SPECTROSCOPIC STUDY OF THE PROPERTIES OF A SUPERSONIC PLASMA STREAM

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A plasma diagnosis has been carried out by spectroscopic methods. The behavior of temperature and concentration of charged particles was measured along the stream as a function of polarity for a stream with a shock wave and a stream with periodic structure. An explanation of the observed phenomena is given. The physical processes occuring in a supersonic plasma stream are quite distinctive [1]. Spectroscopic investigations are necessary since they provide more detailed information on the physical state of the plasma. It is also of interest to study wave processes taking place in the stream from the point of view of the additional plasma heating thus obtained.

1. ANALYSIS OF THE STREAM EMISSION SPECTRUM AND CHOICE OF DIAGNOSTIC LINES

In the region of wavelengths investigated from 3800 to 5500 Å the plasma stream emission spectrum consists basically of the lines of the elements belonging to the material of the electrodes (Cu I, Zn I, Cu II) (Fig. 1). As well as these lines, the molecular bands of cyanogen (CN) are observed particularly distinctly in a stream with periodic structure. One of the distinctive features of the spectrum is the appearance of the forbidden lines of copper 4015.8 and 4056.8 Å. Some lines are much broadened. These, as a rule, are lines with large Stark constants. The qualitative study of the emission spectrum of streams with a shock wave and with periodic structure shows that they do not differ from each other as regards spectral composition.

A continuous spectrum is observed in the main part of the stream for a stream with a shock wave having an intensity which decreases noticeably along the stream, increases abruptly in the shock wave, and subsequently falls off sharply (Fig. 1a). The behavior of the spectral line intensity at various excitation potentials was measured along the stream (Fig. 2). The magnitude of the intensity for lines with different excitation potentials is different. In the shock wave the line intensity of neutral atoms, as well as of ions, increases sharply. The ion lines attain their greatest intensity in the shock wave, while the atomic lines remain strongest in the main part of the stream. Changing the polarity of the annular electrode has an effect of the behavior and magnitude of the spectral line intensity (Fig. 2). For positive electrode polarity a milder decrease of intensity is observed after the shock wave, as well as a somewhat lower line intensity in the shock wave and along the stream in general. At the base of the stream the intensity of the atomic lines is higher and the intensity of the ion lines lower compared with the case of netative electrode polarity.

Alternation of maxima and minima of the continuous intensity occurs in the spectrum of a stream with a periodic structure, and, moreover, the intensities of the spectral lines correspond to the points of compression and rarefaction with a gradual weakening towards the end of the stream (Fig. 1b). The greatest intensity both for the lines of neutral atoms and for the ion lines is situated at the base of the stream. No significant changes are noted in the spectral composition and behavior of the intensity of the continuous emission and spectral lines depending on the polarity of the annular electrode.

For diagnostic purposes it was necessary to choose lines from the emission spectrum thus obtained from which the basic plasma parameters could be determined (temperature, concentration of charged particles, etc.). First of all, the basic constants for these lines must be known, i.e., transition probability, Stark's and Van-der-Walls' constants, etc. The lines which we chose and their basic constants are given in the table. The transition probabilities are taken from [2]. Stark's and Van-der-Waals' constants were calculated applying the matrix elements after Bates and Damgaard [3].

2. DETERMINATION OF TEMPERATURE IN THE PLASMA STREAM

The temperature measurement was carried out by the method of relative intensities using two pairs of copper lines 5105.5, 5153.2 and 5105.5, 4530.8 Å. The self-absorption of these pairs of lines is different and leads to the measured temperature being higher or lower. In other words, when we measure temperature using two pairs of lines we obtain limits within which the excitation temperature being measured is situated. Taking the average, we obtain the resultant temperature allowing for the effect of self-absorption in the measurement error. Temperature measurement by these two pairs is treated in [4].

Before measuring temperature, it was necessary to verify whether the atoms were in a Boltzmann distribution over the excited states. This was done by the method proposed by N. N. Sobolev [5]. Here the lines of copper 5153.2, 5105.5, 4530.8, 4275.1, 4022.7 Å were used. The upper level energy interval occupied by these lines is 32 000 cm^{-1}.

The verification was carried out at various heights in the stream. In particular, for the stream with a shock wave—at the base of the stream, in front of the shock wave, in the shock wave, and beyond the wave; in the stream with a periodic structure—at the base and in the zones of rarefaction and compression. The results of the measurements lie closely enough on a straight line, which proves that

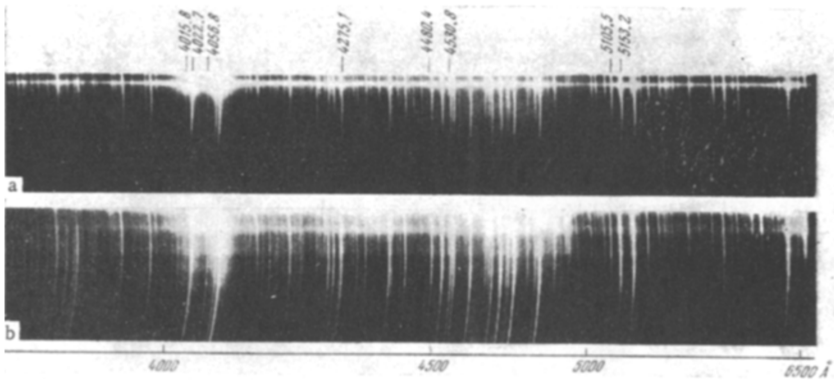

Fig. 1. Plasma stream emission spectrum a) stream with shock wave, b) stream with periodic structure.

the atoms have a Boltzmann distribution over the excited states.

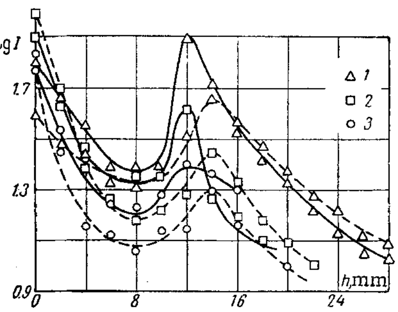

Fig. 2. Intensity distribution of the lines of copper along a stream with a shock wave: the continuous curves correspond to negative polarity of the annular electrode, the broken lines to positive electrode polarity; the points correspond to: 1) CuII 4231.4 Å, 2) CuI 5153.2 Å, 3) CUI 5105.5 Å.

The temperature was measured along the stream both for a stream with a shock wave and for a stream with a periodic structure, for positive and negative polarities of the annular electrode. The temperature behavior along the stream is given in Fig. 3. Here the error in determining the resultant temperature from the two pairs of lines indicated above is 25–30%. This error is higher than the error in determining the temperature from the relative intensity of each pair of lines separately (7–10%). It should be noted that in measuring the temperature over the whole thickness of the stream at a definite distance from the base by means of this or that pair of lines, we measure the temperature of those portions (layers) of the plasma in which the excitation conditions of this pair are most favorable.

It is clear from Fig. 3, that the behavior of the temperature along the stream follows the behavior of the line intensity (see Fig. 2). In the stream with the shock wave a temperature increase is observed in the zone corresponding to the shock wave. The electrode polarity exerts a marked influence on the temperature of the stream. For negative polarity the temperatures at the beginning of the stream and in the shock wave are roughly the same within the limits of measurement error. For positive polarity the temperature at the beginning of the stream is higher than in the shock wave. On the whole it is somewhat lower for negative in comparison with positive polarity.

In a stream with periodic structure the temperature increases at points of compression and falls at points of rarefaction. A temperature maximum is observed in the zone corresponding to the second compression. No marked variations in temperature are observed on altering the polarity of the annular electrode. On the whole, the temperature is higher for a stream with a periodic structure than for a stream with a shock wave, regardless of the fact that the discharge power in the first case is less than in the second.

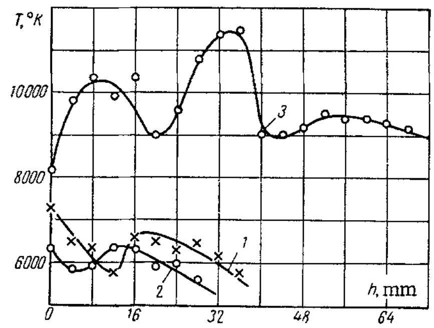

Fig. 3. Temperature behavior along the plasma stream: ×—positive polarity of the annular electrode, ⊙—negative polarity of the annular electrode, 1, 2) stream with shock wave, 3) stream with periodic structure.

3. DETERMINATION OF THE CHARGED PARTICLE CONCENTRATION

A series of strongly broadened copper lines is manifested in the stream spectrum. These are the lines of the diffuse series 4022.7, 4062 Å and the lines of the sharp series 4530.8, 4480.4 Å. Making

Wave-length	Serial transition	Energy difference cm⁻¹	gA, 10^8 sec^{-1}	gf	Stark's constant cm^4 sec^{-1}	Van-der-Waals' constant cm^6 sec^{-1}
4022.7	$4^2P_{1/2}$—$5D_{3/2}$	30535—55388	0.77	0.19	$1.64\cdot10^{-12}$	$3.86\cdot10^{-31}$
4275.1	$Z^4P_{5/2}$—$e^4D_{5/2}$	39019—62403	2.6	0.72		
4480.4	$4^2P_{1/2}$—$6^2S_{1/2}$	30535—52849			$1.80\cdot10^{-13}$	$4.16\cdot10^{-31}$
4530.8	$4^2P_{3/2}$—$6^2S_{1/2}$	30784—52849	0.65	0.20	$1.08\cdot10^{-13}$	$4.16\cdot10^{-31}$
5105.5	$m^2D_{5/2}$—$4^2P_{3/2}$	11203—30784	0.051	0.020		
5153.2	$4^2P_{1/2}$—$4^2D_{3/2}$	30535—49935	4.7	1.9		

use of the broadening of these lines, we can determine the concentration of charged particles in the plasma. The lines of copper 4022.7 and 4480.4 Å were taken with this in view. Estimates made of the influence of different types of interaction on the broadening of the selected lines (plasma temperature 10 000° K, concentration of charged particles 10^{16} cm^{-3}) show that under our conditions the broadening of these lines is caused chiefly by the second-order Stark effect. Other types of interactions consist of broadening due to second-order Stark effect of the line 4022.7 Å – 3% and of the line 4480.4 Å – 16%. For such lines asymmetry of broadening is experimentally observed in the longwave region of the spectrum. This is connected with the substantial influence exerted by the second-order Stark effect. Allowing for all this, we can use the copper lines indicated above with known Stark constants to measure the concentration of charged particles. With this in view, we calculated the dependence of the line width of the charged particle concentration. In the calculations it was assumed that the plasma is quasineutral, that the electron temperature is 10 000° K and that the total line half-width is composed additively of the half-widths due to electron collision interaction and the statistical interaction of ions. The method of measuring the charged particle concentration by the emission spectrum of copper is set out in detail in [6].

In the plasma stream with a shock wave the concentration was measured using the 4022.7 Å line, and in the plasma stream with periodic structure using the 4480.4 Å line. In the case of the stream with periodic structure the 4022.7 Å line is situated in the transition region from second-order to linear Stark effect. The presence of the forbidden line 4015.8 Å close to the line 4022.7 Å points to this. Thus we can not employ the 4022.7 Å line to measure the charged particle concentration in a plasma stream with periodic structure. The results of the charged particle concentration measurements along the stream are given in Fig. 4. Inaccuracy in measuring the line width determines the basic error and is equal to ~ 30%. It is clear from Fig. 4 that in the case of positive polarity of the annular electrode the behavior of the concentration along a stream with a shock wave follows the behavior of the temperature and the line intensity. However, in the case of negative polarity the concentration is almost without variation along the stream from its base to the zone corresponding to the shock wave, and subsequently decreases as in the case of positive polarity.

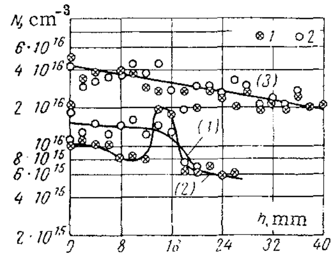

Fig. 4. Concentration distribution along the plasma stream. The points correspond to: 1) positive potential of the annular electrode, 2) negative electrode potential; and the curves: (1), (2)—stream with a shock wave; (3)—stream with periodic structure.

In a stream with periodic structure the concentration falls gradually along the stream. Insignificant increases and decreases of concentration are observed corresponding to the points of compression and rarefaction; these lie within the limits of measurement error. No marked variation in charged particle concentration is observed depending on the change of polarity of the annular electrode. In general, the concentration for a stream with periodic structure is somewhat higher than for a stream with a shock wave.

4. DISCUSSION OF THE RESULTS

Optical [1] and spectroscopic investigations have enabled us to explain a series of the physical peculiarities of a supersonic plasma stream. It was shown in [1] that the structure of a plasma stream is more complicated for negative annular electrode potential than for positive polarity. This is connected with the surface emission of material from the annular electrode. There is reason to suppose that under our conditions the plasma stream has integral currents [7], and the surface emission is probably caused by the discharge between the current-carrying stream and the annular electrode. It is well known that the electrode processes in an ordinary shock discharge are different for cathode and anode [8]. A more violent type of vaporization is characteristic of the cathode, this being connected with the unique current distribution on the electrode. Clearly, in our case, for negative annular electrode polarity a more intense surface discharge occurs for the same reasons, leading to the appearance of lateral plasmoids.

The reduced exit velocity of the plasma stream becomes understandable in the case of negative annular electrode potential (see Table 1 [1]). In this case the plasma stream contains a greater quantity of particles as a result of the surface disintegration of the annular electrode. An increase of the particle content in the stream leads to a lessening of velocity and, consequently, to the compression shock approaching the face of the annular electrode [9]. The measured temperatures display distinctive behavior along the stream, conforming to the character of the wave processes taking place in it. They increase in the shock wave and at points of compression, and decrease at points of rarefaction. Thus, wave processes taking place in a supersonic stream lead to an additional increase in the temperature and density of the plasma. This temperature behavior in the plasma stream of a pulsed oscillating discharge was observed previously in [10]. Spectral investigations carried out on the plasma stream of a unipolar pulse generator, not requiring time resolution, enabled the temperature variation to be followed continuously along the stream, and also the effect of polarity to be determined.

The difference in behavior of the spectral line intensity and temperature depending on the polarity is connected with the discharge pecularities mentioned above for negative annular electrode polarity. In this case the temperature at the commencement of the stream is measured basically within the plasmoids ejected from the surface, which screen the core of the stream. Surface plasmoids are practically absent for positive polarity, and the temperature is measured in the deeper zones. The fact that the temperature is on the whole lower for negative polarity is associated with the large self-absorption effect resulting from the presence of surface ejections of matter from the cathode. Since the shock wave is stronger in the case of positive polarity than in the case of negative polarity (this is clear from the velocity ratio, see Table 1 [1]), the temperature is also somewhat higher in this case.

The significant temperature increase of a stream with periodic structure compared with a stream with a shock wave, even though there is less power in the discharge, is connected with the fact that the electrical energy going into the discharge is chiefly transferred by means of radiative heat exchange. When the power in the discharge is lowered, the radiative capacity of the gas falls off sharply and the plasma temperature rises.

REMARK

I. V. Podmoshenskii and N. N. Ogurtsova give a similar explanation for an analogous phenomenon observed in the source EV-39 (private communication).

The difference in the behavior of charged particle concentration in a stream with a shock wave depending on the polarity is caused by the presence of surface plasmoids from the annular electrode, which create an additional layer of vapor at a lower temperature around the basic stream. The ejection of matter from the surface of the annular electrode is very intense for negative polarity, and so the measured concentrations of charged particles correspond basically to the surface plasmoids. The surface ejection is less intense for positive polarity of the annular electrode, and the behavior of the charged particle concentration conforms better to the wave processes occurring in the stream.

The concentration of charged particles in a stream with periodic structure is higher than in a stream with a shock wave. This is connected with the greater temperature and pressure in the stream.

The velocity-based temperature obtained in [1] is considerably lower than the temperature measured by spectroscopic means. We can not compare these temperatures since in our case spectroscopic measurements give the copper line excitation temperature conditioned by the discharge, while the exit velocities give the temperature of the gas issuing from the nozzle, without allowance for the composition of the plasma being formed.

We take this opportunity to express our sincere thanks to M. A. El'yashevich for discussing the results.

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