STUDY OF THE PLASMA FORMATIONS RESULTING FROM JET INTERACTION IN A HIGH-POWER IMPULSIVE DISCHARGE

L. I. Kiselevskii and M. A. Sultanov

Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 7, No. 4, pp. 96–98, 1966

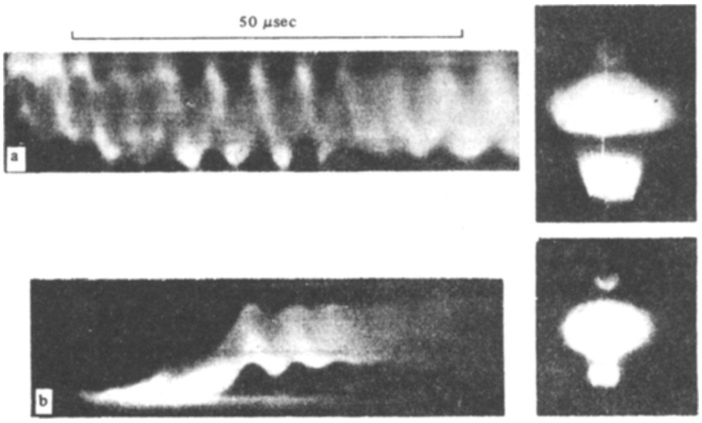
High-speed photography has been used to establish the presence of sonic oscillations in the regions of compressed plasma formed as a result of interaction of the opposing supersonic jets of a high-power impulsive discharge. In time-resolved photographs the propagating sonic perturbations are registered as bands of varying brightness. The plasma temperature in the shock-compressed regions can be determined by measuring the rate of propagation of the sonic perturbations.

Under certain conditions when an impulsive discharge is created at atmospheric pressure in air, the electrode flames form plasma jets propagating at supersonic velocity [1]. Where the jets from opposing electrodes meet, regions of shock-compressed plasma may be formed. Below, we consider certain properties of these plasma formations which are of interest from the standpoint of discharge parameter diagnostics.

The regions of shock-compressed plasma are most clearly manifested in high-power discharges. We studied discharges in air at atmospheric pressure created by a capacitor bank at two values of the capacitance: 200 and 800 μF. The initial voltage was 3 kV, the inductance of the discharge circuit 1 μH. The electrodes were copper with hemispherical tips; the interelectrode gap measured 7 mm. The structure of the discharge cloud was studied by means of high-speed time-resolved and frame photography. In the high-speed photographs the regions of shock-compressed plasma are registered in the form of zones of increased brightness [1–3].

The figure shows typical time-resolved photographs of the discharges in question, together with individual frames corresponding to the middle stage of the pulses; the pictures were obtained at a film speed of 125 000 frames/sec for the following values of the parameters: $U = 3$ kV, $L = 1$ μH, $C = 800$ μF (a), $C = 200$ μF (b). An examination of the photographs shows that, beginning with a certain phase of the discharge, a region of increased brightness, separated from the electrodes, is formed in the interelectrode gap, the upper and lower luminescence fronts executing almost sinusoidal oscillations with a phase shift of 180°. As a rule, the oscillations of the luminescence fronts take place without contact with the electrodes, as may be seen particularly clearly in the discharge at 200 μF. For a fixed electrode gap the frequency of the oscillations is quite well reproduced in successive pictures. On the average it is $1.6 \cdot 10^5$ sec^{-1} and decreases somewhat toward the end of the pulse. It is also characteristic that points on the upper and lower luminescence fronts oscillating in phase are connected by inclined bands of equal brightness.

These observations may be explained as follows. In [1] it was shown that under the discharge conditions in question, the electrode jets are supersonic. It can therefore be assumed that the bright region in the interelectrode gap is a condensed volume of plasma bounded in the direction of the electrodes by compression shocks. This volume of plasma may serve as a plasma resonator in which perturbations in the electrode jets are capable of creating compression and rarefaction waves propagating inside the volume at sonic velocity. According to the laws of hydrodynamics [4], a compression wave, on reaching the opposite shock-supported front, should sweep it away to the electrode. As a rarefaction wave approaches the luminescence front, the latter should move away from the electrode. In the time-resolved photographs the compression and rarefaction waves evidently correspond to the inclined bands of different brightness connecting points on opposite fronts that oscillate in phase. Compression waves must correspond to bands of increased brightness, and rarefaction waves to bands of reduced brightness. In particular, this explanation is in agreement with the fact that the former bands connect points closest to the electrodes, and the latter those furthest away. These bands cannot be ascribed



to ordinary motion of the vapor jets ejected from the electrodes, since they do not extend outside the bright region.

If the inclined bands in question correspond to propagating sonic perturbations, then from their inclination one can easily determine the speed of sound in the plasma contained in the compressed region and hence the plasma temperature.

A method of determining the temperature of a plasma by measuring the speed of sound in a spark discharge through a capillary was considered in [5]. The temperature dependence of the speed of sound in a plasma with allowance for ionization is as follows:

$$c = \sqrt{\gamma(1+x)\,RT/A} \qquad (\gamma = c_p/c_v). \tag{1}$$

Here A is the atomic weight, and x the degree of ionization.

In determining the temperature, Eq. (1) is solved together with the Saha equation

$$p \lg \frac{x^2}{1-x^2} = 2.5 \lg T - \frac{5036}{T} E_u - 6.49 \tag{2}$$

where p is the pressure in atm, and E_u is the ionization potential in eV.

From the inclined bands in the compressed regions we determined the speed of sound at different stages of the discharge and on the basis of (1) and (2) calculated the temperature, taking γ equal to 1.25 and the pressure inside the compressed region equal to 5 atm. This pressure was estimated with allowance for the velocities of the opposing plasma jets. The unavoidable error in estimating the pressure does not have much effect on the results of the temperature measurements. For example, if we assume that jet interaction does not lead to any increase in pressure (p = 1 atm), we obtain a temperature reduction of about 5–10%. The calculations were based on the assumption that the plasma consists primarily of copper atoms and ions. Spectroscopic studies of the discharge show that in these discharges impurities formed by the components of air are present only in insignificant amounts.

We present the results of measurements of the speed of sound c (in m/sec) and plasma temperature T (°K), obtained at several values of the time t in μsec from the beginning of the pulse at capacitances C = = 800 and 200.

t=50	56	62	68	74	80
c=2050	1900	1750	1650	1650	1550
T°=14 000	12 900	11 800	11 200	11 200	10 600

t=86	92	98	30*	36*	43*	50*
c=1500	1500	1200	1450	1375	1250	1050
T°=10 200	10 200	8700	9800	9500	8600	6600

(Here the asterisks denote measurements at a capacitance of 200 μF.)

The beginning of the measurements corresponds to the phase of the discharge in which a condensed region is formed and inclined bands appear in the time-resolved photographs.

It is clear from these data that a higher temperature is reached in the higher-capacitance discharge. In both cases the temperature decreases toward the end of the pulse, which is in agreement with the usual notion that the maximum value of the temperature occurs in the initial stage of the discharge.

Oscillations of the luminescence fronts and inclined bands inside the compressed region are observed not only in the first half-period of the discharges but also in subsequent half-periods. As might be expected, the inclination of the bands in these half-periods decreases, which indicates a simultaneous decrease in the speed of sound and plasma temperature. For example, in the second half-period of 200 μF discharge the maximum temperature, measured by the method described, rises only to 8000° K.

Thus, the above interpretation of the structure of the discharge cloud in the presence of supersonic electrode jets provides a simple means of determining the plasma temperature from measurements of the propagation velocity of the sonic perturbation registered on time-resolved photographs. The proposed method permits temperature measurements with time resolution.

REFERENCES

1. M. A. Sultanov and L. I. Kiselevskii, "Study of the behavior of electrode material in a high-voltage impulsive discharge," Zh. prikl. spektroskopii, 1, 268, 1964.
2. A. O. Babushkin, "Luminescence of the vapors of a condensed discharge flowing from a tube nozzle," ZhETF, 14, 184, 1944.
3. L. I. Grechikhin and L. Ya. Min'ko, "Structure of the plasma jet of an impulsive discharge," ZhTF, 32, 1072, 1962.
4. L. D. Landau and E. M. Lifschits, Mechanics of Continua [in Russian], Gostekhizdat, 1953.
5. A. O. Babushkin, "Temperature, degree of ionization and vapor pressure in a condensed discharge through a narrow tubular channel," ZhETF, 14, 279, 1944.

18 August 1965 Minsk