5.3. Simplified geometrical models of the human body

The models of the human body in a computer-aided analysis of the interaction between electromagnetic field and human body can be included in the classes:

- Complex models (Multi-segmented models)
- Simplified models

Complex models [17] divide the body into many segments as in fig. 4. The disadvantage of these models is: a large amount of empirical data is required to simulate each segment of the body ([17], [12]).

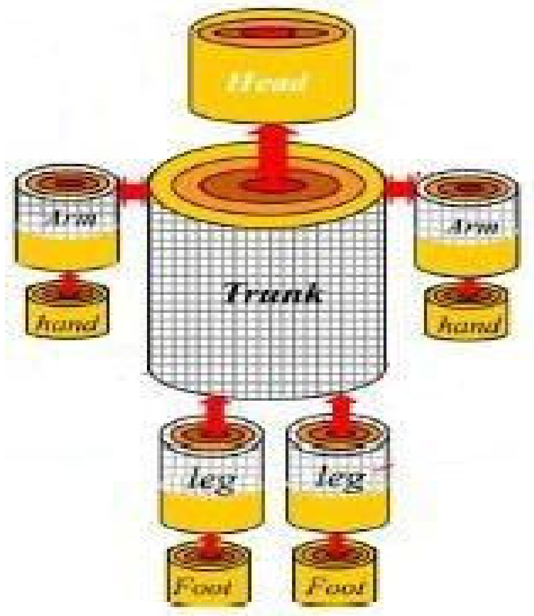

Fig. 4 Schematic of the multi-segment model

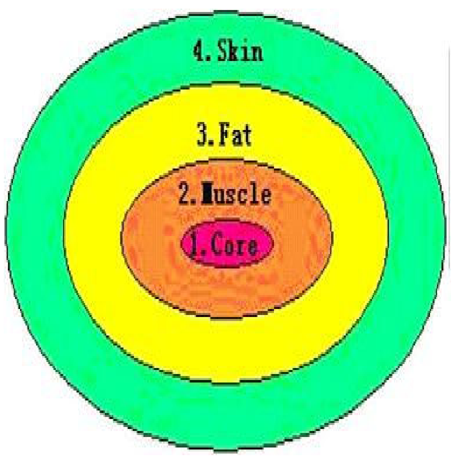

Fig. 5 A cross-section of a body part

The model of the Fig. 4 is based on the division of the human body in more cylindrical segments. The cross-section of a segment is presented in fig. 5. Each segment is a multi-layer model presented in Fig.6. It is obviously that we have covered parts and uncovered parts of the human skin [11]. The clothing is considered an insulation layer in the interaction of the human body with the environment.

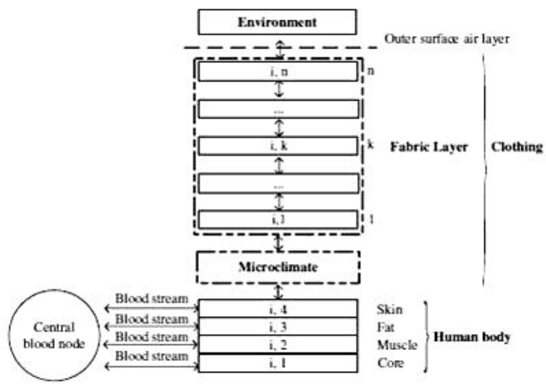

Fig. 6 Unclothed human body segment ***i***

In the class of the simplified models, Gagge's two-node model is commonly used for evaluation of human body thermal response and prediction of thermal sensation under transient personal and environmental conditions [16]. The body is represented by two concentric cylinders in this model as in Fig. 7.

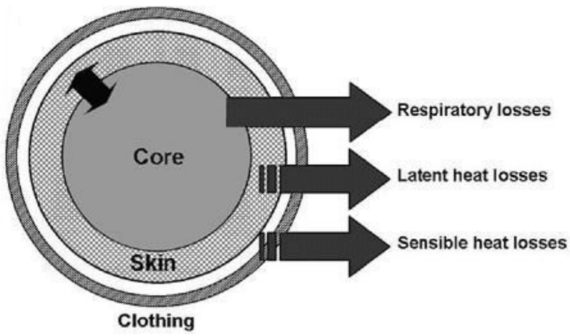

Fig. 7. - A simplified model

The outer cylinder represents the outer layer of the body (skin and its related tissues). The inner cylinder represents the inner parts of the body consisting of skeleton, muscles and internal organs. These inner and outer cylinders are respectively called "core" and "skin" compartments of the body. The clothing system is simulated as an overall insulation over the whole body.

The national systems for energy distribution include substations that operate at high voltages and currents so that the resultant electric and magnetic fields are high. Consequently the risk of the adverse health effects is increased. The electromagnetic environment at substations is very complex because it includes multiple lines, conducting metallic structures, buses and other current-carrying elements with variable current values. But a lot of people work in this environment so that a control of the electromagnetic field level is imposed by international standards in order to protect the health and life of the humans and animals.

Commonly used in bioelectromagnetics, the SAR measures the power absorbed by tissues, its unit is W/kg and can be calculated from the *E* field generated by the variable magnetic field in biological tissues of the human body. The influence of human body shape on the whole body SAR must be estimated because the real body is deformed. There is a relation between the height, weight and SAR of the whole body. The inverse problem is that from a given value of SAR we must find the level of incident field above which the absorption exceeds the limits of safety recommendations.

5. 4. A simplified mathematical model for the human body simulation

A complete physical description of electromagnetic field is given by Maxwell's equations in terms of five field vectors: the magnetic field **H**, the magnetic flux density **B**, the electric field **E**, the electric field density **D**, and the current density **J**. In low-frequency formulations, the quantities satisfy Maxwell's equations:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}}$$

$$div\ B = 0$$

$$div\ D = \rho_C$$

with ρ_c the charge density, σ – the electric conductivity, and μ the magnetic permeability. For simplicity we give up to the bold notations for vectors.

The second set of relationships, called the constitutive relations, is for linear materials:

$$B = \mu H;\ D = \varepsilon E;\ J = \sigma E$$

The problem in a power station is the determination of the electric fields and currents that are induced inside a human body standing at different locations. The difficulty is the model selection of the human body. In reference [12] the human body is simulated as a spheroid (with a height of 2*a* and width of 2*b*). A Cartesian coordinate system is used. The human height is taken in the *Y*-direction while the width is taken in the *X*–*Z* plane. In accordance with Maxwell's laws, a variable magnetic field described by the flux density B produces an internal electric field with the body and consequently an induced current. The following formulas are used [15]:

$$E_x = j\omega\left(\frac{zB_y}{2} - \frac{kyB_z}{1+k}\right)$$

$$E_y = \frac{j\omega}{1+k}(xB_z - zB_x)$$

$$E_z = j\omega\left(\frac{kyB_x}{1+k} - \frac{xB_y}{2}\right)$$

where E is the internal induced electric field; E_x, E_y and E_z are the three components of the internal induced electric field; B_x, B_y and B_z are the three components of the external magnetic field; $k = (b/a)^2$ and ω is the angular frequency of the alternating external magnetic field.

In accordance with Faraday's law, an induced electrical current is produced. Its density is

$$\overline{J} = \sigma \overline{E}$$

where σ is the electrical conductivity of the human body.

In this analytical model there is the possibility to analyze the effects of different geometrical and physical parameters of the human body. Thus, effects of the incident angle of the external magnetic field, the height and width of the human body can be considered.

5. 5. A numerical model for the thermal field

It is obviously that all phenomena depend on the time so that a complete numerical model must include a discretization scheme for the time variable. When applying the FEM to time dependent problems, the time variable is usually treated in one of two ways:

- Time is considered as an *extra dimension* and shape functions in space and time are used
- The *nodal variables* are considered as *functions of time* and the shape functions in space are used.

A common approach for transient problems is to solve time dependent partial differential equations by finite differences approximation of time derivative terms, combined with some weighted residual method in space.

A widely used finite difference scheme for the first-order equations is the so-called θ-rule. Certain values of θ correspond to well known methods for time stepping:

θ =0 the forward difference method;
θ =1/2 Crank-Nicholson's method;
θ =2/3 central difference method;
θ =1 the backward difference method.

We illustrate the method by applying the θ-rule in time and Galerkin method in space for bioheat equation in a simplified form:

$$\rho c \frac{\partial T}{\partial t} = \nabla(k\nabla T) + \omega_b \rho_b c_b (T_a - T) + Q \quad (14)$$

where Q includes all heat sources.

For a typical time interval $[t_{m-1}, t_m]$ we approximate the temperature T(x, t) and its derivative with respect t by a finite difference method [18]. This strategy begins with the time discretization of the mathematical model by a finite difference method.

$$T(x,t) = \theta.T^{(m)}(x) + (1-\theta)T^{(m-1)}(x)$$

$$Q(x,t) = \theta.Q^{(m)}(x) + (1-\theta)Q^{(m-1)}(x)$$

$$\frac{\partial T}{\partial t} = \frac{T^{(m)} - T^{(m-1)}}{\tau}; \quad \tau = t_m - t_{m-1}$$

where the superscripts *m* and *m-1* refer to subsequent time instances and τ is the time step size.

Applying this rule to the bioheat equation (14) results in the following sequence of spatial problems:

$$T^{(0)} = T_0(x); \quad x \in \Omega \quad (15)$$

$$(\rho c)\frac{T^{(m)} - T^{(m-1)}}{\delta t} = \theta\nabla(k\nabla T^{(m)}) +$$

$$(1-\theta)\nabla\cdot(k\nabla T^{(m-1)}) + +\omega_b \rho_b c_b (T_a - T^{(m)}) \quad (16)$$

$$+ \theta Q(x,t_m) + (1-\theta)Q(x,t_{m-1})$$

where superscript *m* represents the index of the time moment. The boundary conditions are discretized in the same manner. For example, a Neuman boundary condition is approximated as

$$-k\frac{\partial T^{(m)}}{\partial n} = h(x,t_m); \quad x \in \partial\Omega \quad (17)$$

Now we do the approximation:

$$T^{(m)} = \sum_{j=1}^{r} T_j^{(m)} N_j(x)$$

where $T_j^{(m)}$ are constants to be determined by the method, and $N_j(x)$ are linearly independent shape functions. The N_j functions span a vector space with finite dimension. In our research we used the finite element grids consisting of linear triangles.

Discretizing the equations (16) by the method of weighted residuals gives a system of algebraic equations for every time step. At each time step we must solve a linear or non-linear system and this is a serious disadvantage in 3D problems.

5.6. A thermal wave model

In computer-aided analysis of the skin tissue temperature rise or estimation of the burn caused by spatial heating such as the electromagnetic apparatus or high-voltage lines, equation of the bioheat must include the heat source due the electromagnetic energy absorbed by tissue. In the professional literature there are some mathematical models based on the wave equation. Thus, in reference [19] a wave model is included in the bioheat equation. For example, if we consider a semi-infinite tissue exposed to incident electromagnetic wave, the right hand in bioheat equation includes a term Q_r defined by formula [19]:

$$Q_r(x,t) = \frac{2I_0\Lambda}{\delta} e^{-\frac{2x}{d}U(t)}$$

where I_0 is the power density of incident electromagnetic wave (W/m^2), Λ is power transmission coefficient between air and tissue, d is penetration depth, and U(t) is the unit step function. The SAR within the tissue can be computed for different particular cases. Thus, for a plane uniform electromagnetic wave incident normally to the skin surface, the SAR can be computed as $Q_r(x, t)/\rho$, where ρ is the density [kg/m^3].

6 Software for coupled fields

The coupled problems are natural problems because of some major motivations:

- Two or more physical systems interact
- Two or more physical fields co-exist in the same electromagnetic device
- The physical properties of the materials are strongly dependent on the temperature, especially the following characteristics: electric conductivity, magnetic permeability, specific heat and thermal conductivity
- The heat sources in thermal systems represent the Joule effect of the electric currents (driven currents or induced currents)

Application software for time-varying problems can be classified into two classes:

- time-domain programs
- frequency-domain programs

First class has the following characteristics:

- Time-domain programs generate a solution for a specified time interval at different time moments
- A large amount of data that must be stored to recover the field behaviour.

The second class is characterized by:

- Frequency-domain programs solve a problem at one or more fixed frequencies
- We obtain a compact and a cheap program in terms of the computer resources
- It is applicable only to linear problems (all phenomena are sinusoidal)

A finite element program for coupled problems has a modular form. The block diagram is presented in fig. 6. Finite element method (FEM) involves three stages:

- Pre-processing
- Solution or processing
- Post-processing

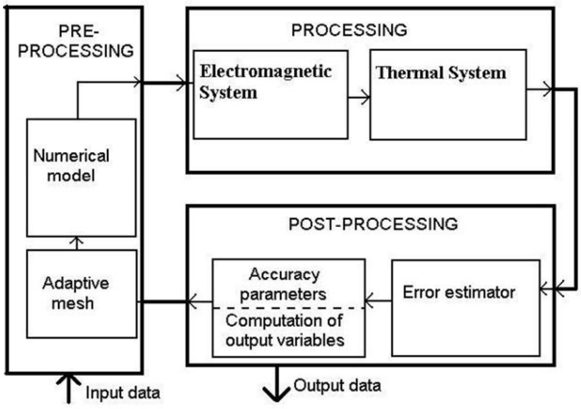

Fig. 8. – Block diagram of a CAD software

7 Conclusions

The influence of human body shape on the whole body SAR must be estimated because the real body is deformed. There is a relation between the height, weight and SAR of the whole body. The inverse problem is that from a given value of SAR we must find the level of incident field above which the absorption exceeds the limits of safety recommendations

The analysis of distributed parameter systems is a complex problem so that the analytical solutions can not be obtained. Many practical engineering problems involve geometric shape and size invariant in one direction. In the case of the electric cables we considered the axis Oz as the co-ordinate direction in which the structure is invariant in size and shape. This is the case of *a plane-parallel field* or *translational field* problem, where A has one component.

The model of large power cable is a combination of an electromagnetic, a thermal, a mechanical and a hydraulic part. The interconnection of the four parts is given on the one hand implicitly by the temperature dependence of the material constants, on the other hand explicitly by the heat sources in the thermal model controlled by the Joule heating in the electromagnetic model.

Domain decomposition offers an efficient approach for large-scale problems or complex geometrical configurations [12]. This method in the context of the finite element programs leads to a substantial reduction of the computing resources as the time of the processor.

Although we limited the presentation to the domain decomposition considering physical properties of the field problem, the partitioning of the domain can be performed according to the mathematical models of the field problem (operator decomposition).

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