PROPAGATION MECHANISM OF AN ULTRAHIGH-FREQUENCY DISCHARGE IN AIR

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Results obtained in an experimental investigation of the propagation mechanism of an ultrahigh-frequency discharge in air are presented. The mechanism of motion of the discharge can have two stages, comprising conductive heating of the gas ahead of the leading edge of the discharge, as shown in[1], and breakdown of the heated gas. This substantially affects the discharge parameters. The relative roles of the different mechanisms depend on the gas pressure and electric field strength in the uhf wave.

A quantitative description of the motion of an ionization wavefront in strong uhf fields in air at atmospheric pressure was attempted for the first time by Raĭzer.[1] His solution was based on an analogy between the motion of an uhf discharge and the propagation of a flame in a combustible mixture. This approach, assuming equilibrium of the heating and ionization of a gas, enabled him to calculate, as functions of the power input level, both the gas temperature in the wave and the velocity of wave propagation. The calculation agrees with the experimental results in[2] when it is assumed that the ionization wave moves within a heated gas, i.e., like a flame propagating from the closed end of a tube. However, this assumption, which yields quantitative agreement between theory and experiment for power under 2000 W, does not account for the steep increase, observed in[2], of ionization wave velocity at generated power levels above 2000 W.

A very much greater discrepancy, both quantitative and qualitative, between the measured and calculated ionization wavefront velocities was obtained by the authors of[3], who investigated uhf discharges in air at pressures from 16 to 150 Torr. Unlike the procedure in[2], the discharge was excited at the frequency f = 2.4 GHz in a long glass or quartz tube positioned along the axis of a rectangular or circular waveguide. Uhf power input within the range 300–1300 W was insufficient for self-initiated breakdown of the gas in the tube. Therefore the discharge was initiated by means of a spark discharger located at the end of the tube that was distant from the uhf source.

Detailed studies of the development of a discharge and the formation of a plasma cloud indicated the existence of two stages of discharge motion with different velocities. In the initial segment the motion of the ionization front proceeds with enhanced velocity; this is associated with adiabatic expansion of the heated gas in the region of plasma cloud formation. This hypothesis is supported by the fact that the gas temperatures determined from the energy conservation equation

$$W_{\mathrm{abs}} = \rho_0 u h_{\mathrm{k}} S \qquad (1)$$

(where W_{abs} is the power absorbed by the discharge, ρ_0 is the cold gas density, u is the ionization wave velocity in the region of steady motion, h_{k} is the enthalpy of the gas in the wave, and S is the cross section of the discharge) are quite consistent with the relation between the velocities in the initial and steady-state regions of motion:

$$\frac{U}{u} = \frac{\gamma_0(\gamma_{\mathrm{k}}-1)}{\gamma_{\mathrm{k}}(\gamma_0-1)}\frac{c_{p\mathrm{k}}T_{\mathrm{k}}}{c_{p0}T_0} \qquad (2)$$

(where U is the velocity in the initial region, γ_0 and γ_{k} are the adiabatic exponents of the cold and the hot gas, c_{p0} and $c_{p\mathrm{k}}$ are the specific heats of the cold and the hot gas, T_0 is the initial gas temperature, and T_{k} is the final gas temperature). Thus, the analogy, proposed in[1], with flame propagation from the closed end of a tube is valid only for the initial stage of discharge motion. As has been shown in[3], the initial region of discharge motion is drastically shortened as the gas pressure increases; it is therefore doubtful that the data in[2] pertain to this stage of motion. Evidently, the discrepancy between the velocities calculated when assuming that the ionization wave propagates in a cold gas[1] and the velocities measured in[2] at generated uhf power ≤ 2000 W is associated primarily with the complexities involved in determining the density of electromagnetic energy flux at the plasma boundary.

An even more interesting conclusion follows from the analysis of the curves in Fig. 1 representing the velocity of the ionization wavefront as a function of the uhf power level in air at pressures of 16 and 22 Torr. According to the energy equation (1), nonlinear enhancement of the velocity with increasing power input indicates lowering of the final gas temperature in the discharge. This fact cannot be accounted for within the framework of the equilibrium theory of slow combustion. We must therefore acknowledge the existence of processes that limit the applicability of the analogy between motion of the ionization wavefront in a strong uhf field and flame propagation in slow combustion, with regard to both pressure and the level of uhf power input. It was suggested in[3] that the reason for the discrepancy between the experimental ionization wave velocities and the calculations lies in nonequilibrium of the plasma in a real discharge.

The measurements in[3] showed that at gas temperatures $T_{\mathrm{k}} \sim 2000° - 3000°$K in the discharge the electron concentration is $n_e \sim 10^{12}$ cm^{-3} and the mean electron energy is $T_{\mathrm{av}} \sim 5-10$ eV. It is the purpose of the present work to determine a concrete mechanism whereby nonequilibrium influences, especially, the velocity of the ionization wavefront.

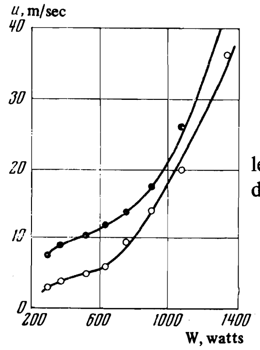

FIG. 1. Velocity of uhf discharge versus level of generated power in a tube of 20-mm diameter: ●—P = 16 Torr, ○—P = 22 Torr.

The discharge investigated in[2] at atmospheric pressure and observed in[3] at reduced pressures comprises a column oriented along the force lines of the electric field. This similarity in the forms of the discharges at different pressures and uhf power inputs suggests that atomic heat conduction plays a definite role in the motion of a discharge within the entire investigated ranges of the parameters. The main difference between the considered scheme and Raĭzer's model[1] will consist in establishing the ionization temperature T_0 corresponding to the jump of charged particle concentration, i.e., at the boundary of the region of the discharge. According to Raĭzer,[1] in the case of equilibrium heating T_0 is determined by thermal ionization of the gas. However, under the conditions of the considered experiments a different ionization mechanism is also possible. In the region of gas heated by thermal conduction ahead of the discharge front there exists an electromagnetic wave whose electric field is given by

$$E_{b.d.} = (E_{inc} + E_{reff} + 2E_{inc}E_{eff}\cos\varphi)^{1/2}, \tag{3}$$

where E_{inc} is the field strength in the incoming wave, E_{refl} is the field in the reflected wave, and φ is the phase difference between the two waves.

Taking $E_{b.d.}$ into account, it becomes obvious that equilibrium propagation of a discharge is possible only if $E_{b.d.} < E_{T_0}$, where E_{T_0} is the electric field strength required for self-initiated breakdown of a gas heated to the temperature T_0 at the ionization boundary according to[1]. When this condition is not satisfied, the propagation of the discharge can depend on breakdown of the heated gas, while the ionization temperature T_0 will depend on $E_{b.d.}$, i.e., on the uhf input of the discharge. If, furthermore, we assume, following[1], that the difference between the final temperature T_k of the gas in the discharge and the ionization temperature T_0 is as small as previously ($T_k - T_0 \ll T_0$), the velocity of the ionization wave will be determined by solving the following system of equations:

$$\begin{gathered} E_{b.d.} = f(T_e(x, y, z)\, n_e(x, y, z)\, W_{inc}), \\ W_{abs} = \rho_0 u h_k S, \quad \nu_i(T_0) = \nu_a(T_0) + D/\Lambda^2, \end{gathered} \tag{4}$$

where, in addition to the already known quantities, we have the ionization frequency ν_i, the electron attachment frequency ν_a, the electron diffusion coefficient D, and the diffusion length Λ. It must be pointed out immediately that any attempt to solve these equations rigorously will encounter great difficulties associated, first of all, with solving the electrodynamic equations that determine $E_{b.d.}$. Nevertheless, it is interesting to analyze the results obtained from the given formulation of the problem and to compare them with experiment.

We note, first, that the field required for breakdown as a function of the gas pressure for the given geometry of the discharge chamber (the Paschen curve) possesses a characteristic minimum. For air in a discharge tube of 20-mm diameter[3] we have the minimum $E_{T_0}^{min} = 200$ V/cm.[4] This means that for $E_{b.d.} \le 200$ V/cm the only mechanism of discharge motion is propagation resulting from equilibrium heating of the gas. Since only the reflection coefficient, and not the phase difference of the reflected wave, was measured in[3] it is impossible to determine $E_{b.d.}$ exactly. We can only state that it lies within limits as follows:

$$E_{b.d.}^{min} = E_n - E_0 \le E_{b.d.} \le E_n + E_0 = E_{b.d.}^{max}. \tag{4a}$$

In the entire given power range, 300 watts $\le$ W $\le$ 1300 watts, we have

$$E_{b.d.}^{min} < E_{T_0}^{min} = 200\ \text{V/cm}, \quad E_{b.d.}^{max} > E_{T_0}^{min} = 200\ \text{V/cm} \tag{4b}$$

Thus the heated gas can break down only when $E_{b.d.}$ is limited as follows: $E_{T_0} \le E_{b.d.} \le E_{b.d.}^{max}$.

If we use $E_{b.d.} = E_{b.d.}^{max}$ the theoretical velocities considerably exceed the experimental values in the entire power range. If $E_{b.d.} = E_{T_0}^{min}$, for W > 600 watts the theoretical velocities are smaller than the measured values, while for W $\lesssim$ 600 watts the theoretical velocities are larger.

Assuming that both the thermal conduction and breakdown mechanisms of motion exist, the foregoing result can be accounted for by the fact that for W $\lesssim$ 600 watts the value of $E_{b.d.}$ determined by the field strength in the incoming wave and by the phase difference in reflection is smaller than $E_{T_0}^{min}$ and the motion of the discharge is determined exclusively by thermal conduction. It is obvious that increased generated power will lead to breakdown of the gas ahead of the wavefront and, in the limit, to self-breakdown of the cold gas at antinodes of the standing wave that is formed by superposition of the incident and reflected waves.

Using the coefficient of reflection of the uhf wave from the plasma cloud (25% according to experiment), we can calculate the power limit W_{lim} for which breakdown of the cold gas occurs at antinodes of the standing wave. At 16 Torr the calculation yields $W_{lim} = 1300$ watts, which accords well with the experimental fact that for W = 1300 watts the velocity of the ionization wave cannot be measured. After a pulse is fed to the spark initiator a discharge flashes immediately throughout the entire length of the tube.

Thus the quantitative comparison of experimental results with conclusions derived from the proposed model confirms the existence of a breakdown mechanism for the development of ionization. However, because of the great ambiguity of the calculated discharge velocities, resulting from the impossibility of obtaining exact data for the phase difference in reflection, an additional experiment is needed which would confirm unambiguously the existence of breakdown ionization in the case of power exceeding ~ 600 watts, as follows from Fig. 1.

The basis of this experiment can be the influence, observed in[5], of a magnetic field on the velocity of the discharge. If the discharge moves because the gas is heated ahead of the front and subsequently breaks down, the magnetic field can influence the motion of the discharge only under the condition $H \perp E$. In this case the effective field at the boundary of the discharge, $E^{eff}_{b.d.}$ and the effective field in the plasma, E^{eff}_{pl}, will be given by

$$(E^{eff}_{b.d.,pl})^2 = E^2_{b.d.,pl}\frac{\nu^2_{b.d.,pl}+\omega^2}{2}\left(\frac{1}{\nu^2_{b.d.,pl}+(\omega-\omega_H)^2} + \frac{1}{\nu^2_{b.d.,pl}+(\omega+\omega_H)^2}\right), \quad (5)$$

where $E_{b.d.,pl}$ is the field at the boundary of the discharge or in the plasma in the absence of a magnetic field, $\nu_{b.d.,pl}$ is the effective frequency of collisions between electrons and neutrals at the boundary of the discharge or in the plasma, ω is the frequency of the generated uhf wave, and ω_H is the Larmor frequency. With increase of the magnetic field strength, because of the diminution of E^{eff}_{pl} there occurs a reduction of the energy input in the discharge and of the thermal current heating the gas ahead of the discharge front, accompanied, of course, by a lower velocity. The diminution of $E^{eff}_{b.d.}$ leads to a rise of the ionization temperature T_0 and therefore also to a reduced velocity of the discharge. Conductive heating of the gas ahead of the discharge front should not be affected by a magnetic field having any orientation. If the motion of the discharge is affected by forward diffusion of the charged particles from the region of energy release in the direction of discharge motion, this mechanism should be sensitive to the magnetic field for $u \perp H$.

To answer the questions that had been raised experiments were performed to investigate the velocity of discharge motion in a region within a uniform magnetic field having three possible orientations: 1) $H \perp E$, $H \perp u$; 2) $H \perp E$, $H \parallel u$; 3) $H \perp u$, $H \parallel E$. For this purpose we used either a transverse magnet [cases 1) and 3)], or a short section of a solenoid [case 2)] surrounding the waveguide containing the investigated discharge tube. Figure 2 shows the velocity of the discharge in a tube of 20-mm diameter at 38 Torr and W = 1000 watts as a function of the magnetic field for the case of $H \perp E$, $H \perp u$. It is here seen that for this orientation of the magnetic field the velocity of the discharge diminishes as H increases and that at the critical field H_{cr} = 4000 Oe the discharge is halted.

In the case $H \perp E$, $H \parallel u$ the discharge loses velocity similarly and is stabilized (Fig. 3). The small (not exceeding 30%) discrepancy between the respective values of H_{cr} for $H \perp E$, $H \perp u$ and $H \perp E$, $H \parallel u$ results from a difference in the geometry of the magnetic field region. The discharge velocity in the case of $H \perp E$, $H \perp u$ does not vary up to the maximum field ~ 9000 Oe reached in this experiment.

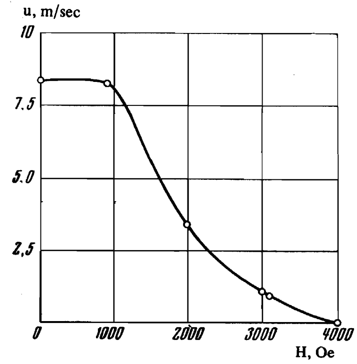

FIG. 2

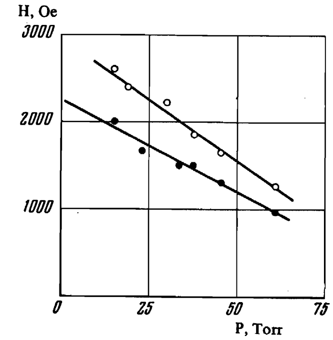

FIG. 3

FIG. 2. Velocity of uhf discharge in a tube of 20-mm diameter versus magnetic field strength; W = 1000 watts, $H \perp E$, $H \perp u$.

FIG. 3. Critical magnetic field as a function of air pressure: ○–$H \perp E$, $H \perp u$; ●–$H \perp E$, $H \parallel u$. Tube diameter 20 mm.

We note that the ambipolar diffusion coefficient in the hot gas is reduced one-half at H = 9000 Oe. This should lead to a decrease of the discharge velocity if its motion depends on electron diffusion.

The rotation of the discharge column in a circular waveguide immersed in a longitudinal magnetic field where $H \perp E$ and $H \parallel u$ constitutes evidence that a region of gas heated to a high temperature exists ahead of the discharge. It follows from [2,3] that at all pressures the discharge is oriented along the electric field lines. It is reasonable to assume that the rotation of the discharge is associated with rotation of the polarization plane of the electromagnetic wave. A plane-polarized wave propagating in a plasma along a magnetic field can be represented by the sum of two waves with left-hand and right-hand circular polarization, respectively.[6] High-speed cinematography (Fig. 4) shows that rotation of the discharge is not accompanied by a change of its shape. It can therefore be assumed that the region where the two waves exist is the region of hot gas ahead of the discharge boundary.

A change in the angle of rotation as a discharge moves through a region in a nonuniform magnetic field can be attributed to diminishing velocity as H increases. Decreasing velocity leads to increased length of the hot gas region ahead of the discharge, i.e., to increasing phase difference between the waves of different polarizations at the discharge boundary. A familiar procedure was used to determine the rotation angle of the polarization plane.[6] For the parameters of the discharge shown in Fig. 4 we obtained quite reasonable values of the electron concentrations and the requisite extent of the hot gas region ahead of the discharge front. For example, with $n = 5 \times 10^{10}$ cm^{-3} the polarization plane rotates within a length ~ 2 cm. The actual length

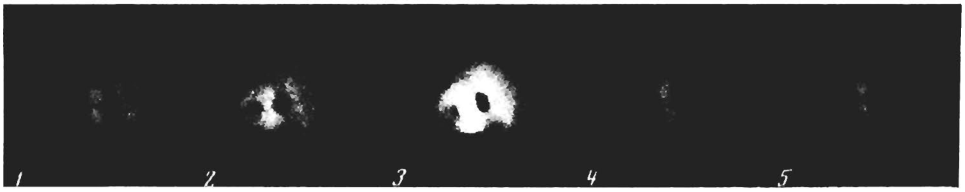

FIG. 4. Rotation of a discharge moving through a magnetic field region.

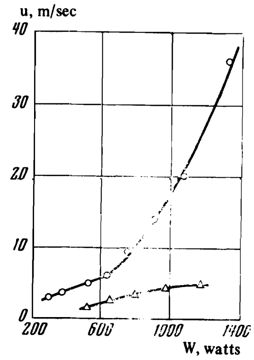

FIG. 5. Velocity of uhf discharge *versus* generated power level in tubes of different diameters at P = 22 Torr: O–ϕ 20 mm, Δ–ϕ 6.5 mm.

l of the heated gas region ahead of the discharge front was of the order of 3 cm. This was estimated using the formula $l = a/u_H$, where a is the thermal conduction coefficient and u_H is the discharge velocity in the magnetic field.

In addition to applying a magnetic field, another experiment was possible, in which at an already investigated gas pressure and generated power level the influence of the breakdown mechanism of ionization can be excluded. We calculated the diameter of the tube where $E_{T_0}^{min} > E_{b.d.}^{max}$ for all the available values of the power; this tube diameter was found to be 6.5 mm. Figure 5 shows the measured velocities of discharges in tubes of 20-mm and 6.5-mm diameter at 22 Torr. The absence of any bend in the curve for the 6.5-mm diameter shows that the breakdown mechanism of ionization was suppressed in accordance with the proposed model of discharge motion for $E_{T_0}^{min} < E_{b.d.}$.

Thus the experiments with a magnetic field and tubes of different diameters confirmed the hypothesis that the mechanism of uhf discharge motion can have two stages consisting in conductive heating of the gas ahead of the discharge front and subsequent breakdown. The respective roles of the two processes depend primarily on the gas pressure and the electric field strength. Even at high pressures the breakdown mechanism can prevail if the field strength of the incoming wave is high enough. An estimate of the region where the breakdown mechanism existed in the experiments of[2] at atmospheric pressure showed that gas breakdown at the discharge boundary is possible with W ~ 2000 watts. In precisely this region a steep rise of discharge velocity is observed with the increase of incoming power.

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