TEMPERATURE DEPENDENCE OF BIOLOGICAL TISSUES COMPLEX PERMITTIVITY AT MICROWAVE FREQUENCIES

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Summary In the paper an universal overview of polarizing mechanisms with an emphasis on dipolar materials as the investigated tissues are regarded. Experimental apparatus is presented with giving its specificity as well as the method used at calculation of complex permittivity. The experimental part is aimed at temperature dependence of complex permittivity measurement of pig biological tissues with different properties. Experimental results are presented graphically with the commentary for courses of particular tissues.

1. INTRODUCTION

We will give some universal information, which can help on the one hand at the assessment of investigated materials in view of usable measuring methods on the other hand at results processing. As we deal in the paper with dielectric materials investigation the attention is primarily fixed on dipolar substances.

For the better realization of possible measuring deviations at dielectric materials investigation added to a certain specific type according to the dominant polarization in the high frequency field, it is necessary to take into consideration also influences coming from other polarizing mechanisms, which can partly influence the results expected for a certain dielectric type.

The dominant quantity at dielectric material investigation is their complex permittivity. The complex permittivity of a material is a measure of the polarization which it undergoes in an applied alternating field, this polarization consisting of the displacement, relative to one another, of the positive and negative charges incorporated in the structure of the material, [1]. Since the atoms in every material incorporate a positively charged nucleus surrounded by electrons, the polarization of every material consists at least in part of a displacement relative to one another of the electrons and the nuclei of the individual atoms. From this point of view as well as displacement of different nuclei relative to one another and displacements arising from changes of orientation of dipolar groups of atoms forming a characteristic part of the structure, different kinds of polarization are possible. According to which type of polarization is dominant, dielectric can be considered as non-polar, polar and dipolar dielectrics. Knowing the type of the investigated dielectric we can choose a suitable frequency of the electromagnetic signal and assess which part of permittivity will be dominant. E.g. at non-polar dielectric for which the polarization consists almost wholly of the elastic displacement of electrons the proper frequencies of such displacements lie in the visible or ultra-violet region and thus the dielectric constant is independent of frequency and loss tangent tg δ is zero.

2. BIOLOGICAL TISSUES AND MICROWAVE FREQUENCIES

In this paper our attention is paid to biological tissues, which are regarded as dipolar materials. These materials show in addition to electronic and atomic polarization a polarization arising from changes in the orientation of dipolar groups of atoms, included in their structure. This orientation is considerably affected by thermal agitation and the corresponding dielectric properties are therefore dependent on temperature. The simplest cases of this type are those in which the dipoles are molecules with an asymmetric structure and therefore a permanent dipole moment. Such typical representative of this structure is water which shows strong dipolar polarization which is evidence for a triangular arrangement of the three atoms. As biological tissues contain high percent of water they behave as dipolar materials. As the relaxation time of water is $53 \cdot 10^{-12}$ seconds microwaves provide a suitable tool for investigation of biological tissues. And because the quantity enabling utilization of microwaves in medical treatment is just complex permittivity, an intensive attention has been paid to measurement of its behavior in different tissues and at different conditions.

Curative effects of microwaves used in medicine are determined by giving off heat at absorption of microwaves in biological tissues. Maximum absorption of heat is realized in good conductive surface tissues and skin. Less absorbing tissues are fat and muscles. Preferential heating of muscles and skin is joined with their large content of liquids, especially water. Absorption processes are complicated in biological tissues by the fact that they are composed of many layers with different dielectric properties. From this standpoint our attention was directed at muscles and bones as typical representatives with different absorptions.

At microwave hyperthermia application there is important the knowledge of skin-layer depth, *d,* [2].

It is defined as the depth at which the energy of field is reduced $1/e$ - times and is given by the relation

$$d = \frac{1}{f\sqrt{\varepsilon\,\mathrm{tg}\delta}}\,, \qquad (1)$$

where f is the frequency and ε is the dielectric constant of investigated material. The relation (1) means the further necessity of information about complex permittivity for individual tissues.

3. MEASURING TECHNIQUE AND WAY OF ASSESSMENT

Waveguide technique was used for measurement and measured samples were placed in rectangular waveguide with dimensions a = 22,9 mm, b = 10,2 mm, Fig. 1.

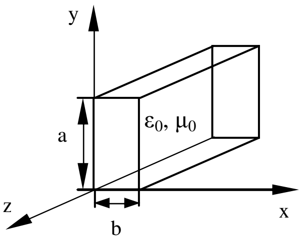

Fig. 1. Rectangular waveguide filled with air

Our measurements were carried out on the standard laboratory set up in the microwave X band (8 – 12 GHz) using the waveguide method. The slotted line is the most accurate measurement device. The principal scheme is in the Fig. 2.

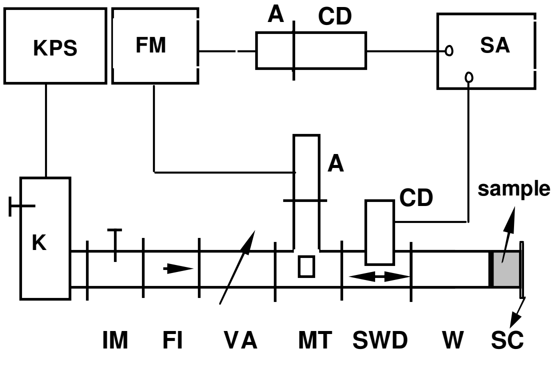

Fig. 2. Experimental set-up for complex dielectric constant measurement. K – klystron, KPS – klystron power supply, FM – frequency meter, SA – selective amplifier, IM – impedance match, FI – ferrite isolator, VA – variable attenuator, MT – magic T, SWD – slotted section, W – waveguide, SC – short circuit, A – adapter, CD – crystal detector

As a source of microwave signal was used the reflex klystron and it was isolated from the remainder part of the microwave line by the ferrite isolator. For matching there was connected the phaser and the signal passed through the directional switch where it could be directed in the slotted line or in the frequency meter. The measuring waveguide was terminated with a short-circuit and the measured sample formed to fit tightly into the waveguide was located at the end of the measuring waveguide. First the standing wave ratio (SWR) was measured without the sample and the minima of standing wave were recorded. This made possible to determine the waveguide wavelength, λ_g. Afterwards in the same way with the sample in the measuring waveguide corresponding SWR was measured and also the position of standing wave minima recorded again. SWR was measured by means of the “twice .- minimum” method. For the calculation of dielectric constant, ε' and the loss tangent, tg δ were for individual temperatures used simpler formulae (used for “minimum shift method”), [3], [4]

$$\varepsilon' = \left(\frac{x\lambda}{2\pi d}\right)^2 + \left(\frac{\lambda}{\lambda_c}\right)^2, \qquad (2)$$

where λ is the wavelength in the free space, d is the length of the sample and λ_c is the cut-of wavelength for the used waveguide, Fig. 1. The quantity x was obtained from the equation

$$\frac{\mathrm{tg}x}{x} = \frac{\lambda_g}{2\pi d}\,\mathrm{tg}\frac{2\pi(\Delta l + d)}{\lambda_g}, \qquad (3)$$

where Δl is the distance between two corresponding standing wave minima without and with the sample in the measuring waveguide and for the tg δ calculation

$$\mathrm{tg}\delta = \frac{\Delta w_s - \Delta w}{\varepsilon' d}\left(\frac{\lambda}{\lambda_g}\right)^2, \qquad (4)$$

where Δw_s is the “twice – minimum width” of the standing wave with the sample and Δw without sample.

The results obtained for sample at individual temperatures were verified for one temperature by the formulae for dielectric constant and loss tangent from Hippel’s method

$$\varepsilon' = \frac{k^2 + \beta^2 - \alpha^2}{\beta_0^2} \qquad (5)$$

and

$$\mathrm{tg}\,\delta = \frac{2\alpha\beta}{k^2 + \beta^2 - \alpha^2}, \qquad (6)$$

where α and β are components of the propagation constant $\gamma = \alpha + \mathrm{j}\beta$, $k = \frac{2\pi}{\lambda_\mathrm{c}}$ and $\beta_0 = \frac{2\pi}{\lambda}$. The propagation constant was calculated from the equation where the hyperbolic tangent instead of ordinary tangent is used. All the other quantities are the same as for the “twice-minimum” method mentioned above.

The simulation of electric field *z* component in the rectangular waveguide (Fig. 3) partly filled with dielectric material at frequency *f* = 10 GHz was performed in application of COMSOL, Electromagnetic module, [5] and result are in Fig. 3.

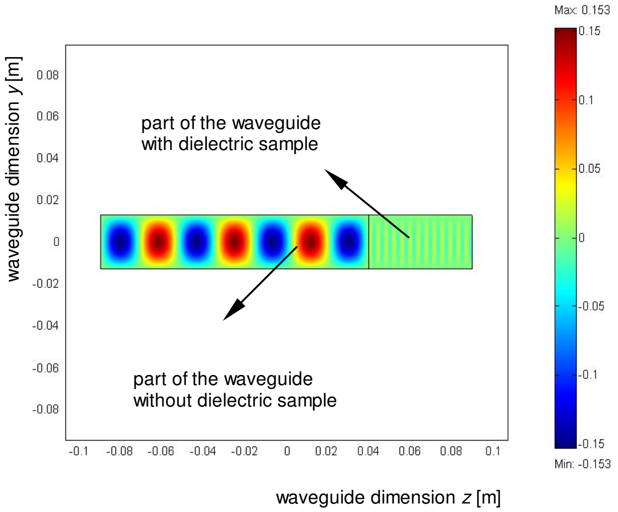

Fig. 3. Model of electric field z component in rectangular waveguide partly filled with dielectric material at frequency f = 10 GHz

4. EXPERIMENTAL RESULTS

Since our paper deals with permittivity of biological tissues we have chosen as the first move for measuring tissues assumed different properties. Owing to different water content in muscle and bone and known high permittivity value of water, we have selected these particular tissues. The measurements were carried out in the way described above and according to Fig. 2, [6]. For the heating of the sample was not used microwave heating but the measuring waveguide with the sample was immersed in heated water and the measurements were performed after temperature balancing. The samples were measured approximately 24 hours after death of the cattle. For verifying the value correctness samples with different lengths were measured from 5 to 25 mm.

Because of clearer comparison we give the temperature dependence of permittivity and loss tangent separately namely on the one hand for the related tissues (bone, marrowbone and marrow) and on the other for the tissues with different water content (bone, muscle). From Fig. 4 it can be seen that tg δ for marrow and marrowbone has similar courses, which is obviously influenced by considerable content of marrow in the bone, whereas for the bone without marrow the course of tg δ has a linearly character.

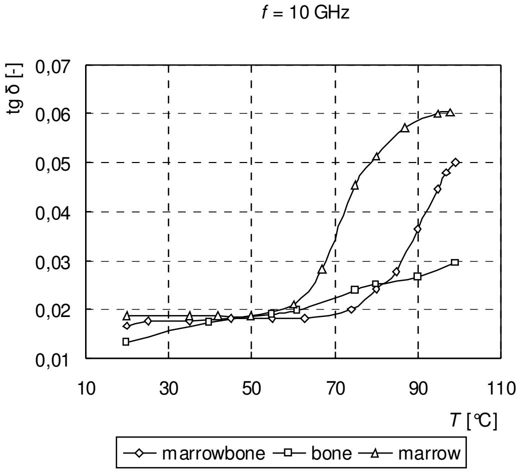

Fig. 4. Thermal dependence of loss tangent, tg δ, for cattle marrowbone, bone and marrow

Fig. 5 with the thermal dependences tg δ for bone and muscle documents distinctly different character of their courses, which is obviously given by the water content, [7].

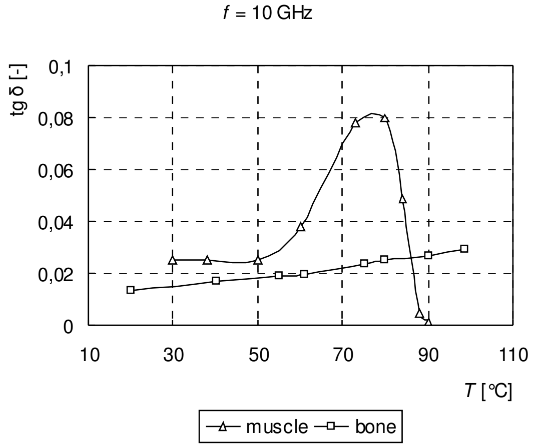

Fig. 5. Thermal dependence of loss tangent, tg δ, for cattle bone and muscle

Fig. 6 gives courses of dielectric constant temperature dependence for the same tissues as in Fig. 4. Apart from small shift, distinctive differences are not shown neither in dielectric constant values nor in their courses. Different courses for dielectric constant, Fig. 7, are obviously again given by different water content and the character of their temperature dependences is similar except the muscle’s at higher temperatures.

For microwave therapy the most interesting part is the temperature dependence up to 45°C.

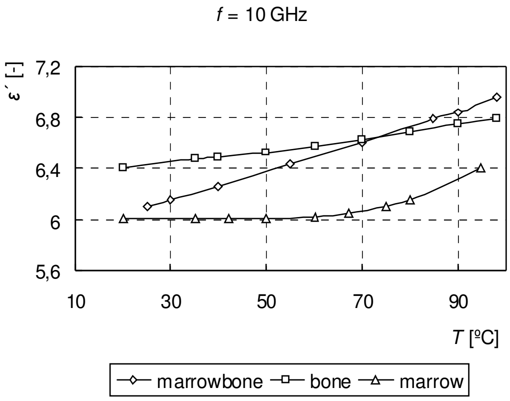

Fig. 6. Thermal dependence of dielectric constant, ε´, for cattle marrowbone, bone and marrow

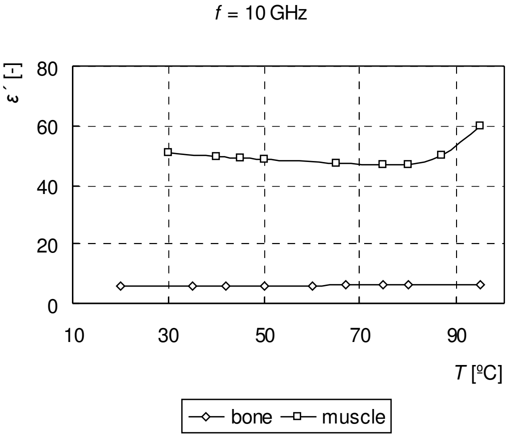

Fig. 7. Thermal dependence of dielectric constant, ε´, for cattle bone and muscle

In given figures apart from the bone sample all samples show loss tangent rising with temperature approximately from 40°C. From the practical point of view it may not be important because the microwave treatment is performed up to 45°C, but in case of hyperthermia connected with microwave ablation, [8], [9] works above this temperature it would be necessary to take this circumstance into consideration.

5. CONCLUSION

In spite of variety of information about the complex permittivity of biological materials our paper brings an integrated view on this problem from its fundamental physical characteristics up to the possible practical application. Moreover increasing use of microwaves in clinical practice will demand more detailed information in this field, especially at penetration through different layers, what is dependent on knowledge of the biological tissues dielectric constant. For instance at hyperthermia it is important to keep certain temperature in irradiated part of tissue and from this point of view it should be necessary to modify the microwave power according to the change of absorption in the irradiated tissue and this situation can solve the knowledge of temperature dependence of tg *δ*.

Further theoretical and experimental investigations will be carried out to frequency dependences of complex permittivity of biological tissues.

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