INVESTIGATION OF A PULSED DISCHARGE IN A HIGH-VELOCITY AIR STREAM

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We present the results of an investigation of prebreakdown phenomena in a pulsed discharge in an air stream characterized by M = 4.5, 3, 1.5, 0.5, and 0. The diagnostic data consist of high-speed photographs, oscillograms of the discharge current and voltage, and conventional photographs. It is found that a high-velocity air flow has a significant effect on prebreakdown phenomena in the discharge gap; in particular, it modifies the shape of the discharge channel. However, the electrical characteristics such as the time dependence of the current and voltage are not affected greatly by the air stream.

INTRODUCTION

A recently published paper by Alferov and Bushmin[1] points out the important effect of hypersonic air flow on the characteristics of an electrical discharge. In particular, these authors have reported new effects associated with electrical breakdown in the presence of such a flow (a significant increase in breakdown voltage and a stable luminous phase before breakdown).

In the present work we report the results of a more detailed investigation of a pulsed discharge and prebreakdown effects with and without hypersonic and subsonic air flow. This work was carried out with the apparatus described in [1].

The discharge was produced with two condenser banks; The capacitance of the first bank was 14,400 pF and that of the second 15 μF. In the first case oscillograms were taken of the current and voltage with an OK-17M oscilloscope and the discharge channel and predischarge illumination were photographed with a Zorkiĭ-6 camera at Mach numbers 4.5, 3, 1.5, 0.5, and 0. In the second case the photographs were taken with a fast movie camera (SFR-2) and the oscillograms of the current and voltage were taken with an OK-25 oscilloscope at M = 3, 1.5, 0.5, 0.05, and 0.

ELECTRICAL CIRCUIT OF THE APPARATUS

A diagram of the apparatus used to obtain the oscillograms and high-speed movie pictures of the discharge is shown in Fig. 1. The condenser bank C_2, with a total capacitance 15 μF, is charged from a high-voltage power supply. The voltage across the discharge gap 5 can be obtained directly from the condenser bank C_2 by closing switch K_1, or through the control gap 3 by opening switch K_1. In the second case the voltage is applied to the discharge gap by means of a trigger pulse from the

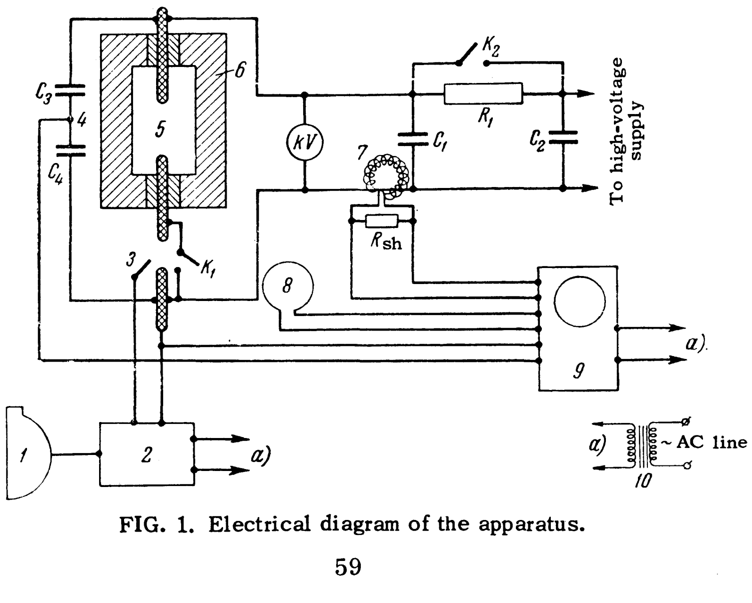

FIG. 1. Electrical diagram of the apparatus.

control panel unit 2 of the SFR-2. The high-speed movie photographs are taken with camera 1.

In investigating the discharges with the 14,400-pF bank C_1 the switch K_2 is opened and the bank C_2 is charged through the 11-MΩ, resistance R_1, at $t_{dis} \approx 0.16$ sec. The discharge current, which is measured with a Rogowski loop 7, and the voltage from the capacity divider 4, are applied to the plates of the oscilloscope 9. The oscilloscope is triggered by the derivative of the current in the circuit by means of the loop 8. The supply for the oscilloscope and the SFR camera are obtained through an isolation transformer 10 because the entire circuit is insulated from ground and from the frame of the wind tunnel 6.

PREBREAKDOWN PHENOMENA

When switch K_2 is open and switch K_1 is closed (cf. Fig. 1) a high voltage appears across the discharge gap. In the presence of a stream between the electrodes there is a violet luminescence with an intensity that increases smoothly with increasing voltage.

In Fig. 2 we show a photograph of the luminescence and of three successive discharges at $M = 3$ with a static air pressure $p_{st} = 30$ mm Hg (air density $\rho = 0.135$ kg/m^3) and a distance between electrodes $l = 3$ cm.

A comparison of the photograph of the luminescence with the flow pattern of the electrodes obtained by Alferov and Bushmin[1] shows shock waves (indicated by dark bands) on the background of the luminescence. Calculations indicate that the ratio of the air density behind the shock wave to that in front is 2. A sharp attenuation of the luminescence is associated with this discontinuity in density. In Fig. 3 we show photographs of the luminescence at $M = 0.5$, $p_{st} = 175$ mm Hg ($\rho = 0.296$ kg/m^3) and an interelectrode distance $l = 3.5$ cm. When $M = 0$ this prebreakdown luminescence is not observed.

FIG. 3. Photographs of the luminescence for $M = 0.5$, $l = 3.5$ cm and $p_{st} = 175$ mm Hg.

We have investigated prebreakdown processes in the discharge gap with switch K_1 open. The condenser bank C_1 is charged to a voltage sufficient for breakdown of both gaps, 3 and 5, without the ignition pulse. In this case, current pulses are produced in the circuit at voltages below the breakdown voltage. The oscillograph is triggered before breakdown.

In Fig. 4 we show oscillograms of the prebreakdown current and voltage pulses at $M = 4.5$, $p_{st} = 16.8$ mm Hg ($\rho = 0.135$ kg/m^3). The distance between the electrodes 3 of the gap is $d = 0.1$ cm. The pulses from the Rogowski loop and the voltage divider are applied to the input of the amplifier in the OK-17M oscilloscope. In the oscillogram one sees clearly sharp bursts in the current and voltage; these evidently trigger the oscilloscope. It should be noted that the gas does not break down in this case.

Increasing the distance between the electrodes of the discharge gap 3 weakens these pulses; increasing the density of flow enhances them. For example, with $M = 3$, $p_{st} = 30$ mm Hg, $d = 0.1$ cm the oscilloscope triggers before breakdown when $l = 2.5$ cm; with $p_{st} = 60$ mm Hg the oscilloscope triggers when $l = 1$ cm. If the distance between the electrodes of the discharge gap is increased to $d = 0.4$ cm, the oscilloscope triggers before breakdown at $p = 60$ mm Hg only when

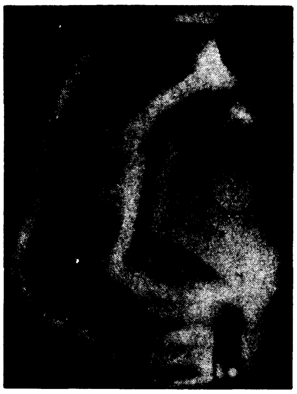

FIG. 2. Photographs of the luminescence and three successive discharges of the bank C_1 for $M = 3$, $l = 3$ cm and $p_{st} = 30$ mm Hg.

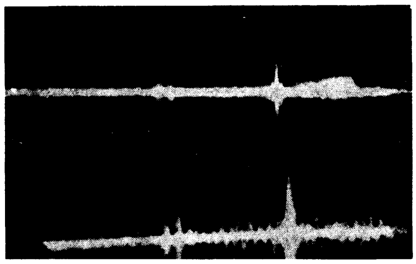

FIG. 4. Oscillogram of prebreakdown pulses of current and voltage for $M = 4.5$, $l = 2$ cm, $p_{st} = 16.8$ mm Hg. The sweep length is 10 μsec.

$l = 2.5$ cm. These effects are not observed at M = 0. If the switch K_1 is closed, the oscilloscope is triggered at breakdown.

Thus, it can be deduced that a high-velocity flow has an effect on prebreakdown processes in a discharge gap and that it produces a discharge that has not been described before in the literature.

THE INVESTIGATION OF THE DISCHARGE WITH THE 14,400 pF BANK

Photographs of the discharge channel with an air flow present indicate that the shape of the channel depends on the prebreakdown luminescence and on the velocity and density of the flow. Thus, the channel is almost straight at M = 0 but at M = 3 it is bent inward with respect to the flow (Fig. 2). As the flow density increases the curvature increases. If the breakdown occurs with switch K_1 open, as described above, the nature of the discharge is somewhat different (Fig. 5). The

FIG. 5. Photograph of the discharge for M = 3, $l = 3.5$ cm, $p_{st} = 30$ mm Hg. The upper electrode is the cathode.

channel is less curved and at breakdown there are bright, thin bands running downstream.

If the discharge is produced without a preliminary luminous phase by triggering the circuit by means of a pulse with K_1 open, breakdown occurs along a straight line even in the presence of flow. Thus, the prebreakdown phase affects the nature of breakdown under flow conditions. The channel

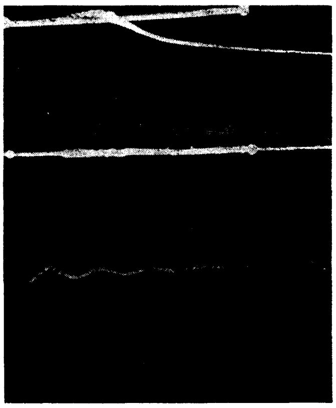

FIG. 6. Oscillograms of the current and voltage: a) M = 0, $l = 2$ cm, p = 252 mm Hg; b) M = 4.5, $l = 2$ cm, $p_{st} = 16.8$ mm Hg.

is bent because the flow removes charges that are produced before breakdown. In Fig. 6 we show oscillograms of the current and voltage taken with the OK-17M oscilloscope with a 10 μsec sweep. An analysis of the oscillograms taken with M = 4.5, 3, 1.5, 0.5, and 0 shows that the flow rate has an effect on the breakdown voltage (cf. [1]); in addition, the resistance of the discharge gap depends on the Mach number M, the flow density, and the distance between electrodes; this resistance varies from 1.5 to 4.5 Ω. Increasing M or the flow density causes the resistance to increase. The period of the characteristic oscillations of the discharge circuit is T = 1.26 μsec (L = 2.8 μH).

THE INVESTIGATION OF THE DISCHARGE WITH THE 15 μF BANK

In Fig. 7 we show oscillograms of the current and voltage taken with bank C_2 (capacitance 15 μF) for the cases M = 0 and M = 3. These oscillograms show that under these conditions the nature of the discharge is determined completely by the parameters of the discharge circuit; the discharge gap plays the role of a switch that closes the circuit. The presence of a flow only affects the breakdown voltage. In fact, an analysis of the oscillogram shows that for all modes of operation of the aerodynamic tube the ohmic resistance of the circuit [computed from the current damping R = (0.28 ± 0.04)Ω] and the measured resistance of the conductors are about the same ~ 0.28 Ω, that is to say, the effect of the resistance of the discharge gap on the discharge is small. The inductance of the circuit L = 25 μH (T = 124 μsec).

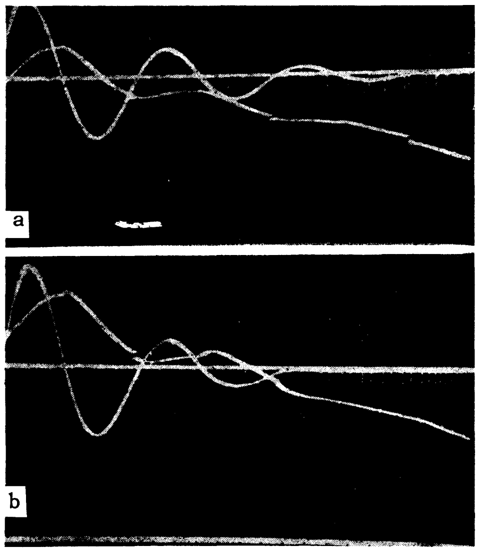

FIG. 7. Oscillograms of the current and voltage: a) M = 0; $l = 2$ cm; p = 169 mm Hg; b) M = 3, $l = 2$ cm; $p_{st} = 60$ mm Hg. The time markers are a frequency of 50 kc/sec.

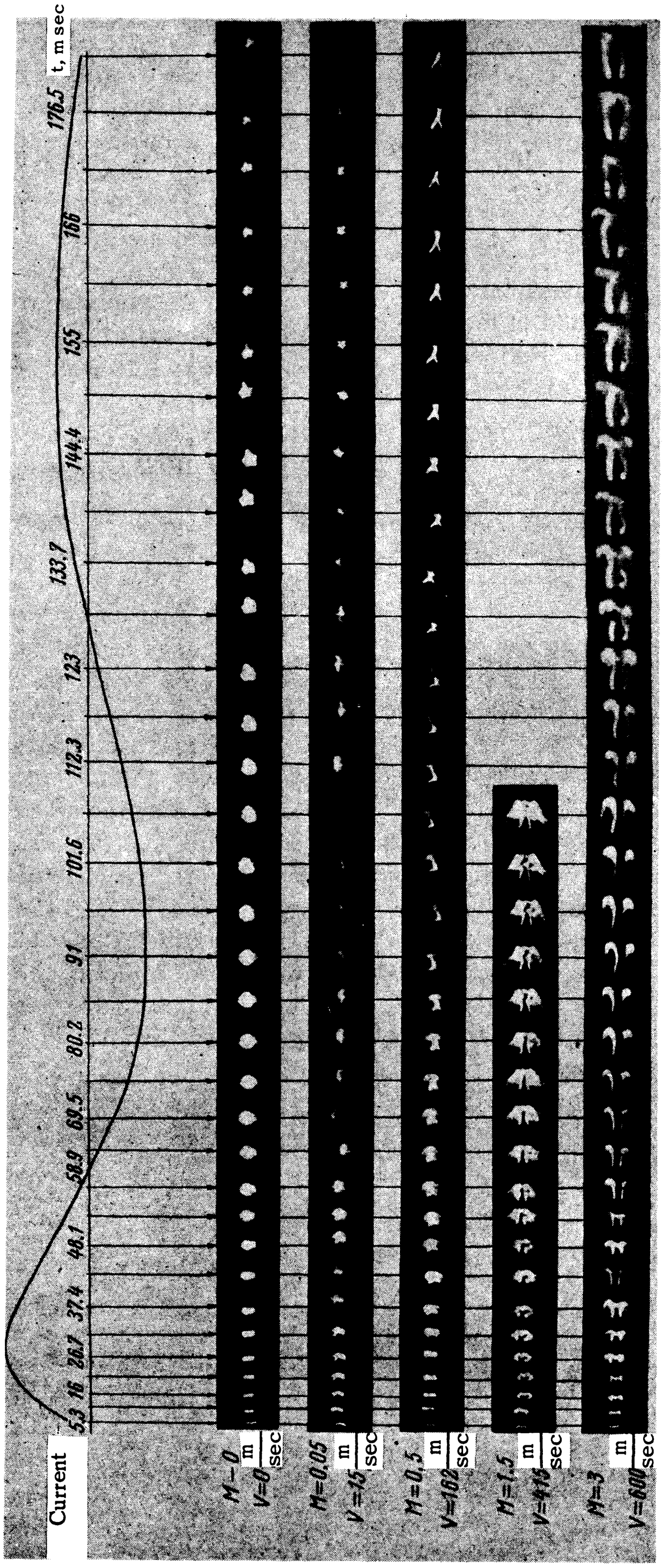

FIG. 8. High-speed photographs of a discharge at different values of M and different flow rates V. The voltage applied to the electrodes is 10 kV.

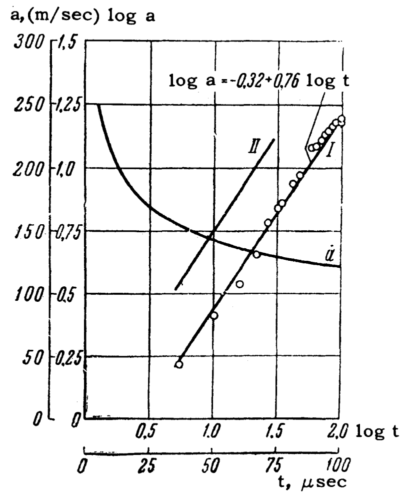

FIG. 9. The channel radius and the velocity as functions of time for M = 0; l = 2 cm; $\rho = 0.27$ kg/m^3. I) experimental dependence of log a on log t, II) the dependence of log a on log t calculated from the formula $a = 0{,}93\ \rho_0^{-1/6} J^{1/3} t^{1/2}$.

However, high-speed photographs indicate that the flow has an appreciable effect on the shape of the discharge. In Fig. 8 we show the development of the discharge for various values of M, with the distance between the electrodes l = 2 cm and the air density $\rho = 0.27$ kg/m^3. The photographs were taken with the SFR-2 at 187,000 frames per second. It is evident from Fig. 8 that the discharge starts along a straight line; the charge then drifts downstream. Measurements show that the rate of removal of the visible cloud is approximately equal to the sum of the velocity of flow and the velocity of the discharge front for M = 0.

Figure 9 shows the time dependence of the visible radius of the channel a for M = 0, l = 2 cm and $\rho = 0.27$ kg/m^3 on a log-log scale where the straight line is plotted by a least-squares technique. The dependence of radius on time can be written in the form $a = 0.48\ t^{0.76}$, where a is in millimeters and t in μsec. The velocity of the channel front $\dot{a}$ is computed as the time derivative of the radius shown in Fig. 9.

Calculation of the channel radius according to the expression $a = 0.93\ \rho_0^{-1/6} J^{1/3} t^{1/2}$ given by Braginskiĭ[2] gives values that are twice as large but with the same dependence of a on the time t (Fig. 9).

In conclusion the author wishes to thank V. I. Alferov for his valuable comments and continued interest and A. S. Bushmin, A. V. Podmazov, and V. I. Grachev for help in the experiments.

[1] V. I. Alferov and A. S. Bushmin, JETP **44**, 1775 (1963), Soviet Phys. JETP **17**, 1190 (1963).

[2] S. I. Braginskiĭ, JETP **34**, 1548 (1958), Soviet Phys. JETP **7**, 1068 (1958).

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