While the temperature profiles of the ideal system level off (Figure 2.10), the measured temperatures start decreasing as the peanuts continue their journey in the waveguide. This temperature reduction was caused by radiative, evaporative and convection cooling, not accounted for in the ideal system. Radiative cooling is caused by energy loss to the environment through radiation (Eqn. [2.36]). Convective cooling is caused by the air flow through the peanut bed that carries away the removed moisture (Eqn. [2.35]), while evaporative cooling is an event inherent to all processes in which evaporation takes place. Radiative and convective cooling increase as the temperature increases, therefore peanuts that heat more also cool faster. Since more water is being evaporated at the higher power (Eqn. [2.26]) the evaporative cooling will also increase at the higher power level.

Figures 2.19 and 2.20 show the internal and external temperature distributions of the same pods of the Runner type peanuts. While the internal temperatures follow the same profiles discussed above, the surface temperatures behave differently.
The initial heat-up region and the constant temperature drying region are present for the surface of the pods. However, the surface temperature is much lower than the internal temperatures, and it enters the second region much faster. This behavior is mainly caused by the different dielectric properties of the shells and the fact that the convective cooling has a faster effect on the surface of the pods.

Another major difference between the internal and surface temperatures as measured with the fiber optic probes is that on the surface, after the constant temperature drying region, the temperatures start increasing before settling to a new equilibrium value. There are two possible explanations for this effect. The first one is that all the free water from the shells was removed, and the shells will continue absorbing heat and experience an increase in temperature (entering region III). At the second position of temperature equilibrium water that was more tightly bound will start being vaporized, and the surface experiences a second constant temperature drying region. A second and more plausible explanation is that in this region of the microwave curing chamber the surface temperatures of the pods starts to increase through conduction and radiation from the surrounding peanuts. While the infrared sensors measure the surface temperature of the whole peanut bed, the fiber optic probes were placed in the middle of the bed, where they were more affected by the heat coming from the surrounding peanut pods. This behavior of the temperature profiles at the pod surface in the middle of the peanut bed is very intriguing and deserves further investigation.

The reduction in moisture content for each of the three passes is more significant at higher moisture content and at the higher power level (Table 2.5 and 2.6). Virginia type peanuts (initially at 45.2% mc) exposed to a microwave energy at 1.2 kW experienced a total reduction in moisture content of 26.5%, or an average of 8.8% reduction per pass.
The same peanuts exposed to microwave energy at 2 kW experienced a reduction of 32.9%, or an average of 11% reduction per pass (Table 2.5). Runner type peanuts with an initial moisture content of 25% experienced a total reduction in moisture content of 32.3% at 1.2 kW, or an average of 10.8% per pass. At a power level of 2 kW, the moisture content was reduced by a total of 39%, or an average of 13% per pass (Table 2.6).

Examples of spatial surface temperature distributions at the exit of the microwave drying chamber, as determined with the infrared camera are shown in Figures 2.21 and 2.22. The average temperature values and their standard deviations in the regions delineated by the rectangles in each image are shown in Table 2.7. For both Virginia and Runners type peanuts the surface temperature increased with increasing power level at the same moisture content. The differences registered between the Virginia type peanuts and the Runner type peanuts are mainly caused by the differences in moisture contents between the two varieties used in this study (45% initial mc for Virginia, and 25% initial mc for Runner type).

**Experimental design 2.**

The temperature profiles of peanuts during microwave drying at the same initial moisture contents and six power levels are shown in Figures 2.23 to 2.26. In this experimental design the temperature profiles approximate the profiles obtained in Figure 2.10 from Eqn. [2.19]. At the same moisture content, assuming a constant belt speed and dielectric constant, the temperature profile was determined solely by the power level. Radiative, evaporative and convective cooling was also observed in this experimental design, having a larger influence on the temperature profiles at the higher power levels.
At the higher power levels, the higher temperatures cause larger convective and radiative cooling (Eqn. [2.35] and [2.36]), as well as more evaporative cooling.

The standard deviations of the measurements are plotted in Figures 2.27 to 2.30. In general a higher power level also corresponds to a larger standard deviation, which was expected considering the higher overall temperatures and the right-edge effect previously discussed.

A plot of internal temperature versus the surface temperatures at the six power levels tested in specific location along the microwave curing chamber for 11% mc peanuts is shown in Figure 2.31. The linear relationships between the internal and surface temperatures (Tables 2.8 to 2.11) have extremely good correlations ($r^2 > 0.95$) and are useful for process control purposes. This linear correlation is much better at the lower moisture contents ($r^2 > 0.99$), while at the higher moisture contents, the linear regressions are better for sensors that are placed closer to the peanut feed input. A temperature feedback control mechanism implemented using these linear relationships could be very efficient in adjusting the power level to maintain a desired temperature profile inside the microwave curing chamber.

Plots of the first derivative of temperature versus distance (Figures 2.32 to 2.35) show that the maximum temperature (derivative is zero) is at the same location for the same moisture content, independent of the power level. The same observation is true for the maximum of the derivative (the maximum rate of temperature increase). These locations of the maximum temperature and of the maximum rate of temperature increase are important for process control purposes. Placement of surface temperature sensors at these locations would maximize the efficiency a feedback control system.
Using the relationships in Tables 2.8 to 2.11, the control system can adjust the power input to maintain a constant maximum temperature and rate of temperature increase.

The moisture loss at the 6 power levels for different initial moisture contents is presented in Table 2.12. In general, the higher power levels removed more moisture than the lower power levels, which is consistent with the analytical solution (Eqn. [2.26]) to Eqn. [2.24] for the second region of the microwave drying process.

Plots of the temperature profiles at the same power level and the four different initial moisture contents tested are shown in Figures 2.36 to 2.41. The variability in temperature profiles in general decreased with the moisture content (Figures 2.42 to 2.47). The maximum temperatures are the same at all moisture contents and confirm the fact that they depend only on the power level and the belt speed (Eqn. [2.19]). However, there are two major differences between the temperature profiles at the same power level, the first one in region I (initial heat-up region) and the second one in region II (constant temperature drying region).

For the constant temperature drying region, the energy loss caused by radiative, convective and evaporative cooling is larger for the higher moisture contents at the same power level. With the assumption that the radiant emissivity of the peanuts is relatively constant at all moisture contents, radiative cooling can be ruled out as a major factor influencing the temperature decrease. With the volumetric heating of the microwaves, the convective cooling at the surface of the peanuts depends only on the temperature and the surface area exposed to the air flow, which are both constants. These imply that the main driving force in the cooling process at the same power level is evaporative cooling. The higher the moisture content, the more water is being evaporated and the larger the cooling effect.
In the initial heat-up region, plots of the first derivative of temperatures with respect to distance (Figures 2.48 to 2.53) show that the location of the maximum temperatures (where the derivative is zero) changes with the moisture content. As the moisture content decreases, the location of the maximum temperature moves further from the entrance to the microwave drying chamber. Even though the maximum temperature is the same for the different moisture contents, the time (or distance in the waveguide) to get to that maximum temperature is longer as the moisture content decreases. The same observation is true for the location of the maximum rate of temperature increase (where the derivative is at its peak). This behavior is again consistent with Eqn. [2.19], where the attenuation factor \( \alpha \) is dependent on the dielectric loss \( \varepsilon'' \), which is mainly dependent on moisture content. The higher the moisture content, the higher the attenuation factor (Eqn. [2.7]) and the faster the temperature increase.

This particularity of the heat-up region of the peanut microwave drying process can be used in designing a feed-forward control mechanism for the peanut curing process. An infrared camera is employed to measure the surface temperature distribution in the heat-up region. The location of the maximum temperature and the location of the maximum rate of temperature change are determined and the moisture content of the peanuts at the exit of the microwave curing chamber can be estimated. This would determine the number of passes required to obtain the desired final moisture content.

This feed forward mechanism can be associated with the feedback control system previously described and with other sensors that monitor other process variables (moisture, ambient temperature, air humidity etc.) to implement a very effective feed forward/feedback control system that would account for all the variables in the process.
The distribution of the surface temperatures at the exit of the microwave curing chamber for all moisture contents and power levels used in this experimental design is shown in Figures 2.54 to 2.57. The average temperature values, with their respective standard deviations, of the regions delineated by rectangles are listed in Table 2.13. The average temperature values and their standard deviations increased with increasing power level. The average temperature values and their standard deviations also increased with a decrease in moisture content. This effect was more visible at the higher power levels than at the lower power levels. This means that the drier the peanuts are, the hotter their surface becomes at the exit of the microwave applicator. While the surface temperatures at the beginning of the process increase proportionally with the moisture content, toward the end of the process the proportionality is reversed. A similar effect was observed on both the heat flux and the convective heat transfer coefficient during immersion frying in oil (Hubbard and Farkas, 2000). While at the beginning of the frying process both the heat flux and the convective heat transfer coefficients were proportional with the oil temperature, toward the end of the process the proportionality was reversed. Hubbard and Farkas (2000) explained this behavior through the different rates of drying that occur at the different oil temperatures and the total amount of water available for drying. Since the rate of drying in microwave is also different for the different initial moisture contents, there will be less moisture toward the end of the microwave drying process that will be converted into heat at the lower initial moisture contents. The lower the initial moisture content, the smaller the rate of drying and more moisture will be available toward the end of the process.
CONCLUSIONS

The internal and surface temperature distribution was determined for farmer stock peanuts undergoing drying in a traveling wave microwave applicator. The transport phenomena equations developed for microwave assisted drying in multimode cavities were successfully adapted to estimate the temperature profiles and moisture losses during continuous microwave drying.

The experimental results confirmed the theoretical predictions that the temperature profiles were determined only by the power level at the same moisture content and only by the moisture content at the same power level. At the same moisture contents, the maximum temperatures and maximum rates of temperature increase occurred in the same time at the same location in the microwave applicator at all power levels tested. The negligible effect of temperature on the dielectric properties of the farmer stock peanuts confirmed previously performed measurements (Boldor et al., 2003). At the same power levels, the maximum temperatures were the same for all moisture contents tested, but the rate at which that maximum was reached increased with the increasing moisture contents. This result shows the dependence of the dielectric loss and the attenuation constant $\alpha$ on the moisture content of the peanuts, an effect that was also previously observed (Boldor et al., 2003).

A very good correlation was determined between the surface temperatures measured using infrared technology and the internal temperatures measured using fiber optic probes. These encouraging results open up the possibility of accurate control of the internal temperatures through a feedback mechanism that uses the surface temperature as the measured variable and the power level as the control variable.
A combination of computer assisted infrared imaging and feedback control mechanisms can use the results of this study to determine not only the maximum temperature, but also its location and the location of the maximum rate of temperature increase. Using the equations presented in this paper, a more advanced feed forward/feedback control system can be developed that will more accurately control the microwave peanut drying process.

The measured moisture losses during microwave drying were also in line with theoretical estimations. The leveling effect of microwaves on moisture content was also confirmed through measurements, and the total moisture reduction in consecutive passes at the same power level was determined.
LIST OF SYMBOLS

a, b - waveguide height and width; m
A_Wg - cross sectional area of the waveguide; m²
A - surface area of a peanut pod; m²
c - speed of light; 3x10⁸ m/s
C_p - specific heat; J/kg K
E, E₀, E_rms, E₀rms - electric field (general, initial, r.m.s., initial r.m.s.); V/m
f - frequency; Hz
h - convective heat transfer coefficient; W/m²K
I - intensity of the electromagnetic field; W/m²
j = (-1)¹/₂ - imaginary part of a complex number
L_h - latent heat of vaporization; J/kg
mc - moisture content dry basis; %
M, M_L, M₀ - moisture content (general, liquid, initial); % db
P_in - power input into the system; W
ΔP - power absorbed per unit volume; W/m³
q_conv, q_rad - heat losses (convective, radiative); W
t - time; s
T, T₀, T_inf - temperature (general, initial, environment); K, °C
z - distance coordinate; m
v_z - belt speed; m/s
w - height of dielectric material on belt; m
α - attenuation constant; m⁻¹, dB/m
α_T - thermal diffusivity; m²/s
ε₀ - dielectric constant of the vacuum = 8.854 10⁻¹² Far/m
ε* - relative complex permittivity or relative complex dielectric constant; -
ε' - relative electric constant or storage factor; -
ε", ε₀" - relative dielectric loss or loss factor (general, initial); -
ε_i - radiant emissivity; -
ε_v - ratio of vapor flow to total moisture flow; -
λ₀, λₜ - wavelength (free space, waveguide); m
µ₀, µ' - magnetic permeability (free space, relative); N/A²
ρ - bulk density; kg/m³
σ - conductivity; siemen/m
σ_T - Stefan - Boltzmann's constant; W/m²K⁴
ω - angular frequency;
REFERENCES


Table 2.1. Locations of the infrared thermocouples.

<table>
<thead>
<tr>
<th></th>
<th>Distance to sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(inch)</td>
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<tr>
<td>Waveguide entrance</td>
<td>0</td>
</tr>
<tr>
<td>Sensor 1</td>
<td>18.75</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>21.75</td>
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<tr>
<td>Sensor 3</td>
<td>38.75</td>
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<tr>
<td>Sensor 4</td>
<td>41.75</td>
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<td>Sensor 5</td>
<td>44.75</td>
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<tr>
<td>Sensor 6</td>
<td>65.75</td>
</tr>
<tr>
<td>Sensor 7</td>
<td>68.75</td>
</tr>
<tr>
<td>Sensor 8</td>
<td>71.75</td>
</tr>
<tr>
<td>Sensor 9</td>
<td>83.75</td>
</tr>
<tr>
<td>Sensor 10</td>
<td>86.75</td>
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<tr>
<td>Sensor 11</td>
<td>89.75</td>
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<td>Sensor 12</td>
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<td>Sensor 13</td>
<td>101.75</td>
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<td>Sensor 14</td>
<td>104.75</td>
</tr>
<tr>
<td>Sensor 15</td>
<td>113.75</td>
</tr>
<tr>
<td>Sensor 16</td>
<td>116.75</td>
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<tr>
<td>Waveguide exit</td>
<td>129</td>
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<tr>
<td>End</td>
<td>164.25</td>
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Table 2.2. Parameters for temperature profiles in Eqn. [2.19] and Figure 2.10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>293 K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1 l/m</td>
</tr>
<tr>
<td>$v_z$</td>
<td>0.0085 m/s</td>
</tr>
<tr>
<td>$f^*$</td>
<td>915 MHz</td>
</tr>
<tr>
<td>$\varepsilon''$</td>
<td>0.7</td>
</tr>
<tr>
<td>$\rho$</td>
<td>400 Kg/m$^3$</td>
</tr>
<tr>
<td>$C_p$</td>
<td>2800 J/Kg K</td>
</tr>
<tr>
<td>$A_{wg}$</td>
<td>0.0268 m$^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>3.0E+08 m/s</td>
</tr>
</tbody>
</table>

Table 2.3. Parameters for convective and radiative losses in Eqns. [2.35], [2.36] and Figure 2.11.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>20 W/m$^2$K</td>
</tr>
<tr>
<td>$A_s$</td>
<td>0.0015 m$^2$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>293 K</td>
</tr>
<tr>
<td>$\sigma_f$</td>
<td>5.67E-08 W/m$^2$K$^4$</td>
</tr>
<tr>
<td>$\varepsilon_i$</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 2.4. Parameters for moisture losses in Eqn. [2.26] and Figure 2.12.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>1 m$^{-1}$</td>
</tr>
<tr>
<td>$v_z$</td>
<td>0.0085 m/s</td>
</tr>
<tr>
<td>$f^*$</td>
<td>915 MHz</td>
</tr>
<tr>
<td>$\varepsilon''$</td>
<td>0.7</td>
</tr>
<tr>
<td>$\rho$</td>
<td>400 Kg/m$^3$</td>
</tr>
<tr>
<td>$A_{wg}$</td>
<td>0.026784 m$^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>3.0E+08 m/s</td>
</tr>
<tr>
<td>$M_0$</td>
<td>0.22</td>
</tr>
<tr>
<td>$L_h$</td>
<td>2100000 J/Kg</td>
</tr>
<tr>
<td>Start point</td>
<td>1 m</td>
</tr>
</tbody>
</table>
Table 2.5. Moisture contents (% db) for Virginia type peanuts in three consecutive passes.

<table>
<thead>
<tr>
<th>Power level</th>
<th>Pass 1</th>
<th></th>
<th></th>
<th>Pass 2</th>
<th></th>
<th></th>
<th>Pass 3</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>% Reduction</td>
<td>Before</td>
<td>After</td>
<td>% Reduction</td>
<td>Before</td>
<td>After</td>
<td>% Reduction</td>
</tr>
<tr>
<td>1.2 kW</td>
<td>45.2</td>
<td>42.4</td>
<td>6.2</td>
<td>41.6</td>
<td>38</td>
<td>8.6</td>
<td>37.2</td>
<td>33.2</td>
<td>10.8</td>
</tr>
<tr>
<td>2 kW</td>
<td>47.4</td>
<td>42.9</td>
<td>9.5</td>
<td>46.5</td>
<td>39.4</td>
<td>15.3</td>
<td>39.2</td>
<td>31.8</td>
<td>18.9</td>
</tr>
</tbody>
</table>

Table 2.6. Moisture contents (% db) for Runner type peanuts in three consecutive passes.

<table>
<thead>
<tr>
<th>Power level</th>
<th>Pass 1</th>
<th></th>
<th></th>
<th>Pass 2</th>
<th></th>
<th></th>
<th>Pass 3</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>% Reduction</td>
<td>Before</td>
<td>After</td>
<td>% Reduction</td>
<td>Before</td>
<td>After</td>
<td>% Reduction</td>
</tr>
<tr>
<td>1.2 kW</td>
<td>25.7</td>
<td>22.5</td>
<td>12.5</td>
<td>22.8</td>
<td>20.3</td>
<td>11.0</td>
<td>19.7</td>
<td>17.4</td>
<td>11.7</td>
</tr>
<tr>
<td>2 kW</td>
<td>24.6</td>
<td>21.5</td>
<td>12.6</td>
<td>20.3</td>
<td>19.1</td>
<td>5.9</td>
<td>16.9</td>
<td>15</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Table 2.7. Surface temperature distribution for Virginia and Runners type peanuts at the exit from the drying tunnel at 2 power levels and three initial moisture contents.

<table>
<thead>
<tr>
<th>Power level</th>
<th>Initial mc (% db)</th>
<th>Virginia</th>
<th>Runners</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial mc (% db)</td>
<td>45.2</td>
</tr>
<tr>
<td>1.2 kW</td>
<td>Temp (°C)</td>
<td>29.8</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>Std (°C)</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>2 kW</td>
<td>Initial mc (% db)</td>
<td>47.4</td>
<td>46.5</td>
</tr>
<tr>
<td></td>
<td>Temp (°C)</td>
<td>32.6</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Std (°C)</td>
<td>3.1</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Table 2.8. Relationship between surface and internal temperatures for 11% mc Runner type peanuts.

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>Equation</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide entrance: 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor 1</td>
<td>$y = 1.35x - 4.67$</td>
<td>0.998</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>$y = 1.39x - 6.18$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>$y = 1.73x - 13.78$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>$y = 1.78x - 14.22$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>$y = 1.76x - 15.25$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 6</td>
<td>$y = 1.83x - 17.29$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 7</td>
<td>$y = 1.80x - 17.10$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 8</td>
<td>$y = 1.85x - 18.21$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 9</td>
<td>$y = 1.76x - 15.69$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 10</td>
<td>$y = 1.60x - 11.96$</td>
<td>0.998</td>
</tr>
<tr>
<td>Sensor 11</td>
<td>$y = 1.70x - 13.81$</td>
<td>0.999</td>
</tr>
<tr>
<td>Sensor 12</td>
<td>$y = 1.58x - 10.81$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 13</td>
<td>$y = 1.62x - 10.77$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 14</td>
<td>$y = 1.67x - 11.82$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 15</td>
<td>$y = 1.61x - 10.47$</td>
<td>0.995</td>
</tr>
<tr>
<td>Sensor 16</td>
<td>$y = 1.53x - 8.17$</td>
<td>0.994</td>
</tr>
</tbody>
</table>

Table 2.9. Relationship between surface and internal temperatures for 14% mc Runner type peanuts.

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>Equation</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide entrance: 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor 1</td>
<td>$y = 1.35x - 2.61$</td>
<td>0.995</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>$y = 1.39x - 4.01$</td>
<td>0.996</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>$y = 1.81x - 13.59$</td>
<td>0.996</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>$y = 1.81x - 13.9$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>$y = 1.80x - 14.02$</td>
<td>0.994</td>
</tr>
<tr>
<td>Sensor 6</td>
<td>$y = 1.99x - 19.51$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 7</td>
<td>$y = 1.95x - 19.15$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 8</td>
<td>$y = 1.99x - 19.76$</td>
<td>0.994</td>
</tr>
<tr>
<td>Sensor 9</td>
<td>$y = 1.96x - 19.21$</td>
<td>0.997</td>
</tr>
<tr>
<td>Sensor 10</td>
<td>$y = 1.78x - 14.91$</td>
<td>0.996</td>
</tr>
<tr>
<td>Sensor 11</td>
<td>$y = 1.84x - 15.66$</td>
<td>0.993</td>
</tr>
<tr>
<td>Sensor 12</td>
<td>$y = 1.75x - 13.53$</td>
<td>0.994</td>
</tr>
<tr>
<td>Sensor 13</td>
<td>$y = 1.77x - 13.17$</td>
<td>0.995</td>
</tr>
<tr>
<td>Sensor 14</td>
<td>$y = 1.83x - 14.46$</td>
<td>0.990</td>
</tr>
<tr>
<td>Sensor 15</td>
<td>$y = 1.82x - 14.41$</td>
<td>0.991</td>
</tr>
<tr>
<td>Sensor 16</td>
<td>$y = 1.70x - 11.3$</td>
<td>0.993</td>
</tr>
</tbody>
</table>
Table 2.10. Relationship between surface and internal temperatures for 21% mc Runner type peanuts.

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>Equation</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide entrance: 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor 1</td>
<td>( y = 1.44x - 5.81 )</td>
<td>0.981</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>( y = 1.49x - 7.28 )</td>
<td>0.984</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>( y = 1.77x - 13.76 )</td>
<td>0.988</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>( y = 1.80x - 14.70 )</td>
<td>0.988</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>( y = 1.84x - 16.26 )</td>
<td>0.989</td>
</tr>
<tr>
<td>Sensor 6</td>
<td>( y = 1.93x - 18.73 )</td>
<td>0.988</td>
</tr>
<tr>
<td>Sensor 7</td>
<td>( y = 1.91x - 18.76 )</td>
<td>0.989</td>
</tr>
<tr>
<td>Sensor 8</td>
<td>( y = 2.01x - 20.94 )</td>
<td>0.989</td>
</tr>
<tr>
<td>Sensor 9</td>
<td>( y = 1.85x - 16.93 )</td>
<td>0.989</td>
</tr>
<tr>
<td>Sensor 10</td>
<td>( y = 1.75x - 14.64 )</td>
<td>0.990</td>
</tr>
<tr>
<td>Sensor 11</td>
<td>( y = 1.81x - 15.55 )</td>
<td>0.991</td>
</tr>
<tr>
<td>Sensor 12</td>
<td>( y = 1.69x - 12.83 )</td>
<td>0.988</td>
</tr>
<tr>
<td>Sensor 13</td>
<td>( y = 1.76x - 13.64 )</td>
<td>0.990</td>
</tr>
<tr>
<td>Sensor 14</td>
<td>( y = 1.82x - 15.43 )</td>
<td>0.991</td>
</tr>
<tr>
<td>Sensor 15</td>
<td>( y = 1.82x - 15.69 )</td>
<td>0.991</td>
</tr>
<tr>
<td>Sensor 16</td>
<td>( y = 1.74x - 13.23 )</td>
<td>0.992</td>
</tr>
</tbody>
</table>

Table 2.11. Relationship between surface and internal temperatures for 33% mc Runner type peanuts.

<table>
<thead>
<tr>
<th>Location (m)</th>
<th>Equation</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide entrance: 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor 1</td>
<td>( y = 1.77x - 12.38 )</td>
<td>0.993</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>( y = 1.81x - 13.52 )</td>
<td>0.990</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>( y = 2.01x - 17.44 )</td>
<td>0.972</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>( y = 2.02x - 17.60 )</td>
<td>0.971</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>( y = 2.02x - 18.09 )</td>
<td>0.967</td>
</tr>
<tr>
<td>Sensor 6</td>
<td>( y = 2.13x - 21.11 )</td>
<td>0.959</td>
</tr>
<tr>
<td>Sensor 7</td>
<td>( y = 2.09x - 20.74 )</td>
<td>0.958</td>
</tr>
<tr>
<td>Sensor 8</td>
<td>( y = 2.15x - 22.02 )</td>
<td>0.956</td>
</tr>
<tr>
<td>Sensor 9</td>
<td>( y = 2.02x - 18.89 )</td>
<td>0.949</td>
</tr>
<tr>
<td>Sensor 10</td>
<td>( y = 1.88x - 15.38 )</td>
<td>0.953</td>
</tr>
<tr>
<td>Sensor 11</td>
<td>( y = 1.94x - 16.41 )</td>
<td>0.950</td>
</tr>
<tr>
<td>Sensor 12</td>
<td>( y = 1.77x - 12.60 )</td>
<td>0.947</td>
</tr>
<tr>
<td>Sensor 13</td>
<td>( y = 1.87x - 14.31 )</td>
<td>0.941</td>
</tr>
<tr>
<td>Sensor 14</td>
<td>( y = 1.90x - 15.32 )</td>
<td>0.940</td>
</tr>
<tr>
<td>Sensor 15</td>
<td>( y = 1.82x - 13.45 )</td>
<td>0.933</td>
</tr>
<tr>
<td>Sensor 16</td>
<td>( y = 1.69x - 9.59 )</td>
<td>0.933</td>
</tr>
</tbody>
</table>
Table 2.12. Moisture losses at 6 power levels.

<table>
<thead>
<tr>
<th>Power level (kW)</th>
<th>0.3</th>
<th>0.6</th>
<th>0.9</th>
<th>1.2</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before (%)</td>
<td>33.02</td>
<td>33.07</td>
<td>34.30</td>
<td>33.04</td>
<td>32.86</td>
<td>32.10</td>
</tr>
<tr>
<td>After (%)</td>
<td>30.66</td>
<td>30.46</td>
<td>30.30</td>
<td>30.15</td>
<td>30.04</td>
<td>26.96</td>
</tr>
<tr>
<td>% reduction</td>
<td>7.1</td>
<td>7.9</td>
<td>11.7</td>
<td>8.7</td>
<td>8.6</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power level (kW)</th>
<th>0.3</th>
<th>0.6</th>
<th>0.9</th>
<th>1.2</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before (%)</td>
<td>20.79</td>
<td>20.56</td>
<td>21.55</td>
<td>19.86</td>
<td>20.74</td>
<td>20.70</td>
</tr>
<tr>
<td>After (%)</td>
<td>20.21</td>
<td>19.57</td>
<td>18.80</td>
<td>18.14</td>
<td>18.64</td>
<td>17.91</td>
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<tr>
<td>% reduction</td>
<td>2.8</td>
<td>4.8</td>
<td>12.8</td>
<td>8.6</td>
<td>10.1</td>
<td>13.5</td>
</tr>
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</table>

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<thead>
<tr>
<th>Power level (kW)</th>
<th>0.3</th>
<th>0.6</th>
<th>0.9</th>
<th>1.2</th>
<th>1.5</th>
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<tr>
<td>After (%)</td>
<td>14.21</td>
<td>13.68</td>
<td>13.74</td>
<td>13.48</td>
<td>12.82</td>
<td>12.28</td>
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<tr>
<td>% reduction</td>
<td>7.8</td>
<td>6.5</td>
<td>6.1</td>
<td>4.1</td>
<td>10.1</td>
<td>14.6</td>
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<table>
<thead>
<tr>
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<th>0.3</th>
<th>0.6</th>
<th>0.9</th>
<th>1.2</th>
<th>1.5</th>
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<tr>
<td>Before (%)</td>
<td>11.01</td>
<td>10.52</td>
<td>10.48</td>
<td>10.40</td>
<td>10.96</td>
<td>11.01</td>
</tr>
<tr>
<td>% reduction</td>
<td>8.4</td>
<td>6.3</td>
<td>5.2</td>
<td>7.2</td>
<td>14.2</td>
<td>15.9</td>
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Table 2.13. Average surface temperature (°C) and standard deviation (°C) for Runner type peanuts at 4 initial moisture contents undergoing drying at 6 different power levels.

<table>
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<tr>
<th>Average temperature (°C)</th>
<th>Standard deviation (°C)</th>
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<tr>
<td>( m_{cin} )</td>
<td>Power</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>2 kW</td>
<td>34.6</td>
</tr>
<tr>
<td>1.5 kW</td>
<td>30.5</td>
</tr>
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<td>1.2 kW</td>
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<tr>
<td>0.9 kW</td>
<td>27.2</td>
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<td>0.6 kW</td>
<td>24.8</td>
</tr>
<tr>
<td>0.3 kW</td>
<td>23.1</td>
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</table>
FIGURE CAPTIONS

Figure 2.1 Mechanisms of ionic interaction (Zhong, 2001).

Figure 2.2 Mechanisms of dipolar interaction (Zhong 2001).

Figure 2.3 Distribution of the electric field in a transversal section of the TE10 waveguide in the presence of a lossy dielectric at the center of the waveguide. Wave is propagating into the paper. a – waveguide height, b – waveguide width, w – height of dielectric load.

Figure 2.4 Temperature distribution during microwave drying. The time coordinate can be changed into distance for a belt moving at constant speed (Metaxa and Meredith, 1983).

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Figure 2.17 Internal temperatures (lines) and surface temperatures (symbols) of Virginia type peanuts at 3 initial mc undergoing drying at 1.2 kW.

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Figure 2.55 Surface temperature distribution at the end of drying of Runner type peanuts at 14% initial mc and 6 power levels: a) 0.3 kW, b) 0.6 kW, c) 0.9 kW, d) 1.2 kW, e) 1.5 kW, f) 2.0 kW.

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Manuscript 3. Control of Continuous Microwave Drying Process of Farmer Stock Peanuts

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ABSTRACT

Feedback control of the continuous microwave drying of farmer stock peanuts (*Arachis hypogaea* L.) of different varieties and initial moisture contents was investigated using the peanut's surface temperature as the controlled variable and microwave power level as the manipulated variable. Process parameters were determined using process reaction curves, and a PI (proportional, integral) controller was implemented in a software routine that controlled the microwave generator's power level. The servo scenario (set point change) was simulated in software to determine the optimum tuning parameters of the PI controller. The potential for a more advanced control of the process based on complete surface temperature distribution measured with an infrared camera placed at the location of maximum surface temperature was evaluated.

Keywords: *Arachis hypogaea* L., peanuts, drying, control, continuous, microwave, temperature, distribution.
INTRODUCTION

Process control methods are widely used in food industry for quality assurance purposes. The characteristics and requirements for various food processing operations are described by Mittal (1996) and McFarlane (1995). For peanut processing, a complex fuzzy control system for the roasting process, based in part on theoretical modeling (Landman et al., 1994) was developed by Davidson et al. (1999).

The study reported here focuses on the process control for continuous microwave drying of peanuts, where the microwave energy delivered to the dryer can be changed as needed. Microwave energy is increasingly used in food processing operations. The utilization of microwave energy in heating and drying applications has been addressed in many books (Decareau, 1985; Metaxa and Meredith, 1983). New microwave cavity designs that eliminate temperature non-uniformity commonly seen in multimode microwave ovens are being developed for food processing applications. These designs, such as focusing structures and traveling wave (or planar) applicators, are currently used for heating of fluids (Coronel et al., 2003) and drying and blanching of various agricultural commodities (Rausch, 2002; Katz, 2002; Boldor et al. 2003). In the drying process, the most important processing parameter is product temperature. Due to the inherent nature of microwaves, traditional temperature sensors, such as thermocouples, cannot be used in the presence of microwave fields. Ramaswamy et al. (1991) developed a shielded thermocouple to be used for feedback control of heating in domestic microwave oven. These are useful when implementing model-based temperature control in microwave-convection heating systems (Sanchez et al., 2000).
While shielded thermocouples can be very useful in microwave heating of fluids, they are rendered useless in continuous drying of agricultural commodities, where continuous monitoring of internal temperatures of seeds is impossible even when using shielded thermocouples or fiber optic temperature probes. However, the correlation between the internal temperatures of peanuts and the surface temperature of the peanut bed (Table 3.1, Boldor et al., 2003) makes remote temperature measurement of peanut bed surfaces a feasible method of peanut temperature measurement for process control purposes. Remote surface temperature measurement are performed using either infrared thermocouples inserted at critical locations along the microwave waveguide (Figure 3.1, Boldor et al., 2003), or a properly calibrated infrared imaging system (Goedeken et al., 1991; Schelssinger, 1995).

**Theoretical considerations**

For process control purposes, the transient behavior of the physical system needs to be determined. The transient response of a first or second order process with dead time (Eqn. [3.1] and [3.2]) can be represented in the Laplace domain using the following transfer functions (Marlin, 2000):

\[
G_p(s) = \frac{Y(s)}{X(s)} = \frac{K_p e^{-\theta s}}{\tau_p s + 1} \quad [3.1]
\]

\[
G_p(s) = \frac{Y(s)}{X(s)} = \frac{K_p e^{-\theta s}}{\tau_p^2 s^2 + 2\xi \tau_p s + 1} \quad [3.2]
\]
Process reaction curves are used to determine $K_p$, $\theta$, and $\tau_p$. They are determined as follows:

1. Allow the process to reach steady state.
2. Introduce a single step change in the input variable.
3. Collect input and output response data until the process again reaches steady state.
4. Perform the graphical process reaction curve calculations. The process gain ($K_p$) is the ratio of the magnitude change of the output to the magnitude change of the input. The time constant $\tau_p$ and dead time $\theta$ are determined according to:

   \[ \tau_p = 1.5 \left( t_2 - t_1 \right) \]  \hspace{1cm} [3.3]
   \[ \theta = t_2 - \tau_p \]  \hspace{1cm} [3.4]

   Where:
   
   $t_1$ - time at which the output reaches 28% of the final steady state value
   
   $t_2$ - time at which the output reaches 63% of the final steady state value.

5. Return to the original input value to make sure that the output returns to original steady state.

The major advantage of using the process reaction curve in determination of the transfer function is that the transfer functions of the sensor and the final control element are included in the model. The disadvantage is that the method is limited to first and second order systems with dead time.

One of the most widely used process control method is feedback control using a PID (proportional, integral, derivative) algorithm. In this control method, the response of the controller is proportional with the difference between the desired value of the controlled variable (set point SP) and the measured value of the controlled variable (CV).
Schematically, a feedback control loop is represented in Figure 3.2 (Marlin, 2000). The transfer function of the PID controller can be written as:

\[
G_c(s) = K_c \left(1 + \frac{1}{\tau_i s + 1} + \tau_d s \right)
\]  \[3.5\]

Once the transfer function of the open loop (the system without the controller) is determined, the transfer function of the closed loop feedback system can be determined using the following formula:

\[
\frac{Y(s)}{X(s)} = \frac{G_p(s)}{1 + G_p(s)G_c(s)}
\]  \[3.6\]

For determination of the control parameters \(K_c, \tau_i,\) and \(\tau_d,\) several methods exists in literature, out of which the most commonly used ones are Ciancone (Ciancone and Marlin, 1992), Lopez (Lopez \textit{et al.}, 1969), and Ziegler-Nichols (Ziegler and Nichols, 1942). The parameters determined using these methods are only starting points, afterward the control loops needs to be fine tuned such that either the integral square of error (ISE) or absolute value of error (IAE) are minimized (Marlin, 2000):

\[
\text{ISE} = \int_0^\infty (SP(t) - CV(t))^2 \, dt
\]  \[3.7\]

\[
\text{IAE} = \int_0^\infty |SP(t) - CV(t)| \, dt
\]  \[3.8\]

In the continuous microwave drying of peanuts, Boldor \textit{et al.} (2003) determined not only the relationship between the temperature of the peanuts and the surface temperature of the peanut bed, but also the locations of the maximum temperature and of the maximum rate of temperature increase, as shown in Figure 3.3.
The location of the maximum temperature (zero derivative) and of the maximum rate of temperature increase (maximum derivative) is determined by the moisture content of the peanuts entering the microwave curing chamber. Therefore, the relationship between the temperature of the peanut bed surface and the internal temperature of the peanut pods are most useful when they are evaluated at the locations of maximum temperatures and maximum rates of temperature increases. These locations are suitable for installation of surface temperature monitoring equipment such as infrared pyrometers, infrared thermocouples or thermal imaging equipment.

In this study, for process control purposes the surface temperature of the peanut bed (CV) was measured with infrared thermocouples; and a feedback control mechanism adjusted the microwave power level (MV) to maintain the surface temperature at the desired set point (SP).

Infrared thermocouples measured an average temperature of a fairly large surface area (a circle of 3 cm diameter). A thermal imager (or infrared camera) would be able to measure the complete surface temperature distribution, determining both the temperature at a specific location as well as the location of the maximum temperature. This data could be used to create a combination of feedback loop (described above) and a feed forward control method that would determine the number of passes required to obtain desired final moisture content.
MATERIALS AND METHODS

Field dried peanuts (Runner and Virginia type) at moisture contents ranging from 22 to 52% (dry basis) were used in this study. Samples were shipped from USDA-ARS Peanut National Laboratory in Dawson, Georgia to the Department of Food Science at North Carolina State University during the months of September - November of 2002.

The microwave system included a planar applicator (Industrial Microwave Systems, Morrisville, NC) that consisted of a conveyor belt running at the geometrical center of an aluminum waveguide. Microwaves were generated by a 5 kW microwave generator (Industrial Microwave Systems, Morrisville, NC) and transported to the applicator through aluminum waveguides. The curing chamber was outfitted with an electrical fan to assist the microwave drying process. Air flow temperature was maintained at 25°C through an electrical heater.

Surface temperature sensors were based on infrared technology (Mullin and Bows, 1993, Goedeken et al., 1991). Infrared thermocouples (model OS36-T, OMEGA Engineering, Inc., Stamford, CN) were placed at various distances along the waveguide as shown in Table 3.1 and Figure 3.1 (Boldor et al., 2003). The surface temperatures were monitored and recorded through a data acquisition and control unit (HP34970A, Agilent, Palo Alto, CA) and a software routine written in LabView (National Instruments Corp., Austin, TX). The same data acquisition and control unit and software routine were used to control the microwave generator and to monitor and record the power output, reflected power and power at the exit of the microwave curing chamber through power diodes (JWF 50D-030+, JFW Industries, Inc., Indianapolis, IN).
The process model \((K_p, \tau_p, \theta)\) was determined using empirical identification based on process reaction curves, graphical method II (Marlin, 2000) for each peanut variety, initial moisture content and group of sensors. The transient response of the process was obtained through analysis of the step response when the power level was changed from 1.2 to 2 kW. Due to the slight non-linearity of the HP unit voltage output and the actual current generating the microwaves, the nominal power levels (or the power output) of the generator were always slightly smaller than the set points.

For each peanut variety and moisture content, the transient response of the system was obtained by performing an average of 9 replicates of the process reaction curves. Bulk moisture contents of the samples were determined using the USDA standard (ASAE, 2000). All temperature and moisture content data was analyzed using Microsoft Excel (Microsoft Corp, Redmond, WA).

The feedback control routine was developed in Labview, using a simulation of the first order process with dead-time. Once the optimum control parameters were determined, the control routine was added to the master Labview program.
RESULTS AND DISCUSSIONS

The process reaction curves determined for all temperature sensors at the locations listed in Table 3.1 are shown in Figure 3.4. Due to infrared thermocouple positioning in groups of 2 or 3 (Figure 3.1), the process reaction curves were very similar for sensors placed in the same group (Figure 3.4). The temperatures recorded by the sensors in the same group were averaged to reduce the number of controlled variables from 16 to 6 (A, B, C, D, E, and F respectively). The resulting six process reaction curves for each peanut variety and moisture content are shown in Figures 3.5 to 3.10. Upon analysis of the process reaction curves, it was determined that at the last two groups of infrared thermocouples (E and F) the process did not reach the required steady state and their measurements were dropped from the analysis. The drying of Virginia type peanuts was a first order process, with time constants and dead-times increasing as the temperature sensors were placed further from the entrance of the drying tunnel. In the case of Runner-type peanuts, the process reaction curves seem to indicate an over-damped second order process (ξ>1), with time constants and dead-time also increasing as the sensors were placed farther away from the entrance of the microwave unit. For process control purposes, the over-damped second order process can be treated as a first order process with dead-time (Luyben, 1990). Therefore, the calculations of process parameters were based on the first-order model with dead-time. The values for the open loop process parameters for all peanut varieties, initial moisture contents and groups of sensors are shown in Table 3.2.
The gain of the process, $K_p$, for Virginia type peanuts at all moisture contents decreased as sensors were placed further away from the microwave entrance, a decrease that is consistent with the lower temperatures caused by the evaporative, convective and radiating cooling experienced by peanuts undergoing drying (Boldor et al., 2003). In the case of Runner type peanuts, the process gain followed a similar dependence on sensor position, with the exception of peanuts at 33% moisture content. At 33% mc, the process gain increased initially from group A to group B, decreasing afterward. At this moisture content, the maximum temperature during drying (Figure 3.3) is located in the same region of the microwave tunnel as the second group of sensors (group B), giving a higher process gain when this group of sensors was used.

The time constants of the processes increased as the sensors were placed further away from the microwave tunnel entrance. While this increase was expected, there was a fairly significant variation between the time constants of the same groups of sensors for different initial moisture contents. This variation was probably caused by difference between the fixed location of the infrared thermocouples and the changing locations of maximum temperatures with moisture content (Figures 3.1 and 3.3).

These peculiarities of the distribution of maximum surface temperature as a function of initial moisture content show that an adequate measurement of surface temperature distribution, would be useful in determining the location of the maximum temperature and subsequently the moisture content of the peanuts in the microwave drying tunnel. This information is critical in the determination of the needed number of passes through similar drying chambers to obtain a desired final moisture content.
Although there are some crude mathematical models of temperature and moisture distribution in continuous microwave drying (Boldor et al., 2003), they cannot be reliably used to create a feed forward/feedback control mechanism for the continuous microwave drying. More data representing the kinetics of the microwave drying, together with better mathematical models of moisture and temperature distribution, are needed to create an advanced control system for the microwave drying process. The limitations of the data acquisition system used for this study and the lack of knowledge described previously, determined the use of a simple feedback control loop to maintain the surface temperature of the peanut bed at a desired value (SP), which was previously related with the internal temperature of the peanuts undergoing microwave drying (Boldor et al., 2003).

The dead time of the process was determined to be negligible for Virginia type peanuts at almost all sensor groups and initial moisture contents. The exception occurred at 26% initial moisture content peanuts and only at the last groups of sensors. For Runner-type peanuts, approximating the step response with first-order with dead-time model, the dead time was negligible for the first group of sensors, while for all other groups of sensors it increased as the sensors where placed further away from the microwave entrance. The slower heating was caused by the decaying electric field as energy is being absorbed first by the peanuts closer to the entrance.

The Ciancone open-loop method (Ciancone and Marlin, 1990) was used to determine the initial parameters of a feedback controller for the two peanut varieties and the three initial moisture contents used in this study (Table 3.3). The lack of dead time for the sensors placed closer to entrance in the microwave applicator (Table 3.2) combined with the low signal-to-noise ratio permitted the use of a PI controller, with no derivative component.
The fine tuning of the PI feedback controller was simulated in Labview (Figures 3.11) using the servo scenario, with the controller acting to track set point changes. The optimum tuning parameters (Table 3.4) were determined such that the process variable never overshot the desired level.

The results of the simulation for Runner-type peanuts at 33% initial moisture content with the temperature from the first group of sensors as controlled variable (servo scenario) are shown in Figures 3.12 and 3.13. The initial temperature and set point temperatures were 27°C and 34°C respectively, matching the temperatures used in the step response analysis. The results of the simulation with the initial and optimal tuning parameters are shown in Figures 3.12 and 3.13 respectively. The process variable arrived at the set point in 33 seconds for the optimum tuning parameters, about 3.7 times faster than for initial parameters (Figures 3.12 and 3.13, Table 3.4). In general, these optimum parameters worked very well in the temperature range used for determination of process reaction curves.
CONCLUSIONS

Process reaction curves were determined for peanuts undergoing microwave drying in a continuous applicator, using the surface temperature as the controlled variable and the microwave power level as the manipulated variable. Process parameters determined using process reaction curves were used to estimate initial tuning parameters of a PI feedback control loop to maintain the surface temperature at the desired level. Computer simulation was successfully implemented to determine the optimum tuning parameters at two different loop speeds. The results of the simulations performed to determine the process response with the PI controller predicted good behavior without overshooting of the controlled variable.

Possibilities of overall improvement of the process control procedure using a combination of feedback/feed forward mechanism were discussed, including the use of an infrared thermal imager or an array of infrared thermocouples placed at the locations of maximum temperature and maximum rate of temperature increase.
LIST OF SYMBOLS

CV(s), CV(t) - controlled variable (Laplace domain, time domain)
CV_m(s) - measured controlled variable (Laplace domain)
E(s) - error (Laplace domain)
G_c(s) - transfer function of the controller (Laplace domain)
G_FCE(s) - transfer function of the final control element (Laplace domain)
G_p(s) - transfer function of the process (Laplace domain)
G_s(s) - transfer function of the sensor (Laplace domain)
K_c - proportionality constant
K_p - process gain, the ratio of final steady state value to the initial steady state value
MV(s) - manipulated variable (Laplace domain)
s - Laplace domain variable
SP(s), SP(t) - set point (Laplace domain, time domain)
t_1 - time at which the output reaches 28% of the final steady state value
t_2 - time at which the output reaches 63% of the final steady state value
X(s) - input function (Laplace domain)
Y(s) - output function (Laplace domain)
θ - dead time of the process
τ_i - integral time
τ_d - derivative time
τ_p - time constant of the process;
ξ - damping coefficient
REFERENCES

ASAE Standards. 2000a. Moisture Measurement – Peanuts. ASAE S410.1 DEC97. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA


Table 3.1. Infrared thermocouples locations, grouping and relationship between internal and surface temperature for Runner type peanuts at 33% initial mc (Boldor et al., 2003).

<table>
<thead>
<tr>
<th>Group</th>
<th>Sensor</th>
<th>Location (inch)</th>
<th>Location (m)</th>
<th>Equation</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Sensor 1</td>
<td>18.75</td>
<td>0.476</td>
<td>$y = 1.77x - 12.38$</td>
<td>0.993</td>
</tr>
<tr>
<td></td>
<td>Sensor 2</td>
<td>21.75</td>
<td>0.552</td>
<td>$y = 1.81x - 13.52$</td>
<td>0.990</td>
</tr>
<tr>
<td>B</td>
<td>Sensor 3</td>
<td>38.75</td>
<td>0.984</td>
<td>$y = 2.01x - 17.44$</td>
<td>0.972</td>
</tr>
<tr>
<td></td>
<td>Sensor 4</td>
<td>41.75</td>
<td>1.060</td>
<td>$y = 2.02x - 17.60$</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>Sensor 5</td>
<td>44.75</td>
<td>1.136</td>
<td>$y = 2.02x - 18.09$</td>
<td>0.967</td>
</tr>
<tr>
<td>C</td>
<td>Sensor 6</td>
<td>65.75</td>
<td>1.670</td>
<td>$y = 2.13x - 21.11$</td>
<td>0.959</td>
</tr>
<tr>
<td></td>
<td>Sensor 7</td>
<td>68.75</td>
<td>1.746</td>
<td>$y = 2.09x - 20.74$</td>
<td>0.958</td>
</tr>
<tr>
<td></td>
<td>Sensor 8</td>
<td>71.75</td>
<td>1.822</td>
<td>$y = 2.15x - 22.02$</td>
<td>0.956</td>
</tr>
<tr>
<td>D</td>
<td>Sensor 9</td>
<td>83.75</td>
<td>2.127</td>
<td>$y = 2.02x - 18.89$</td>
<td>0.949</td>
</tr>
<tr>
<td></td>
<td>Sensor 10</td>
<td>86.75</td>
<td>2.203</td>
<td>$y = 1.88x - 15.38$</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>Sensor 11</td>
<td>89.75</td>
<td>2.279</td>
<td>$y = 1.94x - 16.41$</td>
<td>0.950</td>
</tr>
<tr>
<td>E</td>
<td>Sensor 12</td>
<td>98.75</td>
<td>2.508</td>
<td>$y = 1.77x - 12.60$</td>
<td>0.947</td>
</tr>
<tr>
<td></td>
<td>Sensor 13</td>
<td>101.75</td>
<td>2.584</td>
<td>$y = 1.87x - 14.31$</td>
<td>0.941</td>
</tr>
<tr>
<td></td>
<td>Sensor 14</td>
<td>104.75</td>
<td>2.660</td>
<td>$y = 1.90x - 15.32$</td>
<td>0.940</td>
</tr>
<tr>
<td>F</td>
<td>Sensor 15</td>
<td>113.75</td>
<td>2.889</td>
<td>$y = 1.82x - 13.45$</td>
<td>0.933</td>
</tr>
<tr>
<td></td>
<td>Sensor 16</td>
<td>116.75</td>
<td>2.965</td>
<td>$y = 1.69x - 9.59$</td>
<td>0.933</td>
</tr>
</tbody>
</table>

Table 3.2. Process parameters for Virginia and Runner type peanuts at 3 initial mc.

<table>
<thead>
<tr>
<th></th>
<th>Virginia</th>
<th></th>
<th>Runners</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>mc%</td>
<td>Group A</td>
<td>Group B</td>
<td>Group C</td>
<td>Group D</td>
</tr>
<tr>
<td>Kp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>τp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>0.288</td>
<td>0.325</td>
<td>0.288</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>0.688</td>
<td>1</td>
<td>0.688</td>
<td>1.4</td>
</tr>
<tr>
<td>22</td>
<td>0.325</td>
<td>0.688</td>
<td>1.4</td>
<td>2.325</td>
</tr>
<tr>
<td>θ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>-0.038</td>
<td>-0.087</td>
<td>-0.083</td>
<td>-0.275</td>
</tr>
<tr>
<td>26</td>
<td>0.042</td>
<td>-0.058</td>
<td>0.567</td>
<td>1.433</td>
</tr>
<tr>
<td>22</td>
<td>-0.038</td>
<td>-0.087</td>
<td>-0.083</td>
<td>-0.337</td>
</tr>
</tbody>
</table>
Table 3.3. Initial tuning parameters for Virginia and Runner type peanuts at 3 initial mc.

<table>
<thead>
<tr>
<th></th>
<th>Virginia</th>
<th></th>
<th>Runners</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group A</td>
<td>Group B</td>
<td>Group C</td>
</tr>
<tr>
<td>$K_c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44%</td>
<td>0.175</td>
<td>0.195</td>
<td>0.257</td>
</tr>
<tr>
<td>26%</td>
<td>0.178</td>
<td>0.183</td>
<td>0.282</td>
</tr>
<tr>
<td>22%</td>
<td>0.175</td>
<td>0.195</td>
<td>0.257</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>0.058</td>
<td>0.138</td>
<td>0.303</td>
</tr>
<tr>
<td>26%</td>
<td>0.084</td>
<td>0.217</td>
<td>1.219</td>
</tr>
<tr>
<td>22%</td>
<td>0.058</td>
<td>0.138</td>
<td>0.303</td>
</tr>
<tr>
<td>$\tau_d$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>44%</td>
<td>0.009</td>
<td>0.090</td>
<td>0.284</td>
</tr>
<tr>
<td>26%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.4. Initial and optimum tuning parameters and time to get to the set point for Runner type peanuts at 33% initial mc.

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_c$</td>
<td>0.228</td>
<td>1.75</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>0.127</td>
<td>1.02</td>
</tr>
<tr>
<td>Time (sec)</td>
<td>121.5</td>
<td>33</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Figure 3.1  Schematic of the microwave drying system (top) and infrared thermocouple locations along the waveguide (bottom).

Figure 3.2  Feedback control loop.

Figure 3.3  First derivative of the internal temperature with respect to distance in the microwave tunnel for Runner type peanuts at 2 kW and 4 initial mc.

Figure 3.4  Step response of the 16 infrared thermocouples for Runner type peanuts at 52% initial mc.

Figure 3.5  Step response of the six groups of infrared thermocouples for Runner type peanuts at 33% initial mc.

Figure 3.6  Step response of the six groups of infrared thermocouples for Runner type peanuts at 36% initial mc.

Figure 3.7  Step response of the six groups of infrared thermocouples for Runner type peanuts at 52% initial mc.

Figure 3.8  Step response of the six groups of infrared thermocouples for Virginia type peanuts at 22% initial mc.

Figure 3.9  Step response of the six groups of infrared thermocouples for Virginia type peanuts at 26% initial mc.

Figure 3.10 Step response of the six groups of infrared thermocouples for Virginia type peanuts at 44% initial mc.

Figure 3.11 Diagram of the Labview simulation program

Figure 3.12 Simulation result for initial tuning parameters.

Figure 3.13 Simulation result for optimum tuning parameters.
Figure 3.1. Schematic of the microwave drying system (top) and infrared thermocouple locations along the waveguide (bottom).

Figure 3.2. Feedback control loop.
Figure 3.3. First derivative of the internal temperature with respect to distance in the microwave tunnel for Runner type peanuts at 2 kW and 4 initial mc.

Figure 3.4. Step response of the 16 infrared thermocouples for Runner type peanuts at 52% initial mc.
Figure 3.5. Step response of the six groups of infrared thermocouples for Runner type peanuts at 33% initial mc.

Figure 3.6. Step response of the six groups of infrared thermocouples for Runner type peanuts at 36% initial mc.
Figure 3.7. Step response of the six groups of infrared thermocouples for Runner type peanuts at 52% initial mc.

Figure 3.8. Step response of the six groups of infrared thermocouples for Virginia type peanuts at 22% initial mc.
Figure 3.9. Step response of the six groups of infrared thermocouples for Virginia type peanuts at 26% initial mc.

Figure 3.10. Step response of the six groups of infrared thermocouples for Virginia type peanuts at 44% initial mc.
Figure 3.11. Diagram of the Labview simulation program
Figure 3.12. Simulation result for initial tuning parameters.

Figure 3.13. Simulation result for optimum tuning parameters.
PROJECT SUMMARY

Peanut dielectric properties were determined using methods previously applied to wheat, corn and other agricultural commodities. Dielectric theory mixture equations were found to provide good estimates of the dielectric loss and the dielectric constant as a function of density, and they proved to be very useful in determining the dielectric properties of bulk peanuts in the microwave region of the electromagnetic spectrum. Data for dielectric properties of peanut pods and kernels was provided for a range of moisture contents and temperatures at microwave frequencies used in food processing (915 and 2450 MHz). The dependence on temperature was found to be more significant at lower moisture contents. At higher moisture contents, the significance of temperature effects on \( \varepsilon' \) and \( \varepsilon'' \) was reduced by the high dependence on moisture content of dielectric properties. The dielectric properties of peanuts obtained were similar to those presented in literature (Nelson, 1973), with some variation due to differences in moisture contents and microwave frequency.

The dielectric properties of peanuts were afterward used to estimate internal temperature and moisture distribution of farmer stock peanuts undergoing drying in a continuous microwave applicator. The estimations were performed using transport phenomena equations previously developed for microwave drying in multimode cavities. The equations were successfully adapted to account for the unique distribution of the electric field in a continuous traveling wave microwave applicator. The experimental results confirmed the theoretical predictions that the temperature profiles were determined only by the power level at the same moisture content and only by the moisture content at the same power level.
At the same moisture contents, the maximum temperatures and maximum rates of temperature increase occurred in the same time at the same location in the microwave applicator at all power levels tested. The negligible effect of temperature on the dielectric properties of the farmer stock peanuts confirmed previously performed measurements. At the same power level, the maximum temperatures were the same for all moisture contents tested, but the rate at which that maximum was reached increased with the increasing moisture contents. This result confirms the dependence of the dielectric loss and the attenuation constant $\alpha$ on the moisture content of the peanuts.

The measured moisture losses during microwave drying were also in line with theoretical estimations. The leveling effect of microwaves on moisture content was confirmed through measurements, and the total moisture reduction in consecutive passes at the same power level was determined.

A very good correlation was determined between the surface temperatures measured using infrared technology and the internal temperatures measured using fiber optic probes. These results were used to create an automated temperature control mechanism for the continuous microwave drying process. Process reaction curves were determined using surface temperature as the controlled variable and microwave power level as the manipulated variable. Process parameters determined using process reaction curves were used to estimate initial tuning parameters of a PI feedback control loop that maintained the surface temperature at the desired level. Computer simulation was successfully implemented to determine the optimum tuning parameters. The results of the simulations showed good behavior of the system without overshooting of the controlled variable (temperature).
FUTURE RESEARCH

The mathematical model developed in this study for temperature distribution during continuous microwave drying should be improved upon by integrating the convective, radiant and evaporative cooling effects into the transport equations. Dielectric properties of peanuts at more moisture contents need to be evaluated to help in determining a complete heat and mass transfer model for peanut drying. Also, more data on moisture content of peanuts while in the applicator is required to develop a viable model for microwave drying kinetics. The models developed in this study should be tested on different materials and in different conditions, such as higher air flow temperatures and different belt speeds.

The difference in the rate of heating and in the location of the maximum temperatures at different initial moisture contents determined in this study should be used in combination with infrared imaging to determine the initial moisture content of peanuts entering the applicator, and subsequently the number of passes through similar systems to reach a desired final moisture content. This goal can be achieved through a feed forward/feedback control mechanism that can be coupled with data provided by various on-line moisture sensors. This will create a comprehensive control system for the entire microwave drying process. More advanced process control methods such as fuzzy logic should be evaluated and compared with the performance of the feedback control loop described in this study.