ANALYSIS OF THE ELECTROMAGNETIC FIELD IN A CONTROLLED ENCLOSURE FOR BIOLOGICAL DOSIMETRY

PART 2. ANALYSIS OF ELECTROMAGNETIC FIELD WORKING CONDITIONS

MIHAELA MOREGA, ALEXANDRU MIHAIL MOREGA

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The work presented here is the continuation of the paper with the same title. Part 1 – Design and Validation of the Numerical Model, published in a previous issue of the journal [1], which includes the numerical model and its validation by numerical simulation and experiment. Some characteristics of the enclosure under investigation, the so called TEM-cell, used for controlled exposure of biological material to electromagnetic field (EMF) are also determined, with the aim of assessing the uniformity of the electric field in the region where the analyzed sample is exposed to microwaves (MW) or radiofrequency (RF) waves. Part 2 of the paper reports some results obtained by simulation with the finite element method (FEM); it presents the evaluation of some relevant dosimetric quantities relative to the exposed biological material, and investigates the stability of the exposure conditions at small variations of the EMF frequency.

1. INTRODUCTION

The exposure of biological material to high frequency electromagnetic field (EMF), either MW or RF waves, is currently investigated under planar wave conditions, similarly to the idealized field propagation mode in free space. One of the commonly used exposure devices, which offers the advantage of low cost efficiency in producing adequate EMF conditions, is the TEM-mode chamber or TEM cell, and it is largely presented in [1]. The cell design, performance and the experimental setup used in a research program at the Land Forces Academy in Sibiu [2, 3] are found in [1], together with a FEM model implemented by COMSOL Multiphysics software [4]. Paper [1] reports the validation of the numerical model against theoretical and experimental tests; it also presents the

“Politehnica” University of Bucharest, Electrical Engineering Department, E-mail: mihaela@iem.pub.ro, amm@iem.pub.ro

computation of several functional characteristics of the TEM cell, in order to assess its usability for dosimetric research of non-thermal biological effects in cereal seeds exposed to low-level MW at 0.9 GHz [2, 3]. The results in [1] are considered at the origin of the current work, and refer to:

– the evaluation of the cut-off frequency \( f_c = 0.333 \) GHz, for the first order propagating mode TE\(_{10}\), which theoretically sets the superior limit for TEM wave mode propagation,

– the evaluation of the voltage standing wave ratio (VSRW) in the frequency range (0.8…1.8) GHz; this frequency range is required by the dosimetric analysis, in spite of the fact that it goes beyond the limit stated by \( f_c \),

– the evaluation of the electric field uniformity at the working frequency of 0.9 GHz, situated also above the cut-off frequency.

The working conditions stated by the required dosimetric program, especially the working frequency of 900 MHz, force the functioning of the cell in the domain of higher order propagating modes, which is possible to cause the perturbation of the electric field quality.

2. DOSIMETRIC ESTIMATES

Following previous considerations, we used the TEM cell model in a dosimetric analysis. The biological sample to be irradiated at 0.9 GHz is placed in a Petri dish, set on the septum of the TEM cell, in the region identified as the rectangular test volume (RTV), characterized as the region with the highest uniformity of the electric field [1]. The Petri dish is a glass cylinder, 1.5 mm thick, 90 mm in diameter and 15 mm in height; in our experiment, the biological material (cereal seeds) covers 1/3 of its height. The dish is symmetrically placed in the RTV region, position that allows for the reduction of the computational domain to half, by symmetry considerations. The physical properties of the Petri dish and of the subdomain occupied by the biological material are specified in Table 1; biological material is generally non-magnetic.

The exposed bunch of seeds is introduced here as a homogeneous subdomain because the penetration depth in the biological material at the working frequency of 900 MHz is within the range of centimeters, a dimension considerably larger than the characteristic dimension of the cereal seed. Therefore we conjecture that the true shape and dimensions of the seeds do not affect the electric field distribution.

The dosimetric analysis refers to the electric field distribution, the power absorbed in the biological medium and the heating control, considering that non-thermal biological effects are envisaged (i.e., the power delivered to the biological sample is low enough so that the heating is less than 0.1 degrees above the reference temperature).
The electromagnetic field model is described in [1]. The thermal analysis reported here refers to the unsteady conduction heat transfer inside the exposed sample, and it is governed by the energy equation

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q. \quad (1)$$

Here $T$ is the temperature, $t$ is the time, $\rho$ is the mass density, $C$ is the specific heat, $k$ is the thermal conductivity, and $Q$ is the body heat source (by EMF radiation). The physical domain is represented by the Petri dish and by the biological load. The biological load – the collection of cereal seeds – is associated to a region of homogeneous, thermally equivalent, continuous medium (the physical properties are specified in Table 1). The heat transfer problem is time-dependent, related to the onset of the EMF field through the heat source, which is the specific power absorbed in the seeds, $Q$, evaluated in the electromagnetic field problem.

The plane of symmetry allows for a thermal insulation boundary condition

$$- \mathbf{n} \cdot (-k \nabla T) = 0. \quad (2)$$

On the outer surface of the Petri dish, which is in direct contact with the air inside the TEM cell, a convection heat transfer boundary condition is prescribed

$$- \mathbf{n} \cdot (-k \nabla T) = h(T_{\text{amb}} - T). \quad (3)$$

The ambient temperature inside the TEM cell is $T_{\text{amb}} = 300 \text{ K}$, and the heat transfer coefficient is $h = 1 \text{ W/(m}^2\text{K)}$ – natural convection heat transfer. We assume that between the Petri dish and the metallic septum there is a thermally insulating sheet of material, therefore the dish bottom is adiabatic (2).
First, we computed the \( E \)-field distribution inside the biological sample; the electric field solution provides for the specific power absorbed in the sample, defined as the electric energy rate absorbed in the volume of sample

\[
Q = \frac{d}{dt} \left( \frac{dW}{dV} \right) = \sigma E^2,
\]

and the specific energy absorption rate, a quantity of interest in dosimetry

\[
\text{SAR} = \frac{Q}{\rho} = \frac{\sigma E^2}{\rho}.
\]

\( E \) in eqs. (4) and (5) is the r.m.s. of the electric field strength. Fig. 1 shows the distribution of \( E_z \) in the longitudinal, vertical plane of symmetry; \( E_z \) is the \( E \) component in \( z \) direction, identified in our dosimetric analysis as the most significant component of the electric field (\( E = E_x i + E_y j + E_z k \equiv E_z k \)) [1].

![Slice: Electric field, z component [V/m]](image)

**Fig. 1** – \( E_z \) spectrum in the longitudinal section of the loaded cell (incident power density 0.05 W/m\(^2\), at 900 MHz).

Figure 2 shows the same \( E_z \) and SAR in the exposed biological sample at its half-height, following the longitudinal (\( x \)) and transversal (\( y \)) directions, respectively (distributions in \( y \) direction in Fig. 2 are completed by symmetry). The
power density of 0.05 W/m² characterizes the time-harmonic MW radiation at 900 MHz in the region of exposure.

The $E_z$ field amplitude drops inside the exposed sample to approx. one third of its amplitude in the surrounding air, and has a quasi-uniform distribution, due to the screening effect produced by the insulating glass dish and to the conductive properties of the sample.

The influence of the electric conductivity variation on the electric field amplitude is next analyzed, considering a ±20% dispersion of $\sigma_{bio}$ about the value in Table 1, which is usually a result of the variable water content of the sample. Fig. 3 shows $E_z$-distributions in $x$ and respectively $y$ directions, in the same EMF exposure conditions as the case in Fig. 2 (due to the symmetry, this time only half of the distribution is presented in $y$ direction); $E_z$ resulting dispersion about the values corresponding to $\sigma_{bio} = 0.055$ [S/m] is currently less than ±1%. When SAR is evaluated [see eq. (5)], its proportionality to the electric conductivity leads to dispersions of approx. ±20% around the reference value of SAR, corresponding to $\sigma_{bio} = 0.055$ S/m (dashed lines).

The dosimetric analysis proceeds, finally, to the heating estimation. We solved the heat transfer problem (1–4) with the aim to identify the highest level of the feeding power that still complies with non-thermal exposure restrictions. The power density within the exposure region of the TEM cell is varied in the range (0.05÷5.5) W/m².
Fig. 3 – $E_z$ component distributions, in the exposed biological sample, along the longitudinal ($x$) and transversal ($y$) directions, respectively, at the half-height of the sample, for several values of the electric conductivity (incident power density 0.05 W/m², at 900 MHz).

Fig. 4 shows the average SAR inside the sample and its average heating above the initial temperature (i.e., the ambient temperature $T_{\text{amb}} = 300$ K). Since an increase in temperature less than 0.1 degrees is a reasonable criterion for the non-thermal exposure, one could conclude that the power density of 3 W/m² should be the highest limit allowable for non-thermal experiments. This corresponds to a power level of 600 mW delivered by the MW generator, and to the average SAR = 0.034 W/kg recorded into the biological sample; the power absorbed by the biological sample, 1.02 mW in this case, represents 0.17% of the injected power.

Fig. 4 – Average SAR and average heating of the sample.
The power delivered by the 900 MHz MW source rises up to 0.55 W.
3. EIGENFREQUENCY ANALYSIS

The identification of the eigenfrequencies is important in order to avoid resonant behaviour of the cell; resonance phenomena impede the measurements, alter the field uniformity and the accuracy of dosimetric estimates. The eigenfrequency analysis was performed next on the unloaded vs. loaded TEM cell. The wave equation

\[ \nabla \times \left( \frac{1}{\mu} \nabla \times E \right) - \omega^2 \left( \epsilon - j \frac{\sigma}{\omega} \right) E = 0 \] (6)

is solved for the electric field strength

\[ \mathbf{E}(x, y, z, t) = \Re \left\{ \mathbf{E}(x, y, z) e^{-j\lambda t} \right\}, \] (7)

where \( -\lambda = \delta + j\omega \), is the solution of the eigenvalue problem, a complex number generally. It depends on \( \delta \), which stands for the damping factor (non-zero only for the loaded cell, due to the non-zero conductivity of the biological sample), and \( \omega = 2\pi f \) which points out to the eigenfrequency itself.

Because 900 MHz is planned to be the main exposure frequency in the biological investigation, the eigenfrequency analysis was focused around that value, and the computation of 12 eigenfrequencies was performed. When compared, as shown in Table 2, one may see that no significant differences result for the unloaded against the loaded cell. This behavior is explained by the low contribution of the sample to the whole configuration; the eigenfrequencies result from the entire geometry of the enclosure, where very small dimensions compared to the cell characterize the Petri dish.

<table>
<thead>
<tr>
<th>No.</th>
<th>Unloaded cell</th>
<th>Loaded cell</th>
<th>No.</th>
<th>Unloaded cell</th>
<th>Loaded cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>796.453</td>
<td>796.075</td>
<td>7</td>
<td>922.234</td>
<td>921.869</td>
</tr>
<tr>
<td>2</td>
<td>807.012</td>
<td>806.935</td>
<td>8</td>
<td>925.466</td>
<td>925.295</td>
</tr>
<tr>
<td>3</td>
<td>866.934</td>
<td>866.308</td>
<td>9</td>
<td>940.959</td>
<td>940.767</td>
</tr>
<tr>
<td>4</td>
<td>868.845</td>
<td>868.184</td>
<td>10</td>
<td>995.171</td>
<td>994.892</td>
</tr>
<tr>
<td>5</td>
<td>872.894</td>
<td>872.764</td>
<td>11</td>
<td>1025.374</td>
<td>1024.771</td>
</tr>
<tr>
<td>6</td>
<td>892.524</td>
<td>892.101</td>
<td>12</td>
<td>1032.691</td>
<td>1032.322</td>
</tr>
</tbody>
</table>

When the working frequency of the cell coincides with an eigenfrequency, the uniform distribution requirement for the \( E_z \) may no longer be fulfilled. For certain eigenfrequencies, the EMF distribution presents waves stationarity. The \( E_z \)
component distribution is plotted along the \( x \) axis inside the biological load, for the identified eigenfrequencies.

Fig. 5a presents the plots for seven eigenfrequencies considering that the \( E_z \) distribution is still quasiuniform in the exposed sample. Fig. 5b shows the plots for the other five identified eigenfrequencies, where one could see that important \( E_z \) nonuniformity appears inside the sample (true values of the electric field are not important here, only the distribution is analyzed).

![Fig. 5a](image1.png)

\[ \text{E}_z \text{-component plots, in the exposed biological sample, following the longitudinal (x) direction, at the sample half-height, for several computed eigenfrequencies (Table 2).} \]

![Fig. 5b](image2.png)

\[ \text{a. eigenfrequencies: no. 1,2,4,6,7,10,12 (Table 2)} \]

\[ \text{b. eigenfrequencies: no. 3,7,8,9,11 (Table 2)} \]

The stationarity phenomenon is illustrated in Fig. 6, by the \( E_z \) spectra, determined for two eigenfrequencies that are very close to 900 MHz: 872.764 MHz and 925.295 MHz.

![Fig. 6a](image3.png)

\[ \text{a. eigenfrequency 872.764 MHz} \]

![Fig. 6b](image4.png)

\[ \text{b. eigenfrequency 925.295 MHz} \]

The stationarity phenomenon is illustrated in Fig. 6, by the \( E_z \) spectra, determined for two eigenfrequencies that are very close to 900 MHz: 872.764 MHz.
and 925.295 MHz (no. 5 and 8 in Table 2). From Fig. 6 it is obvious that the RTV region (occupied by the Petri dish with biological sample) is not any more exposed to quasi-uniform electric field.

4. CONCLUSIONS

Dosimetric analysis requires the evaluation of the electric field and derived quantities (SAR, temperature, etc.) inside the exposed biological sample, which is difficult to be performed by experiment. This is the main reason that sustains the importance of EMF numerical modelling as a powerful tool in the study of biological material exposure to microwaves. True dimensions and geometry of the exposed biological material (cereal seeds in our case) could be also considered in a further study, if the trade between economy in computational resources and accuracy of the model will require such an effort. Numerical modelling is also able to take into account the real 3D geometry of the cell, which is an important request for a correct computation of the eigenfrequencies.

In the dosimetric studies, the uniformity of the electric field in the exposure region is important, but this property is highly dependent on the correlation between the geometry of the enclosure (the TEM cell) and the working frequency. The working conditions should be such that eigenfrequencies of the cell are avoided when the tests are designed, because nonuniformity of the electric field is more likely and even stationary distribution may occur.

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