Some Aspects Regarding the Optimization of the Electromagnetic Field Propagation in Microwave Structures

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Abstract *– The paper presents an optimization procedure for the distribution of the electromagnetic field in a microwave applicator used for the drying of a dielectric. There are shown various applications of numerical modelling 3D, using the Method of the Finite Elements, for the study of the heating of some dielectrics with losses, of parallelepiped shape, situated in a multimode applicator, excited with energy through a wave guide. To determine the electromagnetic field we used the Ansoft HFSS 10.1 programme. This programme uses the finite elements method and the nodal functions of the first order. The calculation domain is divided into tetrahedral subdomains and the field in each subdomain is properly defined by the values in the nodes of the tetrahedron. In this paper we present the optimization of the distribution of the electromagnetic field from the following point of view: the placing mode of the wave guide on the applicator. The main problem which appears is represented by the homogeneity of the field and implicitly of the temperature in the material.*

Keywords: *electromagnetic field, optimization, microwave, dielectric, numerical modelling, finite elements method.*

I. INTRODUCTION

One of the most important issues related to the processing of dielectric materials within a microwave structure is the homogenization of both the thermal and the electromagnetic field so that the physical and chemical properties of the material should be preserved intact.

Articles [1] and [2] present a series of theoretical aspects concerning the industrial heating in a microwave field and compares the properties of dielectric materials and their evolution when exposed to radio-frequency and microwave, and [3] describes the recent steps forward made in relation to the numerical techniques that are used when simulating applications in the domain of microwave field heating.

Articles [4] and [5] deal with the numerical analysis of the most widely used multimode applicators, such as kilns. It is demonstrated that, in order to analyze the heating characteristics of a certain type of oven, it is necessary to solve Maxwell's equations for the field within the applicator, in other words to find the distribution of the electromagnetic field within the applicator for real charges. The utilization of numerical techniques makes this possible. In conclusion, it may be asserted that the method of the finite elements represents an important tool in the analysis of the heating systems using microwave, because it allows the utilization of uneven networks that correspond to the geometry of the problem.

The determination of the thermal field implies the calculation of the electromagnetic field in the interior of the applicator.

In [2] are presented mixed methods of calculation of the field in the interior of the microwave applicator.

The works [3], [4] present studies on the distribution of the electromagnetic field in the applicator and in a dielectric situated in the interior of the applicator.

In the present paper we had in view the optimization of the distribution of the electromagnetic field from the following points of view:

– the obtaining of an electric field as uniform as possible distributed on the entire surface of the dielectric;

– a coupling as good as possible between the applicator and the load;

– the placing mode of the wave guide on the applicator.

II. THE ELECTROMAGNETIC FIELD PROPAGATION IN THE MICROWAVE STRUCTURES

In [1] there are presented the heating mechanisms of the dielectric materials. This effects are due, on the one hand, to the polarization of the loaded particles in the material by the electric field of high frequency, and on the other hand, to the Joule effect, due to the conduction of the free loads at the action of the electric field.

At low frequencies, the time requested for the electric field to change direction is longer than the response time of the dipoles and the dipolar polarization is in phase with the electric field. The electric field provides the energy necessary to the orientation of the field molecules.

Part of the energy is consumed by the Brownian movement, when a dipole is moved from its place by concussion and then realigned. The energy transferred is small, the temperature increasing very little.

An electromagnetic system functions at resonance if in a harmonious regime the reactive power received by the system is null.

The systems with resonant microwaves are part of the category of devices used in the heating of the dielectric materials in a microwave field [6].

The sizes of the microwave systems are large in comparison to the wave guide we used. The number of modes that can appear in comparison with the wave length depends generally on the volume of the system and the working frequency.

There are cases in which in the cavity we introduce auxiliary devices able to perturb the field, and, when it is possible, the body exposed to heating can start moving.

At resonance, the behaviour of a system is purely resistive, from the point of view of the alimentation source there takes place an exact compensation of the electric energy with the magnetic one in the interior of the system, and the contribution of active power supplied by the source is compensated by the consumption of active power in the dissipative elements of the system.

At different resonance frequencies, over the resistive behaviour we add a reactive behaviour determined by the lack of balance between the average electric energy and the average magnetic energy in the system, in the oscillating process maintained by the source.

The guiding of the electromagnetic waves through the structures of the microwaves is realized by a strong bound 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 at these boundaries, and not only.

The knowledge of the distribution of the electromagnetic field in the microwave structures makes possible the knowledge of the constant of the propagation of the waves, of its dependence with the frequency, of the propagation speed, of the phase and attenuation constant, etc.

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

$$\nabla \mathrm{x}\mathbf{E} = -\frac{\partial}{\partial \mathrm{t}}(\mu\mathbf{B}) \tag{2}$$

$$\nabla \mathrm{x}\mathbf{B} = -\frac{\partial}{\partial \mathrm{t}}(\varepsilon'\varepsilon_0\mathbf{E}) + \varepsilon''\varepsilon_0\omega\mathbf{E} \tag{3}$$

$$\nabla \cdot (\varepsilon\mathbf{E}) = 0 \tag{4}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{5}$$

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

$$\varepsilon = \varepsilon' + j\varepsilon'' \tag{6}$$

Maxwell's equations can predict the electric field **E** as a function of position and time.

The governing equation for the 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 the microwave can be altered when it encounters boundary or interface.

The change in the microwave propagation in the dielectric – air interface because of change in dielectric properties causes changes in the reflected and transmitted waves through the dielectric.

This natural boundary condition:

$$\mathbf{E}\,xn = (\nabla x\mathbf{B})xn = 0 \tag{11}$$

$\mathbf{E}_{t,air} = 0$ t – tangential direction
$\mathbf{B}_{n,air} = 0$ n – normal direction

In the waveguide and ports Dirichlet boundary condition is applied:

$$\mathbf{B}\mathrm{xn} = \mathrm{V_m} \tag{12}$$

V_m – vector function described by the magnetic field distribution on the wave guide and ports.

On air-dielectric interface, the boundary conditions are:

$$\mathrm{nx}(\mathrm{E}_2 - \mathrm{E}_1) = 0 \tag{13}$$

$$\mathrm{n}\cdot(\varepsilon_2\mathrm{E}_2 - \varepsilon_1\mathrm{E}_1) = 0 \tag{14}$$

$$\mathrm{nx}(\mathrm{B}_2 - \mathrm{B}_1) = \mathrm{P} \tag{15}$$

$$\mathrm{n}\cdot(\mu_2\mathrm{H}_2 - \mu_1\mathrm{H}_1) = 0 \tag{16}$$

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

These equations imply that the magnetic field is chosen for computing the power distribution. This is valid when $\mu_1=\mu_2=\mu_0$ and 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) 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, the boundary condition at the dielectric-air interface disappears.

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

$$\nabla \cdot (\mathrm{K}\nabla\mathrm{T}) + \mathrm{Q} = \rho\mathrm{C_p}\frac{\partial \mathrm{T}}{\partial \mathrm{t}} \tag{17}$$

where: 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 a function of space and time. The heat source term (Q) is a function of space and temperature [8]. 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 does not reach high enough to radiate.

Evaporative cooling on the surface of the dielectric also influences the temperature profile.

Therefore, the boundary condition is:

$$KA\frac{\partial T}{\partial n} = h_t A(T_s - T_0) + \lambda_v \frac{\partial m}{\partial t} \qquad (18)$$

where: T_s - is the 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:

$$\nabla \cdot (D_m \cdot \nabla \cdot m) = \frac{\partial m}{\partial t} \qquad (19)$$

with the boundary conditions:

$$n(D_m \mathrm{grad}(M) = \frac{h_m}{\rho}(P_s - P_a) + \frac{S \cdot C_p}{\lambda_v}\left(\frac{\partial T}{\partial t}\right) \qquad (20)$$

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.

III. THE OPTIMIZATION OF THE ELECTROMAGNETIC FIELD IN THE INTERIOR OF MICROWAVE SYSTEMS

The performances of a microwave system depend both on the geometrical sizes and on the properties of the material that is to be processed.

If the geometrical sizes of the applicator can be chosen by the projector, not the same thing happens to the dielectric and thermal properties of the material, these can not be chosen.

For the optimization of a microwave system in the first phase we define its performance criteria, and in the next phase we define the proportion between the active power and the surface of the dielectric at a given moment. The higher the value of this proportion is, the more reduced are the heat losses through convection and the applicator will have a higher thermal efficiency.

Once we established the criterion of optimizing the applicator, with the help of the numerical modelling programme we can study the influence of each parameter on their performances. The rolling time of the applicator is much smaller in comparison to the construction of a prototype that secures the possibility to vary all the geometrical parameters.

The optimization through numerical modelling is efficient, but supposes the exact knowledge of the dielectric and thermal properties of the dielectric that is to be heated, as well as their dependence on the temperature.

IV. RESULTS

The optimization of the cavities in given conditions (material parameters, geometry parameters, electric parameters), in relation to a variable parameter (position, moisture, etc.), can be obtained through the analysis of the high-frequency electromagnetic field distribution in the guide systems - a cavity that can be obtained using the programme for numerical modelling HFSS 10.1.

The uneven distribution of the electromagnetic field upon the surface of the dielectric can lead to the appearance of uneven temperature surfaces.

Starting from the theoretical considerations we presented, we tried the numerical modelling of the electromagnetic field from an applicator with the sizes: (310 mm x 310 mm x 210 mm). The geometry of the applicator is shown in fig. 1.

We considered a dielectric having the characteristics $\varepsilon_r = 3{,}5$, tg$\delta = 0{,}22$ and the moisture 30%. The position of the dielectric has remained the same in comparison to the basic plan of the applicator.

We changed the wave guide position on the cavity in four different positions, as you can see in the fig. 1 from a) to d).

In the first stage we had in view to obtain a distribution as uniform as possible of the electric field in the interior of the applicator. The distribution of the electromagnetic field is influenced by the position of the feeding guide of the applicator, and the position of the load in the interior of the applicator.

Fig. 2 presents the distribution of the electric field on the surface of the cavity, when the feeding guide is differently placed and the dielectric is placed at the same distances from the basic plan of the cavity.

The solving of the electromagnetic field problem with the Ansoft-HFSS 10.1 program helps us obtain information concerning the density of volume of the power loses inside the load. The evolution of the load’s moisture is dictated by the thermal field.

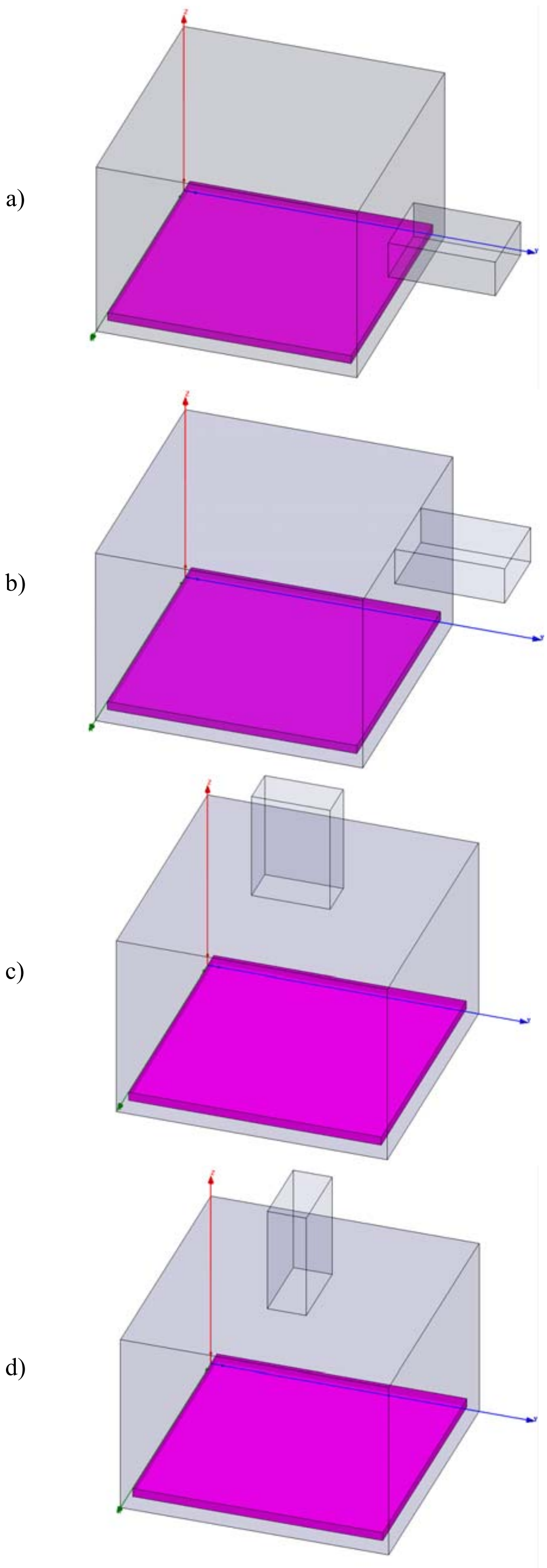

Fig. 1 – The geometry of the applicator

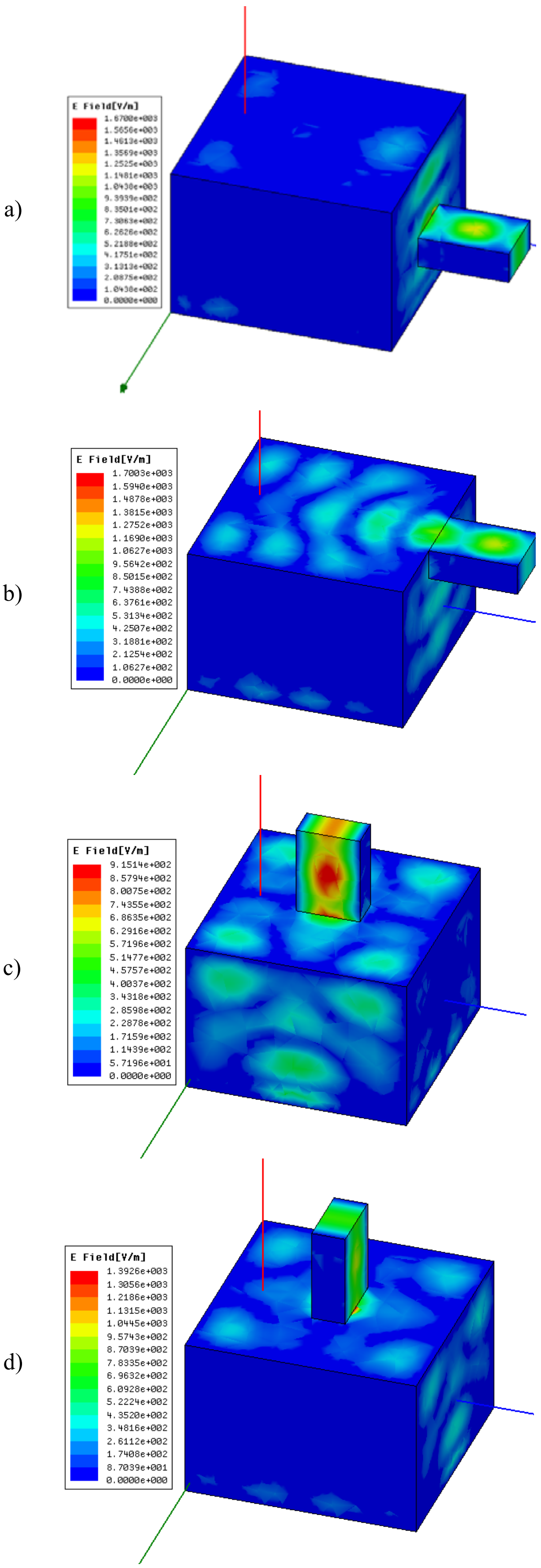

Fig. 2 The distribution of the electromagnetic field
in complex measurements on the inner faces of the applicator
and in the port

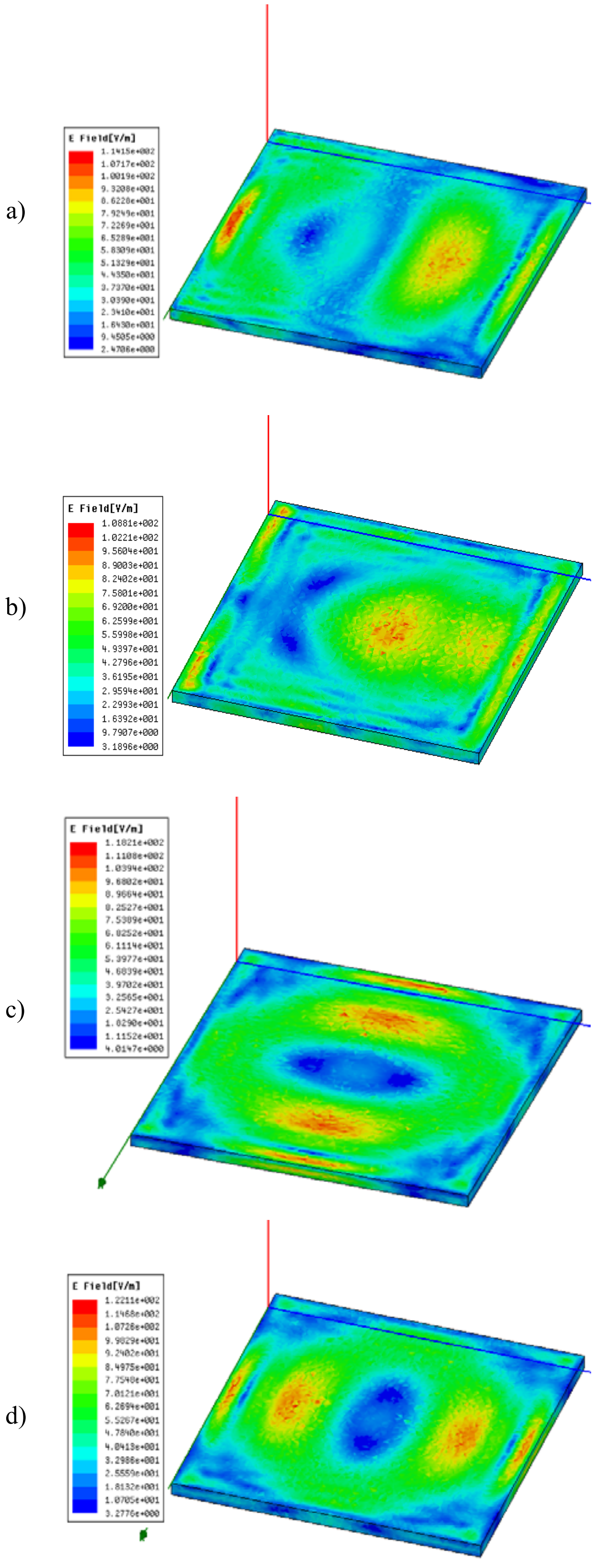

Fig. 5. The distribution of the electric field in complex measurements on the surface of the dielectrics a),b) the electromagnetic wave is placed in a plan parallel with the dielectrics and c),d) the electromagnetic wave is placed in a perpendicular plan with the dielectrics

The analysis of the electromagnetic field offers a founding of the division network with tetrahedral elements, with self refinement in the areas with big variations of permittivity.

This analysis is efficient, but it supposes the exact knowledge of the dielectric and thermal properties of the material that is to be processed, as well as the dependence of these properties on the temperature.

In fig. 5 we present the distribution of the electric field in complex measurements on the surface of the dielectrics, in the case in which the electromagnetic wave is placed in a perpendicular plan on the surface of the dielectric a),b) and c),d) the electromagnetic wave is placed in a perpendicular plan with the dielectrics.

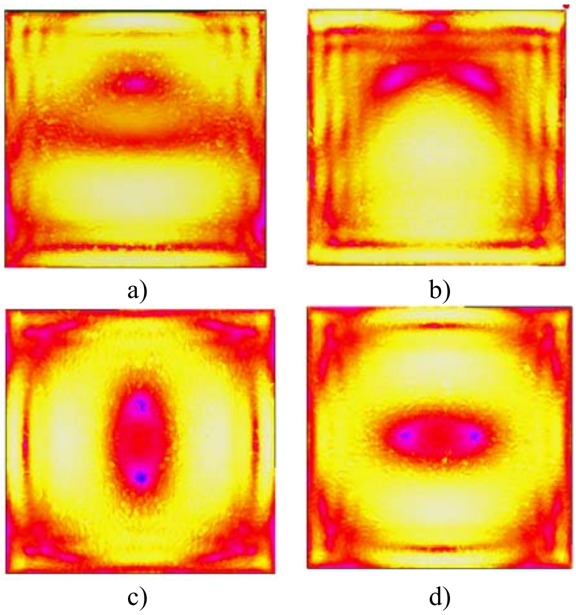

Fig. 6. The distribution of the temperature field in the dielectric mass in the four cases

We presented the variation of the electric field in the most important four cases that we studied.

In the case in that the dielectric is placed in a cavity with the wave guide placed as in fig. 1 b), the amplitude of the electric field has the most uniform variation.

In order to obtain a uniform distribution of the high frequency electromagnetic field it is required either the use of some mode agitators, or the combined use of microwaves – warm air.

After the optimizations we made, we found a decreasing of the relative deviation, with the rising of the dielectric from the basic plan while the drying time increases, but without reaching the time from the first case, when the dielectric is situated on the basic plan of the cavity.

We intend to continue with these researches for a relevant number of materials – dielectrics and to find the most efficient design for the cavity's geometry and for the wave guides.

V. CONCLUSIONS

The advantages of the numerical modelling compared to experimental measurements are obvious: rapidity in evaluation and versatility of the models - in numerical models the anatomical data could be easily changed. Besides, in experimental studies the required laboratory conditions are seldom accessible.

When we first establish the optimization criteria of the applicator, the numerical modelling programme, we can make the study of the influence of any parameter of the applicator on its performances.

On the placing mode of the wave guide on the cavity depends the distribution of the electromagnetic field, the uniform distribution of the losses and the drying time, which imposes a coupling as good as possible between the applicator and the load.

The optimisation study was realised using only one type of dielectric, but with the following research we expect to generalize the phenomena.

Achieving optimisations by using the numerical analysis programmes is a very efficient method, but these results need sometimes an experimental verification, especially to validate the thermal transfer parameters used in the thermal diffusion problem.

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