PHOTOELECTRONIC DEVICE FOR MEASURING PLASMA TEMPERATURES

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Inzhenerno-Fizicheskii Zhurnal, Vol. 14, No. 5, pp. 890–894, 1968

UDC 621.383.27:533.9.07

A photoelectronic device for measuring plasma temperatures with a time resolution on the order of $5 \cdot 10^{-4}$ sec is described. Certain results of measurements are presented.

Plasma jets are now used more and more extensively in various branches of science and technology. For a number of reasons (flow turbulence, arc shunting, nonuniform erosion of electrode material, etc.), the temperature at a certain point of the jet does not remain constant but fluctuates about a certain mean value. In many cases, it is important to know these fluctuations. Data on their spectroscopic determination are presented in [1].

By means of the photoelectronic device described, the temperature is determined from the relative intensity of the spectral lines. The expression for the temperature can be written in the following form [2]:

$$T = [(E_2 - E_1)/k]\left[1 \Big/ \left(\ln\frac{I_1}{I_2} - \ln\frac{\nu_1 A_1 g_1}{\nu_2 A_2 g_2}\right)\right]. \quad (1)$$

For many pairs of lines, the quantities $\nu_n A_n g_n/\nu_m A_m g_m$ have been determined experimentally. Then, knowing E_1 and E_2, we can easily determine the temperature from Eq. (1). For this purpose, it is sufficient to measure $\ln(I_1/I_2)$. Since copper electrodes are usually employed in plasma generators, the copper lines λ_1 = 5153 Å and λ_2 = 5105 Å were selected for the measurements. For these lines, expression (1) can be written as [3]

$$T = \left[2.75 \cdot 10^4 \Big/ \left(4.19 - \ln\frac{I_1}{I_2}\right)\right] {}^\circ\mathrm{K}. \quad (2)$$

The quantity $\ln(I_1/I_2)$, which depends linearly on $1/T$, is determined with the photoelectronic device whose block diagram is shown in Fig. 1. The device operates as follows.

The radiation from a certain point of plasma jet (PJ) is directed by mean of lens 1 to monochromator M, at whose exit there are two slits for separating the required spectral lines. These lines strike reflecting prism 2 and are directed to photomultipliers 3, 4, whose amplification factors are the same in the working wavelength region. These amplification factors are regulated by applying to the modulator a bias negative relative to the photocathode. A ZS-1 filter is used to separate the working wavelength interval from the spectrum of the auxiliary lamp. The photomultiplier loads are type D310 log diode circuits. Each circuit consists of eight diodes. Signals from the photomultiplier loads, proportional to the logarithm of the spectral line intensities I_1 and I_2, are fed to the input of differential amplifier 5. The amplifier output voltage, proportional to $\ln(I_1/I_2)$, is passed through cathode follower unit 6 to loop oscillograph 9 and to the vertical deflectors of a cathode-ray oscillograph.

The cathode followers are required to match the high-resistance output of the differential amplifier with the low-resistance input of the loop oscillograph. In this case, the cathode-ray oscillograph is used to examine a small part of the process recorded on the loop oscillograph with greater resolution. This also makes it possible to check the distortions introduced by the loop oscillograph.

In the starting state, the cathode-ray oscillograph is in the driven mode. When a signal is recorded on the loop oscillograph, its contacts 10 are closed and a positive voltage drop appears at the input of multivibrator 8. This positive drop is used to trigger the multivibrator and the cathode-ray oscillograph. The multivibrator produces a pulse of positive polarity, which is fed to the modulator of the cathode-ray tube and to one of the loops. In this case, the sweep time is made somewhat greater than the length of the intensifier pulse. The oscillograms were photographed by means of a special photographic adapter.

The error δ in measuring the logarithm of the ratio of the spectral line intensities is composed to the errors introduced by the individual units of the circuit and can be written as

$$\delta = \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6.$$

The error δ_1 occurs at a high level of illumination, but since in our case the level is low, it can be neglected. The absolute value of δ_2 is determined from

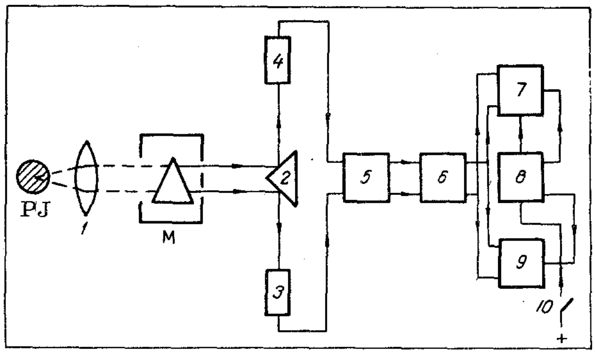

Fig. 1. Block diagram of the photoelectronic device.

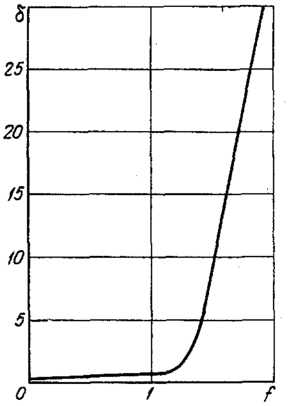

Fig. 2. Dynamic response of the photoelectronic device (δ in %, f in kHz).

the expression $\delta_2 = \ln M$. In our apparatus, M did not exceed 1.01, and δ_2 0.01. This error has a constant value and can be taken into account during calibration. For the diodes employed, the error δ_3 is practically equal to zero at currents above 3 μA. In the circuit in question, the average values of the currents through the diodes were 75–100 μA, so that this error can be neglected. Only the dynamic errors, which for D310 diodes are practically absent up to frequencies on the order of 10 kHz, may be important. The current-voltage characteristics of the diode circuits differ by a constant amount of 14 mV. This leads to the appearance of a constant measuring error δ_4, which is taken into account during calibration. The error δ_5 increases linearly with increase in frequency and at 2 kHz is 1.43%. The error δ_6 also depends on frequency. This error is almost equal to zero up to 1200 Hz and begins to increase sharply at frequencies above 1300 Hz. Thus, whereas at f = 1300 Hz δ_6 = 1.54%, at f = 1500 Hz δ_6 is 9.2% and reaches 34% at 2 kHz. The dependence of the measuring error δ on frequency is shown in Fig. 2.

The calibration of the apparatus involves feeding to the photomultipliers two light fluxes in the working wavelength region with a known intensity ratio. Then the dependence of the deflection of the loop oscillograph spot on the logarithm of the ratio of these fluxes is determined. If the error δ_2 can be neglected, the calibration consists in determining the dependence of the spot deflection amplitude on the logarithm of the ratio of the currents passing through the diodes. The graph of this dependence is a straight line with only a slight deviation at large output voltages, when the nonlinearity of the amplitude characteristics of the amplifier and the cathode follower unit begins to have an effect. For the above reason, the amplifier gain should be such as to ensure operation on the linear interval of the calibration curve. In our particular case, the gain was 500.

The investigations were carried out on a plasma generator without a mixing chamber. The working gas was nitrogen. The gas flow rate was 2 g/sec. The average values of the currents and voltages were 300 A and 240 V. We used the radiation of the jet in the diametral direction at a distance of 2 cm from the outlet. It was established that the quantity $\ln(I_1/I_2)$ fluctuates over a broad frequency range (f = 100–2000 Hz) (Fig. 3). These fluctuations are almost independent of the power in the jet and are random in character. As a manual analysis of the oscillograms showed, the probability characteristics of this random process do not vary with time. This suggests that the logarithm of the ratio of the intensities of the two spectral lines and, hence, the temperature represent stationary random processes. The integral temperature distribution curve, plotted to a probability scale, is close to a straight line (Fig. 4). This indicates that the temperature distribution law is close to normal. In this case, the average value of the temperature was 5857° K, and the standard deviation σ was 175° K, which is much less than in [1]. Obviously, in the peripheral regions of the jet the standard deviation will be greater. From

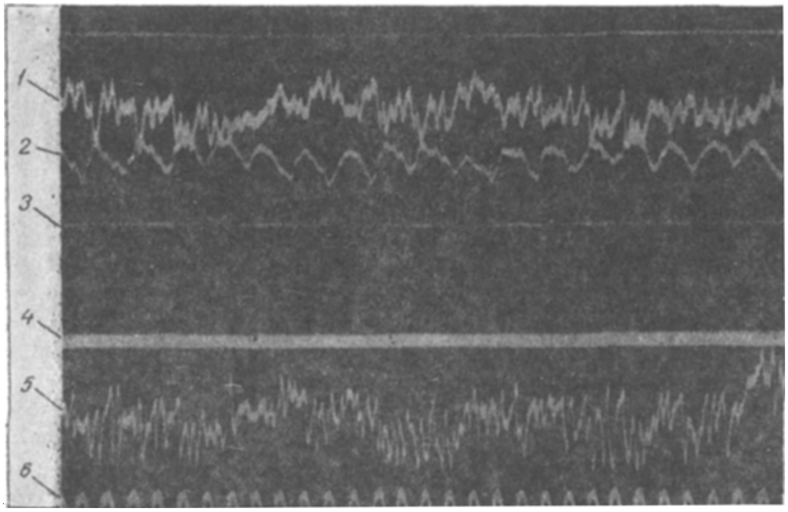

Fig. 3. Oscillogram of plasma jet parameters: 1) voltage; 2) current; 3) $\ln(I_1/I_2) = +1$; zero current and voltage line; 4) $\ln(I_1/I_2) = 0$; 5) $\ln(I_1/I_2)$; 6) time mark (f = 500 Hz).

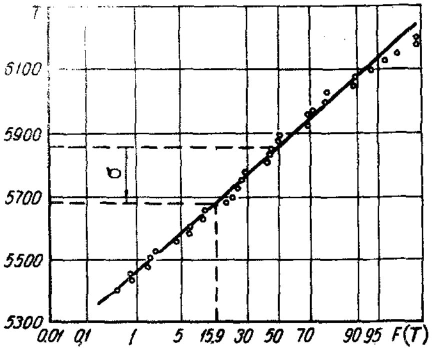

Fig. 4. Integral temperature distribution law (T in °K, F(T) in %).

the oscillograms obtained, we also constructed the autocorrelation function R(τ), which by virtue of the smallness of the standard deviation was found to be practically independent of τ, i.e., the power of the process is chiefly concentrated at the frequency $\omega = 0$.

As already pointed out, the oscillograms were analyzed manually. For this purpose the continuous random process was discretized on the basis of the Kotel'nikov theorem. From the values of $\ln(I_1/I_2)$ obtained and using relation (2), we found discrete values of the temperature, from which it is possible to determine the temperature distribution law and autocorrelation function. To construct the autocorrelation function, we used the relation [4]:

$$R(\tau) = \frac{1}{t_1 - \tau} \sum T_i T_{i+\tau} \Delta t.$$

In conclusion, we note that a more accurate analysis of the results of the measurements would require the use of a special apparatus for automatically obtaining the necessary probability characteristics of the random process.

NOTATION

E_1 and E_2 are the excitation energies, I_1 and I_2 are the spectral line intensities; A_1 and A_2 are the transition probabilities; g_1 and g_2 are the statistical weights; T is the temperature; δ_1 is the error due to nonlinearity of the photomultiplier photoresponse; δ_2 is the error due to inaccuracy in establishing equality of the photomultiplier gains; δ_3 is the error due to the nonideal logarithmic current-voltage characteristics of the diode; δ_4 is the error due to nonidentity of the current-voltage characteristics of the diode; δ_5 is the error introduced by the differential amplifier due to nonideal subtraction; δ_6 is the error introduced by the loop oscillograph; M is the ratio of the photomultiplier gains; t_1 is the realization time; Δt is the sampling interval.

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15 August 1967

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