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Modern Electronic Techniques in Microwave Thermal Processing

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تقنيات النمذجة الإلكترونية والمعالجة الحرارية بالميكروويف

لقد أمكن استخدام طاقة الميكروويف في العديد من التطبيقات الاكلينيكية (الطبية) والعلمية والصناعية. يعتبر التسخين بالميكروويف من التقنيات الالكترونية المستحدثة والتي امتدت لتشمل الصناعات الغذائية والصناعات الكيميائية العضوية وغير العضوية والبلمرات والصناعة بشكل عام ومجالات الطب والزراعة. يعرض هذا البحث للتطورات الحديثة في هذا المجال وأسلوب نمذجة عملية التسخين بالميكروويف حيث يتم التوازن بين الطاقة الإلكترونية للميكروويف الناتجة عن حل معادلات ماكسويل للمجالات الكهرومغناطيسية والطاقة الحرارية التي تنتشر في المادة المعالجة (الناتجة عن طاقة الميكرويف). تم عرض البرمجيات الحديثة المستخدمة كأدوات للبحث والتصميم في هذا المجال بالإضافة إلى تقنيات القياس.ونظرا لإن التوزيع المنتظم للحرارة في كل أجزاء المنتج يمثل أساس المشاكل الناتجة عن استخدام طاقة الميكروويف في الصناعات الغذائية بشكل خاص، والصناعة بشكل عام. فقد أمكن في هذا البحث وضع الأسس العملية والنظرية التي تحقق التوزيع المنتظم للحرارة في كل أجزاء المنتج والمبنية على التوازن الأمثل لطاقة النظام.

ABSTRACT

Microwave energy has been in use for a variety of applications such as medical, scientific and industrial ones. Microwave heating has become one of the active research interests during the last few years. Different techniques have been introduced during these years for microwave thermal processing. This research area has been expanded to include other fields of application such as food industries, general industries, organic and non-organic chemistry, polymers, medicine and agriculture. In this paper, the recent developments of different microwave processing systems are addressed. Some of the modern electronic microwave heating methods are also investigated.

Key words: Microwave, energy, thermal processing, microwave heating, electronic microwave processing.

INTRODUCTION

The research area of microwave heating has been widely expanded in the past few years through many fields. Generally, the categories of applications of microwave heating are either heating or drying. Heating means the use of microwave energy only but drying uses microwaves and hot air (hybrid one) Fig. 1 shows the humidity and temperature change as a function of material thickness in one such hybrid system. Thermal applications are carried out using static, continuous processing (open ended tunnel), or mobile heating systems. This is remarked from the progressive contributions of many related topics in many journal articles, sessions in major conferences and books in this research area. This progress includes research in a wide range such as the dielectric constant and analysis of dielectric heating (Callebaut 2007), and the domestic microwave ovens (Matsumoto et al. 2003). In addition, the heat uniformity and performance have been proposed for general problems of microwave heating (Cresko et al. 2003), as well as microwave power level, temperature and water content measurements applied to scientific researches of microwave heating (Sovlokov 2003). Heating techniques using microwave energy have also been investigated to control profiles of temperature during manipulation and processing .

In fact, the microwave heating is very appealing in several areas including civil engineering (Saber 2003), non-destructive testing, biomedical engineering (Mckinlay et al. 2002), environmental engineering, transportation engineering (Therm 2003), agriculture and nutrients (Decareau 2003), organic chemistry and polymer chemistry (Parodi 2002), and industrial applications (Jerby 2002).

The scattered data for the microwave heating process can be taken versus variations in power, frequency, size, shape, mechanical and thermal properties, and relative permittivity of the material. These data can be processed in the form of reflection coefficient, scattering parameters, coupling, distribution of electric or magnetic field components, pattern of the dissipated power, specific absorption rate (SAR), and the heating pattern. In general, these data are supplied to electromagnetic software, used as a tool, in solving the heating problem with or without a priori data to extract the required parameters of the model, which is normally the temperature evolution distribution. The choice of an electromagnetic algorithm for the solution of a specific microwave-heating problem is based on its efficiency and heating pattern uniformity. This efficiency is measured according to its accuracy, speed, stability and robustness during the heating process.

This paper features out some of the recent developments of the microwave heating approaches & models, the hazards of applications and the techniques used to minimize their effects. The paper is then about addressing and classifying the recent developments, introduced to improve the heating in the microwave frequency range.

VARIOUS MODERN MICROWAVE OVEN TECHNIQUES

Microwave energy is non-ionizing radiation that causes molecular motion by migration of ions and rotation of dipoles as shown in Fig.2. Microwaves don't cause changes in molecular structure. Heat due to microwaves is generated in the polar dielectrics. The dissipated microwave power, P, in the processed material is (International 1998):

$$P=\omega\varepsilon_0\varepsilon' \tan(\delta)\, E^2_{\text{rms}} = \omega\varepsilon_0\varepsilon''\, E^2_{\text{rms}} \qquad (1)$$

Where ε_0 is the permittivity of free space (F/m), $\omega = 2\pi f$, where f is the microwave frequency (Hz), E is the electrical field strength, (V/m), within the material, ε'' is the dielectric loss factor, $\tan(\delta)$ is the loss tangent, and ε' is the real part of the permittivity of the material. The electric field varies with the position of the material. Penetration depth of microwaves in the material is (International 1998):

$$d_p = \frac{\lambda}{2\pi\varepsilon''}\sqrt{\varepsilon'} \qquad (2)$$

Where λ is the free space wavelength.

The most common application techniques can be classified, from wave point of view, to the following three categories:

- Multi Mode Cavity Techniques.
- Single Mode Cavity Techniques.
- Traveling Wave Device Techniques.

Multi Mode Technique

The simplest applicator in this category is a rectangular metal (conductive) box that can accommodate the target load as depicted by Fig.3. When microwaves are launched into such a device via a waveguide, the waves undergo multiple reflections from the walls. The reflected waves interfere and establish a distribution of electrical field strengths within the internal space (including the load) that correspond to many different stable modes of propagation. For this reason it is called a multi-mode applicator.

The most common example of this device is a domestic microwave oven (Risman 2002). A multi-mode device is best suited to a load that is very lossy and occupies a large volume of the applicator. By incorporating a mode stirrer (a rotating reflector) or continuously rotating the load on a turntable (Risman 2002), temperature uniformity can be improved to a limited extent by effectively smearing the electrical field distribution within the load. A major criticism of the use of a multi-mode oven for scientific study is that since the spatial distribution of field strength is unknown, the facility to generalize the results from a particular investigation is compromised.

It is possible to calculate the field distribution within a loaded multi-mode cavity using for example Finite Difference Time Domain (FDTD) procedures. Once such codes are established and more generally available, the reservations over the use of such applicators may disappear. Fig. 4 displays an example of the reflection coefficient at the waveguide feed for the microwave oven with potato as computed with Micro-Stripes. Also Fig. 5 illustrates the distribution of electric field intensity (directly related to the heat generation inside the load) in a plane section of the oven correspondent to the contact surface between the load bottom and the upper side of the glass turntable.

Single Mode Technique

The most efficient applicator, particularly for filamentary materials, is a single mode resonant cavity. Within such a cavity only one mode of propagation is permitted and hence the field pattern is defined in space, and the target load can be positioned accordingly. A single mode cavity may be cylindrical or rectangular .

A rectangular single-mode cavity (Komarov et al. 2002 a) consists of a length of waveguide, which houses a non-contacting plunger that determines the effective cavity length. The mode of operation of such a device is typically $TE_{10\ n}$ with the target load positioned in a region of high field strength. The major limitation of this device is that the width (or thickness) of the load must be less than half a wavelength. One such mode applicator is shown in Fig. 6.

Traveling Wave Technique

A traveling wave applicator means continuous processing. It consists of a waveguide arranged in such a way that the microwave is launched from one end and target load passes in front of the other end as shown in Fig.7.a. Microwaves are absorbed by the load exponentially with distance according to the dielectric properties and size of the load. As a precaution, a dummy load or filter is attached to load-end of the applicator to absorb any microwave energy that is not absorbed by the load (Saber 2002). Sometimes microwave sources with the waveguide are made mobile and the target load is fixed, as shown in Fig.7 b.

SOME MODERN MICROWAVE OVEN APPROACHES

With regards to the application of the previous heating techniques, two approaches are discussed. These approaches are:

- Modeling
- Measuring

Modeling Approaches

The energy balance equation describing the relation between the heat transfer and the electromagnetic fields seems deceptively simple. The difficulty is embedded in the optimization of the equation that couples heat transfer with the heat generated by microwaves, which makes its computation difficult. This equation has the form of (Sung-Lee et al. 2002):

$$\nabla.(K\nabla T)+Q=\rho C_p \frac{dT}{dt} \qquad (3)$$

where T is temperature (^{o}C) and is a function of space and time, t (s) is the time, ρ;C_p and K are density, specific heat and thermal conductivity of the heated material respectively. Q in the above equation is the volumetric heat generation due to microwaves. This term is obtained by one of two ways:

1- Solving Maxwell's equations and obtaining the electric field (using one of electromagnetic software) and using Eq. 1 to get microwave heating power.

2- Using Lambert law (Sung-Lee et al. 2002) in the x direction of the coordinate system:

$$P_x = P_o e^{-x/d_p} \qquad (4)$$

where P_x is the microwave power in the x direction , P_o is the microwave power at the processed material surface, is given by Eq. 1 while d_P is given by Eq. 2. Complete solution of such coupled boundary problem Eq. 3 is a big challenge. Application of numerical approaches (for both heat and electromagnetic problems) is also extremely complicated and requires huge computer resources.

Modern Software Spectrum:

The modern electromagnetic software available in the market with respect to their applicability to the typical problems of microwave thermal processing are addressed in Fig. 8 a.

The most common numerical methods used for solving the electromagnetic part of Eq. 3 are the finite difference time domain (FDTD); finite elements time domain (FETD), moment method (MoM), and transmission line Matrix method (TLM) (Chuang et al. 2003; Cohen et al. 2003; Fidanboylu et al. 2003; Renko et al. 2003; Gronwald 2003). The percentage usages of these methods are depicted in the pie chart of Fig. 8 b.

Solution to the Coupled Boundary Problem:

The software applications shown in Fig. 8 b are purely electromagnetic, able to handle Maxwell's equations under specific boundary conditions, and compute the space distribution of the electric and magnetic fields, power deposition, and heating intensity. So far, none of the commercial packages have been offering options for modeling of applied problems of microwave heating in their entirety i.e., including characteristics of other distinctive physical phenomena. For example, for processing of food products, complete models should take into account not only heat transfer, but also water transport and, in some cases, mass transfer, evaporation, irradiation and some chemical transformations. Thus what contemporary electromagnetic (EM) modeling actually addresses is just one element (though it is definitely a key element) in the multiplicity of physical phenomena forming the microwave heating- the electromagnetic aspect.

So, the real solving of the coupled problem of electromagnetic and heat conductivity Eq. 3 means handling simultaneously Maxwell's equations and heat conduction equations. Such solution must achieve uniform distribution of the heating pattern. So, the most commonly used optimization methods can be classified as:

- Statistical
- Deterministic
- Global

Statistical Methods:

Statistical methods implement principles based on the statistical concept. The multiple modes of the electromagnetic field in a cavity are mixed up to achieve a random field distribution and increase the probability of uniform heat release.

In the last decade, the early techniques of solving such system are analyzed on the basis of one crucial observation, compared to the rate of change of high frequency electromagnetic fields, variation of the heat parameters is very slow. Thus, within the period of variation of the electromagnetic field the heat characteristics might be constant. Hence the electromagnetic field might be computed from Maxwell's equations (use MoM) and the electric field substituted for the heat conduction Eq. 3 and the latter can be solved independently, using MoM method (Palombizio et al. 1999), neither so powerful, nor accurate, and applicable only to certain classes of systems, but requiring much less time. This approximation simplifies the problem since it actually separates the electromagnetic and thermal analysis. The approach is restricted to the processes of quite fast heating by microwaves and materials with low thermal conductivity.

Deterministic Methods:

These methods differ from the statistical ones. Deterministic methods deal only with one or a few modes. The most efficient modern numerical techniques used (FDTM and FEM) (Bellanca et al. 2002; Bellanca et al. 2001; Abd-Elrazzak et al. 2005) need substantial time for computation of each scenario (heat and electromagnetic).

An approach to put the temperature distribution under direct control is the use of optimal material design (OMD) in microwave thermal Processing. The concept of OMD means an optimal placing of supplementary dielectric materials within a part of the operating chamber in order to appropriately focus the electromagnetic field onto the heated product to maintain the desired uniform heat release within it (Murphy et al. 2006). The use of this approach is restricted to fully deterministic systems including materials with well-determined properties and shapes and applicators with a finite number of participating modes. Also, these techniques have been developed only for control and optimization of 2 D traveling wave systems.

There are two electromagnetic characteristics mostly deserving optimization: reflections from the cavity and uniformity of heating pattern. The first one means the efficiency of the system in a frequency range adjacent to the operating one while the second is the main object for most of the microwave heating models (Komarov et al. 2007).

A good deterministic optimization technique that converges much quicker than technique of global optimization is addressed by Mechenova et al. (2002) to optimize the form of the frequency characteristic of the reflection coefficient, which is a function of the geometric parameters of the system. This technique is known as energy coupling optimization. Results obtained using Microwave Studio for the optimum heating are shown in Fig. 9.

Two approaches for Energy coupling optimization are addressed in Mechenova et al. (2004):

(1) Response Surface Methodology:

In this approach, sequential quadratic programming and S-parameters taken from FDTD simulator are processed with the use of hypersurface fitting. The response surface is approximated by a second order polynomial; least square method is applied to find its coefficients. The constructed hypersurface is used as an input data for direct constrained optimization. This method employs the idea intentional rectification of an actual hypersurface; therefore, it is particularly efficient for non-resonant systems.

(2) Artificial Neural Networks (ANN):

Another optimization procedure employing artificial neural networks technology has been proposed in Komarov et al. (2007). A Radial Basic Function network is trained by simulated frequency response of $[\underline{S_{11}}]$ and geometric data on the corresponding system. Making the problem better conditioned for training and helping the network with its learning process, linear scaling is applied to the input parameters. The network is trained with the use of back propagation and the second-order gradient-based techniques. The method inherits a major ANN capability of accurately approximating functions, so it successfully handles systems with strong resonances.

Global Methods:

The global optimization methods are robust and simple in use. They are largely independent of the initial conditions. On the other hand, these methods have much lower convergence rate (Komarov et al. 2007). They are not widely used in optimization of the microwave heating systems. These methods are more suitable for evaluation and imaging of radiation leakages from industrial microwave heating systems, specially traveling wave ones.

Measurement Techniques

These measurement techniques can be classified into the following categories:

- Dielectric properties measurement
- Temperature measurement
- Water content measurement
- Microwave oven power measurement

Dielectric Properties Measurement:

Dielectric constant of the processed material is the principal factor in determining the magnitude of reflection, refraction and absorption of microwave radiation. Measurement techniques can be categorized into reflection or transmission measurements by resonant or non-resonant systems, with open or closed structures for measuring the dielectric parameters of the material (Komarov et al. 2002 b). These methods include the following:

(1) Waveguide and Coaxial Transmission Line Method

The values of dielectric constant and dielectric loss factor are derived from transmission line theory, which indicates that these parameters could be determined by measuring the phase and amplitude of a reflected microwave signal from a sample of material placed against the end of a short-circuited transmission line, such as a waveguide or a coaxial line. In order to use waveguide (cavity) technique, rectangular samples that fit into the dimensions of the rectangular waveguide at the frequency being measured are required . An annular sample is needed for coaxial line method. The thickness of the sample should be approximately one-quarter wavelength within the sample. Therefore, preparation of optimal sample requires guessing the dielectric constant of the material so that the wavelength can be determined. Waveguide method has very narrow operating ranges and generally used for single frequency measurement. Coaxial transmission line measurement technique is somewhat cumbersome because the sample must be annular geometry. These techniques are more suitable to porous materials.

(2) Open-Ended Probe Method

Open-ended probe method measures the dielectric parameters from the phase and amplitude of the reflected signal at the end of an open-ended coaxial line that is in contact with the sample to be measured, as shown in Fig.10. Care should be taken to avoid any air gap between the probe and the sample. This method is convenient for measuring dielectric properties in a wide range of frequencies on non-porous material of relatively high loss factor, which includes most of the food materials .

(3) Cavity Perturbation Meth

Cavity perturbation measures the dielectric constant and loss factor on the basis of the changes in the frequency and the width of transmission characteristics, when a sample is inserted into a tuned resonant cavity. Cavity perturbation is very sensitive and accurate for materials with loss factor less than one. This method is suitable for non-porous materials (Komarov et al. 2002 b). A microwave resonator, partly or completely filled with a material can be used for the determination of permittivity. The partially filled resonators (perturbation method) are often calibrated with known materials. The measurement frequency range is from 50 MHz to over 100 GHz and this is one of the most commonly used measuring methods. If the sample always has the same geometry and volume, the shift in resonant frequency can be directly related to the permittivity. The loss factor can be determined from the change in the Q-factor of the cavity.

These methods can be very accurate and are also sensitive enough to measure low-loss materials. The resonant cavity systems restrict the measurements to a single frequency but, on the other hand, the ISM band regulations already limit the choice of frequencies. Each cavity needs calibration but, once the calibration curves have been obtained, calculations are rapid. Sample preparation is relatively easy; a large number of samples can be measured in a short time. These methods are also easily acceptable for high (up to $+140^0$C) or low (-20^0C) temperatures.

Temperature Measurement :

The control of temperature distribution during microwave heating is important for the quality and safety of the product. Measurements of temperature are carried out in two cases: during microwave heating and just after switch off microwave generator.

Measurements Methods During Microwave Heating

Non-perturbing and non-intrusive temperature sensing systems have been developed such as:

(1) Fiber Optic System: The measurement is based on a light signal, which is sent to the tip of the fiber. In the sensing head, a transformation takes place and this temperature dependent change is then monitored.

The main disadvantage of the fiber optic systems is the price; systems are very expensive and fibers are fragile and may be difficult to place in a certain position in the material. A hole needs to be drilled through the oven wall when the fibers are used in a household microwave oven. Since the probes only provide a temperature measurement at a discrete point, so the method has poor spatial resolution.

(2) Infrared (IR) System: IR imaging is probably best-known ones. It provides a means of observing temperature distribution over a surface of a body. The principle of this method is the fact that all bodies emit electromagnetic radiation, and between the temperatures used in microwave heating the maximum intensity occurs at infrared region (about 6-13 μm).

Commercial IR thermography systems operate between 3 and 5 μm or 8 and 14 μm, and within these wavebands, radiated energy is proportional to the temperature of the object. The main advantage is that it makes it possible to look, at complex heating patterns, and follow the product in real time during the heating process. It helps to use fiber optic systems at special points to measure the internal heating pattern.

Measurement Methods After Switching Off Microwaves

Conventional methods can be used for measuring temperature after microwave heating. Most types of single-point temperature measurement sensors can be used, but the sensors may have appreciable response times, and the product temperature can change rapidly. In this case, an array of sensors that can simultaneously be introduced into the meal can be constructed. The probes need to be thin and of material with low thermal conductivity. The reliably determining of time-temperature history of a food product is possible by combining more than one method of temperature measurement.

Model substances for determining temperature distribution in microwave heating have been developed for both solid and liquid model substances. The most useful substances are those which show the temperature distribution directly visually, for example by changing color due to temperature changes.

Water Content Measurement:

Water content distribution in a processed material can be measured by:

(1) Millimetric Wave (MM) Method: MM waves ensure better spatial resolution and also better sensitivity to water as compared to microwaves. MM waves are less sensitive to conductive impurities as compared to microwaves (waveguide method to measure dielectric properties); in addition, they can be used for water testing in media that are opaque for optical and infrared radiation.

(2) Neural Network and FDTD Methods: Such method uses simple novel technique for determining the dielectric properties of arbitrary shaped material. Complex permittivity is found using a neural networking procedure to control a 3D FDTD model computation of S-parameters and to process their measurements. Network architectures are based on multilayer perceptron and radial basis function networks. The method is cavity independent and handles frequency-dependent media parameters. Such technique achieves high accuracy and practical suitability through numerical testing.

Microwave Oven Power Measurement:

Many methods have been proposed for determining both the oven field pattern and measuring the microwave power output (Wladyslaw et al. 2001). Oven field distribution has been determined (according to the International Electro-technical Commission IEC rules) by, for example, using layers of homogeneous food materials or model substances and measuring the temperature distribution after a certain heating time (Wen et al. 2003). Model substances can visualize the temperature by changing color, or temperature of the product surface can be monitored by IR imaging. Material geometry and composition affect the microwave power distribution, and therefore test loads should be similar when evaluating the heating performance for products.

HAZARDS AND SAFETY IN MICROWAVE HEATING

With regards to the application; microwave heating effects on the human body can be classified into two main groups:

- Direct radiation effects
- Indirect radiation effects

Direct radiation effects

The IEC and the National Health and Medical Research Council (NHMRC) determined the ovens performance testing and issued a standard including direct radiation of 5 milliwatt/cm^2 as the maximum limit of microwave radiation for the human body without any effects. Also, special devices are used to measure the specific absorption rate (SAR) in the human body (Merckel et al. 2003).

Indirect Radiation Effects

Hazards of microwaved foods represent the main indirect heating effects. Non-uniform microwave heating (internal cold and hot spots) may lead to survival of food-borne pathogens, including Salmonella and L. monocytogenes, and Trichinella spiralis in certain locations of foods heated at selected internal locations (International 1998; Palombizio 1999). According to European (UK) recommendation, the food should receive a minimum microwave heating which ensures that every point of the food reaches a temperature of 70 ^{0}C for two minutes to destroy pathogens (International 1998). The only method to achieve this recommendation without food burning is the uniformity of heating pattern. So, the main target of the recent researches modeling techniques for microwave heating systems is to get uniform heating pattern as well as high efficiency.

CONCLUSIONS AND FUTURE TRENDS

The progress of microwave oven techniques has been greatly expanded in the past few years through the development of different techniques as well as the advances in the high frequency measuring instruments. These instruments have acquired high accuracy in measurements and wide dynamic range. Recent developments and classification of different techniques of microwave heating models have been outlined. The majority of these developments are directed to improve both the heating pattern and the efficiency of these techniques and increase their accuracy, stability and robustness.

The problem of providing uniform heat distribution (to avoid internal cold and hot points) for microwaved substances is actually not completely solved. Complete solution to such problem requires development of variable frequency microwave ovens. Academic research in this field and industrial sector could be brought together through information exchange.

Optimization looks quite weak. Extensions of this area are expected. One of the promising approaches is the use of optimization algorithms in the 3-D thermal process model to increase their efficiencies and modify the homogeneity of heat distribution. For example, it is possible to merge the OMD and statistical optimization techniques to obtain uniform heat and better performance.

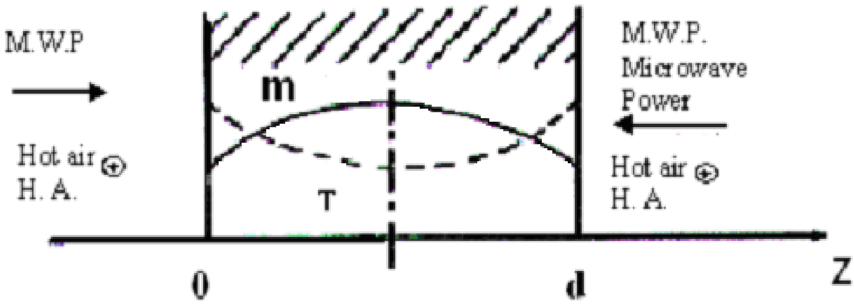


Fig.1 General profile of the change of humidity m, and temperature T as a function of the material thickness d, for hybrid drying (hot air and microwaves).

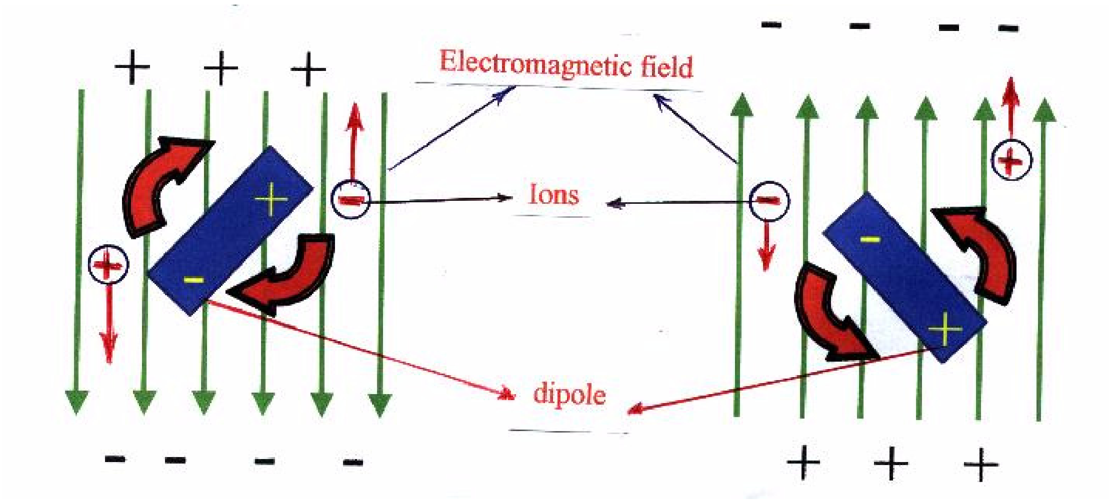


Fig.2. Movement of dipoles and ions due to oscillating electromagnetic field.

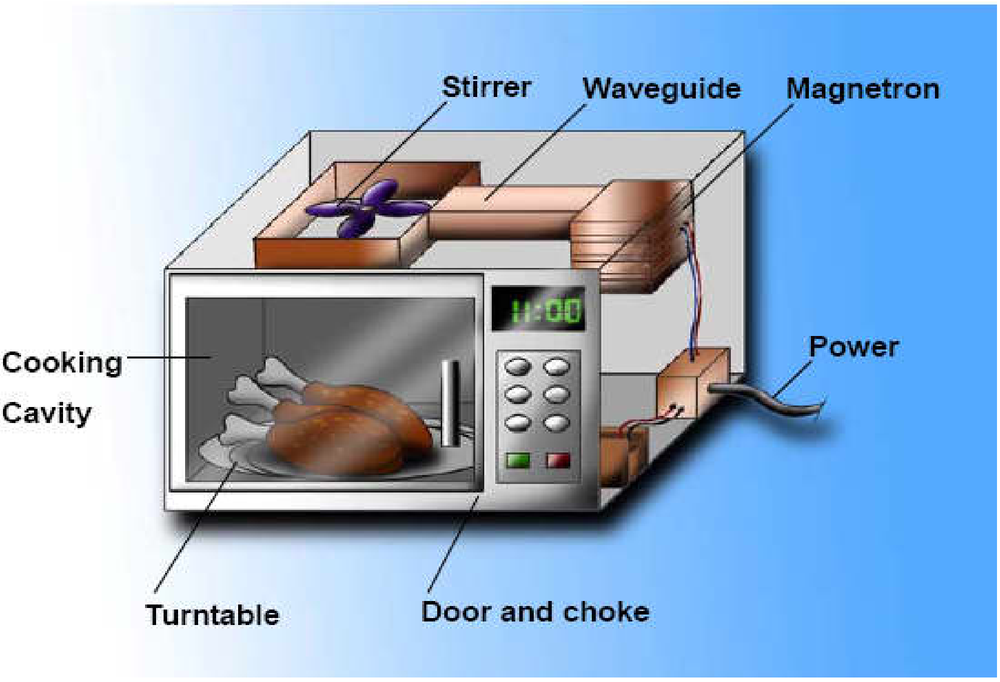


Fig. 3 The household microwave oven basic structure.

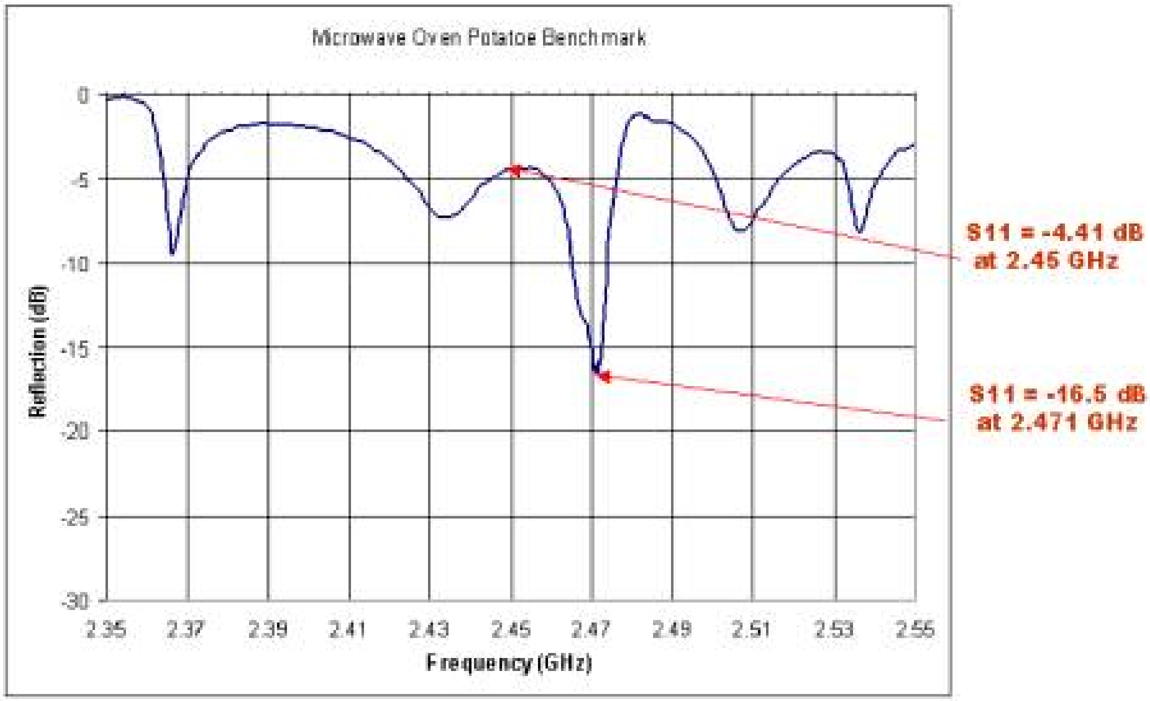


Fig. 4 Reflection coefficient at the waveguide feed for the microwave oven with potato as computed with Micro-Stripes

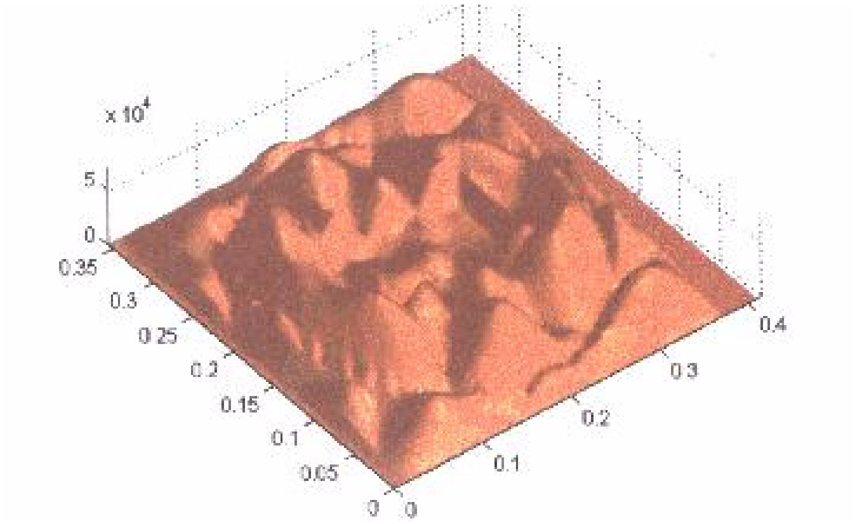


Fig.5 Electric field intensity distribution on the load turntable contact surface.

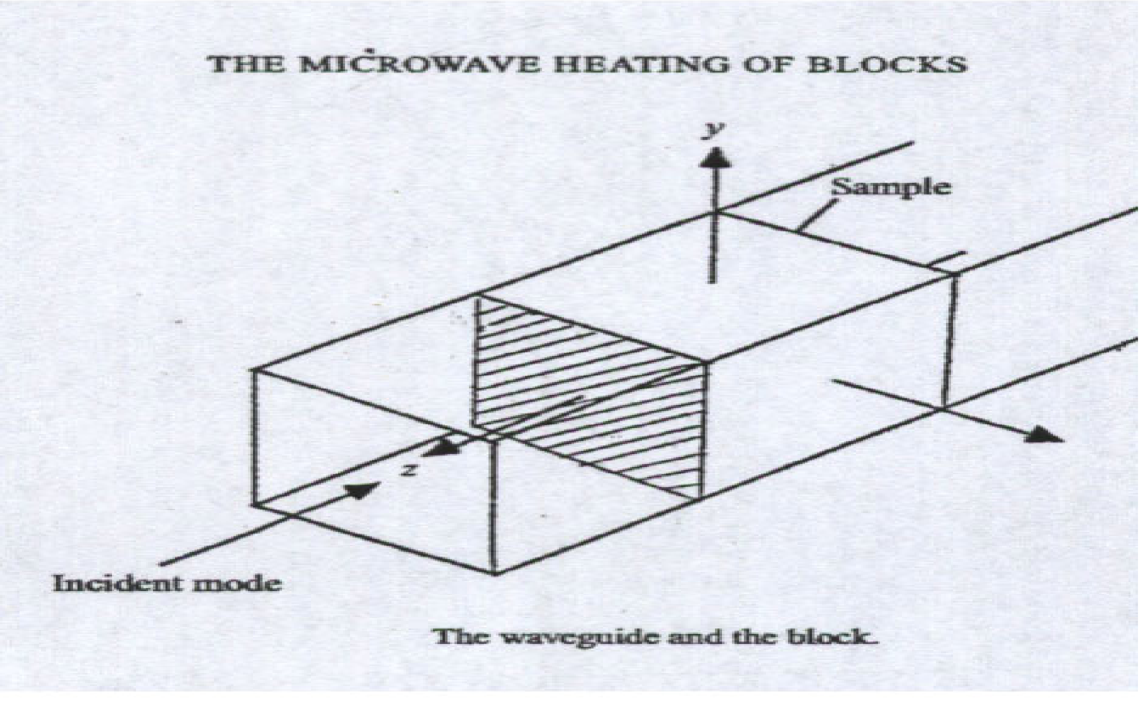
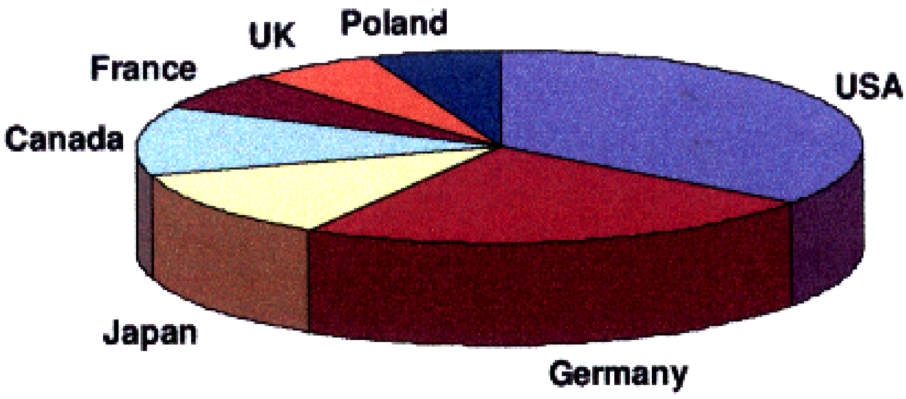


Fig.6 Single mode applicator cavity details.

Fig.7 (a) Traveling wave applicator (Bread industry)

Fig.7 (b) Mobile Microwave Drying- and curing device
(Traveling Wave Applicator)



USA: *EMA3D, EMFlex, FIDELITY, HFSS, Multiphysics, XFDTD*
Germany: *CONCEPT, EMPIRE, MAFIA, Microwave Studio*
Japan: *JMAG-Works, MAGNA/TDM*
Canada: *FullWave, MEFISTO*
France: *EMC2000-VF*
UK: *Micro-Stripes*
Poland: *QuickWave-3D*

Fig.8 (a) Modern market of the EM modeling software applicable to the systems and processes of microwave heating.

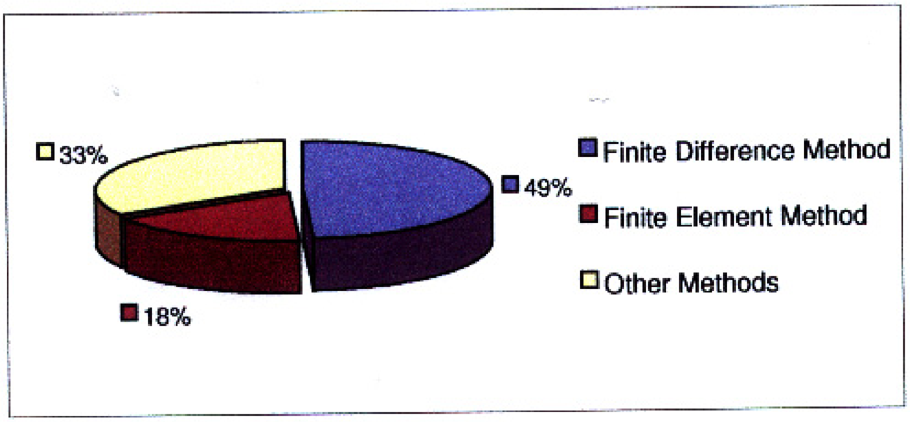


Fig.8 (b) Popularity of numerical methods in microwave power research.

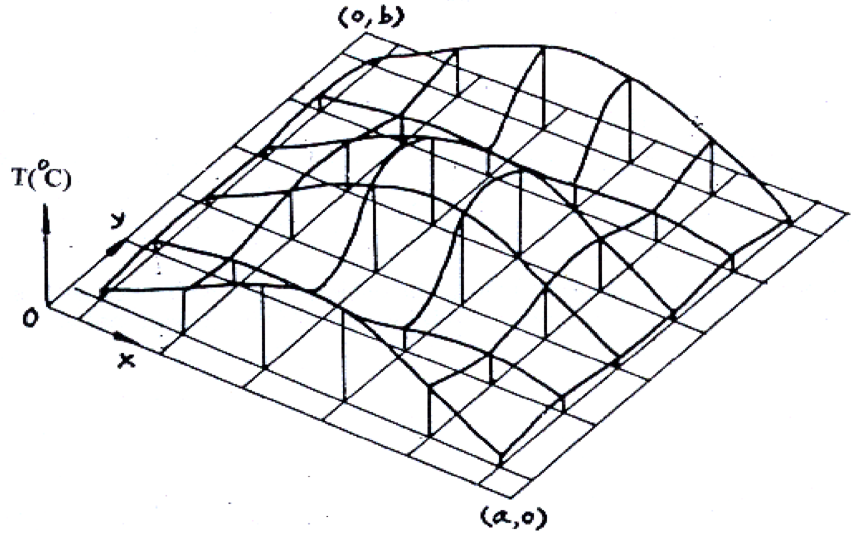


Fig.9 Evolution of temperature T(^{0}C) as a function of x and y coordinates in the case of hybrid drying.

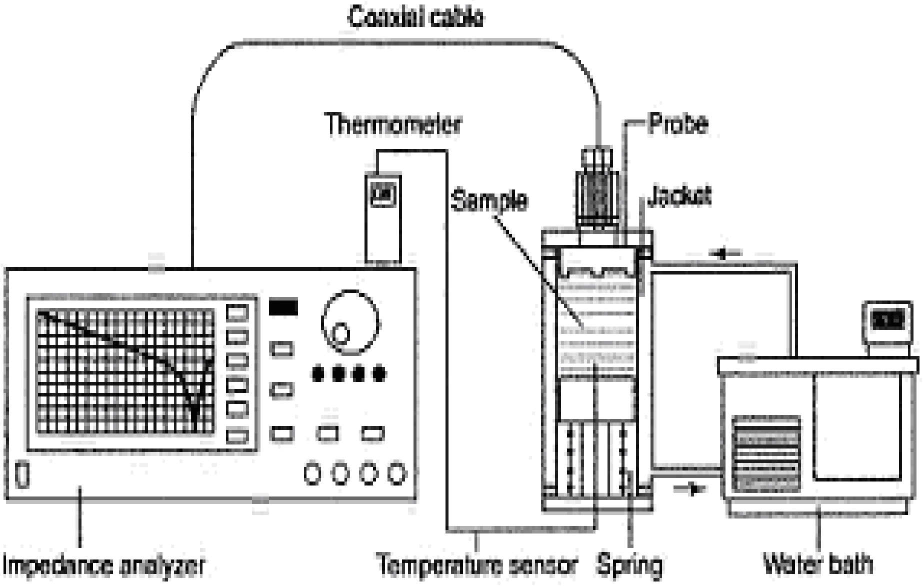


Fig.10: Schematic diagram of experimental setup realizing open-ended coaxial probe method

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