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DYNAMICS OF A MICROWAVE DISCHARGE IN A HIGH-PRESSURE MOLECULAR GAS

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1. A high-frequency discharge in a dense gas ($\nu_e > \omega$) and subthreshold field is formed in two stages. Initially, a non-self-consistent discharge initiated by an external ionization source is excited. The ionization-superheating instability being developed in it transfers it into the self-consistent mode. The same stages govern transport breakdown in the gas, i.e., the formation of ionization waves. A non-self-consistent discharge in unperturbed gas domains is associated here with energy transport from the steady-state discharge domain [1-3]. The self-consistent discharge goes over into the mode in the nonlinear stage of ionization-superheating instability, in its saturation stage. Consequently, analysis of this stage permits estimation of the steady-state discharge parameters and its space—time configuration.

The nonlinear stage of the ionization-superheating instability is characterized by the fact that the exponential growth of the plasma density is replaced by explosive, and under these conditions particle and heat diffusion does not stabilize the instability [4]. Here the evolution of the perturbation in the nonlinear mode is kept in mind with the exacerbation [5-7] in which instability development in the dissipative system results in diminution of the space and time scales of the parameter distribution.

In this stage, the equation [4]

$$\partial P/\partial t = \partial^2 P/\partial x^2 + f(P) \tag{1.1}$$

follows under sufficiently general assumptions on gas and plasma parameter evolution [f(P) is a nonlinear function of the parameter P). It can be shown that under gas breakdown conditions in a subthreshold microwave field under sufficiently general assumptions $f(P) = P^\alpha$ ($\alpha > 1$). Then a simple analysis of the dimensionality of the equation permits estimation of the space Δx and time Δt scales of the distribution $\Delta t \sim P^{-(\alpha-1)}$, $\Delta x \sim P^{-(\alpha-1)/2}$, from which there results that the instability is not saturated in the nonlinear mode while the perturbation collapses.

The analysis presented does not take into account that electromagnetic field interaction with a plasma is characterized by proper spatial scales, the skin layer λ and the field energy absorption length $1/\mu$. Since $\lambda \lesssim 1/\mu$, the skin-layer corresponds to the dimension of the effective field interaction with the plasma. Such a scale asymptotically governs the system behavior by subordinating itself to space—time scales of nonlinear diffusion processes.

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The consistent space and time scales of a nonlinear mode with exacerbation are such that this mode is accompanied by an explosive growth of the perturbation. The appearance of a new scale λ in the system, whose change is not determined by the nonlinear "diffusion" equation and which is not self-consistent in this sense, should result in a scale competition effect. As a result of parameter evolution the scale of variation changes with which the possibility of stabilization of the instability by diffusion processes is associated since the mode with exacerbation is developed into a collapsing space scale where stabilization by these processes is excluded. The stabilization mechanism is particle and energy transport from the discharge domain and introduction of a secondary scale results in a mode change, starting with certain values. The transfer to a mode without exacerbation follows from an analysis of the behavior of the asymptotic (1.1) for a given scale-change law.

2. The model of breakdown development in a molecular gas in a microwave field can be described by a system of energy and particle balance equations for the gas and the plasma:

$$\frac{\partial T_e}{\partial t} = \frac{e^2E^2\nu_e}{3m\left(\omega^2+\nu_e^2\right)} - \left[\delta_{em}\nu_{em} + 2\frac{m}{M}(\nu_{ei}+\nu_{ea})\right](T_e - T) + \frac{1}{n_e}\frac{\partial}{\partial x}\left(\varkappa_e\frac{\partial T_e}{\partial x}\right); \quad (2.1)$$

$$(N_m + N_a)\frac{\partial T}{\partial t} = \left(\delta_{em}^{VT}\nu_{em} + 2\frac{m}{M}\nu_{ea}\right)(T_e - T)\,n_e + \frac{\partial}{\partial x}\left(\varkappa_a\frac{\partial T}{\partial x}\right); \quad (2.2)$$

$$\frac{\partial n_e}{\partial t} = \frac{\partial}{\partial x}\left(D_a\frac{\partial n_e}{\partial x}\right) + \left(\nu_i - \nu_s - \nu_r^d n_e\right)n_e + q; \quad (2.3)$$

$$\frac{\partial N_a}{\partial t} = \nu_d n_e - \beta_{ae}N_a^2; \quad (2.4)$$

$$p = (N_m + N_a)T + n_e(T_e + T) = \text{const}. \quad (2.5)$$

Here T_e, T are the temperatures of the electrons and the heavy component; m, M, their masses; n_e, N_m, N_a, electron, molecule, and atom concentrations; p, pressure; $\varkappa_e$, $\varkappa_a$, electron and gas heat conduction coefficients; ν_i, ν_r^d, ν_s, ionization, dissociative recombination, and trapping frequencies; β_{ae}, coefficient of three-particle atom recombination with electron participation; ν_{em}, ν_{ea}, ν_{ei}, frequencies of electron scattering by a molecule, atom, ion; δ_{em}, coefficient of electron accommodation by a molecule; and D_a, ambipolar diffusion coefficient. We assume all the gasdynamic processes to be isobaric.

The model presented describes the one-dimensional dynamics of the ionization-superheating instability in a microwave field of intensity E and frequency ω in a molecular gas with its dissociation taken into account. Within the framework of the model the breakdown domain is a plane plasma layer bounded in the x-axis direction on which the electromagnetic wave is incident. Field reflection by the layer boundary results in coupling of the intensity values of the incident E_0 and transmitted waves

$$E = 2E_0/\left(\left|\sqrt{\varepsilon_0}+1\right|\right),\ \varepsilon_0 = 1 - \omega_p^2/(\omega^2+\nu_e^2) + i4\pi\sigma/\omega.$$

Here ε_0 is the complex dielectric permittivity, $\omega_p = \sqrt{4\pi ne^2/m}$ is the plasma frequency, and $\nu_e = \nu_{em} + \nu_{ea} + \nu_{ei}$. The field in the layer follows the relationship $\partial E^2/\partial x = -\mu E^2$, where $\mu = 4\pi\sigma/c$ is the absorption coefficient, σ is the plasma conductivity, and c is the speed of light in a vacuum. Analytic study of (2.1)-(2.5) is not possible. Consequently, the system is analyzed by numerical methods.

Estimates of the components in the equations show that the diffusion processes become substantial when the diffusion scale approaches the skin-layer dimension $\lambda = c/\sqrt{2\pi\sigma\omega}$. Under such conditions the absorption coefficient is $\mu \approx 1/\lambda$ and $\lambda < c/\omega$. The diffusion components can be approximated in this scale by an expression of the type $\sim P/\lambda^2$ since parameter inhomogeneity can be neglected in the dimension λ.

For a numerical analysis of the model the values of ν_s, ν_r^d are taken in conformity with [8-10], the values of D_a, $\varkappa_e$, $\varkappa_a$ are taken from [11], the dissociation frequency is calculated from the formula

$$\nu_d = \frac{2}{\sqrt{\pi m}}\frac{N_m}{T_e^{3/2}}\int_{\varepsilon_d}^{\infty}\varepsilon\sigma_d(\varepsilon)\exp\left(-\frac{\varepsilon}{T_e}\right)d\varepsilon,$$

in which the dissociation section by electron impact $\sigma_d(\varepsilon)$ is taken in conformity with the experimental value [12], ε_d is the dissociation energy, ε is the electron energy. The values of ν_{em}, ν_{ea}, ν_{ei}, ν_{im}, ν_{ia} are computed from formulas proposed in [13]. The accommodation coefficient

$$\delta_{em} = 2\frac{m}{M_m}\frac{\nu^y_{em}}{\nu_{em}} + \frac{16\pi}{3}\frac{N_m}{T_e\nu_{em}}\left(\frac{1}{2\pi T_e}\right)^{3/2} m^{-1/2}\sum_j \varepsilon_j \int\limits_{\varepsilon_j}^{\infty} \sigma_{ej}(\varepsilon)\exp\left(-\frac{\varepsilon}{T_e}\right)\varepsilon d\varepsilon \quad (M_m = 2M)$$

takes account of the first component of elastic scattering, while excitation of the molecule vibrational and electron levels from the ground state takes care of the second (ε_j is the j-th level excitation energy). Let us note that the relative contribution of these processes to δ_{em} varies as N_m changes and as it diminishes (molecule dissociation) $\delta = (\delta_{em} + \delta_{ea}) \to 2m/M$.

Experimental values of the excitation section $\sigma_{ej}(\varepsilon)$ are taken from [14], where data are presented for 10 vibrational and certain electron levels, by which the spectrum is indeed limited in the computation of δ_{em}. The summation in δ_{em}^{VT} is performed only over vibrational levels. The initial values of all parameters are taken from the condition for satisfaction of the stationary homogeneous equations with an external ionization source that excites a non-self-consistent discharge whose stationary state is unstable taken into account.

Taking account of molecule dissociation permits following the path of development of the ionization-superheating instability which is associated with electron superheating under these conditions because of the diminution of δ_{em} as $N_m \to 0$ and the growth of E/N during isobaric gas expansion from the ionization domain.

3. Results of a numerical solution for a N_2–O_2 mixture at atmospheric pressure ($E_0 = 10^6$ V/m, $\omega = 10^{11}$ sec^{-1}) are represented in Figs. 1-4 in stages I-IV.

A detailed analysis is performed of the breakdown dynamics within the framework of these parameters since their variation within the limits of conservation of the subthreshold values of the field and satisfaction of the relationship $\nu_e > \omega$ does not result in different paths of discharge evolution. Only its time scale is changed; the qualitative pattern is conserved here. As the microwave field amplitude increases the intensity grows of the processes accompanying the dense gas breakdown, their development time diminishes, and the growth of the pressure p results in an increase in the characteristic discharge evolution times. The ratio E/p = const assures an identical time scale for the functional dependences of the problem parameters. Let us note that the computation included the pressure range $(3\cdot10^4$-$10^5)$ Pa; the field intensity $E = (2\text{-}10)\cdot10^5$ V/m and $\nu_e/\omega = (4\text{-}20)$. Since these results do not induce qualitatively new representations about the dynamics of high-pressure gas breakdown, they are not inserted on the graphs where solutions are given for one set of initial conditions.

Analysis of the curves shows that breakdown development in a microwave field due to excitation of an ionization-superheating instability prior to its saturation follows four characteristic stages provisionally. The first (to $t \approx 2.6\cdot10^{-6}$ sec) is related to the comparatively slow growth of the degree of ionization and temperature of the electrons up to values at which the instability takes on explosive nature. This period is due to the introduction of the non-self-consistent discharge stage in the model, whose stationary state is determined by an external ionization source. Let us estimate Δt, the time of discharge passage into a self-consistent discharge, i.e., the build-up time of the condition $\nu_i \approx \nu_s$. Since the plasma concentration in the non-self-consistent discharge stage is determined by the secondary source intensity $n_e \approx q/\nu_s$ and changes slightly, it can be considered that $E \approx E_0$ and $\Delta t \approx \frac{1}{2}\frac{\gamma}{\gamma-1}\frac{m\nu_e}{e^2E^2}\frac{\nu_s-\nu_i}{q}N_m(T_b - T_0)$ (γ is the gas adiabatic index and T_0 is the initial value of the gas temperature).

The condition $\nu_i \approx \nu_s$ yields N_b, the concentration in the breakdown domain. Substituting the values of the parameters corresponding to the conditions of the numerical computation into this formula ($p = 10^5$ Pa, $E = 10^6$ V/m and we take the mean values for ν_e and N_m as they change from initial to breakdown), we obtain $\Delta t \approx 10^{-6}$ sec.

At this stage of breakdown development, the system parameters behave in a different way. If the plasma parameters, with the exception of T_e, are practically invariant, then the gas parameters vary intensively. By absorbing energy from the field, the electrons transfer it to the gas. Their energy is still small for the development of dissociation and ionization. The gas molecular component $p = N_mT$ yields the main contribution to the pressure for initial values of T_e, n_e. Consequently, the value of N_m drops as T grows for p = const. Small changes in n_e naturally assure conservation of E, while diminution of N_m (growth of the conductivity σ) results in diminution of $\lambda \sim N_m^{1/2}$. At the stage under consideration, the slow

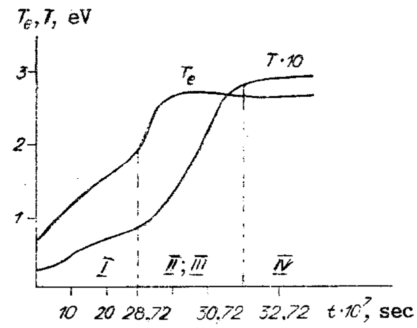

Fig. 1

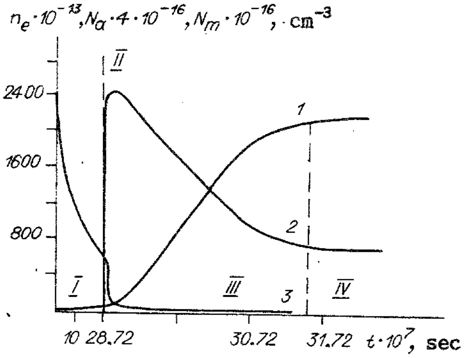

Fig. 2

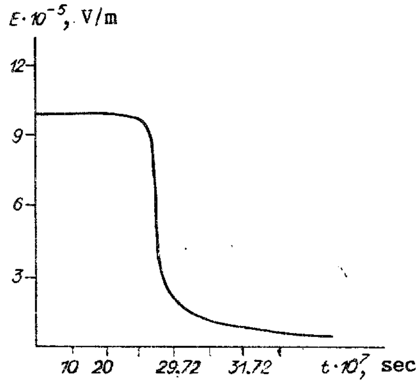

Fig. 3

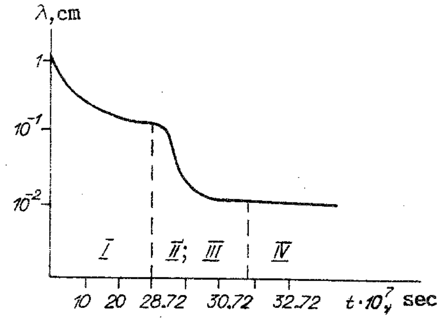

Fig. 4

exponential (not explosive) superheating-ionization instability preceding the explosion stage actually proceeds.

The second stage is associated with the development of a dissociative-superheating instability. Rapid molecule dissociation proceeds in this stage, which results in diminution of the accommodation coefficient that approaches the value $\delta = 2m/M$. Associated with this is also the abrupt rise in electron temperature.

Let us present a simplified scheme that permits performance of a qualitative analysis of this stage:

$$T_e = e^2E^2/3\delta m\nu_e^2; \tag{3.1}$$

$$\partial n_e/\partial t = (\nu_i - \nu_s)n_e; \tag{3.2}$$

$$\partial N_d/\partial t = \nu_d n_e, \tag{3.3}$$

where $2N_d$ is the concentration of atoms being formed because of dissociation, and $\nu_i = \nu_0 T_e^\beta$; $\nu_d = A\exp\left(-\frac{\varepsilon_d}{T_e}\right)$. Let us take

$$\delta = 2\frac{m}{M}\frac{N_a}{N_a+N_m} + \delta_{em}\frac{N_m}{N_a+N_m}$$

(δ_{em} = const, for nitrogen $\delta_{em} \approx 10^{-3}$). The characteristic dissociation time is $\tau_d \approx 1/\gamma_d \gg \tau_T$ (τ_T is the characteristic gas heating time), consequently, the atom and molecule concentration in this stage varies only because of dissociation. Then $N_a = N_{a0} + 2N_d$, $N_m = N_0 - N_d$. Without presenting the awkward computations, let us say that the system (3.1)-(3.3) can be reduced to a second-order equation for $N = N_d/N_0$:

$$\frac{\partial^2 N}{\partial t^2} - \frac{2\varepsilon_d}{T_{e0}(1+N)^2}\left(\frac{\partial N}{\partial t}\right)^2 = \left[\nu_{e0}T_{e0}^\beta\left(\frac{1+N}{1-N}\right)^\beta - \nu_s\right]\frac{\partial N}{\partial t},$$

whose solution in the case $T_{e0} \ll \varepsilon_d$, $N_{a0} \ll N_0$ (the subscript 0 denotes initial values of the parameters) has the form

$$N = t/(a/A_0 - t). \tag{3.4}$$

Here $a = 2\varepsilon_d/T_{e0}$; $A_0 = a(\nu_{i0} - \nu_s) - 4\nu_{i0}$; ν_{i0} is the ionization frequency corresponding to the beginning of effective dissociation. There results from (3.4) that the growth of N is explosive in nature, while the characteristic time of development of the dissociative instability is $\tau = a/2A_0$. Substituting the values taken for the parameters, we find $\tau \approx 10^{-8}$ sec, which is in agreement with the value obtained for the numerical computation. The electron temperature T_e does not grow as abruptly as follows from (3.1). The fact is that in the model (3.1)-(3.3) electromagnetic wave reflection from the plasma layer was not taken into account. Taking into account the diminution of the field intensity in the layer because of reflection (approximately three times in this stage, δ changes approximately 20 times), we have from (3.1) that T_e doubles, which is also in agreement with the computation.

This stage is reflected most clearly in the change of N_a, N_m (Fig. 2, lines 1-3 correspond to $n_e \cdot 10^{-13}$ cm^{-3}, $N_a \cdot 4 \cdot 10^{-16}$ cm^{-3}, $N_m \cdot 10^{-16}$ cm^{-3}). In the $\Delta t \approx 10^{-8}$-sec time scale the molecule concentration diminishes in the fourth order; the atom concentration grows approximately 600 times. The electron energy obtained from the field is expended in dissipation; however, an abrupt diminution in δ results in growth of the rate of change of T_e (see Fig. 1), while the value of T does not change at this stage. This is related to the fact that the scale of the change in T substantially exceeds the scale of the dissociation process $(\delta\nu_{ea})^{-1} \gg 1/\nu_d$ and is $\sim 10^{-6}$ sec. The transient domain between the first two stages is much less than their intrinsic extent for the parameters N_m, N_a, n_e, T_e (Fig. 2). Consequently, the mentioned stages are extracted well and reflect definite mechanisms of breakdown development.

The third stage is the ionization-superheating instability. The term describing microwave field energy absorption in (2.1) does not change in practice in this stage since it has a tendency to slow diminution (its growth, caused by the diminution in the electron collision frequency because of heating and gas displacement from the discharge domain is compensated by a drop in field intensity because of reflection). Consequently, the dependences $T_e(t)$ and $n_e(t)$ are almost linear here. The third stage is completed by an abrupt diminution in λ and the emergence of the discharge at stationary values of the parameters.

Passage to third stage is shifted in time for different parameters. The fact of the onset of the ionization-superheating instability graphically demonstrates the abrupt drop in N_a for $t > 2.9 \cdot 10^{-6}$ sec which is stabilized for $t \approx 3.1 \cdot 10^{-6}$ sec. The change in electron concentration associated with the dissociative-superheating instability goes over into the domain of the ionization-superheating mode continuously; the growth rate of n_e is conserved in practice up to the time of stabilization. The same nature of the change is inherent to T_e and T in the third stage where it is impossible to resolve the passage from the second. Therefore, the dissociative and ionization-superheating instabilities are not distinguishable on the curves of the change in T_e, T, and n_e. This is related to the fact that the former possesses a substantially smaller time scale of development as compared with the latter, for which the largest gasdynamic scales in the problem are inherent.

Despite the fact that different discharge parameters enter the ionization-superheating instability stage with a time shift, they emerge simultaneously at saturation, the fourth stage.

Let us estimate their values from the conditions $e^2E^2n_e\nu_e/[3m(\nu_e^2+\omega^2)] = \varkappa_e T_e/\lambda^2$, $\nu_i = D_a/\lambda^2$. Determining $\varkappa_e$, λ^2, and D_a and substituting the values of the parameters corresponding to the computation ($\beta = 2.5$) into the system, we obtain $1.6 \cdot 10^{-7}E^2 = n_e T_e^2$, $T_e = 2.6 \cdot 10^{-20} n_e^{1/2}$. The approximate solution of this system for stationary values of $E = 7.5 \cdot 10^4$ V/m is $T_e \approx 3$ eV, $n_e \approx 3.5 \cdot 10^{16}$ cm^{-3}.

The discharge parameters vary more slowly than E and λ in the instability stage, whose scale of variation is $\Delta t \approx 10^{-8}$ sec. The transient domain of emergence of all the parameters at saturation is of one order $\sim 10^{-7}$ sec. The fast drop of λ and E into the instability domain specifies the possibility of competition between the transport processes on the dimension $\sim\lambda$ and energy liberation in the electron component in the field E, which indeed results in stabilization of the superheating instability.

The model used is valid when the characteristic discharge dimension is much greater than the electron mean free path $\lambda \gg \ell_e = v_{Te}/\nu_e$. Substituting $v_{Te} \approx 10^6$ m/sec, $\nu \approx \omega \approx 10^{11}$ sec^{-1}, we obtain the condition on the electron concentration $n_e < 10^{18}$ cm^{-3}, which is evidently satisfied.

The model considered is the simplest example within whose framework the breakdown dynamics in a subthreshold microwave field is successfully tracked and qualitatively different stages of this phenomenon are extracted.

Experiment [2] represents a different discharge geometry, a set of plasma filaments. Qualitative agreement of the results of the analysis presented with [2] permits the proposal of mechanisms governing the discharge dynamics in a microwave field in the non-self-consistent discharge stage and saturation of the instability in the self-consistent mode.

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