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PRODUCTION OF STRONG SHOCK WAVES DURING ELECTRICAL DISCHARGES IN GAPS

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The velocity of broadening of the spark channel in slit-like gaps was investigated. Strong shock waves were obtained in various gases at atmospheric pressure. The velocity of shock waves in hydrogen was found to be 28 km/sec.

INTRODUCTION

ELECTRICAL breakdown in a gas produces strong diverging shock waves. According to the hydrodynamic theory of spark channel broadening, the velocity of the broadening is equal to the velocity of the shock wave if the shock wave intensity is sufficient to ionize the gas. [1,2]

The velocity of broadening of the spark channel has been investigated experimentally by several authors. The measured velocities at initially atmospheric pressure have been found to be 2—4 km/sec for free cylindrical broadening of the spark channel. [3,4] Over a small base-line, of the order of 30 μ, i.e., at the very beginning of the formation of the discharge, a velocity up to 80 km/sec has been observed, [5] but the opinion has been expressed [6] that in these experiments it was the phase velocity of streamer formation that was determined, and not the hydrodynamic velocity of a shock wave.

Under normal conditions of free-space breakdown in a gas the pressure and temperature inside the spark channel decrease steeply on broadening of the channel, mainly due to the reduction of the average current density in the channel cross section. In the present work an attempt was made to increase the shock wave velocity by restricting the discharge in one dimension, this being achieved by producing breakdown in a slit-like gap between two parallel nonconducting plates.

EXPERIMENT

The experiments were carried out at current-rise rates of up to 2×10^{11} A/sec. A battery of capacitors with a total capacitance of 14.4 μF charged to 10 kV was used. The circuit inductance, mainly due to the inductance of the discharge and the commutator-discharger, was 5×10^{-8} H.

The gap construction is shown in Fig. 1. Electrodes 1 made of foil of thickness equal to the required gap were placed between transparent side jaws 2 and the whole was gripped tightly between two clamps. To ensure that the channel broadened along one direction a restricting plate 4 was placed in the slit, as shown in Fig. 1. The assembled gap was placed in a hermetically sealed chamber filled with the test gas. When the electrodes were exactly parallel breakdown occurred as a rule simultaneously at several points along the gap. To avoid this undesirable phenomenon the electrodes were placed at a small angle to one another or a thin wire 3 was stretched between the electrodes in order to locate the breakdown point. Control experiments showed that this arrangement had little influence on the velocity of broadening of the spark channel.

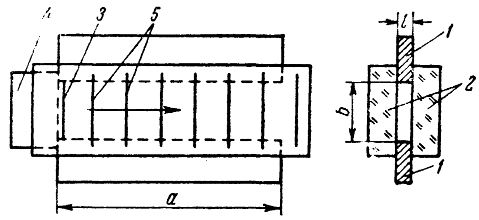

FIG. 1. Construction of the gap: 1) metal electrodes; 2) transparent side jaws; 3) wire for location of the breakdown spot; 4) restricting plate; 5) scale marks. Typical dimensions: a = 20 mm; b = 5 mm; l = 0.2 mm.

The influence of electrodynamic forces on the broadening of the spark channel in these experiments could be neglected because of the relative smallness of these forces compared with the pressure in the discharge plasma. Moreover the position of the return conductor prevented the appearance of electrodynamic forces along the direction of motion of the shock wave. The absence of electrodynamic acceleration of the discharge plasma was also confirmed by the symmetrical broadening of the channel during formation of a discharge in the middle part of the gap (cf. Fig. 6 below).

Measurements of the shock-wave front velocity along the direction shown by the arrow in Fig. 1

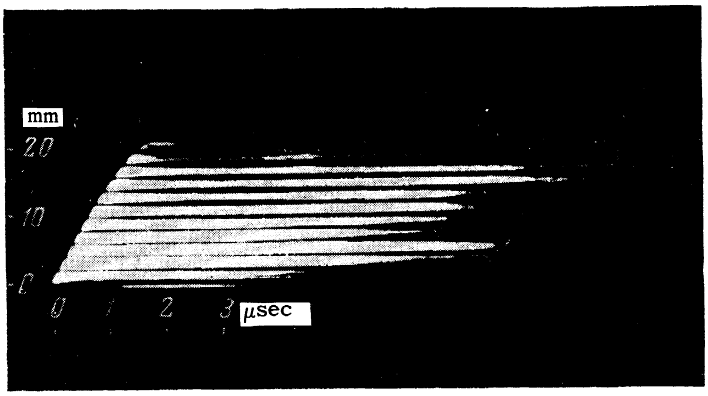

FIG. 2. Photochronogram of a discharge in air at a a pressure of 1 atm. The scale marks are given every 2 mm; $dJ/dt = 1.6 \times 10^{11}$ A/sec.

were carried out using an optical photochronograph with a rotating mirror and a scanning rate of 4.5 mm/μsec. Measurements were carried out over a base-line of 10—20 mm. A chronogram obtained in air at $p_0 = 1$ atm, $l = 0.2$ mm, b = 5 mm, $dJ/dt = 1.6 \times 10^{11}$ A/sec is shown in Fig. 2. The reproducibility of the results for the velocity of broadening of the spark channel was within ±5%.

Figure 3 shows the velocity of broadening of the spark channel in air at atmospheric pressure as a function of the gap width (the dimension l in Fig. 1). A reduction of the gap width down to $l \approx 0.2$ mm increases the current density and shock-wave velocity. Further reduction of the gap width has little influence. Reduction of the separation between the electrodes (b in Fig. 1) from 10 to 2 mm with the gap width unaltered had little effect on the velocity, producing an increase of only about 10%.

The side jaws of the gap were made of transparent materials—glass or Plexiglas. The jaw material made no difference to the velocity. The electrode material did not affect the discharge either, indicating that the impurities entering the gas were of little importance.

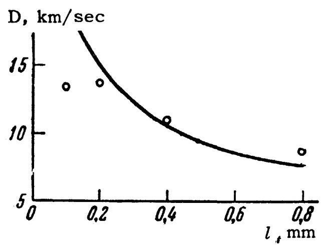

FIG. 3. Dependence of the velocity of broadening of the spark channel in air (1 atm) on the gap width; $dJ/dt = 1.6 \times 10^{11}$ A/sec.

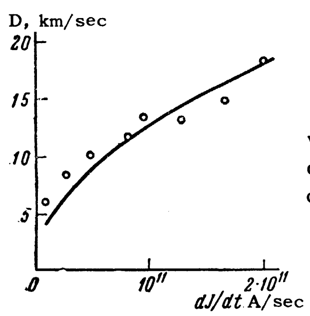

FIG. 4. Dependence of the velocity of broadening of the spark channel in air (1 atm) on the rate of current rise; $l = 0.2$ mm.

Figure 4 shows the dependence of the velocity of broadening of a spark channel in air on the rate of current rise. Figure 5 shows the dependence of the velocity of broadening on the nature of the gas in which the discharge was carried out.

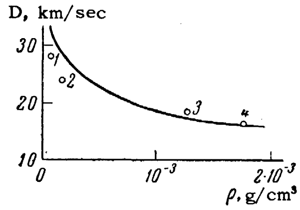

FIG. 5. Velocity of broadening of the spark channel in various gases at a pressure of 1 atm: 1) hydrogen; 2) helium; 3) air; 4) argon; $l = 0.2$ mm, $dJ/dt = 2 \times 10^{11}$ A/sec.

The maximum velocity in a gas at 1 atm for a gap of 0.2 mm width at $dJ/dt = 2 \times 10^{11}$ A/sec was 18 km/sec for air and 28 km/sec for hydrogen.

DISCUSSION

An increase of the shock-wave velocity on restriction of the discharge by means of a gap, compared with the velocity of a freely expanding discharge, is quite natural. The general observations and the results of varying the geometrical dimensions of the gap permit the conclusion that the velocity of broadening of the spark channel in a given gas is determined mainly by the current density in the discharge cross section. Assuming that the total current in the discharge increases linearly (not more than ¼ of the discharge period was used) the current density in the gap is approximately constant in time:

$$\frac{J}{S} = \frac{dJ}{dt}\frac{t}{lDt} \approx \text{const}.$$

For cylindrical expansion with a constant velocity $J/S \approx 1/t$, i.e., the current density decreases with time.

In the initial experiments there was doubt whether the observed velocity of motion of the glow boundary is indeed the velocity of the shock-wave front, and not the phase velocity of propagation of a breakdown along the gap, which is not related hy-

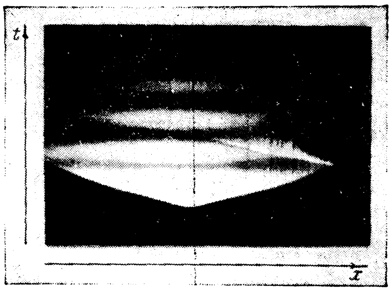

FIG. 6. Photochronogram of a discharge in the middle of a gap and the reflection of a shock wave from the closed end of the gap (t is the time, x is the distance along the gap).

drodynamically to the gas motion. Confirmation of the fact that it is indeed the shock wave that is being recorded can be seen in Fig. 6, which shows clearly the reflection of the shock wave from an obstacle placed in the gas; further proof is provided by experiments with shortened electrodes, in which the expansion of the perturbed region occurred without a high current density in the observed region. Thus for electrodes of 2 mm length along the gap and separated by 5 mm the motion of the wave front at a distance of 20 mm is practically the same as for electrodes of 20 mm length.

It was established experimentally that the velocity of expansion of the spark channel in the gap is approximately constant at the beginning of the discharge, at which time we may assume that dJ/dt = const. In this case the electrical power W (here and later all the quantities refer to unit length of the channel) supplied to the discharge increases linearly with time

$$W = \int_0^t J^2 R dt \sim \int_0^t \left(\frac{dJ}{dt}t\right)^2 \frac{\sigma dt}{lDt} = \frac{1}{2}\left(\frac{dJ}{dt}\right)^2 \frac{\sigma t^2}{lD},$$

where R and σ are respectively the total resistance and the resistivity of the discharge, and t is the time. The mass of the gas through which the shock wave has passed is equal to ρlDt. Since the energy supplied to the gas by a strong shock wave is proportional to D^2, the total energy transferred to the gas is $\approx \rho l D^3 t$. Comparing the energy supplied with that transmitted to the gas we obtain, on the assumption of zero losses,

$$D \sim (dJ/dt)^{1/2} \sigma^{1/4} t^{1/4} l^{-1/2} \rho^{-1/4}.$$

The velocity of broadening of the channel depends weakly on time and the plasma conductivity. The continuous curves in Figs. 3, 4, and 5 represent the above formula. The dependence of the velocity on the gap width becomes different for $l \lesssim 0.2$ mm. Obviously at these dimensions the radiation path length becomes comparable with the gap width.[7] which leads to a reduction of the temperature and pressure of the gas, and consequently a reduction of the shock wave velocity.

From the shock-front velocity the temperature and pressure in the spark channel can be estimated. According to Selivanov and Shlyapintokh,[8] for a shock wave with a velocity of 18 km/sec in air the temperature in energy units is 3.5 eV and the pressure is 3800 atm. For a velocity of 28 km/sec in hydrogen the temperature is ≈ 1 eV and the pressure is ≈ 300 atm. Thus a spark breakdown in a gap with large values of dJ/dt can be used to produce and study strong shock waves in gases and high-temperature high-density plasma.

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278