Use of GTEM-cell and Wire Patch Cell in calculating thermal and non-thermal biological effects of electromagnetic fields

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1. Introduction

The increasing use of technology in our everyday environment has led to the ubiquitous presence of electromagnetic fields. These leads to many new researches in past ten years which deal with biological effects of high frequency fields, especially GSM frequency band. For that purpose developed are appropriate exposure systems.

In 1996, the World Health Organization (WHO) established the guidelines for quality Electromagnetic field experiments, where the importance of well-defined and characterised exposure conditions was emphasised.

Various system designs have been used for the exposure. Most of them belong to one of the following basic design ideas: Transverzal Electromagnetic (TEM) cell, RF chambers, radial transmission lines (RTL), waveguides or Wire Patch Cells (WPC).

In this chapter focus would be on G-TEM cell and Wire Patch Cell, their construction, characteristics, usage, advantages and disadvantages.

Performed were several models and tests with different power output levels in order to see field distribution inside system. As most of biological effects caused by RF electromagnetic radiation are thermal, temperature distribution and increase were also noted in order to separate temperature rise because of exposure system itself and temperature rise due to electromagnetic field levels.

2. Biological effect of Electromagnetic fields

Exposure to electromagnetic fields is not a new phenomenon. However, due to the increasing use of technology in our everyday environment has led to the ubiquitous presence of electromagnetic fields. Such fields arise wherever there is a voltage or a current. All types of radio broadcasting and TV transmitters produce electromagnetic fields, and they also arise in industry, business and the home, where they affect us even if our sense organs perceive nothing. Everyone is exposed to a complex mix of weak electric and magnetic fields, both at home and at work.

Generally we can divide biological effects of electromagnetic radiation on non-thermal and thermal effects. Non-thermal biological effects are related to low frequency electromagnetic field and are mostly manifested as induced currents in human body. Thermal biological effects occur due to high frequency electromagnetic fields. Radio frequency radiation interacts with matter by causing molecules to oscillate with the electric field. This interaction is most effective for molecules that are polar (have their own internal electric field) such as water. The water molecule loses this rotational energy via friction with other molecules and causes an increase in temperature. This effect is the basis for microwave cooking (Michelson et al, 1987).

Temperature increase during exposure to high frequency electromagnetic waves depends on: the specific area of the body exposed and the efficiency of heat elimination; intensity of field strength; duration of exposure; specific frequency or wavelength; and thickness of skin and subcutaneous tissue. Each frequency in the electromagnetic spectrum is absorbed by living tissue at a different rate, called the specific absorption rate or SAR, which has units of watts per kilogram (W/kg). Related to human thermoregulation, organs with the least blood flow are most endangered. The eyes are particularly vulnerable to RF energy in the microwave range, and prolonged exposure to microwaves can lead to cataracts.

The levels of radiofrequency fields to which people are normally exposed are very much lower than those needed to produce significant heating. The heating effect of radiowaves forms the underlying basis for current guidelines. Scientists are also investigating the possibility that effects below the threshold level for body heating occur as a result of long-term exposure.

The IEEE and many national governments have established safety limits for exposure to various frequencies of electromagnetic energy based on SAR.

$$SAR = \frac{\sigma E^2}{\rho} \quad (1)$$

Where E is RMS value of the electric field strength in the V/m, σ is the conductivity of body tissue in S/m and ρ is density of body tissue in Kg/m³

In the area of biological effects and medical applications of non-ionizing radiation approximately 25,000 articles have been published over the past 30 years. However, some gaps in knowledge about biological effects exist and need further research (WHO).

2.1 Regulation and standards

When the problem of electromagnetic pollution became evident, government and many non-governmental organizations came to solution to this problem with limitation of field strength. Over the years this limitations are getting stricter as measurements results showed growing number of new radiation sources. Individual countries have different approaches to the limits stipulated in the various regulations, standards, norms and recommendations.

In Table 1. Are exposure EMF limits by international organizations:

ICNIRP (International Commission on Non-ionizing Radiation Protection), **IEEE** (Institute of electrical and electronics engineering), **CENELEC** (European Committee for Electrotechnical Standardization).

Frequency		FCC occup.	ICNIRP occup.	DIV V EXPO-Range 2
50/60 Hz	Power delivery	----	500 μ T (B-Field)	1.251 μ T (B-Field)
27 MHz	CB radio, diathermy	68.2 V/m	61.0 V/m	61.4 V/m
100 MHz	FM radio	61.4 V/m	61.4 V/m	61.4 V/m
433 MHz	Industrial applications	73.4 V/m	62.4 V/m	62.4 V/m
900 MHz	Cell, pager	106 V/m	90.0 V/m	90.0 V/m
2.45 GHz	Microwave, industry	137 V/m	137 V/m	137 V/m
6 GHz	Digital radio	137 V/m	137 V/m	137 V/m
20 GHz	Satellite transmission	137 V/m	137 V/m	13 7 V/m

Table 1. Exposure limits in comparison

3. Exposure systems

Progress in understanding biological effects of non-ionizing electromagnetic radiation is closely related to measurement capability.

To be able to measure any effect of electromagnetic radiation it is necessary to have appropriate exposure system. During last ten years more various exposure systems were developed for research of biological effects and these systems are from constantly adopting according needs. Most of them belong to one of the following basic design ideas: Transverse Electromagnetic (TEM) cell, RF chambers, radial transmission lines (RTL), waveguides or Wire Patch Cells (WPC).

Well defined exposure conditions are essential to obtain reproducible results and they are a precondition for the repeatability of studies.

All environmental requirements for the specific experiment must be strictly complied to it.

Field distribution should be homogenous, i.e., the deviation from homogeneity should be as small as possible.

In qualitative comparison of five different exposure systems (Table 2.) Schoenberg et al. (2001) came to conclusion that best results were achieved by wire patch cell and RF chambers for the exposure of cells in homogenous suspension in 60mm Petri dishes and T-75 flasks. But none of discussed approaches enabled exposure with reasonable homogeneity.

The decision which exposure system is most appropriate for certain in vitro study depends on numerical and technical requirements. Therefore Schoenberg et al. recommend close cooperation of biological and engineering experts in designing any in vitro exposure setup.

	TEM Cell	RF Chamber	RTL	Waveguide	Wire Patch cell
Frequency range	< 1 GHz	Up to several GHz	< 3 GHz	0.7-2 GHz	0.7-2 GHz
Number of dishes	2	>20	20	4-10	8 ⁽¹⁾
Preferred Polarization	E ⁽²⁾	k ⁽³⁾	E	E ⁽²⁾	E
Efficiency	Low	Medium	Medium	High	High
Power requirements	High	High	Medium	Low	Low
Inhomogeneity	Low	High	Medium	Medium	Medium
Complexity	Low	High	Medium	Low	Low
Size	Small	Large	Medium	Medium	Small
System cost	High	High	Moderate	Moderate	Moderate
Environmental control	Incubator	Self-built	Self-built	Incubator	Incubator
Electromagnetic shielding	Self-contained	Self-built	Self-built	Self-contained	Self-build
Exposure control	Power meter	Power meter	Power meter	Power meter	Field probe ⁽⁴⁾

(1) 3 5mm Petri dishes placed into 60 mm Petri dishes with same medium height.

(2) k and H polarizations lead to poor homogeneity and are not further considered

(3) E polarization leads to excessive power requirements and is not further considered

(4) Field probe must be used for control in resonating structures

(Schoenborn et al, 2001)

Table 2. Qualitative comparison of the performance of five designs for the exposure of plated cells in 60 mm Petri dishes.

3.1 Transverse electromagnetic (TEM) Cell

A transverse electromagnetic (TEM) cells were the most often used in bioelectromagnetic experiments, EMC investigations and other studies as a source of standard electromagnetic field. It was developed by Litovitz et al. [1993] and utilized by Penafiel et al. [1997] for the exposure of cells in T25 flasks at 835 MHz-

TEM cell is an exposure system that combines characteristics as : generation of uniform field or a homogenous plane wave, usable cell volume for placing samples, shielding from electromagnetic influence both from outside and inside, it operates

over a wide frequency band, generates a planewave, field strength can be computed from the radiofrequency (RF) power travelling the cell.

TEM cells can be made in various sizes to suit the experimental requirements. The width of the cell must be less than one-half the wavelength at the highest operating frequency to prevent higher-order-mode or multimoding effects. They are in use for upper frequency limits of 50, 150, 300, 500, and 1000MHz. TEM cells used for frequencies in Giga-hertz area are called Giga-hertz transverse electromagnetic GTEM cells.

Field strengths which can be achieved in TEM cells go from very low to extremely high values depending on the input power.

At higher frequencies the cells are compact, portable, simple to build, and can be used for broadband operation up to higher frequency limit. The major disadvantage of the TEM cell is the restriction on specimen size imposed by the cell dimensions, which is inversely proportional to the upper frequency limit (Donaldson et al, 1978)

Fig. 1. Example of TEM cell.

Fig. 2. Example of GTEM-cell.

3.2 Wire Patch Cell

A wire patch cell has been designed for exposing cell cultures during in vitro experiments studying possible effects of mobile radio telephone. It is based on the wire patch antenna which works at 900 MHz with a highly homogeneous field inside the antenna cavity.

The designed cell structure is symmetric and provides a rather homogeneous field distribution in a large area around its centre. this small open device is easy to construct and fits into an incubator. AS the wire patch cell is a radiating element with the same radiating pattern as a dipole, and thus some absorbing materials are necessary around the system when used for in vitro experiments. Secondly, because of its narrow bandwidth, it is difficult to maintain its working frequency. (Leval et al, 2000)

The 900 MHz WPC consist of two square plates (the ground plane and roof) of the same size (15 x 15 cm²), spaced 2,9 cm apart using four metallic grounding contacts located at each corner of the cell. A coaxial cable is located at centre of the cell, with the ewternal conductor

connected to the centre of the ground plane and the inner one passing through the plate and then connecting to the roof.

Dimensions of radiating structure are related to the signal wavelength and inversely proportional to the frequency (Ardoino et al, 2004).

Fig. 3. Example of Wire Patch Cell containing four Petri dishes.

4. GTEM cell and WPC modelling

Before any constructing begins it is recommended to perform computer modelling of desired exposure system to investigate all needed requirements which are demanded from such systems, for example homogeneous field distribution, frequency range, etc .

As most of biological effects caused by high frequency electromagnetic radiation are thermal, temperature distribution and increase should be also taken into account in order to separate temperature rise because of exposure system itself and temperature rise due to electromagnetic field levels.

If temperature increase due to exposure systems construction itself is noted it is necessary to consider implementation of some cooling system before performing electromagnetic exposure test. Otherwise test results can be misinterpreted.

With QuickField software we have modelled GTEM cell and WPC. Our main goal was to determine possible temperature increase in these two exposure systems.

QuickField is a finite element analysis software package. Main application include computer simulations of electromagnetic fields for scientific and industrial purposes.

Modeled GTEM cell is 40cm high and 60cm wide. Antenna source is placed at $\frac{3}{4}$ of height. Modeled 1800MHz WPC has dimensions 20x20 cm² (model is 2 dimensional), with Petri dishes (radius 3.5cm) placed 5 cm from septum (centre). Dimensions of 1800MHz WPC were suggested by Ardoino et al., 2004 (Salovarda et al, 2007,2008).

4.1 Finite element method

The Finite element method is used to solve complex, nonlinear problems in electromagnetism.[8][9] The first step in finite-element analysis is to divide the analyzed configuration into small homogeneous elements. The model contains information about the device geometry, material constants, excitations and boundary constraints. In each finite element, a linear variation of the field quantity is assumed. The corners of the elements are called *nodes*. The goal is to determine the field quantities at the nodes.

The Finite-element analysis technique solves the unknown field quantities by minimizing energy functional. The energy functional is an expression describing all the energy associated with the configuration being analyzed. For 3-dimensional, time-harmonic problems this functional may be represented as

$$F = \int_v \frac{\mu |H|^2}{2} + \frac{\varepsilon |E|^2}{2} - \frac{J \cdot E}{2j\omega} dv \quad (2)$$

The first two terms in the integrand represent the energy stored in the magnetic and electric fields and the third term is the energy dissipated (or supplied) by the conduction currents.

By expressing H in terms of E and by setting the derivative of this functional with respect to E equal to zero, an equation of the form $f(J, E) = 0$ is obtained. A k th order approximation of the function f is then applied at each of the N nodes and the boundary conditions are enforced, resulting in the system of equations.

$$\begin{bmatrix} J_1 \\ J_2 \\ \cdot \\ \cdot \\ J_n \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \cdot \cdot \\ y_{21} & y_{22} & \cdot \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \cdot \\ \cdot \\ E_n \end{bmatrix} \quad (3)$$

The values of J on the left-hand side of this equation are the source terms. They represent the known excitations. The elements of the Y -matrix are functions of the analyzed problem geometry and the boundary constraints. Since each element only interacts with elements in its own neighborhood, the Y -matrix is sparse.

The terms of the vector on the right side represent the unknown electric field at each node. These values are obtained by solving the system of linear equations. In order to have a unique solution; it is necessary to constrain the field strength at all boundary nodes. (Malaric et al. 2005)

Fig. 4. FEM model of GTEM cell, QickField mesh

Applied mesh is shown in Figure 4 and the field values at the nodes have been calculated. In each finite element, a linear variation of the field quantity is assumed. The corners of the elements are called *nodes*. The goal is to find the electric field values at these nodes. Other parameters, such as the magnetic field, induced currents, and power loss can be obtained from the electric field values.

Fig. 5. Sample of QickField window showing final result.

4.2 Temperature distribution inside GTEM cell

The characteristics of GTEM-cell are: $50\ \Omega$ input impedance, inner conductor at $3/4$ height, inner height to width ratio equals $2/3$ and angle septum/bottom plate is 15° , with angle septum/top plate being 5° . The septum as well as coating is made of copper. The N type connector is placed at the end of the tapered section. If necessary, the connector can be replaced. The septum is supported by dielectric material. At the other end, there are the pyramidal absorbers 0.25 m long which are used for electromagnetic wave termination and two parallel $100\ \Omega$, distributed resistive load for current termination. Figure 2 shows cross-section of the used GTEM-cell.

Fig. 5. GTEM-cell designed at Faculty of Electrical Engineering and Computing (FER)

Fig. 6. Base of GTEM-cell designed at FER

By changing source values we wanted to see what is critical field value where temperatures are increased more than 1° C (1K) in the middle 15 cm below septum. Surrounding temperature in all cases was 300 K. Fig.3 and 5 show the result of numerical modeling analysis of E-strength and fig.4 and 6. results of temperature distribution in cell due to E field. Warmer colors on figures are higher values of E field or temperatures.

Fig. 7. E field distribution in of simulated GTEM. $E=3.28\text{V/m}$ in the middle 15cm below septum.

Fig. 8. Temperature distribution due to E field below the septum from fig.7. Temperature in the middle 15cm below septum is 300.003 K ($E=3.28\text{V/m}$)

Fig. 9. E field distribution in of simulated GTEM. $E=23\text{V/m}$ in the middle 15cm below septum.

Fig. 10. Temperature distribution due to E field below the septum from fig.9. Temperature in the middle 15cm below septum is 300.144 K ($E=23\text{V/m}$)

Fig. 11. Temperature in the middle 15cm below septum is 301.161 K ($E=65.63\text{V/m}$).

Source Voltage (V)	E strenght (V/m)	Power density (mW/cm ²)	ΔT ($T - T^0$) K, $T_0=300\text{K}$
1	3.28	0.00285376	0.003
7	23	0.14032202	0.144
20	65.63	1.14150507	1.161

Table 3. E field in the middle 15 cm below the septum

In case when E field 15 cm below septum is 23 V/m (fig. 5,6,7), temperature on same place is 300.144 K . Similar situation was measured in reference [10], when they observed

influence of EMF on Lemna Minor growth in GTEM cell. Plants were exposed to field strength of 23 V/m for 4 hours. The temperature of plants which were placed 15 cm below septum at the beginning and at the end of measurements varied no more than $\pm 0.1^\circ \text{C}$. This measured temperature corresponds to our model in same environment (Tkalec et al, 2005).

4.3 Temperature distribution inside WPC

Performed were several tests with different power output level in order to see increase of temperature on places where petri dishes (samples) are. Starting temperature (T_0) in all cases was chosen to be 300 K.

Warmer colors in figures below indicate higher values of E-field as well as of temperature.

Fig. 12. Vertical E field distribution in side WPC for source 10V.

Fig. 13. Horizontal E field distribution in side WPC for source 10V.

Fig.14. Temperature distribution for 2V source. Temperature value in centre of WPC is 300.226K (E-field = 26.84V/m). Temperature value 6.5 cm from septum (centre Petri dish) = 300.006K (E-field = 4.4V/m).

Fig. 15. Temperature distribution for 5V source. Temperature value in centre of WPC is 301.140K (E-field = 67.11V/m). Temperature value 6.5 cm from septum (centre Petri dish) = 300.049K (E-field = 10.9V/m).

Fig. 17. Temperature distribution for 10V source. Temperature value in centre of WPC = 305.54K. Temperature value 6.5 cm from septum (centre Petri dish) = 300.195K.

Fig. 18. Temperature distribution for 30V source. Temperature value in centre of WPC = 334.82K. Temperature value 6.5 cm from septum (centre of Petri dish)= 301.52K.

Source Voltage (V)	E strenght in the middle of petri dish, 6.5 cm from septum (V/m)	Power density in the middle of petri dish, 6.5 cm from septum , (mW/cm ²)	ΔT ($T - T_0$) K, $T_0=300K$
1	2.2	0.0013	0.002
2	4.4	0.0051	0.006
5	10.9	0.0319	0.049
10	21.9	0.1278	0.195
20	43.9	0.5114	0.738
30	65.8	1.1507	1.517

Table 4. E-field and temperature increase in 6.5 cm from septum (centre of Petri dish).

4. Conclusion

By comparing WPC simulation results with simulation result performed on G-TEM cell (40cm high and 60cm wide, antenna source placed at $\frac{3}{4}$ of height) similarities are shown.

The low E field levels (2V/m - 11V/m) should not cause any significant change of the temperature, but temperature rise for higher E-field levels should not be ignored (65.8 V/m = ΔT 1.517K).

We see significant temperature increase close to septum (e.g. 65.8 V/m = ΔT 34.82K). Therefore it is recommended to implement cooling system in order to avoid possible biological effects from heating rather than electromagnetic field itself. One example of cooling could be two water spiral-plate jackets placed on external faces of WPC. (Ardoino et al., 2004.) Next our step is to build WPC according gained knowlage. Then we will perform measurements of temperature rise depending on field strenghts both in GTEM cell and WPC.

Fig. 19. Exaple of WPC with cooling system as two water spiral-plate jackets placed on external faces of WPC.

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