THERMOGRAPHY OF LOCAL INHOMOGENEOUS PLASMA FORMATIONS

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Received July 10, 1995

Results of the application of the thermography technique to diagnostics of high-pressure gas-discharge plasma have been presented. The method of thermal imaging allows one to reveal internal structure of plasma formation and temperature zones and to determine thickness of a gas layer between the electrode and plasma as well as velocity of gas-dynamic flow along heated particle tracks.

Infrared thermography is used for investigation of thermal gaseous flows including flame.[1]

Measurements of the IR radiation emitted by a substance allow one to determine remotely the spatial distribution of effective temperature of emitting objects. Emission is due to excitation and ionization of the substance molecules and depends on absolute temperature as well as on integral emission coefficient of a heated object. Of some interest is the study of thermal fields in gas-discharge plasma for which a single-valued connection has been found (like for other substances) between the IR radiation flow and plasma absolute temperature. This connection can be used for the study of the plasma formations with reasonably high level of the IR radiation within the spectral range of sensitivity of thermal imaging systems.

When determining the absolute plasma temperature, the uncertainty appears because the radiation flow recorded by an IR detector is a function of *a priory* unknown radiation coefficient (spectral or integral) and of the plasma temperature. Investigations of the plasma fields by the thermography method are important for determination of the relative temperature distribution of inhomogeneous plasma formations, their shapes, and detection of zones of the immediate plasma contact with an electrode even if direct connection between the integral coefficient of radiation emission and temperature is lacking. Spatially uncorrelated spectral distributions of radiative energy also can be determined by the thermography methods.

In this paper, the thermography method is used for the study of thermal fields in single-electrode high-frequency discharges formed in the air under atmospheric pressure. A single-electrode discharge with power 10–45 W and length 1–4 cm was initiated by a pointed electrode with preionization. An active oscillator built around a beam tetrode with autotransformer feedback was a power supply unit. Its operating frequency was equal to 31.6 MHz. Continuous control of discharge power within the above–indicated limits was provided in the active oscillator. An IR image of a plasma channel within the spectral range 3–5 μm was recorded by the AGA-780 SW computerized thermal imaging system. The image was recorded perpendicular to the discharge axis. The thermal imaging camera was placed at a distance of 1 m from the discharge, i.e., at the distance being much longer than the dimensions of the emission zone of the discharge. In this case, one may assume that the plasma emitting properties obey Lambert's law, and a two-dimensional thermogram is recorded with minimum spatial distortions.

The spectral range 3–5 μm is suitable for the study of inhomogeneous plasma formations because the high thermal contrast allows one to detect the high temperature gradients. Recording of thermal fields with a frequency of 25 Hz enables one to follow the dynamics of discharge formation. Signals recorded by the thermal imaging system are resolved into fixed levels on a computer. These levels characterize isotherms on a temperature scale. Boundaries of individual levels correspond to a fixed temperature of a black body. The image fragments are displayed by different colors divided by isotherms. Each color of the image marks an effective (apparent) temperature in relative units. In the single-electrode high-frequency discharge (without modulation), the entire plasma volume emits IR radiation, and thus the isotherm of minimum temperature determines the boundaries of the plasma channel.

It should be noted that the entire plasma volume of the single-electrode discharge means the plasma channel together with the near-electrode zone and thermal layer of heated gas surrounding the plasma channel. Despite a wide dynamic range (60 dB) of the thermal imaging system, we failed to record the hottest zone of the plasma channel and its thermal shell without a threshold cutoff. When the minimum IR radiation level is not recorded, the central (hottest) zone is recorded rather than the entire plasma channel. In another case, when the maximum IR radiation level is limited, we succeeded in determination of dimensions and volume of the plasma channel, but failed to determine the maximum temperature. This methodical feature should be taken into account when processing thermograms.

0235-6880/95/12 1052-03 $02.00

In Fig. 1 the thermogram of the stationary discharge *1* formed by convective flows and connected with the active oscillator through the pointed electrode *2* is shown. To the left of Fig.1 the plot of the axial distribution of the discharge temperature is shown. To obtain this thermogram, we limited the maximum level of IR radiation. The relative level 10.1 corresponds to the isotherm on the boundary of the plasma channel. As is seen from the thermogram, the temperature distribution along the channel axis is described by nonmonotonic curve with the maximum located far from the electrode edge. Effective temperature in relative units being equal to 25.3 is fixed on the thermogram; if the slope of the curve remains the same, the inflection point will be at 26.4. If we assume that T_1 is the maximum effective temperature of plasma, and T_2 is the minimum temperature at the discharge boundary, then the ratio $T_1/T_2 = 2.61$.

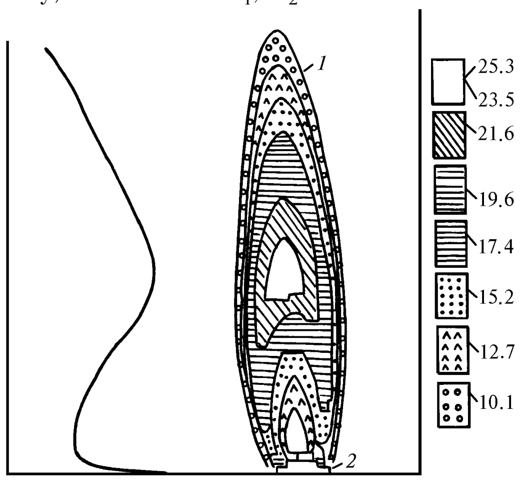

FIG. 1. Thermogram of the stationary discharge 1 formed by the pointed electrode 2.

The study of the discharge by the shadow technique has shown that the plasma channel is formed by two layers divided by the temperature drops. The central layer is separated by the temperature drop from the external plasma layer with $T_1/T_2 = 1.4–1.5$ and the external plasma, layer is separated from the thermal layer by the drop with $T_1/T_2 = 2.61$. The external plasma layer may be replaced by the hot gas, while the central layer and the radial temperature profile remain uncharged. It then follows that such temperature field is formed in the inhomogeneous plasma channel in which the maximum temperature differs from the temperature on the discharge boundary by 40%. With this, the form of the two-dimensional temperature distribution for the central discharge zone influences weakly the variations of T_1/ T_2.

In Fig. 2 the two-dimensional effective temperature distribution is shown for the stationary discharge. In the zone near to the electrode the radial profile has the form of a curve with two peaks and valley between them (double-peak curve). The peaks may differ because of the axial symmetry disturbance due to radial displacement of the plasma channel as a whole. This indicates that the plasma channel exhibits definite degree of elasticity providing the plasma channel integrity. The distance between the peaks decreases in the direction from the electrode toward the zone with maximum heat release and the through between the peaks decreases too. The peaks merge near the inflection point, and the radial profile is of the form of a single-humped curve. The unambiguous radial temperature profile is observed in the zone of the plasma channel behind the inflection point practically in all experiments.

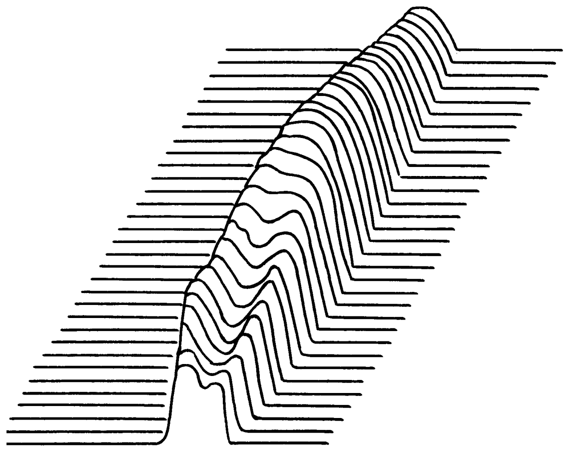

FIG. 2. Pseudovolume thermogram of the stationary discharge 1.

In a transient regime, two forms of the radial temperature profiles may be observed at the stage of discharge formation: single- and double-humped (see Figs. 3 and 4). To obtain the stationary discharge, the plasma center should be formed at the distance 0.5–2.0 cm from the electrode edge. This is due to the fact that an increase in the plasma volume is accompanied by reformation of the temperature profile and simultaneous displacement of the plasma center toward the electrode edge. The discharge is formed for 0.1–0.2 s; in this case, the velocity of its displacement is about 7–15 cm/s and depends primarily on the active oscillator power. In the transient regime, the velocity of convective flows is determined from tracks of particles recorded simultaneously with the thermal image on the thermogram (Figs. 4 and 5).

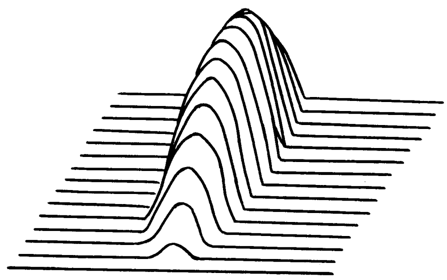

FIG. 3. Pseudovolume single-humped thermogram in the transient regime.

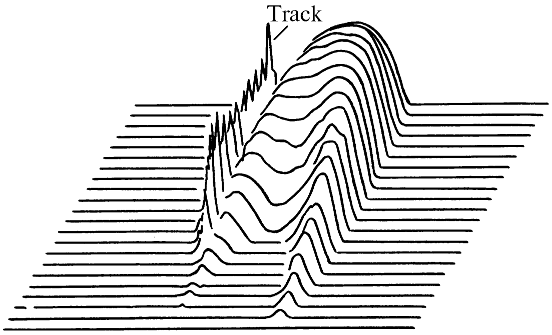

FIG. 4. Three-dimensional double-humped thermogram in the transient regime. To the left of the figure, the particle tracks are shown.

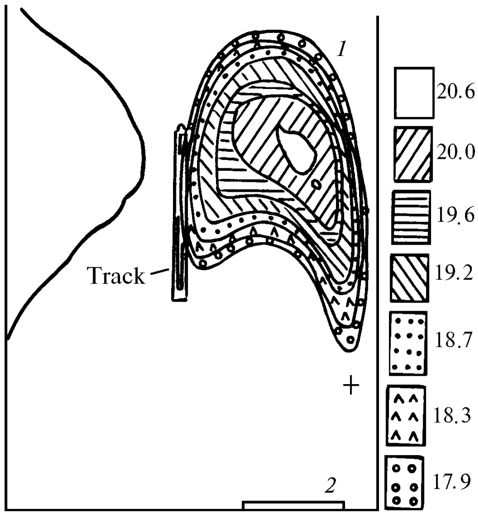

FIG. 5. Thermogram of the transient regime with the particle track shown to the left: discharge 1 and electrode 2.

In stationary regime of the discharge generation, a cone-shaped crater, which duplicates the shape of the pointed electrode, may appear in the near-electrode zone of the plasma channel because the trough in the double-peak profile becomes deeper near the electrode edge. Here, the layer of a relatively cool gas occurs between the electrode surface and the plasma channel. This layer has been recorded by the thermography technique because the wave ranges of radiation of the metallic electrode heated to a temperature of 1250K and plasma radiation with a temperature of about 3300K are uncorrelated. In visible wavelength range, the radiation of the heated electrode edge is more intense than the optical plasma radiation, and therefore it is impossible to detect the cool layer. Thus, the thermography method may be indispensable for investigation of the near-electrode processes. In the contact zone of the plasma channel with the electrode, the layer thickness is 200 μm . Occurrence of this layer is due to not only electrodynamic but also gas-dynamic processes determining the zone of the hot gas inflow in the plasma channel.

CONCLUSION

The use of the thermography in the diagnostics of gas-discharge high-pressure plasma allows one: to detect the internal structure of inhomogeneous plasma formation and to determine its shapes and dimensions; to determine the relative temperature variations in different zones of plasma channels; to determine the thickness of a gaseous layer between the electrode surface and plasma; and, to find the double-peak temperature profile for weakly ionized plasma, which is not connected with the surface HF–currents (skin effect).

REFERENCES

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2. V.V. Reino, A.S. Tobolkin, and M.V. Sherstobitov, in: *Abstracts of Reports at the Second Interrepublic Symposium on Atmospheric and Oceanic Optics,* Tomsk (1995), pp. 335-336.