Temperature rise in the human body exposed to radiation from base station antennas

D. Poljak\textsuperscript{1}, N. Kovac\textsuperscript{1}, T. Samardzioska\textsuperscript{2}, A. Peratta\textsuperscript{2} & C. A. Brebbia\textsuperscript{2}
\textsuperscript{1}University of Split, \textsuperscript{2}Wessex Institute of Technology

Abstract

Thermal analysis of human exposure to base station antennas radiation is presented in this work. The formulation is based on a simplified cylindrical representation of the human body. Knowing the internal electric field and related total absorbed power in the human body, a resulting thermal response of the body due to the exposure to high frequency (HF) radiation can be determined. The temperature rise in the body exposed to base stations antenna radiation is determined by solving the bio-heat transfer equation via both the dual reciprocity boundary element method (DR-BEM) and finite element method (FEM). The temperature rise in the body is found to be rather negligible.

1 Introduction

In the last decade there has been an increasing public concern regarding the possible health effects of human exposure to high frequency (HF) electromagnetic radiation from base station antennas. The principal biological effect of these HF fields has been considered to be dominantly thermal in nature \cite{1} - \cite{4}. Namely, the hazardous electromagnetic field levels can be quantified analysing the thermal response of the human body exposed to the HF 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. This may lead to an uncontrolled rise in the body temperature (hyperthermia). The problem to be considered is by itself twofold. First, the rate of power deposition in tissue due to base stations radiation has to be calculated; and consequently, the related temperature distribution within the body has to be
The electromagnetic analysis includes the incident field dosimetry (modelling of the radiation sources) and internal field dosimetry (modelling of the induced field in the body). In recent years, the electromagnetic modelling of electromagnetic interference (EMI) sources and the human body has been reported in many papers [5] – [10]. On the contrary, the thermal studies on the subject have been performed in a less extent, and moreover, they are mostly related to the mobile phone exposures. The rationale of this study is that biological effects and potential damage to humans due to the exposure to HF fields are caused through temperature increases although the safety standards are, up to now, expressed in terms of induced fields or specific absorption rate (SAR) [4]. This paper extends the previous work by the authors related to the electromagnetic modelling of the low and high frequency human exposures reported in [5], [6] and [6] to the thermal analysis of human exposures to HF radiation. The electromagnetic modelling presented in [5], [6] and [9] has been carried out via Galerkin-Bubnov boundary element method, explained in details in [11] and [12]. In this work, the human body is represented as a cylinder with thermal properties of the muscle. The model based on infinite and finite length cylinder case of infinite and finite length cylinder is used. It is worth noting that the principal feature of the proposed model, compared to the more complex and realistic models [3], [4] is simplicity and computational efficiency in getting the rapid estimation of the phenomenon. Yet, the model provides some research insight and gives results still useful in an average sense. Once knowing the induced electric field and the total power absorbed by the body (This absorbed power is directly related to the heating effect and represents a thermal source) from the analysis presented in [6] and [9] it is possible to obtained a thermal body response. Thermal behaviour of the human body is analysed through the solution of the bio-heat transfer equation representing the balance between 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 [3], [4]. Up to now, this differential equation has been usually treated with classical boundary elements [3] and a finite difference approach [4]. A mathematical details related to the boundary element methods in engineering can be found in [13] and [14]. In this paper, the bio-heat transfer equation is numerically solved using the highly efficient dual reciprocity boundary element method (DR-BEM) [15] based on the domain decomposition concept and via the standard finite element method (FEM). The results obtained via different methods agree satisfactorily. The both methods are very suitable for handling more complex representation of the human body in an ongoing research.

It should be pointed out that, to the best our knowledge, this is the first application of DR-BEM to the solution of the bio heat transfer equation.

2 Thermal model of the human body

Thermal effects are usually defined as the energy deposition higher than the thermoregulatory capacity of the human body. These heat transfer processes
inside the human body can be studied by solving the Pennes’ bio-heat transfer equation [3], [4]. The bio-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. The rate of volumetric heat generation due to the electromagnetic irradiation is obtained from the electromagnetic modelling of the human body that was already presented in [6] and [9].

\[
V(\lambda \nabla T) + W_b C_{pb} (T_a - T) + Q_m + Q_{EM} = 0
\]

where: \( \lambda \) is the thermal conductivity, \( W_b \) is 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 and \( Q_{EM} \) is the electromagnetic power deposition.

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

\[
Q_{EM} = \frac{\sigma}{2} |E|^2
\]

where \( E \) is the maximal value of the electric field induced inside the human body, and \( \sigma \) is the conductivity of the tissue.

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

\[
Q_{EM} = \rho \cdot SAR
\]

where \( \rho \) denotes a tissue density, and SAR is defined as:

\[
SAR = \frac{\sigma}{2 \rho} |E|^2
\]

and represents a standard measure of the local heating rate in numerical and experimental dosimetry [1]. The stationary bio-heat equation (1) 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: $\lambda = 0.545 \text{W/m/°C}$, $W_b = 0.433 \text{kg/m}^3$ and $Q_m = 703.5 \text{W/m}^3$, where $C_{pb} = 3475 \text{J/kg/°C}$. The arterial temperature is assumed to be $T_a = 36.7 \text{°C}$. The boundary condition for the bio-heat transfer equation (1) is to be imposed to the interface between skin and air, and is given by:

$$q = H(T_s - T_a)$$  \hspace{1cm} (5)

where $q$ denotes the heat flux density defined as:

$$q = -\lambda \frac{\partial T}{\partial n}$$  \hspace{1cm} (6)

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 (1) for the case of infinite and finite cylinder is solved using the dual reciprocity boundary element method (DR-BEM) and finite element method (FEM). The mathematical details regarding the DR-BEM can be found in Appendix A, while the finite element method is, for the sake of completeness, outlined in Appendix B.

3 Numerical results

The tremendous growth in the use of cellular telephones has resulted in an increasing number of GSM base stations, particularly in densely populated areas. Thus, a computational examples presented in this section is related to the human body exposed to the radiation of a base station antenna system mounted on a roof-top, Fig 2 (left), and on a free standing tower, Fig 2 (right).

Figure 2: The system of base station antennas mounted on a roof top and (left) on a freestanding tower (right).

The electric field due to the radiation from a roof-top base station (with effective isotropic radiated power – EIRP=58.15dBm) mounted on a 35m high building, in Split, Croatia, Fig 2 has been calculated at 30m distance of the main beam in a nearby flat. The related numerical results are presented in Table I.
Table 1: HF exposure parameters for the roof-top base station.

<table>
<thead>
<tr>
<th>$E^{inc}$ (V/m)</th>
<th>$E^{ind}$ (V/m)</th>
<th>$Q_{EM}$ (W/m)</th>
<th>$\Delta T$ (°C)</th>
<th>$\Delta T$ (°C)</th>
<th>$\Delta T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.1</td>
<td>7</td>
<td>10.98 $\cdot 10^{-6}$</td>
<td>4.66 $\cdot 10^{-6}$</td>
<td>5.39 $\cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

The maximum value of the total electric field tangential to the body and calculated via ray-tracing algorithm is 15V/m. This external field causes the internal field in the body in amount of 0.1V/m. Knowing the internal electric field distribution provides the calculation of related electromagnetic power distribution absorbed by the body. Finally, a temperature rise in the body due to the absorbed electromagnetic energy is determined by solving the bio-heat transfer equation (1) by means of the 2D and 3D dual reciprocity boundary element method (DR-BEM) and FEM. The obtained temperature distribution with related heat flux field inside the cylinder representing the human body is shown in Fig 3.

Figure 3: Temperature distribution in the body model and normal heat flux vector field

The maximum calculated temperature rise is $\Delta T=10.98*10^{-6}$°C (infinite cylinder – 2D DR BEM) $\Delta T=4.66*10^{-6}$°C (finite cylinder – 3D DR BEM) $\Delta T=5.36*10^{-6}$°C (FEM) 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=62.5dBm), Fig 2 (right).
Table 2: HF exposure parameters for the base station on a free standing tower.

<table>
<thead>
<tr>
<th>$E^{inc}$</th>
<th>$E^{ind}$</th>
<th>$Q_{EM}$</th>
<th>$\Delta T(\degree C)$ 2D DR-BEM</th>
<th>$\Delta T(\degree C)$ 3D DR-BEM</th>
<th>$\Delta T(\degree C)$ FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V/m)</td>
<td>(V/m)</td>
<td>(W/m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.265</td>
<td>6.01 $\cdot$ 10^{-3}</td>
<td>7 $\cdot$ 10^{-3}</td>
<td>4 $\cdot$ 10^{-8}</td>
<td>1.56 $\cdot$ 10^{-8}</td>
<td>1.88 $\cdot$ 10^{-8}</td>
</tr>
</tbody>
</table>

The maximum value of the electric field tangential to the body is 1.265V/m. This external field causes the internal field in amount of 6mV/m, which corresponds to the power density value of 0.24µW/m³. The resulting maximal temperature rise in the body, due to the absorbed electromagnetic energy is rather small and it is equal to $\Delta T = 4 \cdot 10^{-8} \degree C$ (infinite cylinder – 2D DR BEM) $\Delta T = 1.56 \cdot 10^{-8} \degree C$ (finite cylinder – 3D DR BEM) $\Delta T = 1.88 \cdot 10^{-8} \degree C$ (FEM). Therefore, it has been shown that the influence of the electromagnetic power deposition is negligibly small.

4 Conclusion

It is well-known that due to the body exposure to intense high frequency (HF) electromagnetic radiation significant thermal damage can occur in sensitive tissues. Consequently, a simplified thermal model of the human body exposed to base station antennas radiation is presented in the paper. The formulation is based on the simplified cylindrical model representation of the human body. The infinite and finite cylinder is used in this work, respectively. It is to be pointed out that the main feature of the presented analysis, compared to the more complex realistic models, is its simplicity and computational efficiency in rapid estimation of the physical problem. If the internal electric field and the absorbed power inside the body are already known, the temperature rise in the body, due to the exposure to base stations can be computed. This analysis has been carried out by solving the bio-heat transfer equation using the dual reciprocity boundary element method (DR-BEM) and standard finite element method (FEM). Analyzing the obtained numerical results it can be stated that the thermal effects due to human exposure to base station antennas radiation are found to be rather negligible. Also, it is to be stressed out that the present study should be considered as an opener to the subject and for a more reasonable understanding of the problem, further theoretical and experimental work is required.

Appendix A: DRM BEM for the bio-heat transfer equation

The steady state thermal model for the human body exposure has been solved with a 2D and 3D Direct Boundary Element Method (BEM-DM). For simplicity, only 2D version of the method is presented here. The governing equation used for steady bio-heat transfer is stationary Pennes equation:

$$\nabla (\lambda \cdot \nabla T) + w_b \cdot c_{pb} \cdot T = w_b \cdot c_{pb} \cdot T_a - Q_M + (-Q_{EM})$$  \hspace{1cm} (A1)

which can be regarded as a Poisson equation in the general form and can be written as:
\( \nabla^2 T = b(x, y, T) \) in the domain \( \Omega \) \hspace{1cm} (A2)

with the ‘essential’ Dirichlet boundary conditions of the type \( T = \overline{T} \) on \( \Gamma_1 \) and ‘natural’ Neuman boundary conditions \( q = \partial T / \partial n = \overline{q} \) on \( \Gamma_2 \). Here \( \Gamma = \Gamma_1 + \Gamma_2 \) is the exterior boundary that encloses the domain \( \Omega \) and \( n \) is its outward normal. Using one of the most popular approaches and the most versatile technique among the numerical and analytical methods for transforming domain integrals to the boundary is the Dual Reciprocity Method (DRM) introduced by Nardini and Brebbia [16], and applying the Green integral representation formula to (A2), it is found that the value \( T \) at a point \( x \) within the domain \( \Omega \) is given by:

\[
\lambda(x)T(x) + \int_{\Gamma} q^*(x, y)T(y)d\Gamma_y - \int_{\Gamma} T^*(x, y)q(y)d\Gamma_y = \int_{\Omega} T^*(x, y)b(y)d\Omega_y
\]

Here, \( T^*(x, y) \) is the fundamental solution of the Laplace equation, which for an isotropic 2D medium is given by:

\[
T^*(x, y) = \frac{1}{2\pi} \log \frac{1}{r}
\]

where \( n \) is the normal to the boundary of the sub-domain and \( r \) is the distance from the point of application of the concentrated unit source to any other point under consideration. The \( b(y) \) term, the only one that is not related to the boundary in the equation (3), represents the sum of the non-homogeneous terms and for this model is given by:

\[
b = \frac{1}{\lambda} \left[ W_b \cdot C_{pb} \cdot T_a - W_b \cdot C_{pb} \cdot T - Q_M + (-Q_{EM}) \right]
\]

The DRM-MD defines it using approximation functions \( f(y, z) \), which can be polynomial, radial functions etc, and they depend only on the geometry of the problem:

\[
b(y) \equiv \widetilde{b} = \sum_{k=1}^{J+I} \alpha \cdot f(y, z)
\]

The approximation is done at \((J+I)\) nodes, with \( J \) boundary nodes and \( I \) nodes inside the domain. Therefore, the domain integral in (A3) becomes:

\[
\int_{\Omega} T^*(x, y)b(y)d\Omega_y \approx \sum_{k=1}^{J+I} \alpha_k \int_{\Omega} T^*(x, y)f(y, z^k)d\Omega_y
\]

If \( b \) is a known function, expression can be written in matrix form as:

\[
b = F\alpha
\]

Hence

\[
\alpha = F^{-1}b
\]

and then carry out the numerical integration of (7). The DRM method depends on the choice of the function \( f \). The most popular choice in the past for the function \( f(y, z) \) in the DRM approach was \( f = 1 + R \).
spline (ATPS) is the radial basis function used for the DRM approximation in this work. It represents a linear combination of RBF and linear functions, and for two-dimensional problems the term \( b(y) \) can be expanded as

\[
b(y) = \sum_{k=1}^{J+1} \alpha_k R^2(y, z^k) \log R(y, z^k) + ax_1 + bx_2 + c
\]

Eliminating the domain integral in the Green's integral representation formula, one finally arrives at a boundary only integral representation formula:

\[
\lambda(x)T(x) + \int_{\Gamma} q^*(x, y) T(y) d\Gamma_y - \int_{\Gamma} T^*(x, y) q(y) d\Gamma_y \approx \sum_{k=1}^{J+1} \left\{ \alpha_k \left( \lambda(x) \tilde{T}(y, z^k) +\right. \int_{\Gamma} q^*(x, y) \tilde{T}(y, z^k) d\Gamma_y - \int_{\Gamma} T^*(x, y) \tilde{q}(y, z^k) d\Gamma_y \left. \right) \right\}
\]

The DRM-MD is used and the original domain is divided into sub-domains, and on each of them the full integral representation formulas are applied.

After the discretization of the domain, equation (A11) can be rewritten in matrix form

\[
H_i T - G_i Q = S = \left( H_i \tilde{T} - G_i \tilde{Q} \right) \cdot F^{-1} b
\]

where \( H \) and \( G \) on both sides of the equations are two matrices consisting of coefficients that are calculated assuming the fundamental solution is applied at each node successively, and depending only on geometrical data, as it was mentioned before. Substituting equation (A5) into (A12) one obtains the more specific expression for the case of bio-heat transfer:

\[
\left( H + S \cdot w_b \cdot c_{pb} \right) T - Gq = S \cdot \frac{1}{\lambda} \left[ w_b \cdot c_{pb} \cdot T_a - Q_M + \left( -Q_{EM} \right) \right]
\]

where:

\[
S = \left( H \tilde{T} - G \tilde{Q} \right) \cdot F^{-1}
\]

In this way (A13) represents one of the matrix system equations for the normal derivative of the temperature at the surface points, and for the temperature at the surface and internal points in each sub-region. Each of the local equations that correspond to each sub-domain has to be assembled with its neighbouring systems according to the field variable and flux-matching conditions:

\[
T_1 = T_2
\]

\[
K_1 \nabla T_1 \cdot \vec{n}_1 = -K_2 \nabla T_2 \cdot \vec{n}_2
\]

A 3D implementation of the Dr-BEM is based on the isoparametric approach with quadratic interpolation functions over triangular and quadrilateral elements that surround a region or subdomain of an arbitrary shape. It is noteworthy that one of the great advantages of the domain decomposition technique, in addition to its capabilities in dealing with piecewise homogeneous material properties and despite of the fact that it is not a necessary requirement in this particular example, is that the final system of equations is sparse and highly banded.
Appendix B: FEM for the bio-heat transfer equation

The stationary bio-heat transfer equation:

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

(B1)

where the electromagnetic power deposition \(Q_{EM}\) is defined as:

$$Q_{EM} = \frac{\sigma}{2} |E|^2$$

(B2)

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

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

(B3)

with an associated Neumann boundary condition:

$$q = -\lambda \frac{\partial T}{\partial n} = -H(T_S - T_a)$$

(B4)

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:

$$[K] [T] = [M] + [P]$$

(B5)

where \([K]\) is the finite element matrix given by:

$$K_{ji} = \int_{\Omega_e} \nabla f_j (\lambda \nabla f_i) d\Omega_e + \int_{\Omega_e} W_b C_{pb} f_j f_i d\Omega_e$$

(B6)

while \([M]\) denotes the flux vector:

$$M_j = \int_{\Gamma_e} \lambda \frac{\partial T}{\partial n} f_j d\Omega_e$$

(B7)

and \([P]\) stands for the source vector.

$$P_{ji} = \int_{\Omega_e} (W_b C_{pb} T_a + Q_m + Q_{EM}) f_j d\Omega_e$$

(B8)

In this paper the calculation is carried out using the linear base functions and triangular elements.

References


