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Near-Field Effect in Thermal Radio-Frequency Radiation

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The near-field effect was experimentally observed in the thermal radiation of absorbing medium in the rf range. The radiation from a temperature-stratified aqueous medium was measured at a wavelength of 31 cm using specially developed electrically small antennas. The effect manifests itself as a decrease in the effective thickness of a layer in which the received radiation is formed and in the dependence of this thickness on the receiving antenna's size and its height over the medium surface. © *2000 MAIK "Nauka/Interperiodica".*

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The near (quasistationary) field of thermal electromagnetic radiation from heated media was predicted by S.M. Rytov as a consequence of his electrodynamic theory of equilibrium thermal fluctuations as early as 1950s [1]. This field is characterized by the absence of energy flux and a sharp drop in the volume energy density with distance from the surface of the radiating medium. It was theoretically proved in [2] that the near-field component of thermal radiation tangibly affects the signal intensity measured by a receiver only if the receiving antenna has small electric size $D \ll \lambda$ (λ is the wavelength) and is situated at height $h \ll \lambda$ over the radiating surface. These features hamper experimental investigations, for this reason, for which reason the near-field component of thermal radiation has not been experimentally detected so far.

As a result of the near-field effect, the effective thickness of a layer forming received radiation decreases compared to the skin layer. The decrease in the effective thickness can be observed experimentally as a function of either the antenna's size (near the surface) or its height (for small antenna). This was precisely the way in which the near-field component of thermal radiation was detected in this study by the measurements at a fixed wavelength.

Investigations were carried out in the decimeter wavelength range (λ = 31 cm). The obvious advantage of the decimeter waves over the shorter radio and infrared waves is that they place substantially less stringent requirements on the antenna's sizes and its height over the surface, because these parameters are specified by the wavelength scale and lie in the interval D/λ, $h/\lambda < 0.1$ [2]. The thermal radiation was detected by a radiometer with operating frequency f_0 = 950 GHz, frequency band Δf = 250 MHz, and fluctuation sensitivity threshold $\delta_T \approx 0.05$ K at the integration constant τ = 1 s.

The key element of the receiving system was an electrically small antenna of size D = 1 cm ($D/\lambda \approx 0.03$). It consisted of two in-phase dipoles connected to a symmetric strip line operating as a matching cavity (a prototype of this system is described in [3]). When antenna was in contact with the medium (h = 0), it was matched to the radiometer input so that the reflection coefficient averaged over the radiometer band Δf did not exceed 0.03. The radiation efficiency was determined from a comparison of the data of calibration measurements at two different temperatures of a uniformly heated medium with the response to the radiation of a matched load and was found to be η = 0.85 at h = 0. An increase in height led to both antenna mismatch (increase in the reflection coefficient) and decrease in the radiation efficiency. The sensitivity threshold to the temperature variations increased from 0.06 K at h = 0 to 1 K at the maximum height of measurements h_{max} = 2.5 mm. Further decrease in sensitivity at $h > h_{max}$ rendered the measurements at larger heights impossible. Thus, the presence of a matched high-efficiency antenna is a fundamental requirement to a near-field radiometric system, in contrast to similar active-location systems, which are usually referred to as near-field microscopes (see, e.g., [4]). Besides the antenna described above, the measurements were also carried out using a standard contact antenna with aperture D = 4 cm, which was developed for the medicobiological radiometric investigations [5].

Water was chosen as a medium for investigation because its complex dielectric constant $\epsilon = \epsilon_1 + i\epsilon_2$ and, hence, the skin depth $d = 1/\gamma$ [$\gamma = (4\pi/\lambda)\mathrm{Im}(\sqrt{\epsilon})$ is the absorption coefficient] can be calculated with a high accuracy, e.g., from data [6] if the temperature T and the salinity S are known. Strong dependence of the skin depth on the salinity enables one to model the conditions in various media by varying the d value in the interval from 1 mm to 10 cm. In addition, it is comparatively easy to carry out contact measurements of the

[1] This article was submitted by the authors in English.

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temperature depth profile $T(z)$ in a fluid. For measurements, stable quasi-linear profile $T(z)$ was formed with the use of a heater near the surface and a cooler near the bottom of a cylindrical vessel. The stationary temperature gradient was as large as $dT/dz \approx 2.5$ K/cm. The radiometer measured effective temperature (antenna temperature) of the radiation received from the medium filling the $z \le 0$ half-space:

$$T_a(h, D) = \int_{-\infty}^{0} T(z)K(h, D, z)dz, \quad (1)$$

i.e., the measured antenna temperature was a certain weighted mean temperature of the medium. The kernel of integral Eq. (1) is normalized and includes two components:

$$K(z, h, D) = \frac{(K_1(z, D) + K_2(z, h, D))}{\int_{-\infty}^{0} [K_1(z, D) + K_2(z, h, D)]dz}, \quad (2)$$

where K_1 and K_2 are the contributions of the wave and quasistationary field components, respectively. The functions $K_{1,2}$ for a medium with dielectric constant uniform in depth, i.e., $\epsilon(z) = \epsilon = \text{const}$, are given in [2]. For a uniformly heated medium [$T(z) = T_0 = \text{const}$], Eqs. (1) and (2) yield $T_a = T_0$ independently of the form of kernel K. If the distribution $T(z)$ is nonuniform in depth, the T_a value is determined by the effective thickness d_{eff} of a layer in which the received radiation is formed and which is of interested to us. This thickness is expressed through the kernel K as

$$d_{\text{eff}} = \int_{-\infty}^{0} zK(h, D, z)dz. \quad (3)$$

The wave component of a radiation in free space is formed by the plane nonuniform waves propagating under the surface of absorbing medium within a certain cone with axis directed along z. If the dielectric constant satisfies the conditions $\epsilon_1 \approx \epsilon_2$ and $|\epsilon| \gg 1$ (as in is the case of the aqueous medium under consideration), the apex angle of this cone is small. One then has $d_{\text{eff}} \approx d$ for the wave component of the field. Since the waves propagating in absorbing medium at angles beyond this cone make contribution in free space only to the near-field component of the received radiation, one has $d_{\text{eff}} < d$ for this component. Thus, for the received radiation including both field components, the condition $d_{\text{eff}} < d$ will also be fulfilled and the effective thickness will be a function of the antenna height and size, i.e., $d_{\text{eff}} = d_{\text{eff}}(h, D)$. In the case that the near-field effect on the received radiation is negligible, i.e., with an increase in the height or size of antenna, the kernel of Eq. (1) tends to its limiting form $K(z, h, D) \longrightarrow K = \gamma\exp(z/d)$, which is independent of h and D, and one has $d_{\text{eff}} \longrightarrow d$.

According to definition (3), Eq. (1) leads to a simple exact expression for a linear profile $T(z)$

$$T_a = T(z = -d_{\text{eff}}). \quad (4)$$

which was used in this work for determining the d_{eff} value from the data of T_a measurements.

The antenna temperature T_a was measured for each height h and antenna size D using two calibrations against the thermal radiation of two identical vessels with water uniformly heated to temperatures T_1 and T_2. In this case,

$$T_a = T_1 + \frac{(n_a - n_1)}{(n_2 - n_1)}(T_2 - T_1), \quad (5)$$

where the readings n_a and $n_{1,2}$ of a radiometer detecting device correspond to the basic and calibration measurements, respectively. The error in determining the antenna temperature with inclusion of all factors (fluctuation sensitivity, time of averaging, and errors of measuring the temperature of the standards) was equal to 0.2 K at $h = 0$ and 0.5 K at $h = 2.5$ mm. For the temperature gradient of 2.5 K/cm, the corresponding error in determining d_{eff} varied approximately from 1 to 2 mm in this height interval.

Experiments were carried out at three different values $S = 0$; 1.8×10^{-3}, and 5.0×10^{-3} g/cm^3 of water salinity. The $d_{\text{eff}}(h)$ dependences measured at $S = 1.8 \times 10^{-3}$ g/cm^3 for antennas with $D = 1$ and 4 cm are shown in Fig.1 together with the results calculated by theory [2]. For this S value, the dielectric constant ϵ of water is virtually independent of temperature and it was then that the agreement between the calculations and measurements was the best. The matter is that the real part of the complex dielectric constant of water depends only slightly on temperature so that the temperature dependence of the skin depth is primarily determined by the imaginary part of ϵ. As the ion conductivity increases with increasing salinity, the temperature dependence typical of dielectrics is transformed to the dependence typical of conductors; i.e., a decrease in Im(ϵ) with increasing temperature is transformed to its increase. At the transition point corresponding to a salinity of about $S = 1.8 \times 10^{-3}$ g/cm^3, the temperature dependence is virtually absent. In this case, the approximation of a dielectrically uniform medium [2] provides the best description of the actual situation. For other S values, the temperature dependence of the dielectric constant ϵ of water becomes appreciable. Nevertheless, even in these cases, the agreement between the calculations and the experiment is quite satisfactory if one assumes $\epsilon = \epsilon(T = T_a)$ in the theory of radiation of a dielectrically uniform medium. It is seen that the data of measurements presented in Fig. 1 agree well with the calculations by Eq. (3) while the theoretically predicted dependences of d_{eff} on antenna's height and size actually take place.

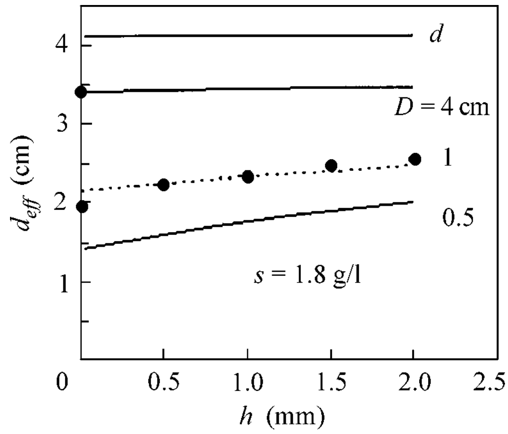

Fig. 1. Effective thickness of the radiating layer vs. antenna's height for different aperture sizes. The circles and lines are the measurements and the calculations, respectively.

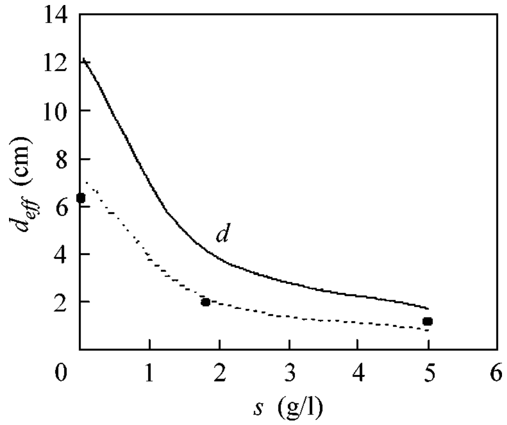

Fig. 2. (circles) Experimental and (dotted line) theoretical effective thicknesses of the formation of received radiation vs. water salinity. Solid line is the calculated skin depth as a function of S.

The dependences of the effective thickness d_{eff} on the water salinity S, as calculated and measured at h = 0 with the antenna of diameter D = 1 cm, are shown in Fig. 2 together with the calculated $d(S)$ dependence. The observed difference between d_{eff} and d (the effective thickness is about half the skin depth), proved to be very close to the theoretical value and clearly demonstrates the near-field effect because, as mentioned above, $d_{\text{eff}} \approx d$ for the field wave component. It is also seen that the difference between d_{eff} and d is maximum for fresh water. For this reason, the dependence $d_{\text{eff}}(h)$ at $S = 0$ is more pronounced than in Fig. 1. In particular, a maximum increase in d_{eff} for fresh water exceeds 7 mm in the height interval considered.

Thus, the results presented in Figs. 1 and 2 testify to the presence of the near-field component in the thermal radiation of medium.

In conclusion, note that further development of these investigations may be associated with increasing the sensitivity of the radiometric system at heights $h > h_{\max}$ (in this study, $h_{\max}$ = 2.5 mm) and decreasing the antenna's size (in the range $D < 1$ cm). To this end, the antenna should be matched for each height, which is not a difficult problem. At the same time, the efficiency of the electrically small antennas inevitably decreases with increasing h. Indeed, a high radiation efficiency near the surface was ensured by the influence of the absorbing medium on the antenna characteristics, but this influence weakens with increasing h. A decrease in the efficiency with decreasing D/λ is a property of the electrically small antennas and is caused by the influence of the ohmic losses in matching circuits.

A possible solution to this problem might be the use of materials with extremely low ohmic losses such as high-temperature superconductors. The effectiveness of using these materials in the problems of miniaturization of antenna devices was examined in [7–9]. Our preliminary calculations show that the near-field radiometric measurements can be accomplished, at least in the height interval $0 \le h \le 0.1\lambda$ and for the antenna's sizes $D/\lambda \ge 0.01$. In this case, the effective depth of radiating layer will vary in the range $0.2d \le d_{\text{eff}} \le d$. The effect considered in this study can then be used to develop new methods of the radio thermal diagnostics of media. In particular, the single-wave methods proposed in [2, 10] for determining the subsurface temperature profile $T(z)$ by solving integral Eq. (1) with the use of measured dependence of the antenna temperature T_a on the antenna's size and height over the surface may be realized. These methods may become simpler in implementation than the known multifrequency methods [11–15].

In summary, the presence of a near electromagnetic field in the thermal radiation of absorbing medium is experimentally demonstrated in this work. The development of near-field radiometry will allow one to devise new methods for medium diagnostics.

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