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THERMAL AND ELECTROMAGNETIC PARAMETERS OF A HIGH-FREQUENCY DISCHARGE IN INDUCTION HEATING OF A GAS

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A procedure for determining the thermal and electrophysical parameters of an hf induction discharge burning inside a short induction heater is proposed.

At present, plasma processes that allow materials and coatings with unique physicochemical properties to be obtained are of ever-increasing interest. In order to control such processes adequately and to develop and optimize high-frequency induction (HFI) plasma reactors it is necessary to have information on the main electromagnetic and thermal parameters in the discharge zone and, what is particularly important, on the temperature distribution.

For HFI-discharge diagnostics a method based on data of magnetic measurements of the active zone shows promise. Such an approach was described for the first time in [1], where results of magnetic measurements made by means of a magnetic probe briefly immersed in the plasma were used to determine the temperature and the main electromagnetic characteristics. However, experimental results were processed only for the one-dimensional case. This did not make it possible to obtain quantitatively reliable data, as was noted by the authors. The essence of the proposed procedure consists in using magnetic measurement results to solve a given system of Maxwell's equations. The initial system of Maxwell's equations may be presented in the form

$$\mathrm{rot}\,\mathbf{H} = \frac{4\pi}{c}\mathbf{j}\,, \quad \mathrm{rot}\,\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}\,, \quad \mathrm{div}\,\mathbf{E} = 0\,, \quad \mathrm{div}\,\mathbf{H} = 0\,, \tag{1}$$

In solving (1), the majority of investigators use, as input information, parameters measured in the primary circuit of the plasmatron, namely, the current of the inductor or the power delivered to the discharge. Since these quantities are not related uniquely to the temperature in the discharge zone, it becomes necessary to use a supplementary equation. For this, the energy balance equation is employed. Application of magnetic measurement results makes it possible not to use additional dependences. The change in the magnitude of the magnetic field over the discharge cross section is determined by the absorption of the electromagnetic energy in the conducting layer of the gas. Therefore for various other conditions it is the electric conductivity of the gas that determines the rate of change of the magnitude of the magnetic field with respect to the discharge radius. Owing to this unambiguous dependence it becomes possible to avoid using additional equations and to solve the problem within the framework of the system of Maxwell's equations.

Experiments with magnetic field measurements were conducted on an experimental setup based on a high-frequency 60 kW plasmatron, model VChI 11-60. For operation with a thermal discharge, a special water-cooled magnetic probe was utilized that permitted long-term operation at the high temperatures typical for such a discharge.

To check the correctness of the above arguments and the reliability of the experimental data of magnetic measurements, in the first stage we used a one-dimensional model. This case assumes that an infinitely long discharge burns inside an infinitely long inductor. With account for the harmonic change in the magnetic and electric fields in time the initial system of Maxwell's equations was written relative to the amplitude values of the fields. For the one-dimensional case the system of Maxwell's equations is as follows:

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$$\frac{\partial E_\varphi}{\partial r} = \frac{\omega}{c} H_z \sin \Delta\varphi - \frac{E_\varphi}{r}, \quad \frac{\partial \Delta\varphi}{\partial z} = \frac{4\pi}{c} \sigma \frac{E_\varphi}{H_z} \sin \Delta\varphi + \frac{\omega}{c} \frac{H_z}{E_\varphi} \cos \Delta\varphi ,$$

$$\sigma = -\frac{\partial H_z}{\partial r} \frac{c}{4\pi} \frac{1}{E_\varphi \cos \Delta\varphi}. \tag{2}$$

The conductivity of the gas is uniquely related to its equilibrium temperature, and therefore the solution to the system yields information about the temperature in the discharge zone. Integration of the system was performed for the following boundary conditions: $E_\varphi = 0$ and $\Delta\varphi = \pi/2$ at $r = 0$.

In order to approach the real picture of the process to the one-dimensional case, we used, as input information, the dependence $H_z(r)$ recorded in the central section of the inductor, where the effect of the boundedness of the discharge was minimum.

As was already mentioned, the ideal model was mainly used for checking the reliability of experimental data. Use of $\sigma(T)$ from [2] allows determination of the temperature distribution over the HFI-discharge radius. Simultaneously, the temperature was determined experimentally by an optical method combined with magnetic measurements. A comparison of the temperatures obtained shows that the data are in satisfactory agreement, thus confirming the reliability of the information obtained about the HFI discharge. However, the one-dimensional model cannot be used for quantitative calculations since neglect of boundary effects inevitably entails significant errors in parameter calculations. The value of such an error is larger, the closer the considered inductor cross section is to its edge. Therefore it is necessary to go over to a complete two-dimensional model. We discussed the problem in a two-dimensional formulation for complex amplitudes of the fields in [3].

In a manner analogous to constructing the ideal model we transform the initial system of Maxwell's equations for the two-dimensional case to the form

$$\frac{\partial E_\varphi}{\partial r} = \frac{\omega}{c} H_z \sin \Delta\varphi_1 - \frac{E_\varphi}{r},$$

$$\frac{\partial \Delta\varphi_1}{\partial r} = -\frac{1}{H_z} \frac{\partial H_r}{\partial z} \sin(\Delta\varphi_1 - \Delta\varphi_2) + \frac{H_r}{H_z} \frac{\partial \Delta\varphi_2}{\partial z} \cos(\Delta\varphi_1 - \Delta\varphi_2) +$$

$$+ \frac{\omega}{c} \frac{H_z}{E_\varphi} \cos \Delta\varphi_1 + \frac{\omega}{c} \frac{H_r^2}{H_z E_\varphi} \cos(\Delta\varphi_1 - \Delta\varphi_2) \cos \Delta\varphi_2 + \frac{4\pi}{c} \sigma \frac{E_\varphi}{H_z} \sin \Delta\varphi_1 ,$$

$$\frac{\partial \Delta\varphi_2}{\partial r} = -\frac{1}{H_r} \frac{\partial H_z}{\partial z} \sin(\Delta\varphi_1 - \Delta\varphi_2) - \frac{H_z}{H_r} \frac{\partial \Delta\varphi_1}{\partial z} \cos(\Delta\varphi_1 - \Delta\varphi_2) -$$

$$- \frac{\omega}{c} \frac{H_z}{E_\varphi} \cos(\Delta\varphi_1 - \Delta\varphi_2) \cos \Delta\varphi_2 + \frac{\omega}{c} \frac{H_z}{E_\varphi} \cos \Delta\varphi_1 , \tag{3}$$

$$\frac{\partial H_r}{\partial r} = -\frac{\partial H_z}{\partial z} \cos(\Delta\varphi_1 - \Delta\varphi_2) + H_z \frac{\partial \Delta\varphi_1}{\partial z} \sin(\Delta\varphi_1 - \Delta\varphi_2) +$$

$$+ \frac{\omega}{c} \frac{H_z H_r}{E_\varphi} \sin(\Delta\varphi_1 - \Delta\varphi_2) \cos \Delta\varphi_2 - \frac{H_r}{r},$$

$$\sigma = \frac{\frac{\partial H_r}{\partial z} \cos(\Delta\varphi_1 - \Delta\varphi_2) + H_r \frac{\partial \Delta\varphi_2}{\partial z} \sin(\Delta\varphi_1 - \Delta\varphi_2)}{\frac{4\pi}{c} E_\varphi \cos \Delta\varphi_1} +$$

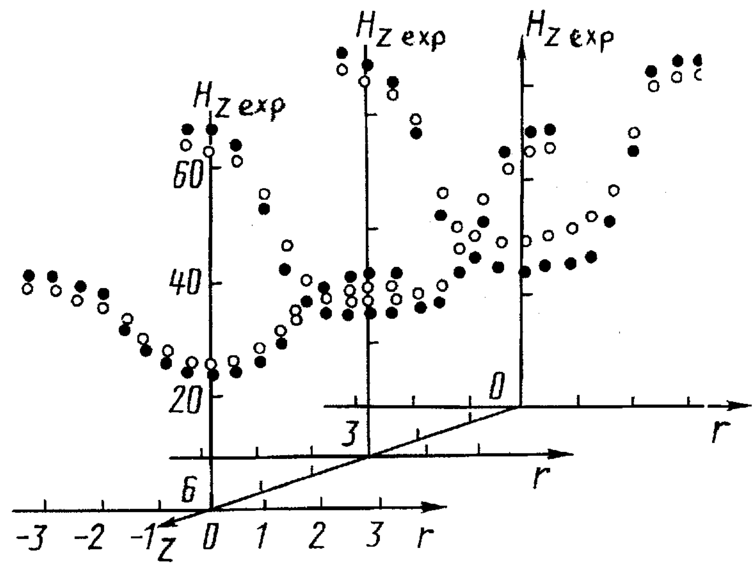

Fig. 1. Radial distributions of the magnetic intensity at flow rates of the plasma-forming gas of 9 (dark points) and 13 m^3/h (light points). r, cm.

$$+\frac{\frac{\omega}{c}\frac{H_r^2}{E_\varphi}\sin(\Delta\varphi_1-\Delta\varphi_2)\cos\Delta\varphi_2-\frac{\partial H_z}{\partial r}}{\frac{4\pi}{c}E_\varphi\cos\Delta\varphi_1}.$$

Supplementing this system with the dependences for the temperature and the specific power of heat release $T(\sigma)$ and $W=\sigma E^2$ makes it possible to obtain a two-dimensional picture of the main thermal and electrophysical parameters of an HFI discharge.

Magnetic measurements conducted in discharges in air produced radial distributions of the longitudinal component of the magnetic field (Fig. 1) in different cross sections along z. The experimental data were subjected to smoothing followed by construction of a two-dimensional spline that had already been used in calculations. Furthermore, the approximation was checked qualitatively with respect to the character of change in the first and second derivatives of $H_z(r, z)$. In the considered coordinate range the spline provided a smooth change in the derivatives. After processing experimental data using the two-dimensional model, radial profiles of the main electromagnetic quantities were found. Simultaneously at each integration point the equilibrium temperature and the specific power of heat release were calculated. The temperature was also determined experimentally by an optical method and compared with the calculated one. Since experimental data obtained by the optical method may be recorded only on plasma sections not closed by inductor coils, the results produced by the two methods were compared not in all the cross sections. Figure 2 presents calculated temperatures for different cross sections, which are compared, where possible, with results of optical measurements. The information is presented for two flow rates of the plasma-forming gas, namely, 9 and 13 m^3/h. A comparative analysis of the two methods shows good fit of the results.

The proposed calculation procedure for a real inductor accounts for edge effects, which is well illustrated by the change in the temperature profiles along the longitudinal coordinate z. Maximum temperatures are observed in the central region of the inductor. With approach to the open part of the burner the plasma temperature smoothly decreases. We might expect that the zone of maximum temperatures must be shifted relative to the central region of the inductor due to deflection of the plasmoid by the plasma-forming gas that arrived in the burner. However, this was not the case. In all probability the explanation lies in the fact that the gas-forming head used in the experiment provides such swirling of the arriving gas that the pressure decrease in the axial region causes back recirculation. At this moment the discharge spreads in the direction opposite to the burner outlet, thus counterbalancing the blowing-out process.

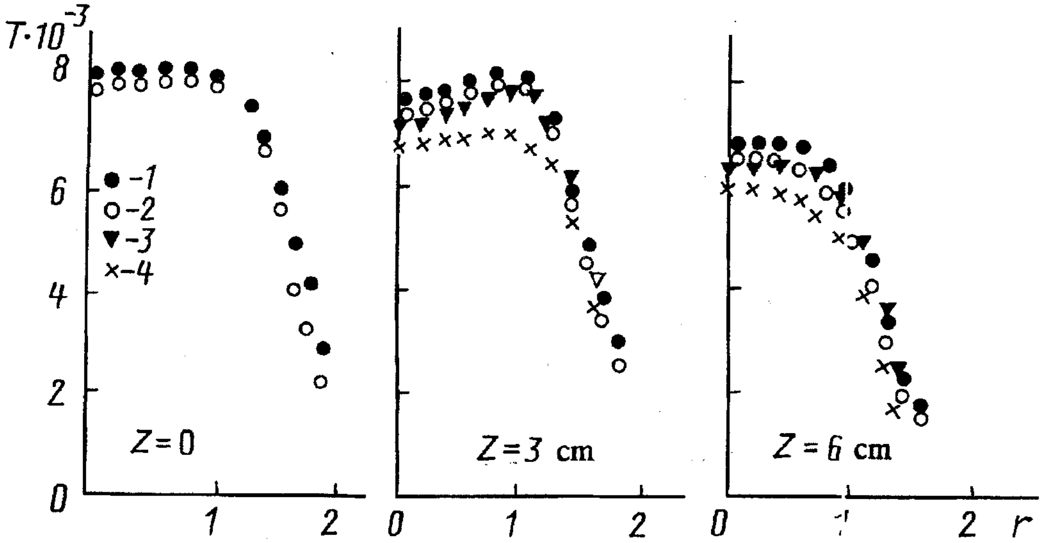

Fig. 2. Temperature distributions (K) at flow rates of the plasma-forming gas of 9 (1, 3) and 13 m^3/h (2, 4): 1, 2) calculation results; 3, 4) results of optical measurements.

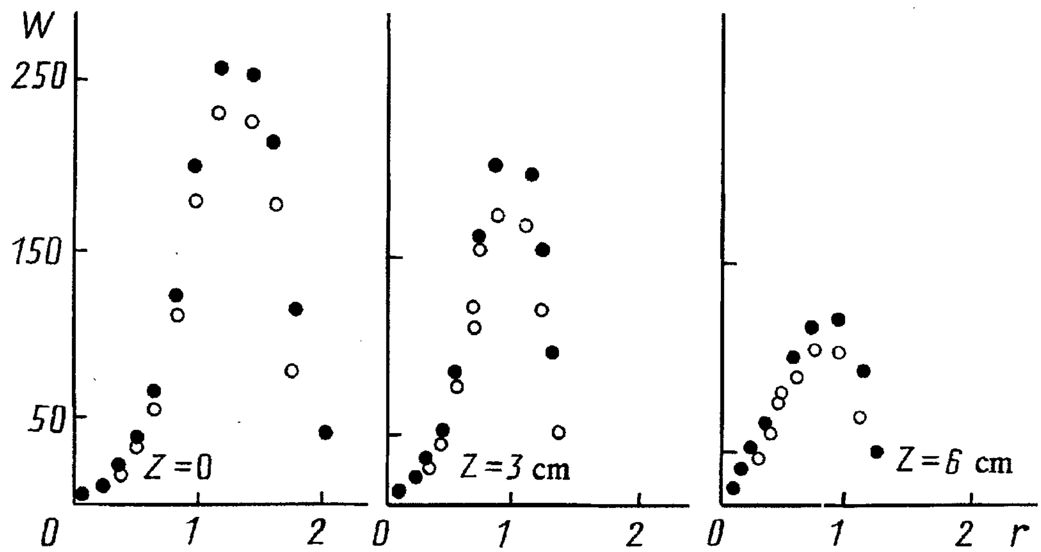

Fig. 3. Radial distributions of the specific power of heat release (W/cm^3) at flow rates of the plasma-forming gas of 9 (dark points) and 13 m^3/h (light points).

Figure 3 shows radial distributions of the specific power of heat release. This important thermophysical parameter demonstrates the distinctive features of an HFI discharge most clearly, characterizing the distribution of the zone active heat release over the plasma volume.

The obtained picture of the distribution of the thermal fields and the determined zones of maximum release of electromagnetic energy play a leading role in the optimization of high-temperature and plasma technological processes in various plasma installations based on the principle of high-frequency induction heating.

Solving the formulated problem, one may obtain complete information about the two-dimensional distributions of the main electromagnetic characteristics of an HFI discharge. The method proposed for temperature determination may be used as an independent diagnostic method, especially in cases where optical measurement methods cannot be used for some reason. The method is advantageously distinguished by the simplicity of the diagnostic equipment. Processing of experimental data using modern PCs does not take much time, thus making the method sufficiently efficient in practice.

NOTATION

H_z, H_r, longitudinal and transverse components of the magnetic field; E_φ, eddy component of the electric field; σ, electric conductivity; j, current density; ω, circular frequency; $\Delta\varphi$, phase difference between the electric and magnetic fields; r, current radius; W, specific power of heat release.

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