STUDY OF THE STRUCTURE OF A SUPERSONIC PLASMA JET AND ITS MECHANISM OF FORMATION

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It is known that a shock system of expansion and compression waves develops on a section of a plasma jet near the nozzle; as a result, the pressure in the jet gradually becomes equal to the environmental pressure. Papers [1-4] are devoted to a study of plasma jets formed by an oscillatory pulse discharge. Since the discharge is oscillatory, the structure of these jets varies in time.

This paper deals with a supersonic plasma jet created by a unipolar pulse generator and flowing into air at atmospheric pressure. Such a jet is characterized by processes that are nearly time-invariant. This makes it possible to perform spectroscopic investigations without allowing for time and to study the physical properties of the jet as a function of polarity.

1. DESCRIPTION OF UNIPOLAR PULSE PLASMA GENERATOR AND EXPERIMENTAL TECHNIQUE

We obtained a plasma jet by producing a discharge between annular electrode 1 (Fig. 1) and rod 2 located on the axis of the annular electrode aperture. The electrodes were made of brass. The electric discharge circuit consisted of a capacitor system 3, a measuring noninductive resistance 4, and connecting busbars. The capacitor system employed IM-3-100 capacitors and consisted of six cells. This arrangement made it possible to form a unipolar current pulse (Fig. 2) registered by a OK-25 oscillograph triggered from the control panel of the high-speed camera (HSC) at a frequency n = 50 kc. Discharge occurred when a high-voltage pulse from the camera control panel was fed to the firing electrode 5. The voltage was strictly controlled by a kilovoltmeter.

The plasma jet was studied both spectroscopically and by high-speed photography (frame and continuous), using SFR-L and ZhFR-1 instruments. With the photorecorder slit placed parallel to the jet axis, it was possible to photograph the jet continuously in a direction perpendicular to its motion. For frame photography, we employed the SFR-L motion picture camera at speeds of up to 125 000 frame/sec. The emission spectrum of the plasma jet was registered by a ISP-51 spectrograph coupled with a camera (F = 270 mm). The jet was focused lengthwise on the slit of the spectrograph by a condenser (F = 90 mm) with reduction by a factor of ten. The spectrum over the jet cross section at various distances from the annular electrode was photographed by means of a SU-78 spectral adapter on the F = = 270 mm camera of the ISP-51. The plasma-jet radiation intensity in one burst was sufficient to give normal blackening of standard No. 45 panchromatic plates. In some cases it was even attenuated by a double neutral filter. The spectrograms were processed on a

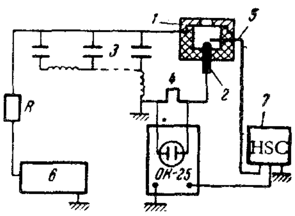

Fig. 1

MF-2 microphotometer, a photomultiplier being used as the photoelement. In measuring the lines photometrically, the continuous background had to be taken into account. This background was measured from the violet side of the line, since all the spectral lines asymmetrically broadened into the red region of the spectrum so that it was not convenient to measure the background in this region. When broad lines were used, the line shape was constructed in intensities and then graphically integrated; these integral intensities were then used in calculation.

2. MECHANISM OF FORMATION OF A SUPERSONIC PLASMA JET

Strong plasma compression by the magnetic field created by the discharge current accompanies a pulse discharge with the above-indicated electrode configuration. The energy of the electrodynamic forces is converted to kinetic energy of plasma motion. In addition, there is another component of plasma acceleration due to pure thermal expansion of the plasma heated by the discharge current. This contribution varies depending on the limits of the space in which discharge takes place. The following experiments were performed. For the same discharge parameters and for the same position of the electrodes, discharge was initiated in a confined space, as in Fig. 1, and in an open space, i.e., discharge took place between a plane electrode with an aperture and a rod electrode. In the latter case, a plasma jet was obtained which did not have a complex wave structure and its exit velocity was much lower. Thus, in a confined space ohmic plasma heating contributes appreciably to jet acceleration.

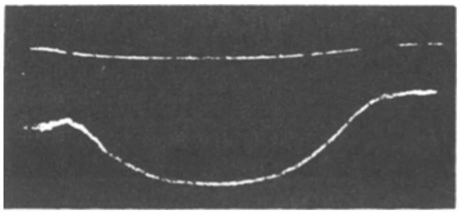

Fig. 2

Therefore, in the case of pulse discharge in a confined space there is a sharp increase in the pressure in the "discharge" space in comparison with the ambient pressure. Thus, the plasma jet flows from the nozzle with an excess pressure which, in hydrodynamics, is still sometimes called flow with incomplete expansion [5]. The emerging plasma jet is supersonic, since it expands at the mouth of the nozzle.

As in [5], if the difference between the pressure in the jet (p) and the ambient pressure (p_1) is small, a beam of rarefaction waves is formed at the exit edge of the nozzle. These waves cross and are reflected from the opposite boundaries of the jet in the form of compression waves (Fig. 3a—for U = 2.25 kV, C = 600 μF, r = 5 mm). The compression waves, in their turn, also cross and are reflected from the opposite jet boundaries in the form of rarefaction waves, and so on. The jet has an almost-periodic structure, i.e., it consists of alternating segments of rarefaction and compression (droplet configuration). The wavelength L of this almost-periodic structure, as experimentally determined by Emden [6], is described by the formula

$$L = 0.89\, d\, \sqrt{(p_2 - 1.9\, p_1)/p_1} \qquad (2.1)$$

for an axisymmetric supersonic jet propagating in a stationary medium.

Here d is the nozzle diameter, p_2 the pressure in the receiver ("discharge" space) and p_1 the ambient pressure.

Since in our experiments the ambient pressure was constant and equal to 1 atm, we can determine p_2 after finding L experimentally.

On the other hand, the wavelength L may be expressed in terms of the Mach number as follows [5]:

$$L = 2.613\, r\, \sqrt{M^2 - 1}\,. \qquad (2.2)$$

Here r is the aperture radius of the annular elecrode, and M is the Mach number. Knowing the wavelength L and exit velocity of the jet, we can determine its gaskinetic temperature from the expression

$$M = \nu/\nu_1\,.$$

Here ν is the jet exit velocity, ν_1 is the speed of sound at the given temperature.

If there is a great difference between the pressure in the jet and the ambient pressure, a shock wave may appear in the jet, even when rarefaction waves are first formed at the nozzle edge (Fig. 3b—for U = = 3 kV, C = 600 μF, r = 2.5 mm). The reason for this is the fact that the pressure in the jet drops when it emerges from the nozzle as a result of expansion and the formation of rarefaction waves. Thus, the pressure in the jet may become lower than the ambient pressure after passage of the rarefaction waves. Accordingly, in order to satisfy the boundary condition, a shock wave should develop, in which the pressure increases until it is equal to the ambient pressure.

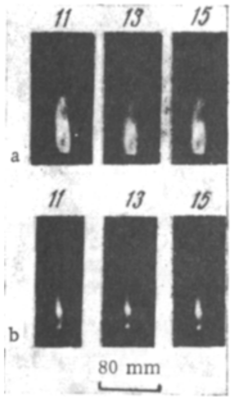

Fig. 3

For a moderate pressure difference, the plasma jet has a mixed structure, i.e. a shock wave and periodic structure are both observed. This is quite clear from the time-resolved photograph in Fig. 4a for U = = 2.5 kV, C = 600 μF, and r = 2.5 mm.

In all the cases considered, the ambient pressure was constant and equal to 1 atm. A change in pressure ratio was achieved by varying the pressure in the "discharge" space as a result of a change in the discharge condition and parameters ("discharge" volume, apertural diameter of annular electrode, discharge energy).

In considering the processes taking place in plasma jets formed by a pulse discharge, it is impossible not to mention the physical untenability of the explanation of the observed effects in reference [7], which is devoted to an investigation of localized pulse discharges. The discharge is localized by means of insulating rings attached to the electrode. This leads to a strong increase in pressure in the space bounded by the ring. As a result, the flow of plasma from the ring is similar to flow from a nozzle with excess pressure. This makes it possible to explain the formation of a dark space (as a region of expansion) and to refute the author's conclusions [7] that "the formation of a dark space is due to the entry of drops of liquid and individual particles into the discharge cloud, where they break down into finer particles and atoms thus inducing the most intense metal vapor luminescence." Actually, the metal vapor luminescence is most intense in the shock, where the vapor density and temperature increase.

It is also necessary to consider the proposition expressed in [1] regarding the similarity between the effects taking place in an ordinary pulse discharge and the effects considered in that article. It has been reliably established that in a spark discharge the electrode material is ejected at supersonic speed in the form of vapor jets [8]. These jets, in turn, have a fine structure, i.e., they consist of separate jetlets of electrode-material vapor, to each of which corresponds a pit (trace) on the cathode.

The ejection of electrode-material vapor and the presence of dark space on the electrode surface [8] point to an analogy with the above-considered effects. In fact, the pit in the cathode conditions a sort of localized discharge. During discharge, the pressure in each pit sharply increases in comparison with the ambient pressure. A jetlet is ejected, as in the case of flow from a nozzle with excess pressure. In other words, each jetlet represents, in miniature, a jet flowing from a nozzle with excess pressure.

3. CHANGE IN STRUCTURE OF PLASMA JET WITH POLARITY

Figures 4 b and c show typical photographs of a plasma jet with a shock wave (for U = 3 kV, C = 600 μF, r = 2.5 mm) and with periodic structure (for U = 2.25 kV, C = 600 μF, r = 5 mm, M = 1.6) as a function of polarity. It was established from numerous such photographs that the plasma jet structure when the annular electrode is negatively polarized is more complex than when the annular electrode is positively polarized. Together with the jetlets which make up the jet as a whole the photos show individual blobs overlapping the jetlets at a smaller angle of inclination to the time axis and without a discontinuity in the shock (Fig. 4b). These blobs are ejected laterally and propagate outside the main jet. Blobs are also observed which gradually increase their angle of inclination to the time axis, i.e., ejection velocity, as they move away from the annular electrode. In this case, the ejected blobs directly enter the main jet and are entrained with it. This fact, along with others, indicates that when the annular electrode is negatively polarized, material is ejected from it. This is also evidenced by the damage to the annular electrode.

The velocity of the plasma jet was measured from the jetlets making up the jet as a whole. The measurement error is 5-10%. The plasma jet velocity v_- when the annular electrode is negatively polarized is less than that for positive polarity v_+ both ahead of the shock (v_- = 6.9 and v_+ = 9.2) and in the shock (v_- = 2.5. and v_+ = 3.2). The decrease in jet velocity is caused by the observed instability of the discharge when the annular electrode is negatively polarized.

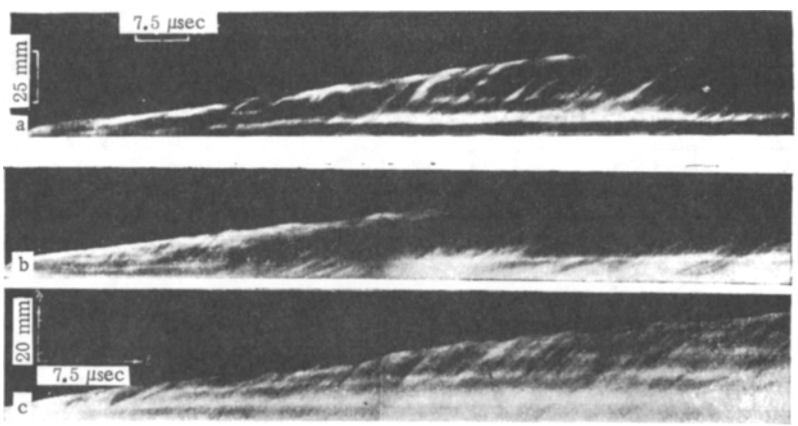

Fig. 4

This instability, in all probability, is associated with the current distribution at the electrode. For jets with periodic structure, there are no appreciable observed differences in velocity as a function of polarity. On the average, the exis velocity is 6 km/sec ($U = 2.25$ kV, $C = 600$ μF, $r = 5$ mm). The wavelength of the almost-periodic structure for such a jet is 16 mm. The mach number and gaskinetic temperature obtained from formulas (2.2) and (2.3) using the experimental data are respectively equal to 1.6 and 3600° K. On the basis of (2.1), the pressure in the "discharge" space is 14.6 atm.

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