Journal of Engineering Physics and Thermophysics, Vol. 71, No. 1, 1998

CONTROL OF DISSIPATION OF MICROWAVE FIELDS BY MEANS OF EXTERNAL SEMITRANSPARENT SCREENS IN HYPERTHERMIA

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UDC 536.2.0172:612.014.425.5

The dissipation of a microwave field in an inhomogeneous plane layer covered by external semitransparent screens is investigated. It is shown that use of the screens makes it possible to control the dissipation process: to displace the nodes and antinodes of the loss power density and to increase and decrease its values at the antinode points. The reported results can be of help in hyperthermia of biological objects in cancer treatment.

1. Introduction. The interaction of microwave radia with continua has long attracted the attention of radiophysicists in connection with problems of transport and processing of information [1-3] (propagation of radiowaves in the atmosphere, propagation by waveguides, and so on). In these cases dissipative losses represent a small parasitic factor and can be evaluated by rough qualitative models.

Recent years have seen other possibilities for using microwave radiation, in which the main working parameter is radiation dissipation [4, 5]. Here two trends can be noticed. The first trend (drying of various materials, microwave ovens for cooking, etc.) is characterized by the fact that the heated medium is homogeneous (or almost homogeneous) and it is desirable to provide uniform heating of it. The other trend (e.g., microwave hyperthermia of biological objects in cancer treatment [5]) is quite opposite in its essence. The heated tissues are considerably inhomogeneous in their electrical characteristics and must be heated locally (heating of definite spatial regions with minimum heating of all other regions).

Therefore for microwave hyperthermia, physical possibilities for control of the electrical-loss distribution in the sample volume are of considerable interest. One such possibility is discussed in the present work. It is based on use of external semitransparent screens. Dielectric layers [6], periodic conducting structures [7], or a combination of the both (metallic planar arrays deposited on dielectric substrates) can be used as such screens.

2. Calculation Model. The configuration of the heated sample is shown in Fig. 1. It represents a longitudinally inhomogeneous plane layer of thickness L characterized by the complex dielectric permittivity $\varepsilon_1(x)(1 - j\tan\delta(x))$ ($\delta(x)$ is the dielectric-loss angle). Heating is carried out in the direction normal to the incident plane wave $\overline{E}^{(0)} = \overline{e}_y \exp(-jkx)$, $k = \omega/c$, ω is the circular frequency, c is the velocity of light in vacuum, $\overline{e}_y$ is the unit vector along the y axis (the time dependence is $\exp(j\omega x)$).

The external controlling screens are placed on both sides of the sample parallel to its boundaries (in Fig. 1 they are shown by dashed lines). In our analysis we do not specify the type or nature of the screen but characterize it by the scattering matrix

$$S_i = \begin{pmatrix} t_i & r_i \\ r_i & t_i \end{pmatrix}, \tag{1}$$

where r_i, t_i are specified complex coefficients, $i = 1, 2$. This an approach makes our analysis general for screens of different types and configurations.

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus." Institute of Nuclear Problems at the Belarusian State University, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 1, pp. 120-123, January-February, 1998. Original article submitted June 13, 1996.

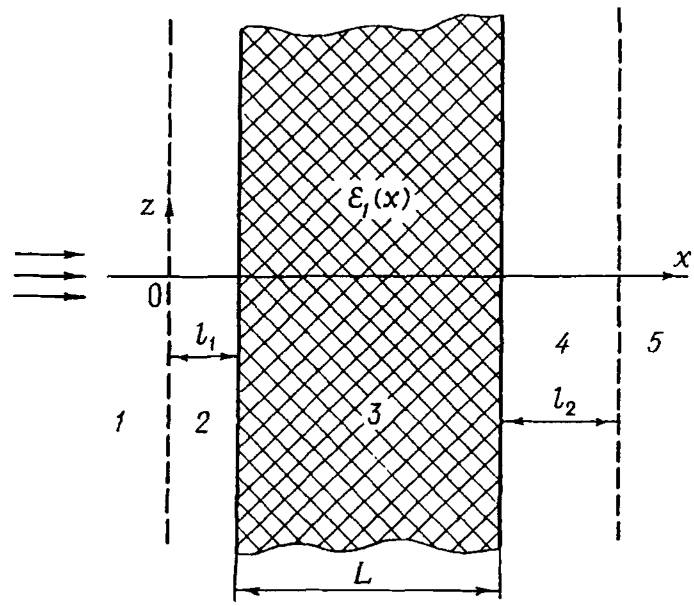

Fig. 1. Geometry of the problem and the basic notation: 1-5) partial regions.

For simplicity's sake we will neglect absorption in the screens, and therefore the matrices S_i are unitary $(S_i S_i^* = I)$.

The goal of the analysis below is to reveal the influence of the screens on the loss power distribution in the sample volume.

3. Basic Relations. The power density of electrical losses in the sample volume is expressed by the equality [8]

$$p^e(x) = \frac{1}{2}\varepsilon_1(x) \tan\delta(x) \, |\varphi|^2, \tag{2}$$

where $\varphi = E_y$. In many cases of practical interest the condition $|\tan\delta(x)| << 1$ is fulfilled. This allows use of the method of perturbations with respect to $\tan\delta$ in calculations of $p^e(x)$, i.e., substitution of φ corresponding to the appropriate nonabsorbing medium into (2) [8].

Then for $\varphi(x)$ we arrive at the equation

$$\frac{d^2\varphi}{dx^2} + k^2\varepsilon(x)\varphi = 0, \tag{3}$$

where $\varepsilon(x) = \varepsilon_1(x)$ in the sample volume and $\varepsilon = 1$ outside it. We assume that $\varepsilon_1(x)$ changes in the sample volume sufficiently slowly that $|d\varepsilon_1(x)/dx| << \varepsilon_1 k$. This allows the field in the sample to be described by the WKB method [9]. We will also assume that $d\varepsilon_1/dx\ (x = 0, L) = 0$

To calculate $\varphi(x)$, the method of partial regions is employed in the sample volume (in the present problem there are five regions; they are shown in Fig. 1 by numerals). The fields in the partial regions can be represented in the following form:

$$\varphi^{(1)} = \exp(-jkx) + R\exp(jkx), \tag{4}$$

$$\varphi^{(2)} = a_1\exp(jkx) + b_1\exp(-jkx), \tag{5}$$

$$\varphi^{(3)} = \frac{A}{\sqrt[4]{\varepsilon_1(x)}}\exp[jk\Phi(x)] + \frac{B}{\sqrt[4]{\varepsilon_1(x)}}\exp[-jk\Phi(x)], \tag{6}$$

$$\varphi^{(4)} = a_2 \exp(jkx) + b_2 \exp(-jkx)\,, \tag{7}$$

$$\varphi^{(5)} = T \exp(jkx)\,, \tag{8}$$

where $\Phi = \int_0^x \sqrt{\varepsilon_1(\xi)}/d\xi$; R, T, A, B, a_i, b_i are unknown coefficients; the index in parentheses indicates the number of the partial region to which the given representation refers.

Matching of the fields will be carried out in the limiting case $l_{1,2} \to 0$ without loss of generality, since the scattering matrices S_i for the screens located at a distance from the sample can be recalculated for the planes $x = 0, L$.

Imposing boundary conditions on the sample boundaries and allowing for the equalities $t_1 + r_1 a_1 = b_1$, $r_1 + t_1 a_1 = R$, $r_2 b_2 = a_3$, $t_2 b_2 = T$, we arrive at a system of four algebraic equations in four unknown:

$$\begin{gathered} \gamma_+ + \theta_+ R = \frac{A + B}{\sqrt[4]{\varepsilon_{10}}}\,, \\ -\gamma_- + \theta_- R = \sqrt[4]{\varepsilon_{10}}\,(A - B)\,, \\ A \exp(jk\tilde{\Phi}) + B \exp(-jk\tilde{\Phi}) = \frac{\sqrt[4]{\varepsilon_{11}}}{t_2}\, T\,(r_2 \exp(jkL) + \exp(jkL))\,, \\ A \exp(jk\tilde{\Phi}) - B \exp(-jk\tilde{\Phi}) = \frac{T}{\sqrt[4]{\varepsilon_{11}}\; t_2}\, T\,(r_2 \exp(jkL) - \exp(-jkL))\,, \end{gathered} \tag{9}$$

where $\tilde{\Phi} = \int_0^L \sqrt{\varepsilon_1(\xi)}\,d\xi$; $\varepsilon_{10} = \varepsilon_1(0)$; $\varepsilon_{11} = \varepsilon_1(L)$; $\theta_\pm = (1 \pm r_1)t_1^{-1}$; $\gamma_\pm = t_1 \mp (1 \pm r_1)r_1 t_1^{-1}$.

For purposes of hyperthermia, the complex amplitudes A and B characterizing the field inside the sample and determining dissipation in it are of interest. From (9) we can write for them

$$B = \frac{2t_1 \sqrt[4]{\varepsilon_{10}}}{1 - r_1 + \sqrt{\varepsilon_{10}}\,(1 + r_1) - \eta \exp(-2jk\tilde{\Phi})\,[1 - r_1 - \sqrt{\varepsilon_{10}}\,(1 + r_1)]}\,, \tag{10}$$

$$A = -\eta B \exp(-2jk\tilde{\Phi})\,, \tag{11}$$

$$\eta = \frac{r_2 \exp(jkL)\,(1 + \sqrt{\varepsilon_{11}}) - \exp(-jkL)\,(1 - \sqrt{\varepsilon_{11}})}{r_2 \exp(jkL)\,(1 - \sqrt{\varepsilon_{11}}) - \exp(-jkL)\,(1 + \sqrt{\varepsilon_{11}})}\,. \tag{12}$$

The equalities (10)-(12) make it possible to represent (2) in the form

$$p^e(x) = \frac{1}{2}\sqrt{\varepsilon_1(x)}\,\tan\delta(x)\,|B|^2 \left\{1 + |\eta|^2 - 2\,|\eta| \cos\theta(x)\right\}, \tag{13}$$

where

$$\theta(x) = 2k \int_L^x \sqrt{\varepsilon_1(\xi)}\,d\xi + \varphi_\eta\,; \tag{14}$$

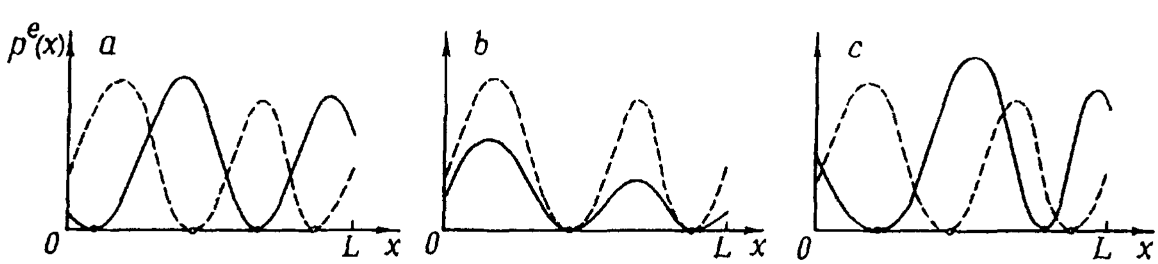

Fig. 2. Qualitative character of the loss power distribution in the sample volume in the presence of semitransparent screens: a) without the first screen; b) without the second screen; c) in the presence of both screens; dashed line) in the absence of both screens.

here φ_η is the phase of the complex coefficient η defined by (12).

Equalities (13), (14) are the main result of the calculations performed.

4. Results and Discussion. As follows from (13), the power distribution of microwave losses over the sample volume is an oscillating function of the coordinate x. Local minima are determined by the condition $\theta(x) = 2n\pi$, and local maxima by the condition $\theta(x) = (2n - 1)\pi$, $n = 0, 1, \dots$. It is important that the quantity $\theta(x)$ includes the term φ_η containing elements of the scattering matrix of the second screen. Hence it follows that by varing the parameters of the second screen we can displace the local extrema in space, i.e., cause maximum heating of specified spatial regions. At the same time $\theta(x)$ does not depend on the elements of the matrix S_1, and therefore the first screen does not influence the position of the local extrema.

It is also convenient to characterize the power distribution of microwave losses in the sample volume by the nonuniformity coefficient $\alpha = p^e_{(\min)}/p^e_{(\max)}$, where the subscripts (min) and (max) indicate the value of the considered function at points of a local minimum and maximum, respectively. From (13) we obtain

$$\alpha \approx \left(\frac{1 - |\eta|}{1 + |\eta|}\right) \sqrt{\left(\frac{\varepsilon_{(\min)}}{\varepsilon_{(\max)}}\right)} \frac{\tan \delta_{(\min)}}{\tan \delta_{(\max)}}, \tag{15}$$

and η, in accordance with (12), can be represented in the form

$$\eta = -\frac{\tilde{r} + \eta_0}{1 + \eta_0 \tilde{r}},$$

where $\tilde{r} = r \exp(2jkL)$; $\eta_0 = (\sqrt{\varepsilon_{11}} - 1)/(\sqrt{\varepsilon_{11}} + 1)$. Hence it follows that the nonuniformity coefficient determined by (15) depends considerably on elements of the matrix S_2 and can be regulated by the second screen.

The elements of S_1 enter only the amplitude coefficient B determined by (12). This means that the first screen exerts an influence only on $p^e_{(\max)}$. It should be noted that for large ε_{10} the influence of the first screen not only can decrease but also can increase $p^e_{(\max)}$. From the physical point of view this means that a semitransparent screen acts as a matching transformer. The qualitative character of the power distribution of losses in the sample volume for different cases is shown in Fig. 2.

Thus, external semitransparent screens provide an effective tool for control of microwave hyperthermia. A comprehensive study of the considered possibilities requires numerical calculations for various types of samples and screens, account for the curvature of sample boundaries, etc.

The highest frequency used in hyperthermia is $f = 915$ MHz. At this value typical biological tissues are dielectric. In the case of lower frequencies, it is necessary to take into account the influence of the ohmic conductivity of the medium. In a first approximation, this can be done by the substitution $\tan \delta \to \tan \delta + \sigma/\omega\varepsilon_1$ (σ is the static conductivity), with the above relations and qualitative conclusions being retained [8].

The authors thank the Foundation for Fundamental Research of the Republic of Belarus for financial support (contract B94-009).

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