THEORETICAL AND EXPERIMENTAL STUDY OF MECHANISMS GOVERNING THE OCCURRENCE OF ELECTRIC DISCHARGES IN GASES

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Abstract

Some mechanisms governing the occurrence of electric discharges in air at atmospheric pressure have been analyzed theoretically and demonstrated experimentally. It has been shown that several electron avalanches can be simultaneously and randomly initiated on the active surface of the cathode; at the same time, the plasma ions can cause additional avalanches both on the cathode surface and in the gap.

Keywords: plasma, electron, ion, avalanche, homogeneity

1.Introduction

Electric discharges in gases have found wide application in various fields of physics [1–5] and engineering [6–10]; however, some problems of ignition, plasma formation, plasma homogeneity or heterogeneity, energy transformation and energy balance, etc. remain open. The concept of electric discharge in gases is applied in all cases where an electric current flows through a gaseous medium. To provide the electric current circulation through a gaseous medium, it should be subjected to ionization using any effective method. Electric discharges in gases can be produced for a wide range of pressures, while the current can be varied in very wide limits (from 10^{-8} to 10^{6} A and even higher). Electric discharges in gases can be of two types: stationary and nonstationary; both exist for a very short time.

An important role in electric discharges in gases is played by the parameters of the circuit of loading and unloading of the current pulse generator, because even the gap formed by the electrodes in which the plasma arises is part of this electric circuit.

At present, electric discharges are divided into three distinct types as follows [5]:
(i) Townsend discharge, or dark discharge (discharge current $I < 10^{-8}$ A);
(ii) glow discharge ($I \sim 10^{-6}–10^{-1}$ A);
(iii) arc discharge ($I > 10^{-1}$ A).

The dark discharge current is very low; therefore, it is difficult to register it. A dark discharge is nonstationary; that is, a current does not cause ionization capable of maintaining the discharge; therefore, it is necessary to affect the medium of the gap with an external ionizing agent, such as UV radiation, X-rays, laser radiation, or other types of actions capable of ionizing the working medium.

With an increase in the potential difference applied to the gap and at low pressures of the active gaseous medium, a dark discharge is transformed into a glow discharge at which the diffuse illumination of a color that is characteristic of the used gas (or gas mixture) is observed, while an electric current up to a few milliamperes circulates in the working medium.

The gas pressure on the order of atmospheric pressure and a low external circuit resistance provide conditions for the transition to an arc discharge. The current is a function of parameters of the external discharge circuit.

The initial structure of the plasma formed in the gap in the case of electric discharges is determined by the breakdown voltage.

The breakdown voltage is considered to be a potential difference applied to the gap in a gaseous medium, an increase in which provides a self-discharge in the gas. This quantity is a function of properties of the electrode material, the medium in which the discharge occurs, and the size of the gap.

2. Theoretical Analysis of the Conditions for Electric Discharge Ignition in Gases

Let two electrodes be arranged in a given volume of a gas to form a gap with size L and a constant-value potential difference U be applied to the gap. The appearance of free electrons and ions in the gap is caused by the action of an external agent and by the action of an electric field with intensity E. In this case, they receive a certain amount of energy exceeding the ionization potential of the neutral particles. Under these conditions of action of external energy sources and application of electric fields to the gap, the following was found [4]:

—In the gas, only one type of singly charged ions can appear, and the ion concentration is so small that the number thereof remains constant in time owing to recombination.

—The rate of occurrence of electron–ion pairs caused by an external ionizer in the entire volume is also a constant quantity.

—The pressure in the gap (L) has such a value that both the free path of electrons and the transmission of the kinetic momentum and energy are much smaller than the gap size $\lambda<<L$.

—The drift velocity of electrons and ions is directly proportional to the intensity of the local electric field expressed by the relationships [4]

$$v_e(x) = \mu_e E(x);$$

$$v_i(x) = \mu_i E(x) \tag{1}$$

where μ_e and μ_i represent the mobility of electrons and ions.

The mobility of electrons and ions can be expressed in terms of collision frequency through the following relationships [4]:

$$\mu_e = \frac{e}{m_e \nu_{e0}};$$

$$\mu_i = \frac{e}{m_i \nu_{i0}} \tag{2}$$

The distribution function of electrons with respect to energy is determined by the intensity of the local electric field. For a small degree of ionization of the plasma, the electron distribution function in any gas is determined by the ratio of the intensity of the local electric field ($E(x)$) and the neutral particle concentration (N) through the relationship: $\frac{E(x)}{N}$. Depending on the $\frac{E(x)}{N}$ parameter and ionization frequency, the rate of increase in electrons and ions owing to collisional ionization is determined through the relationships [4]

$$\frac{\partial n_e}{\partial t} = S + v_i n_e - \frac{\partial}{\partial x}[\mu_e n_e E(x)] \tag{3}$$

$$\frac{\partial n_i}{\partial t} = S + v_i n_e + \frac{\partial}{\partial x}[\mu_i n_i E(x)] \tag{4}$$

where v_i is the ionization frequency that, in the case of collision with a molecule or an atom in the working medium, gives rise to an electron at a point in space per second.

Conditions for electric discharge ignition in gaseous environments depend on both the potential difference applied to the gap and the free path of electrons and ions. In the case of motion of electrons in gaseous environments, they collide with molecules or atoms of the gas and cause the formation of free electrons. This process is characterized by the first Townsend coefficient [3]:

$$\alpha = \frac{v_i}{v_e} \tag{5}$$

It characterizes the number of electrons that form a free electron in the working medium at a distance of 1 cm in the path while moving in the opposite direction to the electric field with intensity *E*.

If we take into account that the electrons are initially emitted from the cathode and move to the anode, then the following boundary conditions can be established for this situation [3]:

at the cathode ($x = 0$): $\gamma_i j_i(0) = j_e(0)$; $\quad j_e = en_e v_e$

at the anode ($x = L$): $j_i(L) = 0$. $\quad j_i = en_i v_i$ (6)

Plasma ions in collision with the cathode can cause secondary electron emission. To take this fact into account, the second Townsend coefficient γ_i is used; its values lie in a range of $\gamma_i = 10^{-4} - 10^{-1}$.

The electron and ion current density varies depending on the area of the gap with respect to the origin of coordinates and can be expressed by the relationships [3]

$$\begin{cases} \dfrac{\partial j_e}{\partial x} = eL + \alpha j_e; \\ -\dfrac{\partial j_i}{\partial x} = eL + \alpha j_i, \end{cases} \tag{7}$$

The total density of electron and ion currents in the gap is constant and described by the equation [3]

$$j = j_e + j_i = const \,. \tag{8}$$

Taking into account the intensity of the electric field applied to the gap and the variation in the size thereof in accordance with the Townsend breakdown criterion, we can determine the breakdown voltage in the gap for a gaseous medium through the relationship [3]

$$Ubr = \int_0^L E(x)dx \tag{9}$$

Considering equation (9), we can write the following equation [3]:

$$\gamma_i \exp \int_0^L \alpha[E(x)]dx = 1 + \gamma_i \tag{10}$$

The condition given by equation (10) can be achieved only if the gap size (*L*) is smaller than the Debye radius [3]:

$$L < \left(W / 4\pi n_e e^2\right)^{-1/2} \equiv r_D \tag{11}$$

Based on relations (10) and (11), in accordance with [4], we can write

$$\gamma_i \exp \alpha \left[U_{str} / L\right] L = 1 + \gamma_i \, . \tag{12}$$

Executing the required transformations, we obtain the following expression for the first Townsend coefficient [3]:

$$\alpha = \frac{2N}{v_e} \int_{\varphi}^{\infty} f(W) \sigma_i(W) \left(\frac{W}{m}\right)^{1/2} dW \, , \tag{13}$$

where *f(W)* is the energy distribution function, $\sigma_i(W)$ is the ionization section of the gas molecules, φ is the ionization potential of the gas molecules, and *N* is the total number of particles in the gap. The *f(W)* and v_e quantities are determined by the $\frac{E}{N}$ ratio.

Taking into account relations (10), (12), and (13) and executing the required transformations according to [3], we obtain

$$\frac{\alpha}{N} = \psi\left(\frac{E}{N}\right) . \tag{14}$$

The last equation is in a good agreement with the Paschen similarity rule, according to which the breakdown voltage is determined by the product of the gas pressure (which expresses the density of neutral particles *N*) by the discharge gap length $P \cdot L$.

Dependence $\psi\left(\frac{E}{N}\right)$ as a function of $U_{br}(NL)$ takes the form [3]

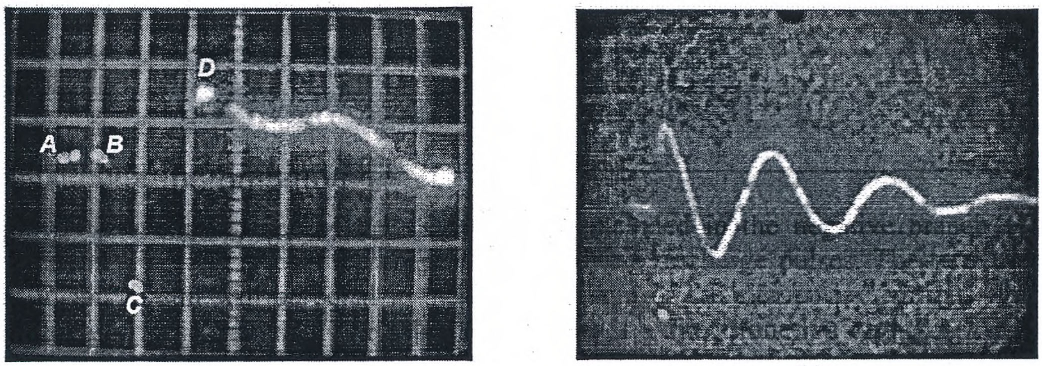
$$\psi\left(\frac{E}{N}\right) = A \exp\left(-\frac{BN}{E}\right) . \tag{15}$$

Here, *A* and *B* are empiric constants.

3. Experimental Analysis

The mechanisms governing the occurrence of electric discharges in gases were determined as in the case of classical schemes with the release of the energy stored in a bank of capacitors into the gap with a gaseous medium formed by two electrodes. The experimental installation, the circuit of which is shown in [11–13], consists of the following elements: a DC power source at a voltage of $U = 25$ kV, a circuit-breaker CB, a bank of capacitors (C), a ballast resistor R, a tool electrode, and a workpiece. With the use of a tool electrode (specifically designed), division of the discharge current occurs in a few channels. This feature facilitates the development of pulse discharges leading to high current densities and thereby to an improvement of the efficiency of consumption of the discharge energy. The interelectrode gap is $S = 5$ mm. The tool electrode composed of a large number of channels (about 800 channels/cm^2) electrically separated from each other limits the current in each channel and provides the homogeneity of the resulting plasma.

Measurement of current pulse parameters (length, shape, and amplitude value) [11] and visualization thereof are conducted using an Osc (C8-13) memory oscilloscope and a coaxial shunt with an active resistance of $R_s = 0.003\ \Omega$ [8] included in the negative branch of the discharge circuit. Figure 1 shows the shape of the resulting discharge pulses. The total current measured in this circuit will be equal to the algebraic sum of the elementary currents flowing parallel in each of these channels. The shape of the pulse is a direct function of the capacity and resistance (active, capacitive, and inductive) of the discharge circuit of the current pulse generator. The shape of pulse discharge oscillations obtained in the studies is determined by the capacitive and inductive components of the discharge circuit [11–13]; they can be modified through the construction of the electrodes and the deviation from straightness of the wires that form the discharge circuit.



(a) (b)

Fig. 1. Shape of the electric discharge pulse [11]: the scale interval along the vertical axis of 200 V/div; the scale interval along the time axis: (a) 0.1 and (b) 10 μs/div.

Under laboratory conditions, plasma was obtained using a voltage multiplier circuit (voltage pulse generator) to a potential difference of about 80 kV. Plasma was formed in an air environment at atmospheric pressure and a vacuum chamber pressure of 50 torr. Figures 1a and 1b show oscillograms of electric discharges for different scan times. The *AB* curve in Fig. 1 corresponds to autoionization (in this case, a special electrode acts as an electron gun); the *BC* curve corresponds to the basic discharge (plasma formation); and the *CD* curve corresponds to the relaxation process followed by the recharging of the bank of capacitors of the generator.

Only about 7–10% of the energy stored by the bank of capacitors of the generator is consumed for preventive ionization, while the other portion is released in the active medium which is already maximally ionized.

4. Results and Discussion

Examination of electric breakdowns in gases under the action of pulse voltage is a separate problem of physics of electric discharges in gases. It is these studies where the breakdown mechanisms were determined: Townsend and streamer.

To provide a self-discharge on electrodes placed in a gaseous environment, it is necessary to apply a potential difference, which in turn is a function of pressure and type of the gas, electrode configuration, the distance between the electrodes, the type of preventive ionization applied to the active medium, etc. A critical potential difference is considered to be a static breakdown applied to the gap (U_{br}). As the voltage applied to the gap achieves a value of breakdown voltage ($U = U_{br}$), the current that flows through the active medium abruptly increases (see the *BC* portion in Fig. 1) and visible illumination of the working medium between the electrodes is apparent owing to the fact that the resistance of the medium becomes comparable with the resistance of the external discharge circuit.

A completely different situation is observed if a pulse voltage is applied to the gap (see Fig. 1b). In this case, voltage pulses applied to the gap are much shorter than the time of development of a breakdown. In this case, the discharge occurs at voltages exceeding the static breakdown voltage. Overvoltage is characterized by coefficient K_p which represents the ratio between voltage pulse amplitude U_a and static breakdown voltage U_{br}:

$$K_p = \frac{U_a}{U_{br}} \tag{16}$$

It was experimentally found that, with an increase in coefficient K_p, the time of ignition of the discharges decreases; accordingly, in this case, pulses applied to the gap should have a voltage front with the duration on the order of a nanosecond.

At the breakdown of the gap in a gaseous medium, the active resistance decreases almost from ∞ to very low values. In [8, 9], for conditions of pulse electric discharges, it was shown that the gap resistance in the air at normal pressure decreases to 0.1 Ω; therefore, at the initial time of application of voltage U_a to the gap, the current through the active medium increases and the voltage between the electrodes decreases resulting in the ignition of a pulse electric discharge, which is a glow discharge. The transition from a glow discharge to an arc discharge is characterized by an abrupt decrease in the gap resistance and the transition from an aperiodic to oscillatory current discharge.

At a pulsed breakdown of gases, between the time of application of the voltage to the gap and the beginning of a breakdown, which is evident from an abrupt decrease in voltage, there is a time interval referred to as the delay time. The delay time is measured from the moment when the voltage achieves a breakdown value to the moment of voltage decrease to a value of 0.9 U_a. The beginning of a breakdown in gases is equivalent to a sudden decrease in voltage, while the level of the current that determines the decrease in voltage depends on the external electric circuit resistance.

The decrease in the gap voltage occurs at different stages of increase in the gap conductivity as a function of both the electric circuit resistance and different physical and chemical processes that cause an increase in the charged particle concentration. Until the beginning of ionization in the working medium between the electrodes, there must be at least one free electron; therefore, the ignition delay time for electric discharges should be decomposed into two components [3]:

(a) static delay time t_s, during which an electron capable of ionizing the gaseous medium appears in the interelectrode gap and

(b) the time of formation of a conductivity channel t_f during which a breakdown occurs owing to the development of an electronic avalanche and the intensification of ionization.

Depending on the established initial conditions, the correlation between t_s and t_f can be different. During the ionization of the active medium with an external agent, $t_s = 0$; after that, the delay time of the discharge will be determined only by the time of formation t_f. Experimental tests conducted under these conditions provide the possibility of deriving information on the ionization mechanism in the case of delay of the breakdown.

The pattern of development of a breakdown in the gap in a gaseous medium for arc electric discharges is determined by the initial number of electrons present in it at the moment of application of a potential difference. This feature is responsible for the condition of a spatial homogeneity of plasma in a direction perpendicular to the lines of force of the electric field and caused by the electronic avalanche field.

This condition can be shown through the expression for the diffusion radius of the avalanche for time τ [3]:

$$R = (4D\tau)^{1/2} \tag{17}$$

where D is the diffusion coefficient of the electrons. This coefficient is a function of the average energy; the electron mobility can be expressed in terms of the Einstein relationship [3]:

$$D = \frac{2W\mu_e}{3e} \tag{18}$$

where W is the average energy of the electrons; $\mu_e = \frac{e}{m_e\nu_e}$ is the electron mobility, m_e is the electron mass; ν_e is the electron collision frequency; and e is the electron charge.

Critical radius R_{cr} of the electronic avalanche at time τ_{cr} (time within which the intrinsic electric field becomes equal to the applied electric field) can be determined by the relationship [3]

$$R_{cr} = \left(\frac{eN_e}{E}\right)^{1/2} \tag{19}$$

where N_e is the number of electrons in the avalanche and E is the intensity of the external electric field (applied).

The number of electrons in the avalanche at time τ_{cr} is determined by the ionization in the direction of electron drift from the relationship [3]:

$$N_e = \exp(\alpha v_e \tau_{cr}) \tag{20}$$

where α is the collisional ionization coefficient, or the first Townsend coefficient and v_e is the electron drift velocity. The latter is equal to the product of the electron mobility by the intensity of the electric field applied to the gap [3]:

$$v_e = \mu_e E \tag{21}$$

Executing the necessary transformations, from relationships (19)–(21), we obtain the following expression for the critical radius of the electronic avalanche [3]:

$$R_{cr} = \left[\frac{8}{3}\frac{W}{\alpha eE}\ln N_e\right]^{1/2} \tag{22}$$

Using equation (22), we can write the condition for the minimum spatially homogeneous electron concentration required for the breakdown in the gaseous medium in the gap [3]:

$$n_e > (2R_{cr})^{-3} = \left(\frac{3}{32}\frac{\alpha eE}{W}\right)^{3/2}\left(\ln\frac{ER_{cr}^2}{e}\right)^{-3/2} \tag{23}$$

Depending on the type and pressure of the gas, the calculations conducted using relationship (23) show that the initial electron concentration required for the breakdown of the gap is as follows: $n_e > (10^4 – 10^6)\ \text{cm}^{-3}$.

Another condition for spatial homogeneity of the plasma at the time of breakdown of the gap is the rapid emergence of electrons in regions that they have left and the movement of these electrons towards the anode. If this condition is not fulfilled for the time interval of $\frac{L}{v_e}$, then the electron concentration in the volume of the gas in the gap will be at a level of background and a breakdown will not occur outside the dielectric medium between the electrodes.

An important contribution will come to the reproduction of electrons in the space between the electrodes from the secondary ionization caused by the electron emission as a result of ion bombardment of the cathode and the photoionization of the gas under the action of the intrinsic emission of plasma.

To meet the condition of complete compensation of the number of electrons moving to the anode, it is necessary to fulfill the following condition [3]:

$$\gamma_i \exp\left(\int_0^L \alpha dx\right) > 1, \tag{24}$$

where L is the distance between the electrodes and γ_i is the second Townsend coefficient that takes into account secondary electron emission.

During the development of a breakdown of the working medium (i.e., in the case where the electric field in the interelectrode gap is strongly distorted), with allowance for relationship (24) and the data of [3], the following dependence can be found:

$$\gamma_i \exp\left(\int_0^L \alpha dx\right) > \gamma_i \exp(\alpha L). \tag{25}$$

Analysis of the above reveals the following inequality:

$$\gamma_i \exp(\alpha L) > \exp(\alpha v_e \tau_{cr}) = N_e . \tag{26}$$

Taking into account relationships (19) and (23), we can deduce that

$$\gamma_i \exp(\alpha L) > \gamma_i \frac{E}{en_e^{2/3}}. \tag{27}$$

The right-hand side of inequality (27) can be determined taking into account the fact that the initial electron concentration is $n_e = 10^6$ cm^{-3}, the second Townsend ionization coefficient has a value of $\gamma_i \approx 10^{-4}$, and the typical value of the electric field intensity at the time of development of the discharge is $E = 10^2\ \frac{V}{cm}$; then, according to [3], we obtain

$$\gamma_i \frac{E}{en_e^{2/3}} = 10^{13} \tag{28}$$

Thus, we can state that the main advantage of a multichannel electrode is that it, on the one hand, excludes an auxiliary preventive ionization installation and, on the other hand, determines a substantial increase in the first Townsend coefficient and an increase in the critical number of electrons in the avalanche in the case of electric discharges in an air environment at atmospheric pressure.

The time of formation of breakdown pulses is a function of the intensity of ionization of the gas in the gap at the time of development of an electronic avalanche and at later stages. This fact depends on the increase in the charged particle concentration in the gap. To correctly describe this process, collisional ionization coefficient is applied. In accordance with [3], an increase in the number of charge carriers in a single electron avalanche over time obeys the law

$$N = \exp(\alpha v_e t), \tag{29}$$

where v_e is the electron drift velocity.

In a homogeneous electric field, the emission current at the cathode can be determined by the relationship

$$i = i_{em} \frac{\exp(\alpha d)}{1 - \gamma[\exp(\alpha d) - 1]} \Rightarrow \ln \frac{i}{i_{em}} = \alpha d . \tag{30}$$

Based on the fact that the collisional ionization coefficient is a function of electric field intensity and gas pressure, in accordance with the similarity law, we can write

$$\frac{\alpha}{p} = f(\frac{E}{p});$$

$$\frac{\alpha}{p} = A \exp(-\frac{B}{E/p}). \tag{31}$$

For the air: $E/p = (36–180) \frac{V}{cm \cdot Torr}$, $A = 8.6$ (cm · Torr)$^{-1}$, $B = 254 \frac{V}{cm \cdot Torr}$; applying equation (31) we obtain $\alpha = 38$. The calculations conducted for a nitrogen working medium under the same conditions have revealed that $\alpha = 32$.

The Townsend mechanism of breakdown of an active gaseous medium assumes that the volume load of the electronic avalanche does not distort the electric field in the gap. In this case, the number of electrons in the avalanche will be lower than a critical value (N_{cr}) [3]:

$$\exp(\alpha L) < N_{cr} \tag{32}$$

Substituting values of α and L in (32) we obtain [3]

$$N_{cr} > e^{\alpha L} = e^{38 \cdot 0.5} = e^{19} \approx 1.8 \cdot 10^8$$

In this situation, it is clear that, under the studied conditions, the condition for self-discharges is also satisfied [3]:

$$\mu = \gamma_i [\exp(\alpha L) - 1] \geq 1 \tag{33}$$

The meaning of this coefficient is that the formation of a solitary avalanche as a result of secondary processes (characterized by coefficient γ_i) at the cathode gives rise to a secondary electron that acts as an initiator of a new electronic avalanche.

If these conditions are satisfied, the initial phase of the breakdown is determined by a large number of consecutive electronic avalanches and the parameter μ determines how many times greater is the number of electrons in each presiding avalanche than in the previous avalanche.

Since the avalanches were formed randomly on different portions of the active surface of the cathode (this fact is visually confirmed by electrode spots on the cathode surface [12]), this mechanism, in most cases, leads to a volumetric flow (transition) of current at the delay of the breakdown and initial moments after an abrupt decrease in voltage.

Thus, the following criteria can be established for the transition of pulse electric discharges in arc discharges:

$$\exp(\alpha L) \geq N_{cr}$$

$$\ln(N_{cr}) = 18 \div 20 . \tag{34}$$

In the case of the circuit applied in experimental research [11–13], the critical value of the number of electrons for the transition from glow discharges to arc discharges (breakdown) is $\ln(N_{cr}) \approx 30 \div 50$, which improves conditions for the development of glow discharges.

5. Conclusions

Taking into account the theoretical and experimental findings from the literature and our own results, we can make the following conclusions.

—The main role in pulse electric discharges is played by the first Townsend coefficient.

—The necessary and sufficient condition for the ignition of glow electric discharges is the critical number of electrons of $N_{cr} \leq 1.8 \cdot 10^8$.

—The circuit applied in the experimental research does not require preventive ionization of the studied environment (air) because of the increased excitation capacity owing to the special construction of the electrodes, which makes it possible to exceed the critical number of electrons described in the literature.

—The basic discharge with the formation of plasma in the used circuit occurs after the autoionization of the continuous active medium in a pulsed discharge cycle.

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