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Abstract— In this paper, we describe the numerical modeling of magnetically induced heating of tissues in magnetic fluid deep hyperthermia. When placed in sinusoidal varying electromagnetic field, the Brownian particle rotation and Neel relaxation mechanisms induce in ferrofluid heat generation. In order to destroy tumors cells while preventing healthy tissues, such parameters as susceptibility of nanoparticles, exciting current parameters and intensity of magnetic fields should be calculated precisely. In this publication, coupled field problem resulting from Maxwell's equation and Penne's bioheat equation is discussed. Both sets of equations are solved using the finite element analysis method. We use a simplify model of human thorax with blood perfusion mechanism and tumor placed in it. Heat generation source in tumor is obtained by ferromagnetic nanoparticles. Magnetic and temperature field distribution is discussed in context of optimal tumor treatment.

Keywords— hyperthermia, magnetic nanoparticles, coupled field problem, finite element method.

I. INTRODUCTION

The temperature distribution in tissues and tumor depends on the generated energy and the physiological characteristic of the patient tissues. In the case of using electromagnetic field to generate heat, the energy distribution is a depends on in complicated way from frequency and amplitude of the applied fields, and also from tissues geometry, and size of the heating arrangements as well as the material properties. Essential role plays the location of the tumor in human body [1]. Generally, tumors situated deep in body are much difficult to treat, as that located on the skin or in not big distance from it. The temperature distribution in body not only depends on the energy source but also on blood parameters and thermal constants of the tissues. In present state of hyperthermia research and application, thermal treatment planning and dosimetry using radiofrequency and microwave electromagnetic waves is far from satisfactory [2].

Nanoparticles are usually defined as material parts with dimension less than 100 nm, though particles up to 1000 nm or greater in size are also treated as nanoparticles. In the case of metallic particles, materials at a nanoscale exhibit distinctive properties which can be used for therapeutic purposes. This is caused by the considerable larger surface area compared to volume of nanoparticles that permits single atoms at the surface to have highest energetically potential for interface with surrounding atoms [3].

Let us at beginning consider collection of ferromagnetic particles consisting of only single magnetic domains placed in a non-

magnetic medium and assume that the nanoparticles are separated enough far in such way that there is no interparticle interactions between them. Then, if $k_B T \gg KV$, where T is the temperature, k_B is the Boltzmann constant and K is the anisotropy constant, such particle collection will behave like a paramagnetic material. Independent magnetic moments in such material are not from single atoms, but rather from a single domain of ferromagnetic particles, which could contain more than 10^5 atoms, which are ferromagnetically coupled together by magnetic forces. Such particles are called superparamagnetic. The vector of the magnetization oscillates with a frequency f or with a characteristic relaxation time, $t = 1/f$. For Brownian relaxations time τ_B the rotation of the magnetic nanoparticle with the hydrodynamic volume V_H (which contains the adsorbed molecules on its surface) in a viscous fluid is equal [4].

In frequency domain susceptibility of magnetic nanoparticle has complex value $\chi = \chi' + j\chi''$, where [5]

$$\chi' = \frac{\chi_0}{1 + (2\pi f \tau)^2} \quad (1)$$

$$\chi'' = \frac{2\pi f \tau \chi_0}{1 + (2\pi f \tau)^2} \quad (2)$$

where χ_0 is equilibrium susceptibility and τ is the effective relaxation time related with Brownian and Néel relaxation [6]. Only imaginary part of complex susceptibility is relevant in nanoparticle heating. Heat generated by magnetic nanoparticle placed in magnetic field H is given by [2]

$$Q_{nano} = \pi \mu_0 \chi'' H^2 f \quad (3)$$

All calculations were done for particles with diameter $d = 40\text{nm}$, $\delta = 0.1 \cdot d$, $T = 293.15\text{K}$, $K = 2 \cdot 10^5 \text{J/m}^3$, $M_s = 446 \cdot 10^3 \text{kA/m}$, $\tau = 5 \cdot 10^{-9}\text{s}$ and $\phi = 1$. In the case of other value of the ϕ , one needs to multiply power P though this value.

II. EQUATIONS DESCRINING FIELDS DISTRIBUTION

As an example of magnetic field and temperature distribution calculation, realistic situation with real physical tissue parameters was considered [7-10]. It was assumed that tumor is placed inside human thorax, as it is shown in Fig.4.

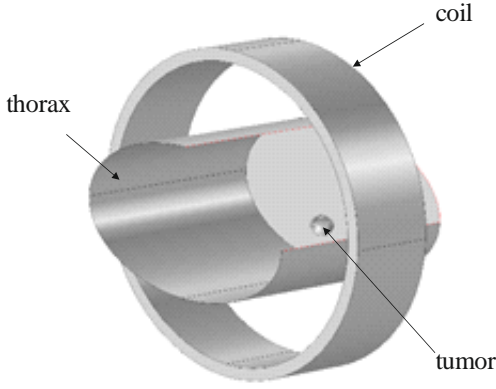


Fig. 1. Human thorax with tumor and exciting coil.

The thorax has elliptical cross section with semiexes 0.15 and 0.25 m, the length of the thorax is equal 0.7m and tumor radius has value 0.02m. The inner coil radius is 0.65m, cross section has rectangular shape $0.05 \times 0.3 \text{m}^2$ and has made from cooper 500 turns. Current 2A with frequency 300kHz flows in it. Tumor is placed 0.3m from main axes on greater thorax semiexes. This arrangement is surrounded by sphere radius 1m. Most important tissue values are given in Tab. I [11-14].

TABLE I. PYSICAL PROPERTIES

Tissue	σ S/m	k W/m/K	c_p J/kg/K	ρ kg/m ³	μ
Thorax	0.4	0.52	3540	1079	1
Tumor	0.2	0.52	3421	1090	1

Electromagnetic field describe following relations [6]:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (4)$$

$$\mathbf{J} = \sigma \mathbf{E} + j\omega \mathbf{D} + \mathbf{J}_{ex} \quad (5)$$

In terms of magnetic potential \mathbf{A} , first Maxwell's equation has form:

$$(j\omega\sigma - \omega^2 \epsilon_0) \mathbf{A} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) = \mathbf{J}_{ex} \quad (6)$$

where $\mathbf{M} = \chi \mathbf{H}$.

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (7)$$

$$\mathbf{E} = -j\omega \mathbf{A} \quad (8)$$

where \mathbf{A} is magnetic potential and ω angular frequencies. Other variables have their usual meaning and are complex values. Modulus of magnetic field strength is given by

$$H = \sqrt{\mathbf{H} \cdot \mathbf{H}^*} \quad (9)$$

Eddy current flowing in whole body generate heat, which averaging over time period gives resistive heating [7]

$$Q_{res} = \frac{1}{2} \text{Re} \left(\mathbf{J} \cdot (\mathbf{E}^* + \frac{1}{\sigma} \mathbf{J}_{ex}^*) \right) \quad (10)$$

According to Pennes heat model, the total energy interchange by flowing blood is proportional to the entire volumetric heat flow and the temperature difference between blood and surrounding tissues. The three-dimensional equation of Pennes bioheat equation in a tissues with material properties uniform in subdomains is given by [6]

$$\nabla \cdot (-k \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{res} + Q_{met} + Q_{nano} \quad (11)$$

where T is temperature °K, ρ , the tissue density kg/m³, C_b , the blood specific heat J/(kg° K), k , the thermal conductivity W/(m°K), ω_b , the blood perfusion rate 1/s, T_b , the arterial temperature, Q_{met} , the metabolic heat generation rate W/m³, Q_{res} , the induction heat source W/m³ and Q_{nano} , the heat generated by nanoparticles W/m³. The values of these physical quantities are shown in Table II.

TABLE II. PYSICAL PROPERTIES

Tissue	T_b K	ω_b 1/s	c_b J/kg/K	ρ_b kg/m ³	Q_{met}
Thorax	310.5	0.008	3567	1056	200
Tumor	310.5	0.005	3555	1056	300

Thermal boundary condition for temperature on thorax surface is given by [21]

$$\mathbf{n} \cdot (-k \nabla T) = h(T_{air} - T) \quad (12)$$

where h is the heat transfer coefficient $10[\text{W}/(\text{m}^2 \cdot \text{K})]$, T_{air} is the temperature of the surrounding air 293.15 [K] and k thermal conductivity $0.52[\text{W}/(\text{m} \cdot \text{K})]$.

III. NUMERICAL CALCULATIONS

Heating by means of magnetic fields is accomplished typically by two physical phenomena: Joule heating and magnetic field interacting. Joule heating results from eddy current generation by Faraday's Law. Heating tissues by magnetic field consist of relaxation losses in ferromagnetic dipoles (Néel relaxation) inside a nanoparticle when the magnetic dipole moments oscillate, and also motional heat dissipation, due to Brownian motion of particular particles in response to an external time-varying electromagnetic field. Other heat generation mechanism can result from particle-particle interactions between individual iron oxide nanoparticles located in a surrounding starch coating, such as in the super-paramagnetic iron oxide.

In order to simplify human model, we consider only part of the body, namely thorax with tumor inside it. Thorax tissue parameters were obtained as mathematical mean of all real tissues contained in it. Volume fraction of magnetic nanoparticle was assumed as $\phi = 0.01$. As magnetic nanoparticle we used magnetite given in Tab. I. In Fig. 2 magnetic field strength along thorax and tumor cross section is shown. Magnetic field strength attains 12.7 kA/m and cannot be greater because of overheating thorax

tissues by eddy current. One can see that minimal field value occurs on main symmetry axis. It is assumed that temperature in healthy tissues should not exceeds 38°C. Thus only in limited range field strength can be used to control temperature distribution in body.

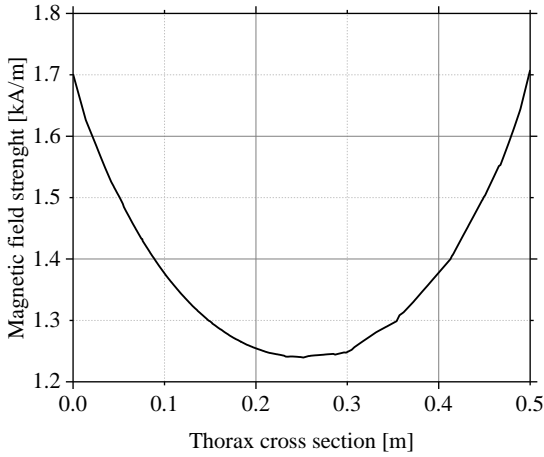


Fig. 2. Magnetic field strength along thorax and tumor cross section.

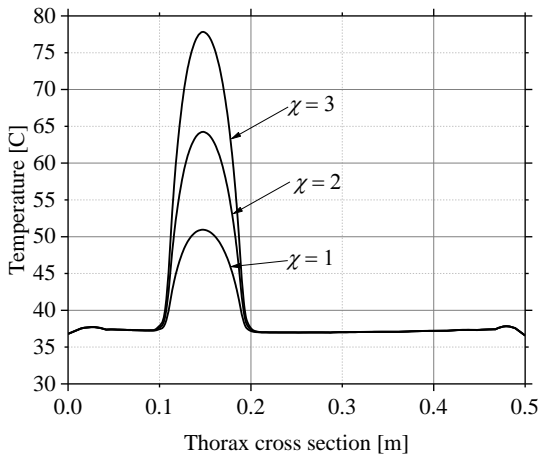


Fig. 3. Temperature distribution along thorax and tumor cross section.

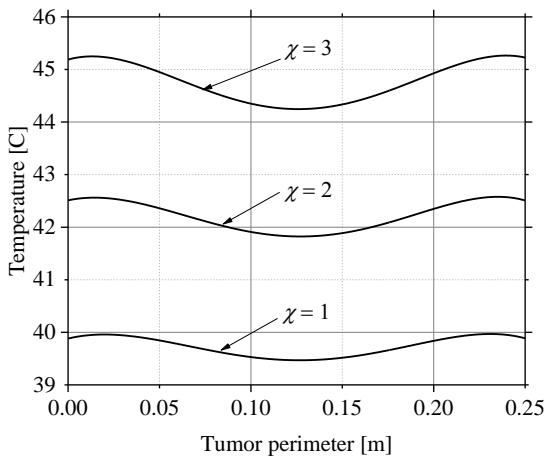


Fig. 4. Temperature distribution tumor perimeter.

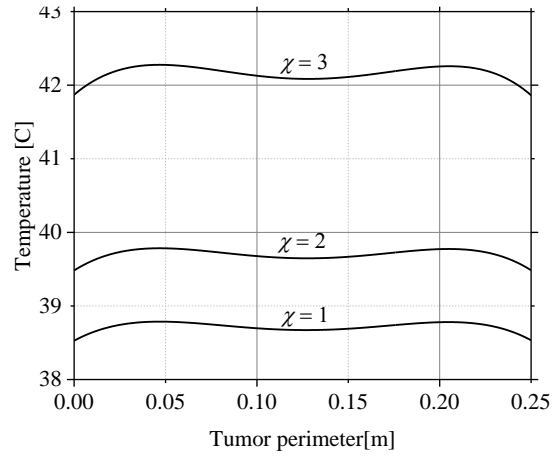


Fig. 5. Temperature distribution tumor perimeter.

In Fig. 3 different distribution of temperature in function of particle susceptibility are given. From this relation one can determine volume fraction of magnetic fluid which is needed to thermal therapy. In Fig. 4 temperature distribution along tumor perimeter on plane parallel to main semiexes of thorax is depicted. For value susceptibility value $\chi = 3$ we obtain optimal temperature distribution in the range 44 to 46 °C degree. This range can be easy modified by changing volume fraction ϕ of nanoparticles in tumor. Temperature distribution in Fig. 5 confirm this fact. In Fig. 6 eddy current generated heat generated according with (17) is shown. It is considerably less then heat generated by magnetic particles needed to obtain therapeutic effect in tumor, which in our example is equal 200 kW/m³. Changing different current ex-acting or particle parameters we can obtain optimal distribution of temperature in tumor and its vicinity.

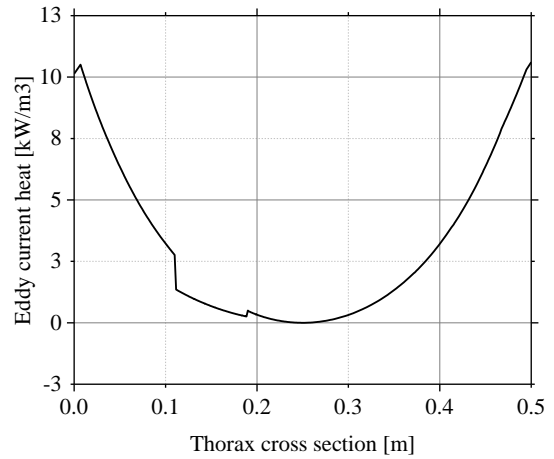


Fig. 6. Temperature distribution along thorax and tumor cross section.

IV. CONCLUSIONS

In all our computations we have assumed a uniform distribution of magnetic particles in tumor. Of course there are also possible other spreading of nanoparticles with another influence on temperature profile. Because in real nanoparticles only part of them is made from magnetic material and this restricts their heating possibilities. For example, fluidMAG-D, made by Chemicell

GmbH, contains only 16.5% magnetic iron oxide and the rest is made from starch. The volume fraction of particles, which is present in tumor, also limits the heating power that can be obtained. Therefore, by choosing appropriate coil parameters and exciting current, the real heat distribution within the tissues can be estimated in such a way, to have therapeutic values. Another factor, which has influence on generated heating power is magnetic field strength. It cannot exceed same value, by which tissue temperature surrounding tumor is not greater than, say 38°C, when healthy tissues become overheated. In our case this is 1.7kA/m. While heat is primarily generated by the magnetic core of particles, in [1] authors have shown that particle coatings can have substantial influence on heat generation value. The coated nanoparticles can collect in large aggregates, and because of the particles are closely bound in such clusters they experience some dipolar interactions. This could explain the hysteresis loop in magnetization curve, which also have some influence on generated heat.

In this study authors considered heating of the tumor placed in thorax in some extent from the surface. As can be seen from Fig. 2, magnetic field strength in the tumor is substantially lower than in the skin and has value 1.3kA/m. Power generated by this field value is equal 134 kW/m³, whereas power generated by eddy currents has value 0.7Kw/m³, what is substantially less. This means, that value of the heat delivered to tumor can be determine either by susceptibility nanoparticles or volume fraction particles in tumor. In our simulation three distinct values of susceptibility were examined. Only susceptibility $\chi = 3$ and volume fraction $\phi = 0.02$ fulfils therapeutic requirements. The method described in this publication allows simulation different treatment scenarios.

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