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A Simplified Electromagnetic-thermal Analysis of Human Exposure to Radiation from Base Station Antennas

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Original scientific paper

Electromagnetic-thermal analysis of the human body exposed to base station antennas radiation is presented in this paper. The formulation of the problem is based on a simplified cylindrical representation of the human body. Electromagnetic part of the analysis involves incident and internal field dosimetry, while the thermal model deals with the bio-heat transfer processes in the body. The electric field induced in the body is determined through the corresponding axial current induced in the body. This current distribution along the body is obtained by solving the Pocklington integral equation for a thick cylinder. The Pocklington integral equation is solved numerically via the Galerkin-Bubnov Boundary Element Method (GB-BEM). Once the internal electric field and related total absorbed power in the human body is obtained, it is possible to calculate a corresponding temperature rise in the body due to the GSM exposure. This temperature rise is determined by solving the bio-heat transfer equation via the conventional finite element method (FEM).

Key words: base station antennas, cylindrical body model, electromagnetic-thermal analysis, human exposure

1 INTRODUCTION

The presence of GSM electromagnetic fields in the environment due to cellular phones and base stations has become an essential part of modern society causing also an increasing public concern of possible adverse health effects. In particular the possible link between the high frequency (HF) fields and certain forms of cancer in human has generated much controversy.

It is worth emphasizing that the human body is particularly sensitive to high frequency (HF) electromagnetic fields. Namely, at high frequencies the body may absorb a significant amount of the radiated energy, as the dimensions of organs become comparable to the wavelength of the incident electromagnetic field. Therefore, the principal biological effect of high frequency (HF) exposures is heating of the tissue [1–4].

The hazardous electromagnetic field levels can be quantified considering the thermal response of a human being exposed to the GSM radiation. Thermally harmful effects can occur if the total power absorbed by the body is large enough to cause protective mechanisms for heat control to break down, resulting in uncontrolled rise in the body temperature (hyperthermia).

The problem being considered is by itself twofold: first the rate of power deposition in tissue due to the electromagnetic radiation has to be estimated; and then the related temperature distribution within the body has to be calculated.

This paper deals with the electromagnetic-thermal modelling of the human body exposed to base station antennas radiation. The principal feature of the proposed approach, compared to more complex and realistic models, is simplicity and computational efficiency.

Incident field dosimetry is based on a simple analytical formula (ray tracing algorithm) arising from the geometrical optics approach [5, 6].

Internal field dosimetry including the calculation of currents and fields induced in the human body is based on the cylindrical model of the human body [7, 8]. This problem is formulated via the Pocklington integro-differential equation.

The Pocklington equation is solved using an efficient boundary element solution method [9, 10]. Once the current distribution along the body is obtained one can then readily calculate the induced electric field and the total power absorbed, which is directly related to the heating effect representing a thermal source.

Finally, the heat transfer phenomena in the human body are formulated in terms of the so-called bio-heat transfer equation. A thermal response of the man can be analysed by solving the bio-heat transfer equation with internal heat generation due to metabolism, internal convective heat transfer due to blood flow, external interaction by convection and radiation and cooling of the skin by sweating and evaporation.

This differential equation is numerically solved via the conventional finite element method (FEM).

2 ELECTROMAGNETIC-THERMAL ANALYSIS

2.1 Incident field dosimetry

The magnitude of the far-field radiated by the base station antenna system is determined by using the ray tracing algorithm based on the geometrical optics method. Thus, the total field can be expressed as a superposition of the incident and reflected field components [5, 6]:

$$E^{tot} = E^{inc} + E^{ref}, \tag{1}$$

where corresponding incident and reflected field components are given by [5, 6]:

$$E^{inc} = \frac{E_0(\phi,\vartheta)}{r} e^{-j\beta r} \tag{2}$$

and

$$E^{ref} = \Gamma_R(\phi',\vartheta') \frac{E_0(\phi',\vartheta')}{r'} e^{-j\beta r'}, \tag{3}$$

where Γ_R is the appropriate reflection coefficient and E_0 is the magnitude of the incident wave defined as:

$$E_0(\phi,\vartheta) = \sqrt{30 N P_{rad} G(\phi,\vartheta)}, \tag{4}$$

where P_{rad} is the radiated power, N is the number of carriers and $G(\phi,\vartheta)$ is the radiation pattern for a particular antenna.

In addition, using a concept of effective isotropic radiated power (EIRP) and the perfect ground (PEC) approximation it follows:

$$E^{tot} = 2\frac{\sqrt{30 N \cdot EIRP}}{r}, \tag{5}$$

where factor 2 represents the worst case scenario of the reflection of the wave from the PEC ground.

2.2 Electromagnetic modeling of the human body

When exposed to GSM electromagnetic fields the human body behaves as an imperfectly conducting cylinder of length L and radius a shown in Figure 1. Thus, the currents and fields are induced inside the organs which gives rise to thermal effects.

At GSM frequencies near 900 MHz the average conductivity of the body is $\sigma = 1.4$ S/m and the corresponding permittivity is $\varepsilon_r = 55$, approximately.

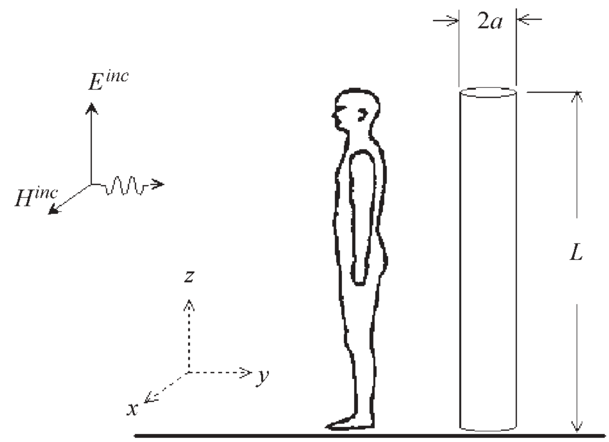

Fig. 1 The equivalent antenna model of the human body

The current distribution along the body is obtained as the solution of the Pocklington integro-differential equation for a thick loaded straight wire given by [7]:

$$E_z^{inc}(z,a) = -\frac{1}{j4\pi\omega\varepsilon_0} \int_{-L}^{L}\int_{0}^{2\pi} \left[\frac{\partial^2}{\partial z^2} + k^2\right] \frac{e^{-jkR}}{R} I(z') \mathrm{d}z' \mathrm{d}\phi + Z_L(z) I(z) \tag{6}$$

where $I(z')$ is the axial current distribution along the body, k is the free space phase constant and, R is the distance from the source point to the observation point, both of which are located on the wire surface,

$$R = \sqrt{(z-z')^2 + 4a^2 \sin^2\frac{\phi}{2}}. \tag{7}$$

Z_L in (6) is the impedance per unit length of the cylinder by which the electrical properties of the body are taken into account. In the frequency range of order of MHz and higher the impedance per unit length is given by [7, 10, 11]:

$$Z_L(z) = \frac{1}{a^2\pi\sigma}\left(\frac{ka}{2}\right)\frac{J_0(j^{-1/2}ka)}{J_1(j^{-1/2}ka)} + Z_c. \tag{8}$$

The current density induced in the body can be expressed via the axial current [7, 10, 11]:

$$J_z(\rho,z) = \frac{I(z)}{a^2\pi}\left(\frac{ka}{2}\right)\frac{J_0(j^{-1/2}k\rho)}{J_1(j^{-1/2}ka)}, \tag{9}$$

and the induced electric field is determined as:

$$E_z(\rho,z) = \frac{J_z(\rho,z)}{\sigma + j\omega\varepsilon}. \quad (10)$$

The Pocklington integro-differential equation (6) is numerically solved via the indirect Galerkin Bubnov boundary element method [9–10].

The mathematical details regarding this numerical solution method are given in Appendix A.

2.3 Thermal modeling of the human body

Thermal effects can be defined as an energy deposition higher than the thermoregulatory capacity of the human body.

The bio-heat transfer equation expresses the energy balance between conductive heat transfer in a volume control of tissue, heat loss due to perfusion effect, metabolism and energy absorption due to radiation.

These thermal processes inside the human body can be studied by solving the Pennes' bio-heat transfer equation [3, 4]. The rate of volumetric heat generation due to the electromagnetic irradiation is obtained from electromagnetic modelling of the human body presented in previous section.

The stationary bio-heat transfer equation has the following form [3]:

$$\nabla(\lambda \nabla T) + W_b C_{pb}(T_a - T) + Q_m + Q_{EM} = 0 \quad (11)$$

where:

- λ is the thermal conductivity,
- W_b the volumetric perfusion rate,
- T is the tissue temperature,
- C_{pb} is the specific heat of blood,
- T_a is the arterial temperature,
- Q_m is the power produced by metabolic process,
- Q_{EM} is the electromagnetic power deposition.

The electromagnetic power deposition Q_{EM} is a source term deduced from the electromagnetic modelling, and determined by relation:

$$Q_{EM} = \frac{\sigma}{2}|E|^2 \quad (12)$$

where E is the maximal value of the electric field induced inside the human body, and σ is the conductivity of the particular tissue.

The dissipated power density Q_{EM} is directly related to the specific absorption rate (SAR), as follows:

$$Q_{EM} = \rho \cdot SAR \quad (13)$$

where ρ denotes a tissue density, and SAR is defined as:

$$SAR = \frac{\sigma}{2\rho}|E|^2 \quad (14)$$

and represents a standard measure of the local heating rate in numerical and experimental dosimetry [1].

The stationary bio-heat equation (11) is a linear equation in terms of temperature T. Thus, the steady state temperature increase in the body is proportional to the SAR or the radiated electric field from the base station antennas.

The average thermal properties of the cylindrical body model (muscle properties) are given as follows: $\lambda = 0.545$ W/m °C, $W_b = 0.433$ kg/m^3 and $Q_m = 703.5$ W/m^3, $C_{pb} = 3475$ J/kg°C. The arterial temperature is $T_a = 36.7$ °C.

The boundary condition for the bio-heat transfer equation (11) is to be imposed to the interface between skin and air, and is given by:

$$q = H(T_s - T_a) \quad (15)$$

where q denotes the heat flux density defined as:

$$q = -\lambda \frac{\partial T}{\partial n} \quad (16)$$

while H, T_s and T_a denote, respectively, the convection coefficient, the temperature of the skin, and the temperature of the air. The bio-heat transfer equation (11) is solved by using the conventional finite element method (FEM). The mathematical details regarding the finite element solution method is, for the sake of completeness, outlined in Appendix B.

3 COMPUTATIONAL EXAMPLES

The tremendous growth in the use of cellular telephones has resulted in an increasing number of GSM base stations being built in densely populated areas. Thus the computational examples presented in this section are related to the human body exposed to the radiation of a base station antenna systems mounted on a roof-top, Figure 2, and on a free standing tower, Figure 3. All the antenna parameters are listed in Table 1.

The electric field due to the radiation from a roof-top base station (with effective isotropic radiated power – EIRP = 58.15 dBm) mounted on a 35 m high building, in Split, Croatia, Figure 2 has been calculated at 30 m distance of the main beam in a nearby flat. The related numerical results are presented in Table 2, while the distribution of the electric field induced inside the human body due to the base station antenna radiation is shown in Figure 4.

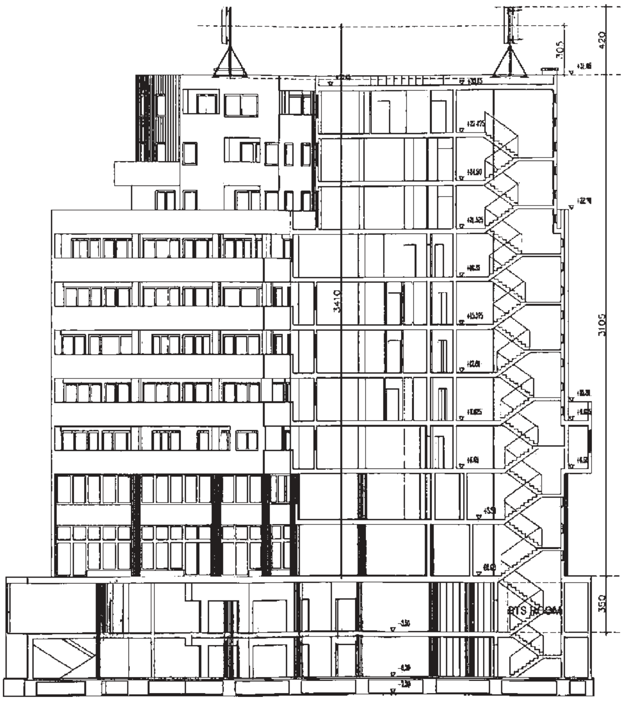

Fig. 2 The system of base station antennas mounted on a roof--top

Table 1 **Technical parameters of base station antenna system**

Operational frequency	GSM downlink band (935–960 MHz)
Number of sectors*	3
Main radiation directions*	sector A: 0° sector B: 120° sector C: 240°
Antennas*	sector A: Celwave APXV906514 6 antennas sector B: Celwave APXV906514 6 antennas sector C: Celwave APXV906514 6 antennas
Antenna system height	34 m
Max. No. of channels per sector	sector A: 6 sector B: 6 sector C: 6
EIRP per channel	58.15 dBm
Celwave APXV906514 antenna gain	14 dBi
Horizontal beam-width	65°
Vertical beam-width	9°

The maximum value of the total electric field tangential to the body and calculated via ray-tracing algorithm is 15 V/m. This external field causes the internal field in the cylindrical model of the body in amount of 0.1 V/m. Knowing the internal electric field distribution provides the calculation of related electromagnetic power distribution absorbed by the body. The related temperature distribution with related heat flux field inside the cylinder representing the human body is shown in Figure 5.

Fig. 3 The system of base station antennas mounted on a free-standing tower

Table 2 **HF exposure parameters from GSM base station**

Incident field E (V/m)	Induced field E_{ind} (V/m)	Power density Q_{EM} (W/m^3)	Temperature rise ΔT (°C)
15	0.1	$7 \cdot 10^{-3}$	$5.3926 \cdot 10^{-6}$

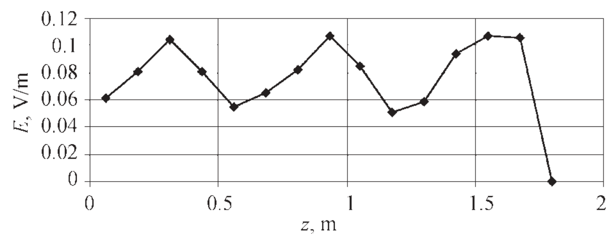

Fig. 4 Calculated electric field inside the human body

The maximum calculated temperature rise is $\Delta T = 5.39 \cdot 10^{-6}$ °C and found to be rather negligible.

The second computational example is related to the human exposure to the radiation of a free--standing tower base antenna (with effective isotropic radiated power – EIRP = 62.5 dBm), Figure 3. The related numerical results are presented in Table 3.

Table 3 **HF exposure parameters for the base station on a free standing tower**

E^{inc} (V/m)	E^{ind} (V/m)	Q_{EM} (W/m^3)	ΔT (°C)
1.265	$6.01 \cdot 10^{-3}$	$2.52 \cdot 10^{-5}$	$1.88 \cdot 10^{-8}$

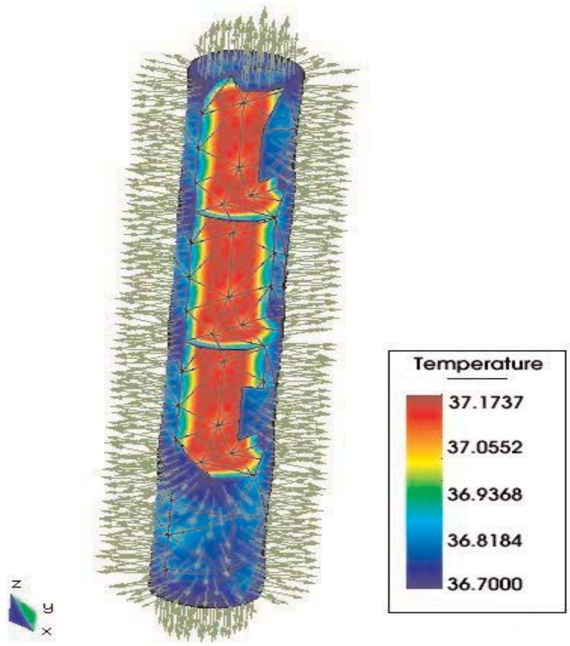

Fig. 5 Temperature distribution in the body model and normal heat flux vector field

The maximum value of the electric field tangential to the body is 1.265 V/m for this case. This external field causes the internal field 6 mV/m, which corresponds to the power density value of 25 μW/m^3.

The resulting maximal temperature rise in the body, due to the absorbed electromagnetic energy is rather small and it is equal to $\Delta T = 1.88 \cdot 10^{-8}$ °C. Therefore, it has been shown that the influence of the electromagnetic power deposition is negligibly small.

4 CONCLUSION

The simplified electromagnetic-thermal model for human exposure assessment to base station antenna radiation is presented in the paper. The formulation of the problem is based on the simplified cylindrical model of human being.

The electromagnetic analysis involves the incident and the internal field dosimetry, while the thermal analysis includes modeling of the bio-heat transfer phenomena in the body. The incident electric field is determined using the ray-tracing algorithm while the corresponding internal field is calculated from the axial current induced in the body. The axial current distribution is obtained as a solution of the Pocklington integro-differential equation for straight thick wires. Once the internal electric field is known, it is possible to compute the absorbed power inside the body.

Finally, the temperature rise in the body, due to the human exposure to GSM radiation, is determined by solving the bio-heat transfer equation via the standard finite element method (FEM).

The presented analysis is an opener to the subject and further theoretical and experimental work is needed for better understanding of the problem.

APPENDIX

Appendix A: Indirect Galerkin-Bubnov Boundary Element Solution of the Pocklington Integral Equation

The Pocklington integral equation:

$$E_z^{inc}(z,a) = \\ = -\frac{1}{j4\pi\omega\varepsilon_0}\int_{-L}^{L}\int_{0}^{2\pi}\left[\frac{\partial^2}{\partial^2 z}+k^2\right]\frac{e^{-jkR}}{R}I(z')\mathrm{d}z'\mathrm{d}\phi + \\ +Z_L(z)I(z) \qquad \text{(A1)}$$

can be numerically handled via the Galerkin-Bubnov variant of the Boundary Element Method.

The unknown current is first expanded into finite sum of linearly independent basis functions $\{f_i\}$ with unknown complex coefficients α_i, i.e.:

$$I \cong I_n = \sum_{i=1}^{n}\alpha_i f_i. \qquad \text{(A2)}$$

Utilizing the integral equation kernel symmetry and taking into account the zero boundary conditions for current at the free ends of the thin wire, after integration by parts it follows:

$$\sum_{i=1}^{n}\alpha_i\frac{1}{j4\pi\omega\varepsilon}\left\{-\int_{-L}^{L}\frac{\mathrm{d}f_i(z)}{\mathrm{d}z'}\int_{-L}^{L}\frac{\mathrm{d}f_i(z)}{\mathrm{d}z'}g_E(z,z')\mathrm{d}z'\mathrm{d}z + \right. \\ \left. +k_1^2\int_{-L}^{L}f_j(z)\int_{-L}^{L}f_i(z')g_E(z,z')\mathrm{d}x'\mathrm{d}x\right\} + \\ +\int_{-L}^{L}Z_L(z)f_j(z)f_i(z)\mathrm{d}z = \\ = -\int_{-L}^{L}E_z^{inc}(z)f_j(z)\mathrm{d}z, \quad j=1,2,\ldots,n \qquad \text{(A3)}$$

where g_E is the exact kernel:

$$g_E = \int_0^{2\pi}\frac{e^{-jkR}}{R}\mathrm{d}\phi, \qquad \text{(A4)}$$

where R is the distance from the source point to the observation point.

Applying the boundary element algorithm to eqn. (A3) leads to the following linear equation system:

$$\sum_{i=1}[Z]_{ji}\{I\}_i=\{V\}_j \text{, and } j=1,2,\ldots,M, \quad \text{(A5)}$$

where $[Z]_{ji}$ is the local matrix presenting the interaction of the i-th source boundary element to the j-th observation boundary element:

$$[Z]_{ji}=$$

$$=-\frac{1}{4j\pi\omega\varepsilon}\left(\int_{\Delta l_j}\{D\}_j\int_{\Delta l_i}\{D'\}_i^T g_E(z,z')\mathrm{d}z'\mathrm{d}z+\right.$$

$$\left.+k^2\int_{\Delta l_j}\{f\}_j\int_{\Delta l_i}\{f\}_i^T g_E(z,z')\mathrm{d}z'\mathrm{d}z\right)+$$

$$+\int_{\Delta l_j}Z_L(z)\{f\}_j\{f\}_i^T\,\mathrm{d}z\,, \quad \text{(A6)}$$

where vector $\{I\}$ contains the unknown coefficients of the solution. Matrices $\{f\}$ and $\{f'\}$ contain shape functions while $\{D\}$ and $\{D'\}$ contain their derivatives, where: M is the total number of segments, and Δl_i, Δl_j is the width of i-th and j-th segment.

Functions $f_k(z)$ are the Lagrange's polynomials and $\{V\}_j$ is the local right-side vector for j-th observation boundary element:

$$\{V\}_j=\int_{\Delta l_j}E_i^{inc}\{f\}_j\,\mathrm{d}z \quad \text{(A7)}$$

and represents, in fact, the local voltage vector.

Appendix B: Finite element solution of the Bio-Heat Transfer Equation

The stationary bio-heat transfer equation:

$$\nabla(\lambda\nabla T)+W_bC_{pb}(T_a-T)+Q_m+Q_{EM}=0, \quad \text{(B1)}$$

can be written in the form of the inhomogeneous Helmholtz-type equation:

$$\nabla(\lambda\nabla T)-W_bC_{pb}T=-(W_bC_{pb}T_a+Q_m+Q_{EM}) \quad \text{(B2)}$$

with an associated Neumann boundary condition:

$$q=-\lambda\frac{\partial T}{\partial n}=-H(T_s-T_a), \quad \text{(B3)}$$

while H, T_s and T_a stand for, respectively, the convection coefficient, the temperature of the skin, and the temperature of the air.

The standard finite element discretization of Helmholtz equation results in the following matrix equation:

$$[K]\{T\}=\{M\}+\{P\}, \quad \text{(B4)}$$

where $[\mathrm{K}]$ is the finite element matrix given by:

$$K_{ji}=\int_{\Omega_e}\nabla f_j(\lambda\nabla f_i)\mathrm{d}\Omega_e+\int_{\Omega_e}W_bC_{pb}f_jf_i\,\mathrm{d}\Omega_e, \quad \text{(B5)}$$

while $\{M\}$ denotes the flux vector:

$$M_j=\int_{\Gamma_e}\lambda\frac{\partial T}{\partial n}f_j\,\mathrm{d}\Omega_e \quad \text{(B6)}$$

and $\{P\}$ stands for the source vector:

$$p_j=\int_{\Omega_e}(W_bC_{pb}T_a+Q_m+Q_{EM})f_j\,\mathrm{d}\Omega_e\,. \quad \text{(B7)}$$

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Pojednostavljena elektromagnetsko-toplinska analiza izloženosti ljudi zračenju antena baznih stanica. U ovom radu izložena je elektromagnetsko-toplinska analiza ljudskog tijela izloženog zračenju antena baznih stanica. Formulacija problema zasniva se na cilindričnom modelu ljudskog tijela. Elektromagnetski dio analize uključuje dozimetriju upadnog i unutarnjeg polja, dok se toplinskim modelom opisuje prijenos topline u tijelu. Električno polje inducirano u tijelu određuje se preko struje inducirane u tijelu. Raspodjela struje uzduž tijela dobivena je rješavanjem Pocklingtonove integralne jednadžbe za »debeli« cilindar. Pocklingtonova integralna jednadžba numerički je riješena primjenom Galerkin-Bubnove metode rubnih elemenata. Jednom kada je dobiveno unutarnje električno polje i ukupna snaga apsorbirana u tijelu, moguće je izračunati odgovarajući porast temperature u tijelu zbog izloženosti GSM zračenju. Ovaj porast temperature određuje se rješavanjem bio-toplinske jednadžbe primjenom metode konačnih elemenata.

Ključne riječi: antene baznih stanica, cilindrični model tijela, elektromagnetsko-toplinska analiza, izloženost ljudi zračenju

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