THE STUDY OF A SUPERSONIC JET OF RAREFIED ARGON PLASMA

V. M. Gol'dfarb, E. V. Il'ina, I. E. Kostygova, G. A. Luk'yanov, and V. A. Silant'ev

Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 8, No. 1, pp. 111-116, 1967

ABSTRACT: We have carried out an experimental study of a supersonic jet of argon plasma flowing in a rarefied medium. We have measured the distribution of total thrust along the axis of the jet at various temperatures in the arc chamber of the plasmatron. Using spectroscopic methods, we obtained the axial and radial distributions of the electron concentration and temperature and of the concentration of excited atoms. With the help of a probe we measured the electron temperature and concentration at large distances from the nozzle tip.

§1. **Experimental apparatus.** A schematic drawing of the experimental apparatus in which the study of a supersonic jet of argon plasma was carried out is shown in Fig. 1. As the source of the jet we used a constant-current plasmatron with vortical gas stabilization. The argon jet flowed from the nozzle of the plasmotron into a vacuum chamber with a pressure on the order of 2 to 4 N/m^2. The pressure in the arc chamber of the plasmatron was from 4 to $5 \cdot 10^4$ N/m^2. In the experiments carried out here the mean enthalpy per unit mass reached $12 \cdot 10^6$ J/kg, corresponding to a temperature of $11 \cdot 10^{3\circ}$ K.

The results of the measurements described here were obtained with the use of a nozzle with a critical diameter of 2.75 mm and an exit diameter of 3.3 mm. The half-angle of the nozzle opening was 10°.

§2. **Measurement of total thrust.** To study the distribution of total thrust in the argon plasma jet, we used both cooled and uncooled cylindrical Pitot tubes with flat heads. The water-cooled tube was used near the nozzle tip, where the gas density and heat current are large. The uncooled Pitot tube was used at greater distances. In analyzing the results of the measurements, we took into account the correction due to the influence of viscosity on the entrance aperture of the tube at low Reynolds numbers [1].

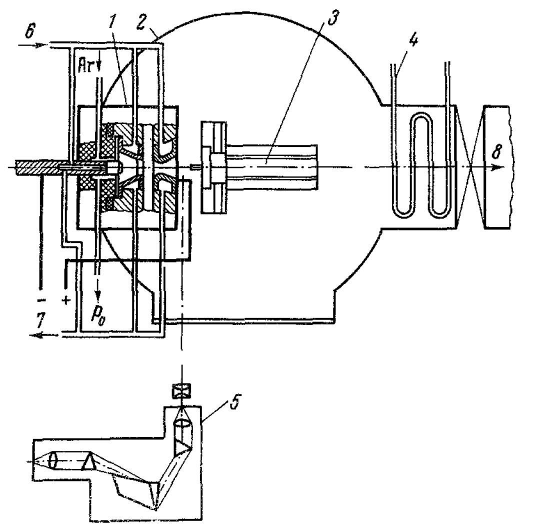

Fig. 1. Schematic of the experimental appratus: 1) plasmotron, 2) vacuum chamber, 3) coordinated mechanism for movement of the data units 4) cooling coil, 5) ISP-51 spectrograph, 6) water input, 7) drain, 8) to the pumps.

The effects of temperature gradients in the measuring canal on the tube reading can, as has been shown by analysis, be neglected under the conditions of the present experiment. Figure 2 shows the distribution of the relative total thrust p_+/p_0 along the jet axis for three different effective temperatures T_0 in the plasmatron chamber. The temperature of the plasma on the axis is higher than the effective temperature. It has been shown by measurement that an increase in the temperature in the plasmotron chamber leads to a decrease of the total thrust on the jet axis.

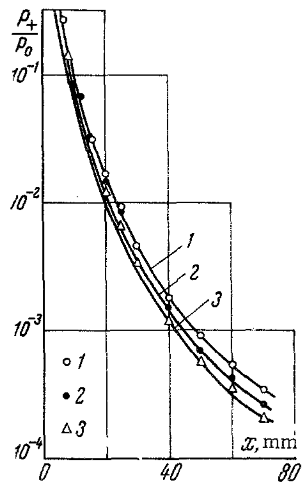

Fig. 2. Distribution of relative total thrust along the jet axis: 1) $T_0 = 7 \cdot 10^{3\circ}$ K, 2) $T_0 = 9.1 \cdot 10^{3\circ}$ K, 3) $T_0 = 11.2 \cdot 10^{3\circ}$ K.

§3. **Spectroscopic measurement of the electron concentration and temperature.** The lack of equilibrium in a plasma jet at low pressure forces us to be cautious in the choice of spectroscopic methods for determining the plasma parameters. In this work the electron concentration was determined from the absolute intensity of the continuum and from the Stark widening of the lines, and the electron temperature from the relative intensity of the Ar I line. The conditions under which these methods are applicable are discussed below.

The plasma spectra were photographed with the help of an ISP-51 spectrograph and a 270 mm camera. Camera objectives with focal distances of 135 or 90 mm were used to obtain an image of the plasma jet in the plane of the slit on a scale of 1:4 or 1:7. To determine the intensity of the plasma radiation in absolute terms we used a reference source, a constant-current anode arc burning between spectroscopically pure carbon electrodes. The operating mode of the standard arc and the data about its emissivity were taken from [2] To obtain comparable darkening from the reference source and the plasma jet, we used neutral weakening light filters; additional weakening of the light current from the reference arc was accomplished by reflection from a color-selective plate. We used "spectrographic type 2" photoplates; the spectrograms were analyzed by the ordinary methods of photographic photometry (of necessity, heterochromatic). Since the small dispersion of the spectroscopic device forced us to work with a narrow slit, the relative and absolute intensities were found by the method of plotting the line shapes.

Figures 3a and 3b show typical spectra of the plasma jet for cross sections at x = 5 mm and x = 35 mm. In the first spectrum there are visible the lines of the neutral argon atoms, the lines of the Balmer series of hydrogen (which is present in the form of a slight impurity), and a continuous spectrum, the argon recombination continuum. In the second spectrum there also appear the molecular bands of nitrogen (the second positive system), whose presence can be explained by a constant small leakage of air into the vacuum chamber. Along the jet the intensity of the continuum falls off very rapidly, while the intensity of the line spectrum decreases more slowly. Impurity lines (copper, tungsten) are absent from the plasma spectra.

The electron concentration was determined from the absolute intensity of the argon recombination continuum in the 4500 Å region, and also, at short distances from the nozzle tip, from the widening of the H_β line (only in this region of the jet does the Stark widening of H_β significantly exceed the instrumental width). The applicability of the latter method is not limited by any thermodynamic conditions. The determination of n_e from the continuum is possible in the case when the electron velocity distribution is Maxwellian.

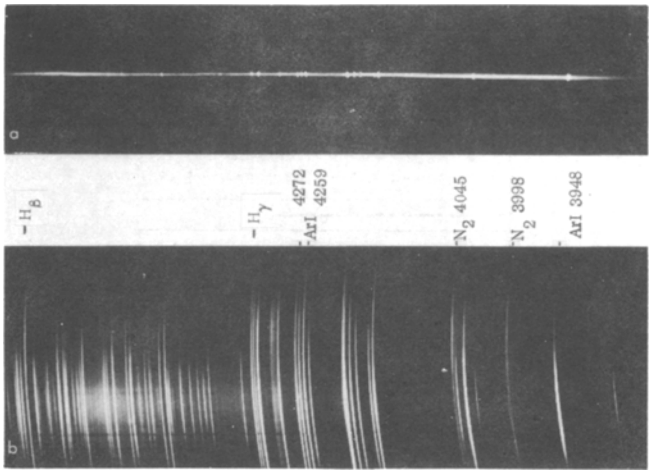

Fig. 3. Spectra of the plasma jet for the cross sections at: a) x = 5 mm, b) x = 35 mm.

The intensity of the continuum is given by the relation $J = 7.3 \cdot 10^{-35} \xi n_e^2 T^{-1/2}$ (V/cm^3-ster-Å), where the coefficient ξ, based on the calculations of Biberman and Norman [3] and the experimental data of [4], is chosen to equal 2.3. The probable error in this value is 20%, which gives an error only half as large in n_e. At large distances from the nozzle tip the continuum intensity falls off strongly and becomes comparable to the intensity of the nitrogen molecular spectrum. Under these conditions, photographic detection with the ISP-51 spectrograph did not permit us to determine n_e for $x \geqslant 6$ cm. In order to find the radial distribution of n_e in the various cross sections, the transverse distribution of the continuum intensity was transformed into the radial distribution by the familiar numerical method of [5].

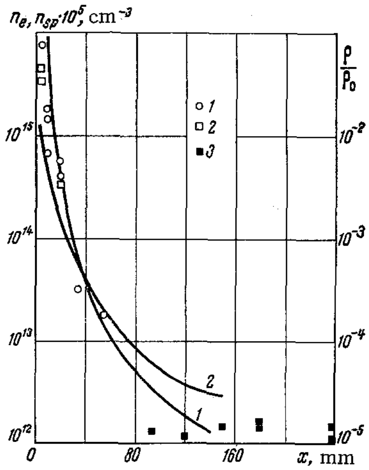

Fig. 4. Distribution of electron concentration: curve 1) relative density, curve 2) concentration of excited atoms along the jet axis; points 1) from the continum, 2) from the widening of the H_β line, 3) from the probe method.

For the determination of n_e from the H_β line widening we have, from [6], $n_e = 3.7 \Delta\lambda^{3/2}$. Figure 4 shows the results of the measurement of n_e along the jet axis. The H_β widening gives somewhat smaller values. This can be explained in part by the fact that the radial distribution of the H_β line halfwidth was not constructed, and this method gives, not the "axial," but the average values of n_e for some region around the axis. However, the discrepancy in the values does not greatly exceed the combined error from both methods of measurement (30 to 40% from the continuum and 20% from the widening). The radial distribution of n_e is given in Fig. 5.

The electron temperature of the plasma jet can be measured from the relative intensity of the spectral lines, if the relative populations of the corresponding excited states are given by the Boltzmann equation. At small n_e and T_e the Boltzmann distribution will hold for the higher excited states and, in general, for levels with small differences in their excitation energy. The latter include, for example, the sublevels of the $3p^5 5p$ state. We chose the lines ArI4272.2 Å $|5p(3p_7) \rightarrow 4s(1s_4)|$ and ArI4259.4 Å $|5p(3p_{10}) \rightarrow 4s(1s_2)|$, for which the energy difference is $\Delta E = 0.21$ eV. The small value of ΔE increases the measurement error, but it is better in this case to satisfy the above-mentioned condition. Besides, the photometric measurement error for the chosen pair is significantly reduced by their close similarity in intensity and line shape.

In order to increase ΔE and simultaneously assure the correctness of the Boltzmann distribution, it is necessary to use several lines which strongly differ in intensity and wavelength, which would lead unavoidably to an increase in the photometric errors. To determine the temperature we must know the quantity $(Ag)_{4272}/(Ag)_{4259}$ (A is the transition probability, and g is the statistical weight of the upper state).

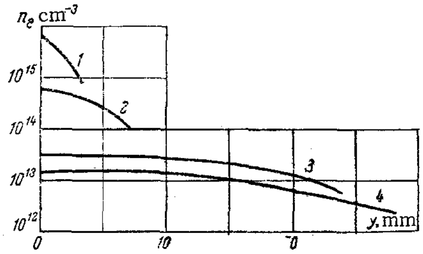

Fig. 5. Radial distribution of the electron concentration for the cross section at: 1) x = 5 mm, 2) x = 20 mm, 3) x = 35 mm, 4) x = 55 mm.

Drawin [7], Gericke [8], Olsen [9], and Popenoe and Shumaker [10] have obtained for it the values 0.571, 0.645, 0.447, and 0.705 respectively. In order to choose the most valid value of $(Ag)_{4272}/(Ag)_{4259}$, we measured this quantity for an equilibrium arc plasma at high current strength, the temperature of which is measured simultaneously by several methods (by the widening and the absolute intensity of the lines and the absolute intensity of the continuum). The data were interpreted by the same method used in the case of a low-pressure jet. The value obtained was 0.575, very close to the result found by Drawin. The temperature is determined from the formula

$$T_e = 1060 \left(0.23 - \lg \frac{J_{4259}}{J_{4272}}\right)^{-1}.$$

The measurement error is very high for $T \approx 10\,000°$ K, but amounts from 3000 to 5000° K.

The distribution of T_e along the jet axis is shown in Fig. 6. Figure 7 gives the radial distribution of T_e for several transverse cross sections.

Besides the relative intensities, we also measured the absolute intensities of the lines corresponding to transitions from the 5p state, and the populations of some sublevels of this state were calculated according to the formula $n = J/h\nu A$. Figure 4 shows the variation of the concentration of atoms in the $5p(3p_7)$ state (calculated from the 4272.2 Å line) along the length of the jet.

§4. Probe measurements. For the measurement of the electron temperature and concentration we also made use of a single cylindrical Langmuir probe. The axis of the probe coincided with the direction of the current, which reduced the influence of the directed ion velocity on the volt-ampere characteristics of the probe. The usual assumption in the theory of Langmuir probes, that the characteristic dimension of the probe is much shorter than the mean free path, was satisfied in all cases when the probe was used. The analysis of the volt-ampere characteristic established a semilogarithmic dependence of the electron current i_e on the probe potential φ. The presence of a straight segment in this dependence testifies to a Maxwellian distribution of electron velocities. From the slope of this segment we determined the electron temperature:

$$T_e = 5040 \left(\frac{d \lg i_e}{d\varphi}\right)^{-1}.$$

The electron concentration can be found from the current i_{e0}, corresponding to the inflection point in the volt-ampere characteristic:

$$n_e = 4.03 \cdot 10^{13} \frac{i_{e0}}{S} \frac{1}{\sqrt{T_e}}.$$

Here S is the area of the collecting surface of the probe in cm^2.

Under our conditions the Debye length is small by comparison with the probe diameter, so that the collecting surface was taken to be the surface of the probe itself. The results of the measurement of T_e and n_e along the jet axis are shown in Figs. 4 and 6.

§5. Analysis of the results. The spectroscope and probe measurements showed that the electron temperature decreases rapidly near the nozzle tip and remains practically constant at large distances from the tip. In the region of the jet, where the measurements were carried out by both methods, their results coincide within the limits of accuracy of each method.

The nature of the electron concentration variation along the jet axis is similar to that of the electron temperature. A substantial electron concentration remained in all regions of the jet which we studied, and it significantly exceeded the equilibrium value.

The radial distributions of the electron temperature and concentration proved to be nearly constant for cross sections far from the nozzle tip, which agrees with the ordinary gas-dynamic picture of gas discharge. The experimentally observed dependence of the total thrust on the plasmotron chamber temperature testifies to the incomplete cooling of the current. The decrease of the total thrust as the temperature in the arc chamber increases can be explained by a decrease of the Mach number in the nozzle tip and of the specific heat ratio c_p/c_v as the argon ionization increases.

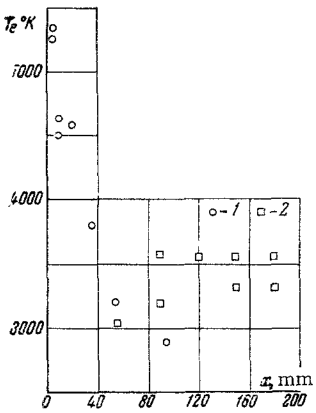

Fig. 6. Distribution of the electron temperature along the jet axis: 1) from the method of relative line intensities, 2) from the probe method.

The departure of the current from the cooled state is not large, at least for x ≥ 1 cm. This is indicated by the data of Fig. 4; the variation of the concentration of atoms along the length of the jet, as determined from the total thrust (calculated from the ideal gas formulas), coincides with the variation of the electron concentration. It does not, however, follow from this that the current is completely cooled, since the variation in the degree of ionization can differ from the value near the nozzle by several dozen percent and yet lie within the limits of probable error of the measurement of n_e and the calculations of the gas density.

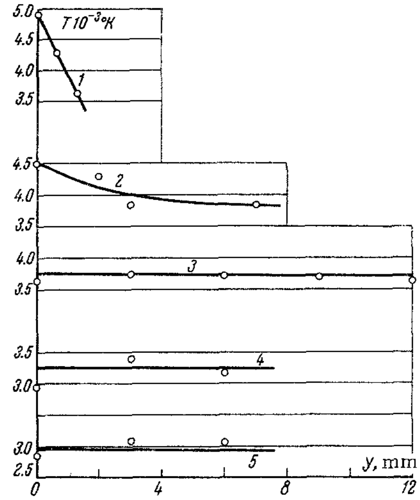

Fig. 7. Radial distribution of the electron temperature for the cross sections at: 1) 5 mm, 2) 20 mm, 3) 35 mm, 4) 55 mm, 5) 90 mm.

Assuming the collision-radiation mechanism of recombination [11, 12], we can calculate the recombination coefficient as a function of n_e and T_e (i.e., as a function of x), correct to within a factor of 2–4. The calculations which we performed for argon gave values of the recombination coefficient of from $1 \cdot 10^{-10}$ to $1 \cdot 10^{-12}$. Under these conditions the degree of ionization drops by no more than 10% in the region 1 cm < x < 10 cm.

Let us now consider the variation of the concentration of excited atoms along the length of the jet (Fig. 4). At an electron temperature of order 0.25 to 0.45 eV, the excitation of the higher states in argon, which have energies from 13 to 15 eV, directly from the ground state is insignificant. The measurements show that the concentration of excited atoms exceeds the equilibrium value by several orders of magnitude. It has been suggested in [13, 14] that the higher argon levels are populated from the metastable levels 4s ($^3p_0$ and $^3p_2$) having energies ≈11.5 eV. A high concentration of metastable atoms in the jet could be established in the arc chamber, and would not significantly decrease during the short time of flight of the atoms in a supersonic jet. In [13] it is also assumed that the population of the higher states is in Boltzmann equilibrium with the population of the metastable state. Calculation shows that this does not occur at low electron concentrations. The delayed decrease in the concentration of excited atoms, compared with the electron concentration and the gas density, can be explained by recombination into the higher levels. This does not contradict the observed slow variation in the degree of ionization; since the concentration of excited atoms is small compared with n_e, a tiny reduction in the latter quantity leads to a large increase in the population of the higher levels.

REFERENCES

1. V. A. Sukhnev, "Determining the correction to the readings of a Pitot tube in a supersonic current of rarefied gas," Izv. AN SSSR, Mekhanika i mashinostroenie, no. 5, 1964.

2. M. R. Null and W. W. Lozier, "Carbon arc as a radiation standard," J. Opt. Soc. America, vol. 52, no. 10, 1962.

3. L. M. Biberman and G. E. Norman, "The calculation of photoionization absorption," Optika i spektroskopiya, vol. 8, no. 4, 1960.

4. D. Schülter, "Der kontinuierliche absorptionskoeffizient des Argons," Z. Astrophys., B. 56, H. 1, 1962.

5. W. Pierce, "The radial distribution of photon radiators in symmetric sources," collection: The Preparation and Study of High-temperature Plasma [Russian translation], Izd-vo inostr. lit., 221, 1962.

6. H. P. Griem, Plasma Spectroscopy, N. Y., 1964.

7. H. Drawin, "Wirkungsquerschnitte von neutralen Wasserstoff.— Helium- und Argonatomen gegenüber Electronenstoss," Z. Physik, B. 146, H. 3, 1956.

8. W. E. Gericke, "Messung der Ubergangswahrscheinlichkeit sowie Halbwertsbreite und Verschiebung von Ar-linien in Thermish Leuchtenden Plasmen," Z. Astrophys., vol. 53, no. 1, 1961.

9. H. N. Olsen, "The electric arc as a light source for quantitative spectroscopy," J. Quantit. Spectros. and Radiat. Transfer, vol. 3, no. 4, 305, 1963.

10. C. H. Popenoe and J. Shumaker, "Arc measurement of some argon transition probabilities," J. Res. Nat. Bur. Standards A, vol. A, 495, 1965.

11. D. R. Bates, A. E. Kingston, and R. W. P. McWhirter, "Recombination between electrons and atomic ions," Proc. Roy. Soc. A, vol. 267, no. 1331, 1962.

12. E. Hinnov and J. Hirschberger, "Electron-ion recombination in dense plasmas," Phys. Rev., vol. 125, no. 3, 1962.

13. L. E. Brewer, W. K. McGregor, and M. Dooley, "The influence of metastable atoms of the population of excited states in a thermal plasma," J. Opt. Soc. America, vol. 52, 829, 1962.

12 May 1966 Leningrad