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ASPECTS REGARDING THE PROCESSING OF DIELECTRIC MATERIALS IN A MICROWAVE FIELD

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Abstract. *The paper includes the main results obtained in the domain of the processing of dielectric materials in a microwave field. It has the character of an applicative research, the obtained results being of practical use, with the main purpose of optimizing the functioning of some heating devices in a microwave field. This analysis is efficient but it implies the exact knowledge of the dielectric and thermal properties of the material that is to be processed, and also the dependence of these properties on the temperature. The main problem we follow is represented by the homogeneity of the field and, consequently, of the temperature in the material.*

Keywords: Electromagnetic field, microwaves, propagation, numerical modelling, optimization dielectrics

1. Introduction

The effect of the microwaves on the material depends a lot on the physical properties.

Studies concerning the processing of different products were made more recently by Paltin, 1992, S. Lefeuvre, 1993, performed studies on the properties of dielectric materials and the mode they influence the processing in a microwave field [1]. An analysis of the multimode applicators was presented by Metaxas and Meredith, 1994, [2].

They showed the mode of over positioning of the waves after three octagonal directions, developing successfully a simple technique of measurement of the modes in an empty cavity. This study was then extended by Chow Ting Chan and Reader, 1995, for a loaded cavity. D.C. Dibben, 1996 studied the results of the numerical modelling comparing them with the experimental results for more types of applicators, information which were subsequently used for the developing of complex calculation methods.

H.C. Reader, 1997, [3], developed a method for the determination of distribution of the electric field, which develops between the interior surfaces of the applicator – on the interior metallic surface of the applicator there is a tangential component

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of magnetic field and a phase different perpendicular component of electric field which develop in space.

The scope we follow is to secure optimum conditions for the processing of the dielectrics, the realization of a microwave installation which can accomplish the following processes:

- the processing of the dielectrics, optimum moisture content and the active substance for the securing of an adequate storing process;

- the successful elimination of different bacterial and micotic pathogenic through the treating with microwave of the dielectrics.

2. The propagation of the electromagnetic field in the microwave structures

The guiding of the electromagnetic waves through the microwave structures is realized through the close relation between the electromagnetic field of the wave on the one hand and the loads or currents on the boundaries of the structure, with certain conditions of reflection on these boundaries, and not only. In most cases, the guiding structures of the electromagnetic waves are rectangular structures and have conductive boundaries. The knowledge of the distribution of the electromagnetic field in the microwave structures makes possible the knowledge of the constant of propagation of the waves, of its dependence on frequency, of the propagation speed, of the phase and attenuation constant etc.

Modelling represents a phenomena using set of mathematical equations. The solutions to these equations are supposed to simulate the natural behaviour of the material.

Modelling can be a design tool to develop food that will provide optimum heating results in the microwave oven. In the modelling work, the food system is represented as being made up of many small elements in the simulation process. These discrete elements are joined together to make up the product [4].

Modelling of microwave drying process can involve two separate parts, one being modelling of heat and mass transfer and another being modelling the electromagnetic field inside the microwave oven cavity for calculating heat generation term [4]. Modelling of electromagnetic field arises when Maxwell's equations are used for calculating the heat generation term.

Modelling of heat and mass transfer equations uses standard heat transfer equation and the mass transfer terms are included in the boundary conditions of the governing heat transfer equation.

The electromagnetic field inside the microwave oven can be represented by Maxwell's equations [5]:

$$\nabla x\mathbf{E} = -\frac{\partial}{\partial t}(\mu\mathbf{B}) \tag{1}$$

$$\nabla x\mathbf{B} = -\frac{\partial}{\partial t}(\varepsilon'\varepsilon_0\mathbf{E}) + \varepsilon''\varepsilon_0\omega\mathbf{E} \tag{2}$$

$$\nabla\cdot(\varepsilon\mathbf{E}) = 0 \tag{3}$$

$$\nabla\cdot\mathbf{B} = 0 \tag{4}$$

For dielectrics materials, heating is done by electric field primarily through interaction with water and ions. The complex permittivity ε is given by:

$$\varepsilon = \varepsilon' + j\varepsilon'' \tag{5}$$

Maxwell's equations can predict the electric field **E** as a function of position and time. Microwave heat generation term (Q) in the heat transfer equation is calculated using this electric field E:

$$Q = \frac{1}{2}\omega\varepsilon_0\varepsilon''E^2 \tag{6}$$

Using Maxwell's equations and appropriate boundary conditions electric field distribution inside a dielectric can be calculated. Then the heat generation term (Q) is calculated from the electric field by equation (6). Since the Q varies with respect to position, non-uniform increase in the temperature is observed. This changes the dielectric properties and consecutively the electric field distribution.

The governing equation for electric field is:

$$\nabla^2\mathbf{E} + k^2\mathbf{E} = 0 \tag{7}$$

The wave number k = α + jβ where:

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon'\left(\sqrt{1+\tan^2\delta}+1\right)'}{2}} \tag{8}$$

$$\beta = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon''\left(\sqrt{1+\tan^2\delta}-1\right)'}{2}} \tag{9}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{10}$$

The behaviour of microwave can be altered when it encounters boundary or interface. For example, the metallic walls in a microwave oven can impose a boundary condition on Maxwell's equation. As the metallic walls are good conductors and reflect the microwave, electric field parallel to wall is zero. In addition, dielectric-air interface in the microwave oven and packaging material-dielectric can impose boundary conditions [5].

For example, the change in the microwave propagation at the dielectric-air interface because of change in dielectric properties causes changes in the reflected and transmitted waves through the dielectric.

Boundary Condition on Walls

Since the walls of a typical microwave oven are metallic conductor, electric field parallel to wall (or tangential) and hence the magnetic field normal to wall disappears:

$$\boldsymbol{B}\times\boldsymbol{n}=0 \tag{11}$$

This natural boundary condition:

$$\boldsymbol{E}\times\boldsymbol{n}=(\nabla\times\boldsymbol{B})\times\boldsymbol{n}=0 \tag{12}$$

$\boldsymbol{E}_{t,air}=0$ t – tangential direction

$\boldsymbol{B}_{n,air}=0$ n – normal direction

Boundary condition on waveguide and ports:

In the waveguide and ports is applied Dirichlet boundary condition:

$$\boldsymbol{B}\times\boldsymbol{n}=\boldsymbol{V}_m \tag{13}$$

$\boldsymbol{V}_m$ – vector function described by the magnetic field distribution on the waveguide and ports.

Boundary Conditions on air-dielectric Interface

Suppose the permittivity and permeability of the dielectric and air are ε_1, μ_1 and ε_2, μ_2 respectively, then the following conditions has to be satisfied:

$$\boldsymbol{n}\times(\boldsymbol{E}_2-\boldsymbol{E}_1)=0 \tag{14}$$

$$\boldsymbol{n}\cdot(\varepsilon_2\boldsymbol{E}_2-\varepsilon_1\boldsymbol{E}_1)=0 \tag{15}$$

$$\boldsymbol{n}\times(\boldsymbol{B}_2-\boldsymbol{B}_1)=\boldsymbol{P} \tag{16}$$

$$\boldsymbol{n}\cdot(\mu_2\boldsymbol{H}_2-\mu_1\boldsymbol{H}_1)=0 \tag{17}$$

where *n* is unit outward normal originating from the dielectric.

This set of equations implies that the magnetic field is chosen for computing the power distribution. This is valid when $\mu_1=\mu_2=\mu_0$ and $\boldsymbol{P}=0$, i.e., the magnetic field is continuous across the interface and the electric field is discontinuous across the interface. In addition, tangential components of electric and magnetic field are continuous across the interface.

However, Datta (2001) [5], argues that the interior of the cavity is to be treated as a dielectric with appropriate dielectric properties of air and the dielectric. The dielectric -air interface does not have to be taken into account in modelling the entire cavity. In that case, boundary condition at the dielectric-air interface disappears.

3. The Equation and the Boundary Conditions for Heat and Mass Transfer

The prediction of temperature profile in the dielectric exposed to microwave is done by solving the following energy balance equation:

$$\nabla \cdot (K \nabla T) + Q = \rho C_p \frac{\partial T}{\partial t} \tag{18}$$

ρ – density;
C_p – specific heat;
K – thermal conductivity.

The above equation assumes that the heat is transported only by conduction in the dielectric and the temperature is function of space and time. The heat source term (Q) is function of space and temperature [5]. The surface of the dielectric loses temperature to the surroundings by convection and radiated heat loss is not possible in a typical microwave-heating situation since the temperature do not reach high enough to radiate. Evaporative cooling on the surface of the dielectric also influences the temperature profile.

Therefore, the boundary condition is:

$$KA \frac{\partial T}{\partial n} = h_t A(T_s - T_0) + \lambda_v \frac{\partial m}{\partial t} \tag{19}$$

where: T_s – is surface temperature of the dielectric;
h_t – is the convective heat transfer coefficient;
λ – represents the evaporative heat loss λ is latent heat of vaporization;
$\frac{\partial m}{\partial t}$ – rate of evaporation or moisture transport.

Is calculated from the following equation:

$$\nabla \cdot (D_m \cdot \nabla \cdot m) = \frac{\partial m}{\partial t} \tag{20}$$

with boundary conditions:

$$n(D_m \nabla M) = \frac{h_m}{\rho}(P_s - P_a) + \frac{S \cdot C_p}{\lambda_v}\left(\frac{\partial T}{\partial t}\right) \tag{21}$$

where:

D_m – diffusivity;

S – shape factor;

λ_v is latent heat of vaporization;

h_m - is surface mass transfer coefficient,

P_a and P_s are partial vapour pressure of air and partial vapour pressure at the product surface, respectively.

Mass transfer of the dielectric is temperature dependent and the energy balance equation depends on the mass transfer equations. In addition, dielectric properties are temperature dependent.

4. Numerical results

In this paper it is shown an application of 3D numerical modelling, using the Method of the Finite Elements with an adapted solution (HFSS 10.0), which delivered results regarding the evaluation of the uniformity grade of the electric field both in the interior of the dielectrics and on their surface [6], [7], [8].

The dielectrics (wood) are static and have the same humidity (M= 60%), the dielectric constants (ε'=5,5; tg δ = 0,20). The dielectric material is considered uniform and homogenous, with constant dielectric and thermal properties. In fact, it is non homogenous, and the dielectric constants vary with the temperature.

In figure 1, we present the geometry of the microwave applicators. The two domains, the wave guide and the cavity are coupled between them by a slit.

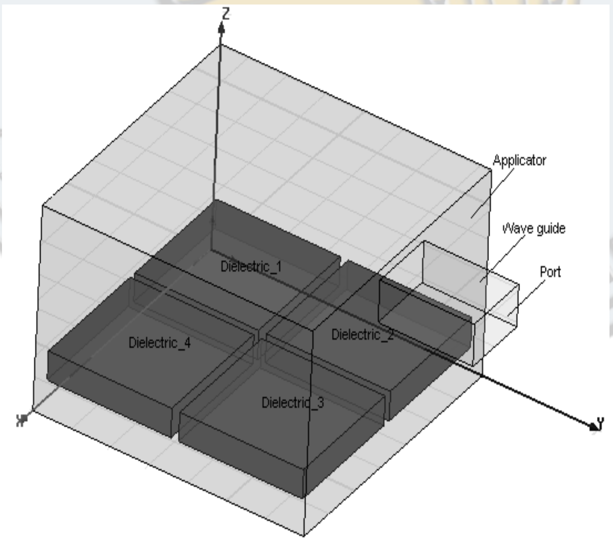

Fig. 1. The geometry of the applicator.

In figure 2, 3 we present the distribution of the electric field in the dielectrics which are in diagonal.

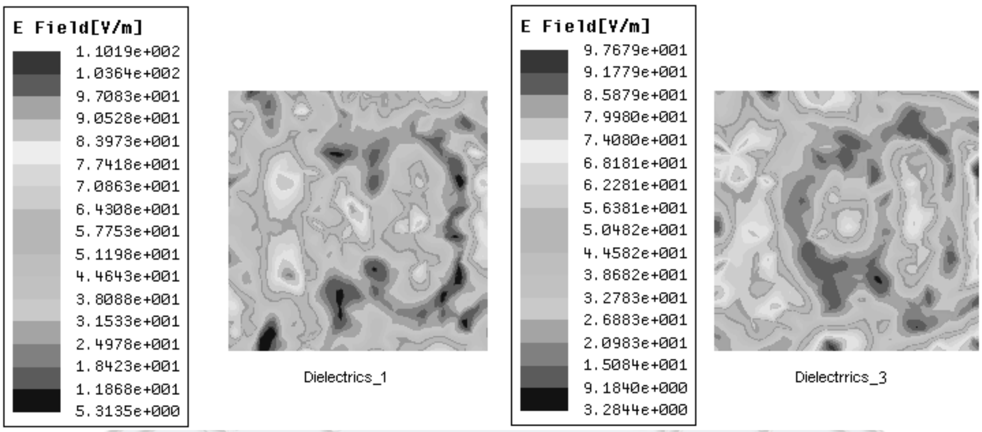

Fig. 2. The electric field in the dielectrics which are in diagonal (1,3).
a. Description; **b.** Description.

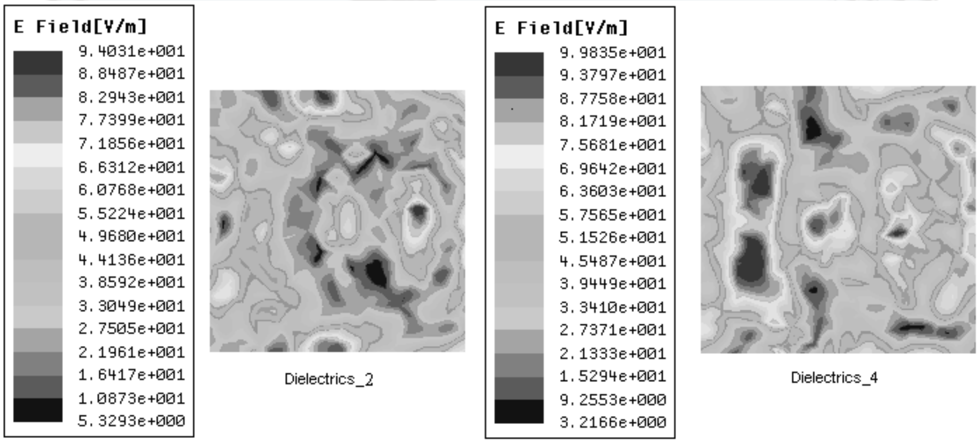

Fig. 3. The electric field in the dielectrics which are in diagonal (2,4).

We followed the calculation of the distribution of the electromagnetic field in the multimode cavity and in the dielectric material, the power density dissipated in the dielectrics with losses and then of the temperature in the material after a certain time of exposure to microwaves. The obtained results offer information regarding the evaluation of the uniformity degree in an electric field both in the interior of the dielectrics and on their surface. By analysing the obtained results we observe that the distribution is that of stationary waves, with maximums and minimums. The highest value being obtained near the wave guide, what clearly will create surfaces in which the temperwill be higher, this will alternate with surfaces in which the temperature will be smaller.

The plane uniform electromagnetic wave propagates diminished in real dielectrics, the attenuation being the more marked the larger the losses (ε' tg δ) are. In figure 4 we show the magnitude of the matrix *S*.

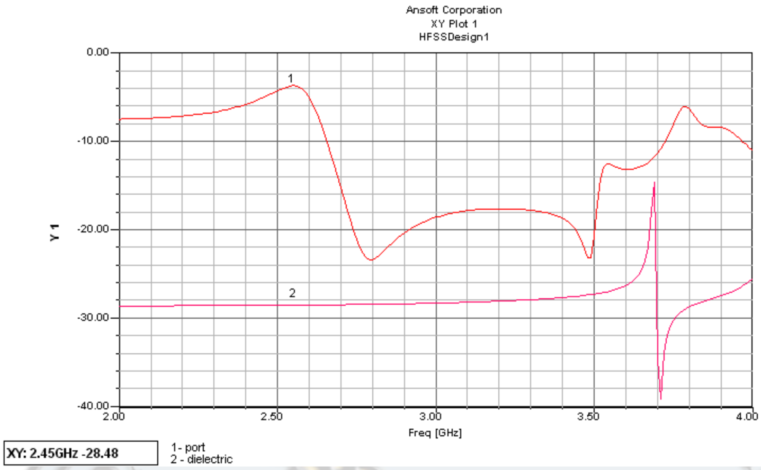

Fig. 4. The magnitude of the matrix S in a port and on the surface of the dielectric.

The bigger the value in the mode of the matrix S is, the smaller the power reflected back to the guide, that is the dielectric absorbs a maximum quantity of power. With the help of the parameter S we can determine the optimum positions for the placing of the dielectrics in the interior of the cavity.

The repartition matrix is the proportion between the amplitude of the tension wave reflected at the entrance terminal and the amplitude of the tension guide incident to the exit terminal, when all the other terminals are adapted.

By analyzing the magnitude of the matrix S (characteristic 2) we observe that the dielectric absorbs a maximum quantity of power when it is placed in the centre of the cavity.

In figure 5 we present the geometry of the microwave applicators.

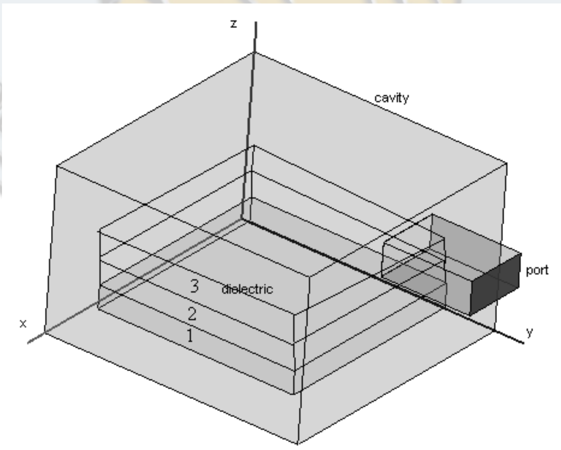

Fig. 5. The geometry of the applicator.

In figure 6, 7, 8 we present the distribution of the electric field in the dielectrics.

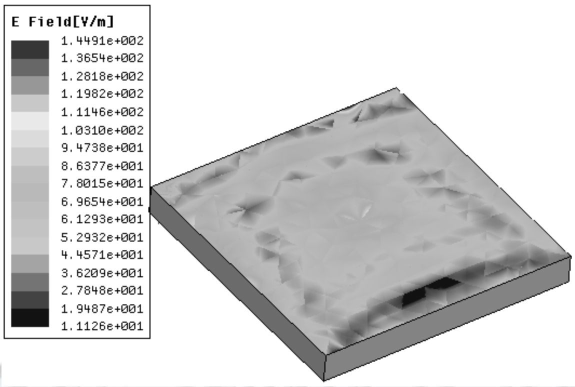

Fig. 6. The distribution of the electric field in complex measures on the surface of the dielectric_1.

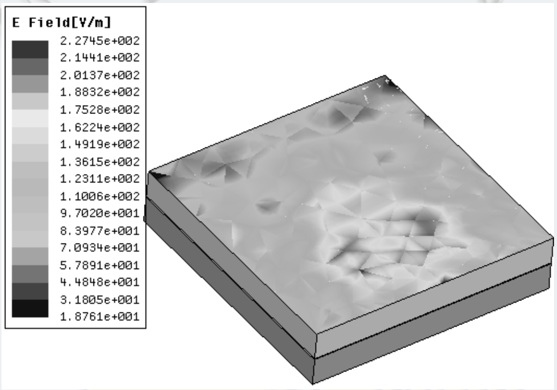

Fig. 7. The distribution of the electric field in complex measures on the surface of the dielectric_2.

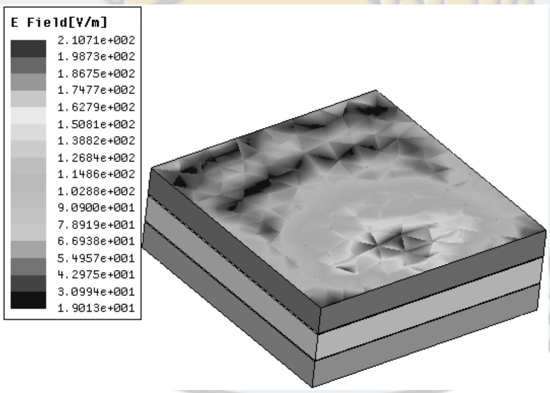

Fig. 8. The distribution of the electric field in complex measures on the surface of the dielectric_3.

In the case of the processing of superposed dielectrics we remark a nonuniform distribution of the electric field on their surface. For its uniformization it is necessary the presence of a conventional source with warm air or of an agitator of modes. With the help of the HFSS programme we solved the problem of the electromagnetic field, the obtained results being used then in the programme for the determination of the thermal field.

Conclusions

(1) The application of the method of the finite elements is the solving of the problems of the high frequency electromagnetic field implies a study of the main properties of the operators of the problem.
(2) The analysis of the electromagnetic field with the help of the HFSS 10.0 programme offers a generation of the division of the network with tetrahedral elements, with auto refinement in the areas with large variations of permittivity.
(3) This analysis is efficient, but it supposes the exact knowledge of the dielectric and thermal properties of the material that is to be processed, and the dependence of these properties on temperature.
(4) The non uniformity of the field remains a problem, although out of various reasons we want its diminishing.
(5) In most of the cases, the factor of losses grows at the same time with the growth of the temperature, what amplifies the non-uniformity effect.
(6) The phenomenon of non-uniformity can be removed by modifying the position of the wave guide, the use of the modes agitators or, in the case of the cavities of large sizes, through the movement of the load in the interior of the oven.
(7) Taking into account all these problems, which appear during the processing in a microwave field, we can however state that the transfer phenomenon of the electromagnetic field in microwave structures is performed faster, assuring thus higher efficiency, the absence of the energy losses through thermal radiations.

REFERENCES

[1] M. Audhuy, M. Majdabadino, *Caractérisation Microounde des Matériaux Absorbants*. Limoges, 1991.

[2] A.C. Metaxas, R.J. Meredith, *Industrial Microwave Heating*. Peter Peregrinus Ltd., London, 1983.

[3] V.V. Yakovlev, *Efficient Electromagnetic Models for Systems and Processes of Microwave Heating*. International Seminar on Heating by Internal Sources 11-14 Sept. 2001 Padova, Italia, pp. 285-292.

[4] Roussy G, J.A. Pearce, *Foundations and industrial applications of microwaves and radio-frequency fields*. British Library Cataloguing in Publication Data, Great Britain, 1995.

[5] S. Ryynanen, *The electromagnetic properties of food materials: a review of the basic principles*. Journal of Food Engineering. 26(4), 1995, pp. 409-429.

[6] T. Leuca, Livia Bandici, Carmen Molnar, *The Study of the Drying of Wood in a Microwave Field.* Progress in Electromagnetic Research Symposium – March 28-31 Pisa, Italy, 2004, pp. 349-352.

[7] Livia Bandici, Carmen Molnar, *The Influence of the Electromagnetic Field on the Thermal Diffusion in Drying Processes in a Microwave Field*. 12th International IGTE Symposium on Numerical Field Calculation in Electrical Engineering, September 17 – 20. 2006, Graz – Austria, pp.410-415.

[8] T. Leuca, Livia Bandici, Carmen Molnar, *Aspects regarding the propagation of the high frequency electromagnetic field in the dielectric materials.* 11th International Conference on Microwave and High Frequency Heating, Oradea, Romania, September, 3-6, 2007, pp. 79-82.