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EXPERIMENTAL INVESTIGATION OF THE PROPERTIES OF AN ELECTRIC DISCHARGE IN AN AIR STREAM

V. I. ALFEROV, A. S. BUSHMIN, and B. V. KALACHEV

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The results are given of an experimental investigation of an electric discharge in an air stream. The investigation was carried out in the range of flow velocities v = 0—600 m/sec in air of density $\rho = 0.127$, 0.27, and 1.29 kg/m^3. The discharge current did not exceed 5 A. The discharge assumed various forms, depending on the parameter of the air stream and of the electric circuit. The characteristics of these forms are described, as well as the conditions for the transition from one type of discharge into another.

INTRODUCTION

SOME properties of electric discharges in a gas stream have been described in the papers of Alferov and Bushmin,[1] Kalachev,[2], and Baranov and Vasil'eva.[3] The present paper reports the results of further investigations of discharges, carried out using apparatus described earlier.[1]

When a high voltage was applied to electrodes in a gas stream, at some value of the voltage (which depended on the interelectrode distance and on the gas stream parameters), a glow appeared between the electrodes. The glow was due to a discharge which we shall arbitrarily call the pre-breakdown discharge. When the voltage was increased, the pre-breakdown discharge ended with a spark discharge if there was no ballast resistance in the circuit. If the circuit did include a ballast resistance, an increase in the voltage altered the pre-breakdown discharge to a form which, when observed visually, appeared as a diffuse luminous region. We shall call the diffuse discharge.

An arc discharge subjected to a stream of gas also changed, at some flow velocity, to a diffuse discharge.

The pre-breakdown discharge was investigated using air flow velocities v = 600 m/sec (Mach number M = 3), air densities $\rho = 0.35$ and 0.54 kg/m^3, and interelectrode distances $l = 10$ and 15 mm. We recorded the current—voltage characteristics of the discharge, using an electrostatic kilovoltmeter and a milliammeter, and the current and voltage oscillograms.

To investigate the transition of an arc discharge into a diffuse discharge, observed when the flow velocity was increased, and to study the influence of the flow velocity on the nature of the burning of the diffuse discharge, we recorded oscillograms of the current and voltage, and simultaneously we photographed the discharge for $\rho = 1.29$ kg/m^3 ($l = 1.7$ mm, v = 0—130 m/sec) and $\rho = 0.27$ kg/m^3 ($l = 10$ mm, v = 50—600 m/sec).

A more detailed investigation of the diffuse discharge was carried out at v = 600 m/sec (M = 3), $\rho = 0.127$ kg/m^3, $l = 8$ mm. The oscillograms of the current and voltage were recorded, the discharge was photographed, probe measurements were carried out, and the current—voltage characteristics were obtained. The selection of the discharge and air stream parameters in the experiments was governed by the technical capabilities of the apparatus and by the need to follow the nature of the burning of the discharge in a range of air stream velocities from zero to the maximum possible velocity. In all the experiments, the current and voltage oscillograms were recorded by means of an oscillograph of the H102 type with timing marks at 500 cps. The discharge was photographed using a "Zorkiĭ-6" camera.

1. PRE-BREAKDOWN DISCHARGE

The current-voltage characteristics are given in Fig. 1. According to Fig. 1, variation in the interelectrode distance and in the air stream density had a considerable influence on the characteristics: when the interelectrode distance and the density were increased, the characteristic shifted toward higher voltages and became less steep. The current and voltage oscillograms of a pre-breakdown discharge are shown in Fig. 2. This figure shows parts of oscillograms for a voltage close to the breakdown value, where the current-voltage characteristic was very steep (cf. curve I in Fig. 1), and, therefore, the voltage was not affected when the current was altered by a considerable amount. The current fluctuated at a frequency of ~ 2000 cps.

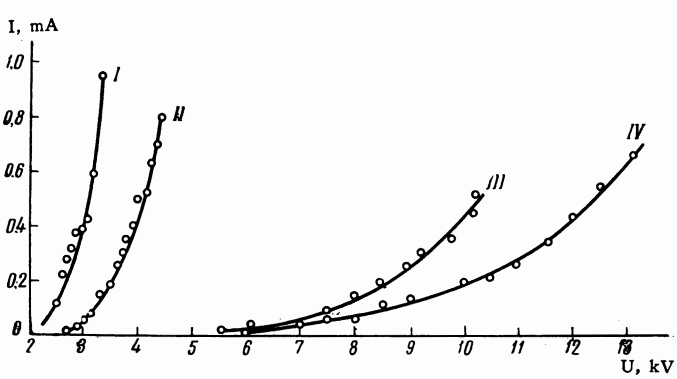

FIG. 1. Current-voltage characteristics (I in mA) of a pre-breakdown discharge. I) $l = 10$ mm, $\rho = 0.135$ kg/m^3; II) $l = 15$ mm, $\rho = 0.135$ kg/m^3; III) $l = 10$ mm, $\rho = 0.54$ kg/m^3; IV) $l = 15$ mm, $\rho \neq 0.54$ kg/m^3.

A comparison of the current-voltage characteristics, the oscillograms, and the photographs of the pre-breakdown and corona discharges gave grounds for concluding that the pre-breakdown discharge was closest to the corona discharge, as described, for example, by Kip,[4] Pollock and Cooper.[5]

2. CHANGE OF AN ARC INTO A DIFFUSE DISCHARGE

Figure 3 shows the current and voltage oscillograms and the photographs of a discharge for various air stream velocities. The air stream density was kept constant: 1.29 kg/m^3. During the experiments, the average current in the discharge circuit was measured with an ammeter and was $I_{av} = 2.5$ A. The ballast resistance in the circuit was $R_b = 1000\ \Omega$. The exposure time in the photographs was 1/500 sec.

The oscillograms and photographs show that, in the absence of air flow (v = 0), the usual arc discharge was obtained: the burning voltage was low (the voltage oscillogram in Fig. 3, frame 1 practically coincides with the zero level) and the discharge channel constricted. Under these conditions, the current and voltage did not fluctuate. In an air stream having a velocity v ≈ 7 m/sec (Fig. 3, frame 2), the arc channel remained constricted but the burning process became unsteady and proceeded as follows: the arc channel between the electrodes began to bow out, the burning voltage increased, but the current remained practically

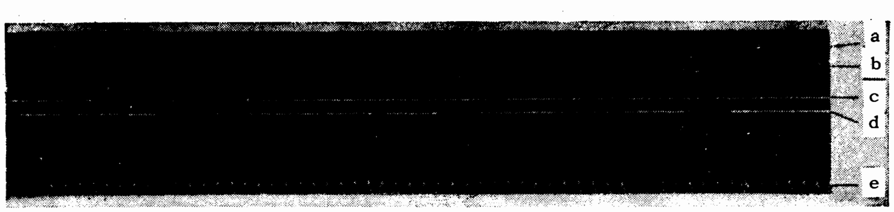

FIG. 2. Current and voltage oscillograms for a pre-breakdown discharge. $\rho = 0.135$ kg/m^3, $l = 10$ mm, M = 3. a) Voltage oscillogram; b) current oscillogram; c) zero voltage level; d) zero current level; e) timing marks. Current amplitude scale: 1 cm = 4.5 mA; voltage amplitude scale: 1 cm = 4 kV.

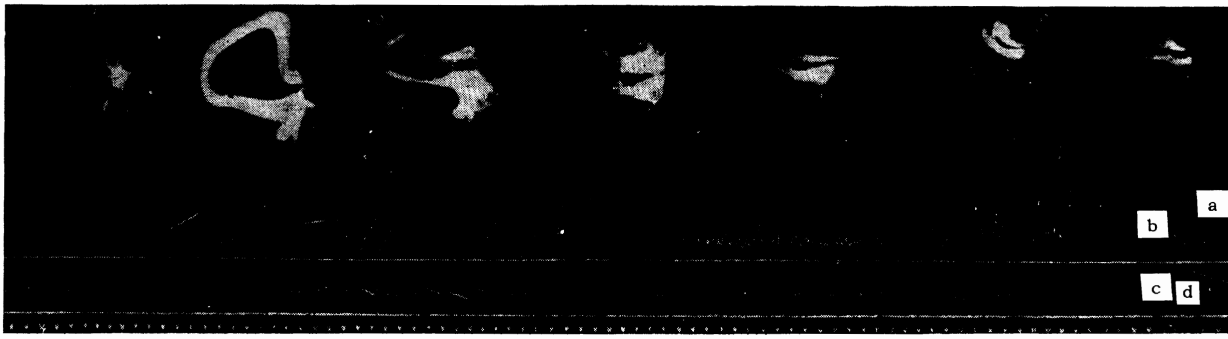

FIG. 3. Current and voltage oscillograms, and discharge photographs for various air stream velicities. $\rho = 1.29$ kg/m^3; $l = 1.7$ mm. a) Voltage oscillogram; b) zero voltage level; c) current oscillogram; d) zero current level. Current amplitude scale: 1 cm = 7.4 A; voltage amplitude scale: 1 cm = 1.32 kV.

Frame No.:	1	2	3	4	5	6	7
v, m/sec:	0	7	14	38	55	92	109

constant. At some value of the voltage (~ 800 V), the discharge gap broke down again, the voltage fell, and the newly formed channel again bowed out. The process was periodic. Similar effects have been described by Smolyakov.[6] When the stream velocity was increased, the nature of the process did not change, only the frequency of successive breakdowns increased (Fig. 3, frame 3).

However, beginning from some air stream velocity (in our case, v = 38 m/sec), the burning process of the discharge changed. The discharge channel was no longer constricted and became diffuse. This can be seen in frames 4–7 of Fig. 3. These frames show that the diffuse discharge was in the form of two luminous bands emerging from the cathode and the anode (the "cathode band" and the "anode band") without a definite channel between them. The amplitude of the voltage fluctuations about an average value decreased as the air stream velocity increased. When this velocity was v > 100 m/sec, the diffuse discharge became unstable and from time to time was extinguished (frame 7 in Fig. 3).

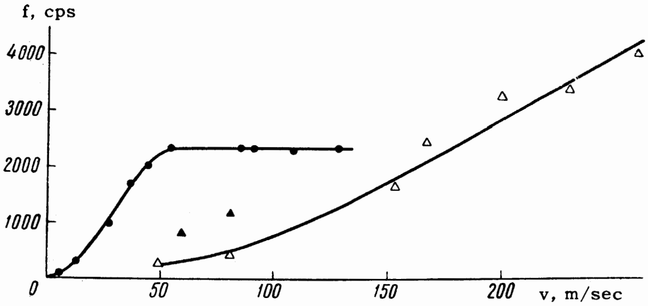

FIG. 4. Dependence of the frequency of the current and voltage fluctuations on the air stream velocity: ● – $\rho = 1.29$ kg/m^3; $l = 1.7$ mm; ▲ – $\rho = 0.14$ kg/m^3; $l = 10$ mm; Δ – $\rho = 0.27$ kg/m^3, $l = 10$ mm.

The dependence of the frequency f of fluctuations the discharge current and voltage on the air stream velocity, for $\rho = 1.29$ kg/m^3 and $l = 1.7$ mm is given in Fig. 4. The frequency of fluctuations increased with the air stream velocity but on reaching a value of ~ 2300 cps it remained constant.

Figure 5 shows the current and voltage oscillograms of a diffuse discharge for various air stream velocities and a constant air density of 0.27 kg/m^3. The average current I_{av} was 2 A and the ballast resistance was $R_b = 1000\ \Omega$. The photographic exposure was 1/250 sec.

For technical reasons, it was impossible to produce an air stream of 0.27 kg/m^3 density flowing at velocities v < 50 m/sec and, therefore, the arc discharge was not investigated under such conditions.

According to the oscillograms in Fig. 5, the diffuse discharge under these conditions was unsteady and represented a series of flashes. The repetition frequency and duration of the flashes depended on the parameters of the power supply system and on the characteristics of the discharge itself, and these characteristics depended, in their turn, on the air stream velocity.

The burning process was as follows. When a breakdown voltage (~ 5–8 kV) was applied, a diffuse discharge appeared. Since the power unit could not supply the current necessary for steady burning of the discharge at a voltage of ~1–1.5 kV (this very high burning voltage was due to the presence of an air stream), the capacitors in the rectifier filter became discharged and the diffuse discharge stopped at a voltage of ~1 kV. Then the capacitors became charged again, the voltage across the electrodes increased, the gap broke down, etc.

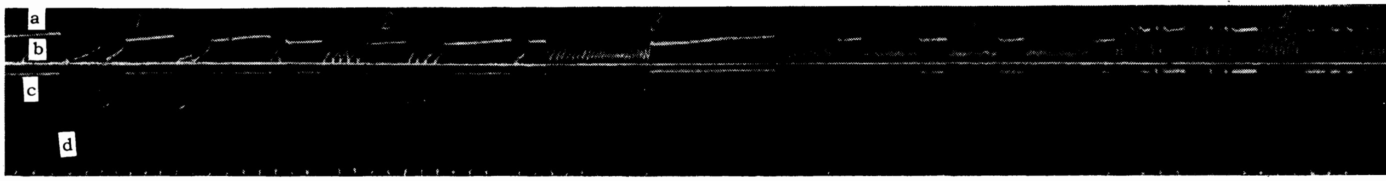

FIG. 5. Current and voltage oscillograms of a diffuse discharge for various values of the air stream velocity. ρ = 0.27 kg/m^3, l = 10 mm. a) Voltage oscillogram; b) zero voltage level; c) zero current level; d) current oscillogram. Current amplitude scale in frames 1–3: 1 cm = 9.3 A; in frames 4–5: 1 cm = 7.4 A. Voltage amplitude scale in frames 1–3: 1 cm = 19 kV; in frames 4–5: 1 cm = 15 kV.

Frame No.:	1	2	3	4	5
v, m/sec:	50	90	150	200	600

According to the oscillograms, the nature of the burning of the discharge in an air stream of 0.27 kg/m^3 density during a flash was similar to the nature of burning of a diffuse discharge in an air stream of 1.29 kg/m^3 density.

The analysis of the results obtained indicated that the velocity of the air stream affected considerably the parameters of the discharge as long as it was an arc discharge. The parameters of the diffuse discharge did not vary greatly with the air stream velocity. The only exception was the frequency of the current and voltage fluctuations during a flash. The dependence of the fluctuation frequency on the air stream velocity for ρ = 0.27 kg/m^3 and l = 10 mm is presented in Fig. 4. The latter gives two values for the fluctuation frequency for an air density of 0.14 kg/m^3 The frequency of fluctuations increased with increasing velocity of the air stream. Reduction in the air density at a fixed velocity resulted in an increase in the fluctuation frequency. A prebreakdown discharge appeared between diffuse flashes. The glow caused by this discharge was recorded in the photographs.

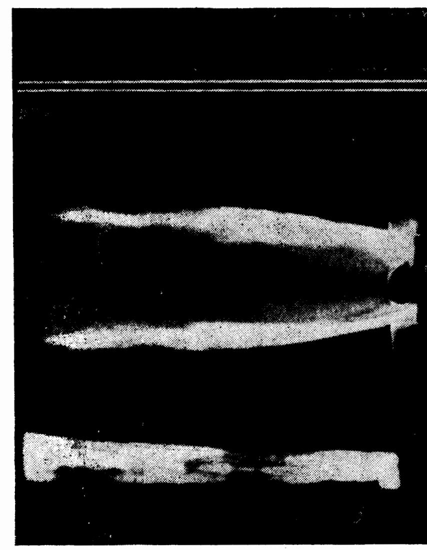

FIG. 6. Current and voltage oscillograms, and photographs of a diffuse discharge. 1) Oscillograms; 2) lateral view; 3) view from top. ρ = 0.127 kg/m^3, l = 8 mm, v = 600 m/sec. The relative positions of oscillograms are the same as in Fig. 5. Current amplitude scale: 1 cm = 7.4; voltage amplitude scale: 1 cm = 8 kV.

3. STEADY DIFFUSE DISCHARGE IN A STREAM OF v = 600 m/sec (M = 3) VELOCITY

A steady discharge was obtained for ρ = 0.127 kg/m^3, $I_{av} \geq 1.6$ A, R_b = 1000 Ω, l = 8 mm (for smaller values of l, the velocity field in the discharge zone became considerably distorted). The current and voltage oscillograms and the photographs of the discharge (exposure time 1/500 sec) for these conditions are given in Fig. 6. The photographs given in this figure and the oscillograms were recorded for I_{av} = 2.5 A.

The current-voltage characteristic of the steady diffuse discharge, obtained from an analysis of the oscillograms, was horizontal for the investigated range of currents (1.6–5.1 A). The striking voltage of the discharge was 1.3 kV, which was considerably higher than the striking voltage of the arc discharge.

The current-voltage characteristics of the discharge given in [1] differed from the characteristics obtained in this experiment. The characteristics reported in [1] were recorded under unsteady diffuse discharge conditions using a kilovoltmeter and an ammeter, which indicated the average values of the current and voltage. Therefore, the measured current was lower than the current during a flash and the measured voltage was higher than the striking voltage. When the power supply was increased, the repetition frequency of the flashes increased and the value of I_{av} increased, approaching the value of the steady-discharge current, while the average value of the voltage decreased, approaching the value of the striking voltage of the steady discharge. For this

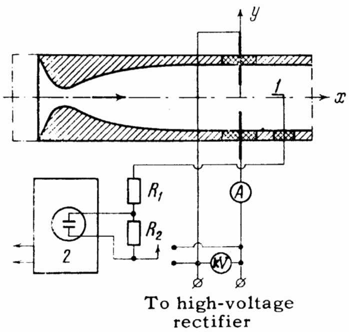

FIG. 7. Schematic diagram of the apparatus used in probe measurements: 1) probe; 2) cathode-ray oscillograph; R_1 and R_2 are measuring resistances.

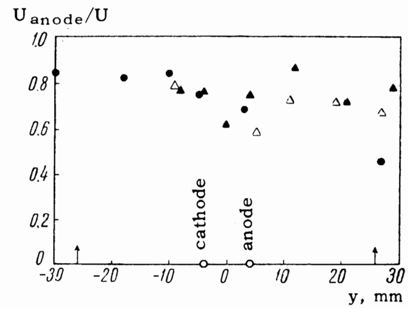

FIG. 8. Distribution of the potential in a steady diffuse discharge: ● – x = 47 mm; Δ – x = 90 mm; Δ – x = 120 mm. Arrows indicate the positions of the cathode and anode bands for $x \geq 47$ mm.

reason, the characteristics reported in [1] were of the falling type.

The distribution of the potential in a steady diffuse discharge was investigated by means of a probe. The apparatus used is shown schematically in Fig. 7. The probe was a thin molybdenum wire, 0.2 mm in diameter and 8 mm long, protruding from a porcelain tube of 2 mm diameter; the probe was placed in the diffuse discharge region, parallel to the air flow direction, and was moved in the xy plane (cf. Fig. 7). We measured the voltage drop across a high resistance (7.4 MΩ), connected between the probe and one of the electrodes. The voltage was measured with a cathode-ray oscillograph, the image on whose screen was photographed. For each position of the probe, we measured the voltage between the probe and the anode, U_{anode}, as well as the voltage between the probe and the cathode, $U_{cathode}$. At the same time, we measured the voltage U between the electrodes, which remained constant during these experiments. In air analysis, we used only those measurements for which $U_{anode} + U_{cathode} \approx U$.

Figure 8 shows the values of U_{anode}/U for various coordinates x and y of the probe. The distribution of potential found in this way showed that the potential in the anode and cathode bands, even at distances x = 50 mm from the electrode, had values which differed considerably from the anode and cathode potentials (otherwise the ratio U_{anode}/U would have varied from 0 to 1 when the probe was moved from the anode to the cathode band).

CONCLUSIONS

1. From the investigations carried out, we may conclude that several forms of discharge may exist in an air stream, depending on the parameters of the air stream and the parameters of the electric circuit: a pre-breakdown discharge, a spark discharge, an unsteady arc and a diffuse discharge.

2. The pre-breakdown discharge appears when a sufficiently high voltage is applied to the electrodes placed in a stream of air. The characteristics of this discharge are similar to those of the corona discharge. The pre-breakdown discharge ends either with a spark discharge or changes to a diffuse discharge.

3. At low air stream velocities, an arc discharge with a constricted channel is observed. The burning process is unsteady. The arc is formed between the electrodes and is gradually bowed out by the air stream, and this is accompanied by an increase in the striking voltage at a constant discharge current. Breakdown takes place at some value of the voltage, a new channel appears between the electrodes, and is accompanied by a sharp drop in voltage. The process is periodic. The frequency of the process increases as the air stream velocity rises.

4. As the air stream velocity increases, the unsteady arc discharge changes, under certain conditions, to a diffuse discharge exhibiting the following differences from the known forms of discharge: the topological shape of the discharge channel is in the form of two branches which are not closed by a clearly defined region; the relationship between the discharge voltage and current differs from the known relationships by higher values of the voltage; the current and voltage during the discharge exhibit high-frequency (of the order of several kilocycles) fluctuations.

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151