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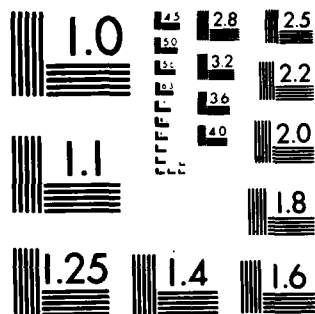
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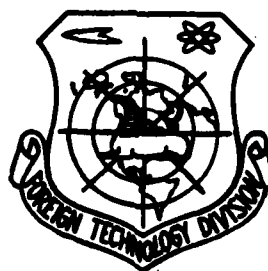
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IN GASSES UNDER HIGH PRESSURE

by

G.N. Aleksandrow



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CONCERNING VARIATIONS OF THE DISCHARGE MECHANISM IN GASSES UNDER HIGH PRESSURE

G. N. Aleksandrow

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The use of pressurized gasses in high tension apparatus and facilities, particularly those gasses with greater electrical resistance than air, e.g., SF₆, presupposes a thorough analysis of the physical processes of the gas discharge. Until now there was no practical theory of the development of discharge in pressurized gasses, so that its use in high tension technology has proceeded with caution, especially because of the well known "anomaly."

In this work an explanation is given for some well known experimental results for pressurized gasses, by analysis of the conditions for spontaneous discharge, with consideration of the photoelectric process.

1. Homogenous Field

Analysis of the causes of the variation of the discharge mechanism in gasses in a homogenous field during variation of the spark distance s and the gas density ρ , showed that the increase in the numbers of electrons in the first avalanche is a consequence of the absorption coefficients of the photons in the gas [1, 2, 3]. The condition for spontaneous discharge in this case (without consideration of photoelectric generation in the gas) is:

$$\frac{\rho}{4\pi} k_{\text{ph}}(\mu) \frac{s}{s - \eta - \mu} e^{(\rho - \eta - \mu)s} \geq 1 \quad (1)$$

- Spatial angle from which the cathode is viewed from the midpoint of the anode
- Proportionality coefficient between the number of effective photons and positive ions generated by the first avalanche
- (μ_s) Geometry factor which takes the differential degree of absorption into account, which photons move along the shortest paths in arbitrary directions within the spatial angle θ towards the cathode (numerical values in [1] and [3])
- Absorption coefficient (accumulation coefficient) of the electrons in the gas
- Spark distance
- Absorption coefficient of the photons
- Ionization coefficient
- Yield of electrons caused by photons hitting the cathode during the first avalanche

This condition can be described in the following form:

$$N_{01} = e^{(\alpha - \eta)s} = e^{\mu_s \frac{4\pi(\alpha - \eta - \mu)}{\theta \alpha k \eta x g(\mu_s)}} \quad (2)$$

N_{01} Number of electrons in the first avalanche of the spontaneous discharge.

It follows from (2) that the number of electrons N_{01} rises exponentially with increase of the product μ_s . Thus, for example, in air at normal atmospheric conditions (relative air density $\delta=1$ at $p=760$ Torr and $t=20^\circ\text{C}$) at $s_1=1\text{cm}$, $N_{01}=3.3 \cdot 10^3$ and at $s_2=3\text{cm}$ already $N_{01}=2.9 \cdot 10^5$ [1 and 3].

The increase of N_{01} with the increase of the product μ_s also leads to an increase in the number of positive ions which are left by the avalanche in the

region of the anode. At $N_{\alpha} > 1.5 \cdot 10^7$ the effect of the spatial charge of these positive ions is so great that the field strength at the anode drops to such an extent that avalanche-like ionization processes are no longer possible ($\alpha < \eta$).

At a certain distance from the anode, however, the field strength is considerably increased [1, 2, 3]. The consequence of this is that the secondary avalanches cannot extend themselves to the anode, and the centers of ionization move rapidly away from the anode and form a streamer. Therefore, in a homogenous field, the discharge develops at $\mu \leq 8$ only into an avalanche form; however, at $\mu \geq 8.5$ the discharge takes the form of a streamer. This threshold condition does not apply just to variation in spark distance, but also to variation in the gas density (e.g., increasing gas pressure at constant temperature). With increasing gas density δ , the absorption coefficient μ of the photons increases proportionately:

$$\mu = \mu_0 \delta \quad (3)$$

μ_0 Absorption coefficient at $\delta = 1$.

Since $\mu s = \mu_0 \delta s$, the gas density δ and spark distance s have an equal effect on the development of the discharge. Thus for example, at $\delta = 30$, the number of electrons in the discharge space at $s = 1 \text{ cm}$ is $N_{\alpha} = 2.9 \cdot 10^9$, as in the case of $s = 3 \text{ cm}$ under normal atmospheric conditions. Therefore, when $N_{\alpha} > 1.5 \cdot 10^7$ in both cases, the discharge is in streamer form. Therewith, the well known manifestation of variation of discharge processes independent of $p \cdot s$ has its physical explanation.

With consideration of the photoelectric processes in the gas and at the cathode, the effect of the surfaces on the breakdown pressure at a constant spark distance can be explained. According to equation (2), with increasing angle θ (the surface of the electrodes increases), the number of electrons N_{α} declines, and the breakdown pressure sinks. (In order for s to be reduced, the tension must be reduced.)

Consideration of photon absorption through the gas makes it possible to

bring into accord the theoretically and experimentally obtained dependency of the breakdown pressure on the gas density.

It is sufficiently well known that the breakdown pressures obtained in various gasses in a homogenous field at various densities ($\delta = 1$ bis 20) can give satisfactory results only with the values obtained from the Townsend equation

$$\gamma(e^{(\delta-1)\delta} - 1) = 1 \quad (4)$$

when γ varies by several orders of magnitude, which is not physically possible (when δ increases, γ becomes smaller even though the breakdown field strength increases).

Equation (1) is also satisfied for experimentally obtained values of breakdown pressure at the corresponding values for δ and γ when r_E and μ_0 remain constant. Thus, the hypothesis that grants the absorption of photons in the gas the determining role is justified.

2. Nonhomogenous Field

In strongly nonhomogenous fields, the breakdown pressures obtained are difficult to explain theoretically only if no consideration is taken of the absorption of photons in the gas. A vivid example is the "anomaly" in the curves of the breakdown pressure as a function of the gas density (Fig. 1). The maximum breakdown pressure as well as the subsequent nearing of the breakdown and starting pressures cannot be explained with the Townsend theory.

In the case of cylindrical or spherical fields, the conditions for spontaneous discharge [equation (1)] must be altered insofar as the variation of the field strength along the path of an avalanche must be calculated. If the inner electrode of a cylindrical condenser is negative, one obtains the following relationship:

$$k \eta_E \int_0^r \left[g(\mu r) e^{-\mu(r-r_0)} + \int_0^r (s-1) dr' \right] dr = 1 \quad (5)$$

- Radius of the inner electrode (where the greatest field strength is)
- Radius of the boundary of the ionization range (where $\alpha = \eta$)
- $g(\mu)$ Geometry factor, which has the same meaning as the factor $g(\mu_0)$ in equation (1) (numerical value in [5]).

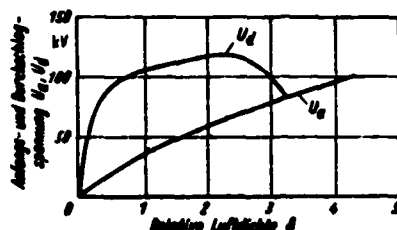


Fig. 1. Influence of density on the starting and breakdown pressures in air (after [4]).

spark set-up: positive sphere - plate
 sphere diameter 1cm
 spark distance 10cm

Key: ordinate: starting U_a and breakdown U_d pressures; abscissa: relative air pressure δ

The condition for the spontaneous discharge in that case where the inner electrode is positive has as analogous form [5], only ηx is substituted with the factor η_0 , which takes the generation of photo electrons in the gas into consideration. At the constant values $k \eta x \approx 2 \cdot 10^{-2}$, $k \eta_0 \approx 1 \cdot 10^{-2}$ and $\mu = 3.3 \cdot 10^{17} \text{ cm}^{-1}$ these conditions for spontaneous discharge agree well with the empirical equations for corona starting tension in air as a function of the radius of a cylindrical spark set-up:

$$E_0^+ = 24 \cdot \delta \cdot \left(1 + \frac{0.638}{\delta^{0.3} r_0^{0.36}} \right) \text{ in } \frac{\text{kV}}{\text{cm}} \quad (6)$$

$$E_0^- = 24 \cdot \delta \cdot \left(1 + \frac{0.62}{\delta^{0.3} r_0^{0.36}} \right) \text{ in } \frac{\text{kV}}{\text{cm}} \quad (7)$$

Equation (5) describes, analogous to equation (1), the connection between the number of electrons in the first avalanche of the spontaneous discharge and the radius of the inner electrode as well as the gas density. This is valid also

for the equation for the positive inner electrode. With a known value for the starting field strength, which can be determined either by the condition for the spontaneous discharge or by the empirical equations (6) and (7), the calculated number of electrons in the first avalanche is

$$N_{01} = e^{\int_0^{r_0} (\alpha - \gamma) dr} \quad (8)$$

The values therewith calculated for a positive cylinder with a radius r_0 in air are depicted in Fig. 2. For all adduced values of r_0 , the number of electrons increases rapidly with increasing air density. N_{01} is also a function of r_0 . The greater the radius, the broader the ionization zone is (longer avalanches). In other words, more photons are absorbed by gas on their way to the boundary of the ionization area. The most effective secondary electrons are generated at the boundary. (Longer avalanches which have the greatest number of electrons are generated.)

Just as in a homogenous field, an increase in the number of electrons N_{01} causes a greater distortion of the field in the area near the anode. At $N_{01} \geq 1.5 \cdot 10^7$ a streamer occurs as a result of the field distortion. This threshold value is depicted in Fig. 2 with a line parallel to the abscissa and is designated N_{0s} . With increasing radius r_0 , the threshold number δ_s of electrons occurs with ever decreasing density N_{0s} ; that is, the spontaneous discharge in streamer form occurs with increasing r_0 with ever less air density (Fig. 2).

At small spark distances ($\delta \approx 1 \text{ cm}$), the occurrence of a streamer immediately leads to breakdown, since the streamer bridges the entire distance between the electrodes. (The electron stream heats the streamer channel to such an extent that the discharge becomes a stream of light.) Under these conditions, the breakdown and initial pressures lie close together at $\delta = \delta_s$; however, at $\delta < \delta_s$ the breakdown tension is greater than the starting tension. The less the density δ is, the greater is the difference between the two; thus, the maximum of the curve $U_s = f(\delta)$ in Fig. 1 is also explained.

At large spark distances (or greater gas densities), the streamer effected by the initial tension does not bridge the gap between the electrodes. In order

for breakdown to occur, the greater the spark distance or gas density is, the greater the tension must be raised over that of the initial tension. Thus also, when $\delta > \delta_s$ at large spark distances, the breakdown tension is greater than that of the initial tension. If the gas pressure is raised further, the values for breakdown and initial tension approach each other. As the number of electrons N_α increases, the streamer channel is heated up by the electrons. When a certain amount of electrons moves from the streamer towards the anode ($N_\alpha \geq N_{0L} \approx 10^{10}$), the portion of the streamer channel in the region of the anode is heated to such an extent that thermoionization occurs. This enables the formation of a new streamer and the development of the discharge in a leader form [3 and 6].

The air density δ_L , at which the number of electrons is $N_\alpha = N_{0L}$, represents the upper limit of the range where $U_s \geq U_i$; that is, at $\delta \geq \delta_L$ the discharge immediately takes the form of a leader. The point of intersection of the curve $N_\alpha = f(\delta)$ with the parallel II to the abscissa (Fig. 2) represents the density δ_L . With increasing r_0 , δ_L as well as δ_s decreases; that is, the longer r_0 is, the less the density, where the curves $U_s = f(\delta)$ and $U_i = f(\delta)$ intersect, independent of the spark distance. At large spark distances at $\delta < \delta_L$ the breakthrough tension is naturally also higher than the initial tension, since very long streamers with a large amount of electrons are necessary for the development of a leader breakthrough, through which the maximum in the curves $U_s = f(\delta)$ is also limited at relatively large spark distances. It is clear that the condition $\delta_s < \delta_L$ must be satisfied; therefore, at large spark distances, the breakthrough tension drops at higher air densities than it does for short spark distances. Naturally, this comparison is valid only for equal r_0 .

It must be mentioned that the experimentally determined values of δ_L lie considerably below those to be determined in Fig. 2; however, they are still greater than δ_s . This is limited in that the number of electrons in a streamer which occurs at the initial tension is greater by an order of magnitude in the first avalanche ($\bar{N}_\alpha$) since the streamer is composed of a number of sequential avalanches. The number of electrons in a streamer therefore reaches the threshold value of N_{0L} at even low air densities.

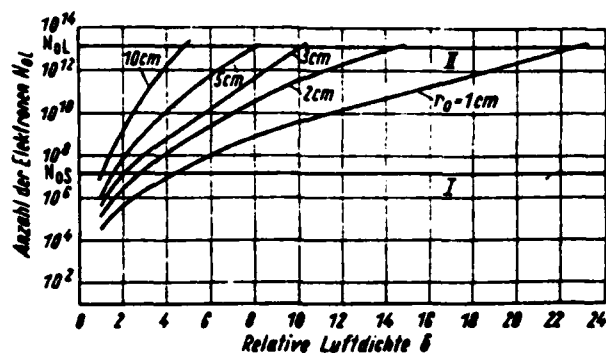


Fig. 2. Influence of air density on the number of electrons in the first avalanche of a spontaneous discharge.

Cylindrical condenser, radius of the positive inner electrode = 1; 2; 3; 5 and 10cm

- I. Minimum number of electrons of the first avalanche of a spontaneous discharge at which a streamer forms
- II. Number of electrons in a streamer that is sufficient for the formation of a leader

Key: ordinate: number of electrons N_{0L} ; abscissa: relative air density δ

During the formation of leaders at relatively large spark distances, the possibility must be considered that an electron stream can exist in a streamer channel which can lead to an elevation of the temperature in the channel. If one considers the values of absorption coefficients η created in relatively weakly ionized gasses, then in a streamer channel at $\delta = 1$ ($E_g \leq 20$ kV/cm), practically all electrons along a stretch of less than 1cm must be absorbed by neutral molecules. On the other hand, however, in many experiments with streamers with lengths of several centimeters up to more than 10cm, an electron stream can still be measured (e.g., in [7]). This can be explained only by assuming that the absorption coefficient in the streamer channel is smaller by several orders of magnitude. Indeed, the concentration of charges particles in the streamer channel (which were generated by a different ionization) is in the order of magnitude of 10^{13} cm^{-3} . Along with the ionization, there is also an excitement of neutral molecules, so that there are a great number of molecules in an excited state present in the gas (excitement energy .5 to 1 eV). When the excited molecules collide with negative ions, the latter disintegrate, and free electrons are generated [5]. If these occurrences are considered, then the Toepler theory of the creation of the spark channel from the first ionized

channel by means of the conversion of the energy of the electrical field into heat energy, as a consequence of the rapid movement of the discharge in the channel, can be applied [9]. I. Loeb offered the opinion that negative ions in gas discharges at $E/p < 90 \text{ V/cm} \cdot \text{Torr}$ cannot disintegrate. Therefore, he had to discount Toepler's hypothesis and find another mechanism which would explain the considerable elevation of the charge carrier concentration in the first ionized channel (secondary streamers and the like). Thus, the quantitative analysis of the discharge events was made impossible, and the further development of the theory of gas discharge was seriously hindered.

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