HOLOGRAPHIC-INTERFEROMETRY STUDY OF HIGH-FREQUENCY TEMPERATURE FLUCTUATIONS IN THE STREAM OF A VORTICAL PLASMATRON

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The method of holographic interferometry in real time is used to determine the temperature fluctuations of a subsonic turbulent stream of a nitrogen plasma which are caused by shunting. The stream is generated by a vortical plasmatron.

One of the important processes which occur in the discharge chamber of an electric-arc plasmatron with a self-adjusted arc length is the large-scale shunting [1] which causes fluctuations in the energy delivered to the discharge gap and, correspondingly, in the density and temperature of the gaseous plasma in the stream. Furthermore, the motion of the parts of the arc cut off by the shunting leads to the appearance of characteristic "bunches" at the exit from the nozzle.

Spectroscopic methods are not always suitable for determining the temperature of such streams of a weakly ionized gas for the following reasons:

1) There are technical difficulties involved in measuring low temperatures with a high time resolution (when the order of a few to several tenths of microseconds).

2) In a nonequilibrium, weakly ionized plasma, the governing factor is the gas temperature, rather than the electron temperature, which is the temperature usually measured by spectral methods.

3) There are difficulties involved in measuring the temperature of the peripheral regions of the stream and those far from the end of the nozzle.

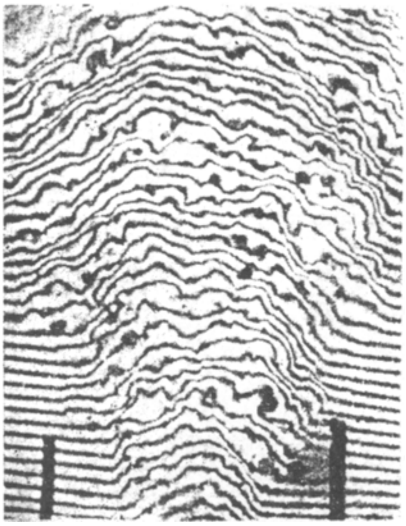

Fig. 1. Frame from a time sweep of interferograms during turbulent subsonic flow of a stream from a nozzle.

An extremely effective method for studying low-temperature plasma streams is interferometry, although this method has a disadvantage of its own: a very nonlinear temperature dependence of the refractive index. This circumstance reduces the sensitivity of the method at high temperatures.

The use of interferometry in studying cool plasma streams with those reported in [2, 3]; here laminar plasma flow was studied.

The method of pulsed holographic interferometry with a turbulent stream flowing out of a nozzle was first used in [4].

In the present experiments, we determined the gas temperature and the magnitude of the temperature fluctuations in a nitrogen stream generated by a single-chamber dc arc plasmatron with

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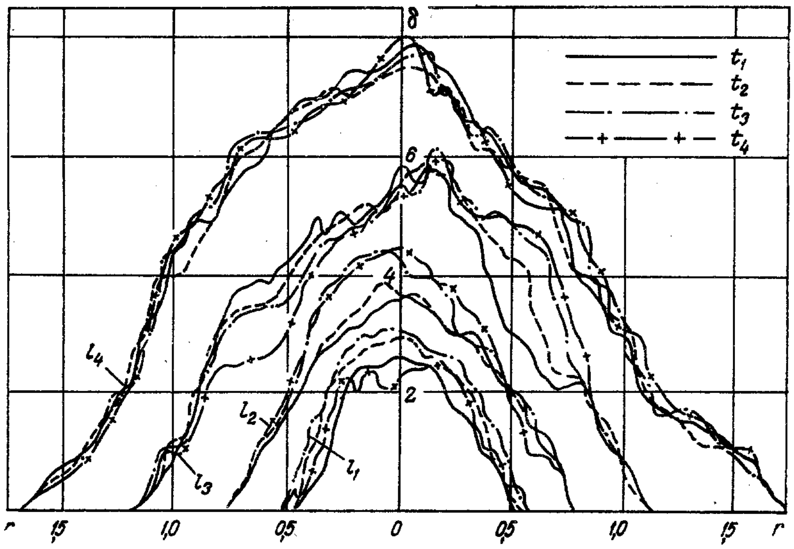

Fig. 2. Fringe shift (relative units) for various cross sections of the stream at various times. Here r is given in cm.

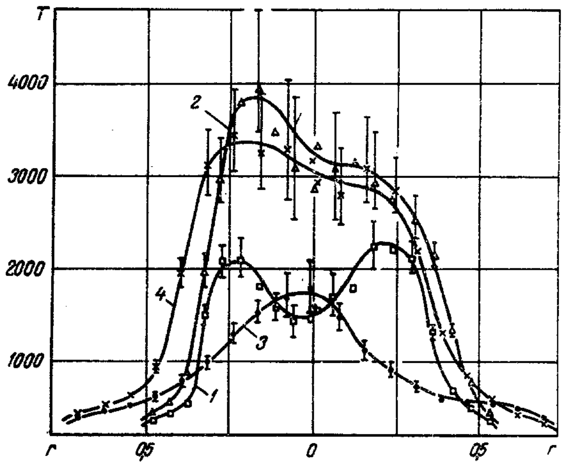

Fig. 3

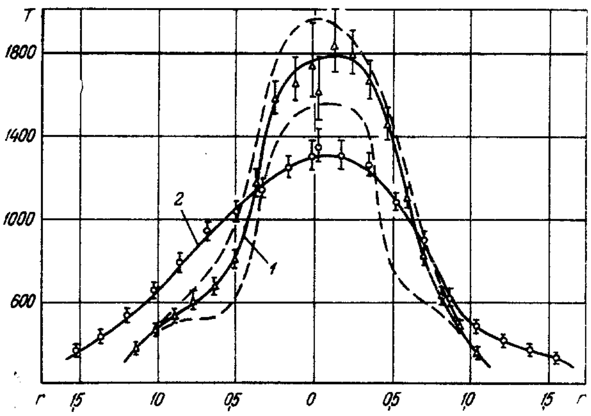

Fig. 4

Fig. 3. Radial profiles of the maximum and minimum stream temperatures (°K) over a time ~300 $\cdot 10^{-6}$ sec at distances l_1 = 0.25 cm and l_2 = 0.4 cm from the nozzle. Here r is in cm.

Fig. 4. Radial profile of the stream temperature (°K) at distances l_3 = 1 cm and l_4 = 2.8 cm from the nozzle. Here r is in cm.

vortical gas stabilization of the arc; we used a holographic interferometer in real time. In contrast with the interferometer arrangement described in [5], we use an arrangement in which the plane of the test object is focused onto the hologram, so that it becomes possible to significantly improve the quality of the interferograms, through a suppression of the influence of light refraction by inhomogeneities of the stream. With this experimental apparatus, it is possible to obtain up to 30 interferograms in fringes of finite width with a time resolution as short as $1 \cdot 10^{-6}$ sec during the free generation of the ruby laser, $(300\text{–}400) \cdot 10^{-6}$ sec. The interferograms were analyzed quantitatively on a microdensitometer; the fringe shift was determined within 1/16 of a fringe.

We transform from the refractive index of the nitrogen plasma to the temperature by working from the dependence of the refractive index on the component densities:

$$(n-1)_{\mathrm{pl}} = 2\pi(\alpha_1 N_2 + \alpha_2 N + \alpha_3 N^+) - (n-1)_{\mathrm{el}} \tag{1}$$

where $(n-1)_{\mathrm{el}} = 4.46 \cdot 10^{-14}\lambda^2 N\mathrm{e}$ is the refractive index of the electron component. The values for the average polarizability of the heavy particles are taken from [6, 7]. The static pressure in the stream is assumed to be equal to atmospheric pressure.

Under the conditions of the present experiments, the quantity $(n-1)_{pl}$ is governed primarily by the first two terms in Eq. (1).

If there is a local thermodynamic equilibrium in the weakly ionized stream, the plasma composition is governed entirely by the plasma temperature; in other words, Eq. (1) unambiguously relates the temperature to $(n-1)_{pl}$. If there is a deviation from thermodynamic equilibrium, the plasma refractive index is governed by the gas temperature, since collisions between heavy particles predominate under these conditions.

From the interferograms of the stream we can draw qualitative conclusions regarding the nature of the plasma flow. At low gas flow rates, on the order of 0.1-0.5 g/sec (depending on the arc current, 30-130 A), the flow is laminar; as the flow rate is increased, the turbulence extends progressively to the entire stream, starting from points far from the nozzle.

Figure 1 shows a typical frame from a time sweep of the interferograms during tubulent subsonic flow of the stream from the nozzle. The exposure time for a frame is no longer than $5 \cdot 10^{-6}$ sec; the distance between the markers is 1.92 cm.

In addition to the turbulence caused by the interaction of the stream with the surrounding medium, the unsteady behavior of the plasma properties as a function of the gas flow rate is not only affected by the turbulence caused by the interaction of the stream with the surrounding medium; shunting also begins to have a strong effect, since the pulsations in the input power increase.

For a quantitative evaluation of the stream properties, we plotted the fringe shift in a particular cross section as a function of the radius. Figure 2 shows such profiles for the following operating conditions: $I_{av} = 125$ A; $U_{av} = 105$ V; G = 1 g/sec; $P_{av} = 13.1$ kW, $\Delta P \approx 1.9$ kW, d = 0.5 cm, and a shunting frequency on the order of 14-15 kHz. The curves are plotted for various times (μsec) (t_1; $t_2 = t_1 + 60$; $t_3 = t_2 + 60$; $t_4 = t_3 + 80$) and for various cross sections, at the following distances (cm) from the end of the nozzle: $l_1 = 0.25$; $l = 0.4$; $l_3 = 1$; $l_4 = 2.8$.

These curves clearly illustrate the space–time behavior of the fluctuations in the stream properties.

At distances up to (2-3)d from the end of the nozzle, the stream pulsates as a whole with a frequency near the shunting frequency; there is even a change in the stream radius (see the group of curves for l_1). It is natural to assume that in this region the pulsations are due primarily to the shunting. At (4-5)d from the end of the nozzle, the situation is much more complicated. The fringe shift decreases at the left side of the stream, while it increases on the right side. This behavior can be attributed to rotation of the stream core. Far from the nozzle, the pulsations take the form of slight random deviations from certain average values; i.e., in this region, turbulent mixing of the jet with the surrounding medium is predominant.

The information obtained from the interferograms is the integral over the path of the light transmitted by the stream. To obtain local values of the refractive index, we solve the integral Abel equation by a numerical method [8] which provides good smoothing of the experimental data under the assumption that each half of the stream is axisymmetric. This assumption is, of course, not strictly correct. In the calculation of each experimental curve of the fringe shift, a spatial averaging over adjacent sections is introduced; this approach eliminates the influence of small-scale fluctuations on the calculated results.

Figures 3 and 4 show some of the calculated results. Curves 1 and 2 (Fig. 3) correspond to the minimum and maximum temperature distributions during an experiment ($\sim 300 \cdot 10^{-6}$ sec) at a distance l_1 from the nozzle; curves 3 and 4 correspond to a distance l_2 from the nozzle. The time interval between curves 1 and 2 is $80 \cdot 10^{-6}$ sec, while that between 3 and 4 is $200 \cdot 10^{-6}$ sec.

We see that the high-frequency temperature fluctuations can reach a large magnitude, ~1500-2000°K.

In determining the temporal fluctuations at a distance l_3 from the nozzle, we recalculated the specially averaged curve of the fringe shift having the maximum axial symmetry. The magnitude of the fluctuations was determined from the reference fringe.

The result is shown by curve 1 in Fig. 4, where the range of the temperature variation during the experiment is shown by the dashed lines.

Curve 2, obtained by a time averaging of the fringe shift, corresponds to the radial temperature profile at a distance l_4 from the nozzle. In transforming from the refractive index to the temperature here we neglected the change in the plasma composition due to the mixing of the stream with the atmosphere, because of the smallness of this effect. The interferometric determination of the fluctuations in this region gives results which are too low, since the spatial scale of the fluctuations is much smaller than the optical path length in the stream, so that there is an averaging of the fluctuations.

Accordingly, the method of holographic interferometry in real time demonstrates both qualitatively and quantitatively that shunting processes significantly affect the space–time distribution of the properties of the stream and arc plasmatron.

NOTATION

$(n-1)_{pl}$	is the refractive index of plasma;
N_2, N, and N^+	are the densities of molecules, atoms, and positive ions, respectively;
α_1, α_2, and α_3	are the average polarizabilities of the molecule, atom, and ion, respectively;
N_e	is the electron density;
λ	is the wavelength of ruby laser;
I_{av} and U_{av}	are the average current and arc voltage of the plasmatron;
G	is the gas flow rate;
d	is the nozzle diameter;
P and ΔP	are the average power dissipated in the arc and fluctuation of this power;
t	is the time;
r	is the radial coordinate;
T	is the temperature.

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