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EVOLUTION OF PERTURBATIONS IN A HIGH-PRESSURE NON-SELF-SUSTAINING DISCHARGE

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UDC 537.521.7

An experimental and numerical investigation is conducted of the evolution of perturbations, which are excited in a non-self-sustaining discharge, which is controlled by an electron beam at pressures close to atmospheric in various gases and gas mixtures. The perturbations were generated by the discharge itself or with the aid of a specifically introduced external source. As a result, spatially inhomogeneous structures arise, which are oriented along or transverse to the electric field and which degrade the optical properties of the active medium created by the discharge.

A high-pressure, non-self-sustaining discharge which is controlled by an electron beam makes it possible to obtain an active medium of practically unlimited cross section. Such a medium is constantly subjected to the action of external perturbations, which locally change some of its parameters. Local deviations from average values of macroscopic characteristics are also constantly generated within the medium. Stationary and transient structures are formed during development of the excited perturbations. Therefore a homogeneous plasma exists only for a rather short time in an experiment, thereby limiting its possible applications.

I. V. Kurchatov Institute of Atomic Energy, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 62, No. 5, pp. 701-706, May, 1992. Original article submitted November 12, 1991.

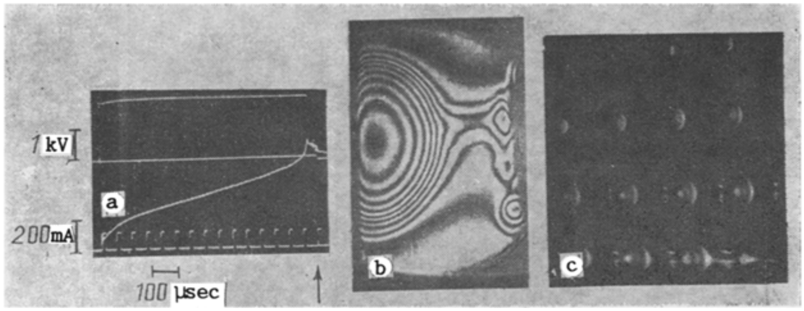

Fig. 1. a) Oscillograms of the discharge current and voltage in N_2 (P = 1 atm) and pulses built up on the zero current line which correspond to a 16-exposure converter tube image; b) interference pattern of the discharge at the time noted by the arrow in a; c) converter tube image for 15 μsec exposures with 45 μsec between exposures. Exposures are made from left to right and top to bottom. In b and c the cathode is to the left and the anode is to the right.

The evolution of the perturbations is affected by detailed mechanisms of processes which occur in the non-self-sustaining discharge and which depend strongly on the type of gas. Therefore the results of the evolution are very specific for each gas mixture. A small change in the composition or the presence of uncontrollable impurities leads to a qualitatively different behavior of the perturbations.

Investigations conducted up to now [1, 2] make it possible to separate structures which arise as a result of the evolution of perturbations into two groups: those oriented along the applied field and those transverse to the discharge. Theory gives a completely satisfactory qualitative, and in some cases also a quantitative explanation of the observed effects, but as the investigation of the non-self-sustaining discharge is extended, the number of effects increases. We will discuss some of them below.

The near-electrode layers are a powerful source of perturbations in a non-self-sustaining discharge. The cathode layer is unstable relative to the formation of cathode spots [2]. Perturbations which arise from the spots can propagate in the interelectrode gap and lead to a filamenting of the discharge. Various forms of the developed perturbations have been observed in [3], which depend on the type of gas. In this setup, in which the dimensions of the electrodes and the interelectrode gap were 1 cm, it was possible to investigate the evolution of single perturbations. In nitrogen, these perturbations have a mushroomlike shape. Detailed experimental investigations of these structures showed that single "mushrooms" arise under conditions of relatively small electron beam currents and voltages in the discharge gap. Here the luminescent formations consisted of a "stem," a "bow," and a "cap" (Fig. 1). The luminescent front propagates to the anode with a velocity of ~5 m/sec. Interferometric measurements show that the observed structure is accompanied by a significant perturbation of the gas density, which corresponds to heating the gas to temperatures above 10^3 K.

These results are fit qualitatively within the framework of concepts reported earlier [2]. The increased current density at the cathode spot accelerates local gas heating, which is accompanied by propagation of density perturbations and, as a result, an electric field in the region of the perturbations. These perturbations should be accompanied by a nonuniformity in the gas luminescence. Attempts to model this situation numerically are published in the literature [4], but such structures were not predicted. Calculations [5] showed that the luminescence pattern, similar to the experimental results, can be obtained only if the gas density drops at the luminescence locations.

Figure 2a shows the calculated distribution of the relative gas density, which corresponds to the largest experimental integrated distribution of the luminescence intensity shown in Fig. 2b. The distribution of the gas density was specified by cylindrical symmetry and had three regions where the gas density dropped, which were separated from each other by regions of higher density. The accuracy of reproducing the gas density from experimental interference patterns did not make it possible to produce similar structures. However schlieren measurements of the density gradient makes it possible to predict the existence of an internal void within much of the volume.

The slow evolution of the perturbation near the cathode is concluded by a rapid propagation of the perturbation from the anode. The flashing of the discharge gap is accompanied by a cylindrical shock wave. As the beam current, the field, and the electrode dimensions are increased, the number of spots and perturbations also increases and gradually becomes an almost continuous luminescence layer. The character and propagation velocity of the near-electrode perturbations also depend on the surface state of the electrodes [6]. Long-term radiation from gas-discharge flashes evidently change the emission and absorption

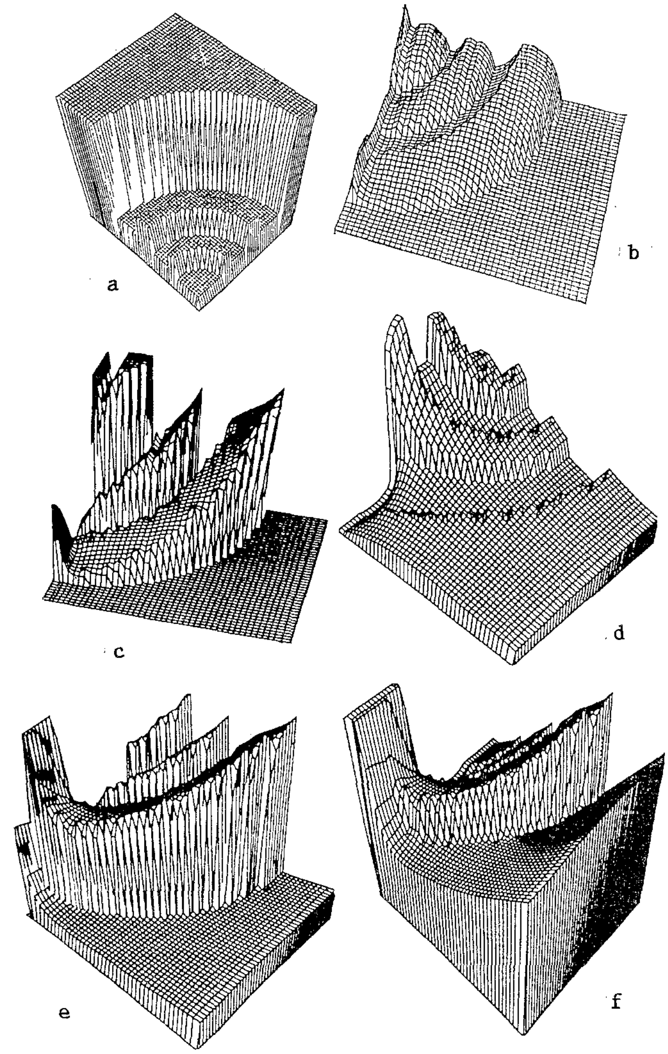

Fig. 2. a) Numerical results with a modeled distribution of the relative gas density; b) distribution of the integrated intensity of the gas luminescence; c) local [differential] intensity of the gas luminescence; d) electron concentration; e) applied electric field voltage; f) modulus of the electric field voltage; in a the cathode is to the right, in b-f it is to the left.

properties of the surface of the same electrodes. As a result, perturbations on the cathode form at a later stage of the discharge. Most of the time the discharge glows uniformly. In this case, spatial processes, which lead to a sharp increase in the conductivity of the whole discharge at once, are the principal reason for instability, and filamenting is a consequence of aggravation and strengthening of the initial nonuniformities of the plasma.

In a non-self-sustaining discharge in pure helium [3], against a background of an essentially constant discharge current, the perturbation is observed to propagate from the electrode opposite the one through which the electron beam is injected. Numerical modeling showed that the ionization nonuniformity causes a perturbation to form near the electrode and then propagate into the volume. The model considered the mechanism of the ionization-overheating instability. The times obtained for developing the instability at room and cryogenic temperatures agree well with those obtained experimentally.

In a CO_2 laser mixture of CO_2:N_2:He = 1:7:8, the non-self-sustaining discharge glows uniformly most of the time, in spite of the existence of cathode spots. Filaments start to propagate rapidly from the anode only ahead of the breakdown itself. In this case the discharge is well described by the model [7] of a volume instability using conditions of constant pressure. The presence of oxygen and water vapor impurities in the non-self-sustaining discharge changes the picture of the discharge glow.

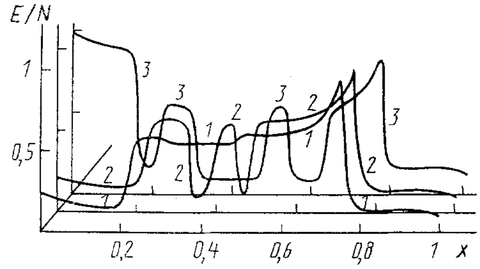

Fig. 3. Calculated distribution of the applied electric field voltage in the discharge gap in a non-self-sustaining discharge in a mixture of 2% H_2 + Ar at various moments of time after the start of the discharge: 1) 4.4 μsec; 2) 4.26 μsec; 3) 4.5 μsec; x is in centimeters.

The reaction of a non-self-sustaining discharge in an external perturbation created by a laser flash has been studied [8]. As a result, the plasma volume breaks up into three regions, which almost simultaneously come together again. The filament which is visible on photographs and which is formed several microseconds before the gap is closed make it possible to think that volume processes play a determining role in the filamenting process.

As a result of the evolution of homogeneous perturbations, a series or plane layers or domains is generated. The domains propagate either along or transverse to the discharge current [1]. The domains exist because of oscillations in the discharge current and luminescence. Depending on the generation mechanism, two types of domains are known: 1) Gunn domains, which are related to a decreasing flight path as a function of the drift velocity of electrons from the field, and 2) attachment domains, which are caused by a sharp growth in the rate of dissociative attachment with increasing domain energy or degree of oscillatory excitation of the molecules. The Gunn domains move from the cathode to the anode with a velocity roughly equal to the drift velocity of electrons outside the domain. The velocity of the attachment domains is much less and, depending on the plasma parameters, is determined by the transport of the field due to 1) its induction by uncompensated charges, 2) diffusion of electrons, and 3) ion drift. Measured domain velocities in a non-self-sustaining discharge in a 2% O_2 + Ar mixture as a functions of the field agree qualitatively with results of a calculation which considers the effect of the nonlocal nature of the attachment rate constant.

In an O_2–He mixture, lowering the oxygen content from 1% to 0.05% leads to a decrease of the domain velocity from $2 \cdot 10^5$ to $0.35 \cdot 10^5$ cm/sec. Under conditions where the domain velocity is close to the sound speed in the mixture, a significant decrease is observed in the domain thickness as it moves from the cathode to the anode, up to where the domain is extinguished. This can be related to the vibration of the domain by the acoustic waves.

In a non-self-sustaining discharge in H_2 (D_2)–Ar mixtures, the existence of luminescence structures were observed, which were oriented transverse to the discharge [9]. The experiment gave a complex picture for establishing this state, including 1) a spontaneous stratification of the discharge, 2) a movement of the layers in different directions with different velocities, and 3) their interaction. A numerical calculation of the initial stage of the non-self-sustaining discharge showed [10] that the interaction of the Gunn and vibrational-attachment instabilities leads to a predominant formation of one or two Gunn domains with a sharply varying time-dependent velocity. When the discharge ceases, the domain is divided into three parts (Fig. 3). At the last stage (~40 μsec) an immobile domain is formed at the cathode, and when the nonuniformity of the ionization is considered, domains are formed which move from the anode to the cathode (opposite to the Gunn domains), as in the experiment.

Formation of a stationary pattern of the luminescence bands can be related to the presence of a decaying flight path as a function of the current of positive ions from the field [9]. The decreasing flight path is caused by the increase and decrease of the loss rate of electrons with the field due to inclusion of attachment to H_2 (D_2) molecules at high vibrational levels and by the subsequent annihilation of negative ions.

In the same mixtures there is a growth of filaments from the perturbations near the cathode and anode. Their interaction with the bands changes the dynamics of filament formation in the non-self-sustaining discharge and leads to jumps in the contraction time [11].

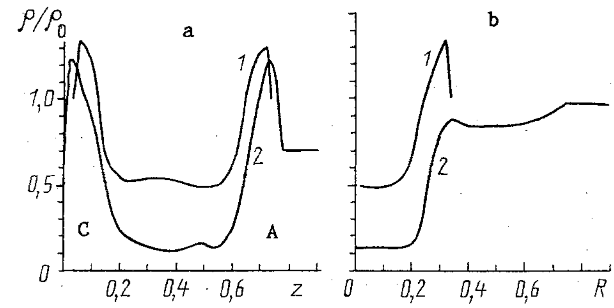

Fig. 4. Distribution of the gas density in the discharge space 5 μsec after initiation of a flash in CO_2: a) along the discharge current (cathode to the left, anode to the right); b) transverse to the current; 1) without discharge; 2) with discharge; z and R in cm.

The destruction of the homogeneity of the non-self-sustaining discharge also causes the evolution of the acoustic perturbations which exist in the discharge. It is known that when the acoustic perturbations propagate along the current, they can undergo acceleration proportional to the specific heat production rate in the gas [12]. In electronegative gases in a non-self-sustaining discharge there is an instability of acoustic waves when they propagate transverse to the current [13]. A new mechanism [14] has been predicted for an acoustic instability for the longitudinal propagation of acoustic waves. This mechanism is related to the presence of a decreased flight path as a function of the drift velocity from the electric field. Acceleration of weak shock waves has been observed [15], which are generated by an electric spark outside a non-self-sustaining discharge in CO_2, as the waves propagate perpendicular to the electric current, which [behavior] is explained by the instability mechanism discussed in [13].

Experiments were conducted on the propagation of the shock wave generated by the laser flash in the center of the discharge space in a non-self-sustaining discharge in pure CO_2 under conditions where the attachment instability was observed. Figure 4 shows the distribution of the gas density in the discharge space along the discharge axis and perpendicular to the discharge 5 μsec after the flash was initiated. The increase in the shock wave amplitude can be seen in the direction along the current, as well as the decrease in the direction perpendicular to the discharge current. The wave velocity is larger in the perpendicular to the current than along it. Both the mechanism in [13] and an extrusion of the field from the region of high conductivity, which is created by the flash, lead to the anisotropy of the density distribution. As a result, a region of reduced heat production is formed ahead of the wave front in the current direction, and the energy contribution transverse to the current remains unchanged.

The nature of the shock wave propagation in unionized gas is practically the same as that in gas acted upon by an electron beam created by an electron concentration of $\sim 10^{12}$ cm^{-3}, but without an imposed electric field.

Investigations of the instability of a non-self-sustaining discharge, which were conducted in the last decades with the use of 1) a large number of diagnostics and 2) numerical modeling of the diagnostics within the framework of rather complete theoretical models, have substantially developed the level of understanding and the possible applications to the physics of a low-temperature plasma.

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SHOCK WAVES IN A GAS-DISCHARGE PLASMA

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UDC 533.951

We experimentally determine the dynamic characteristics, and also the parameters (concentration and temperature of the electrons) and the ionic composition of a plasma before and behind the front of a shock wave which is propagating in the gas-discharge plasma. We show that during shock wave propagation in a nitrogen plasma in the initial stages of the discharge, the shock wave is accelerated and amplified, because of the release behind the shock wave front of energy stored in the gas discharge.

It is widely known that various elementary processes take place in any medium at the front of a shock wave (SW) and in its relaxation layer, and the characteristic times of these processes can differ significantly. This leads to the appearance of different physical effects, including SW instability. Shock waves in a gas-discharge plasma are of special interest, because in addition to the usual processes in strong SWs (dissociation, ionization, recombination, diffusion, precursers, etc.), there is an electric field and discharge current, which impose additional conditions on the kinetics of the ongoing processes.

The diversity and complexity of the processes which take place during SW propagation in a gas-discharge plasma make a theoretical examination extraordinarily difficult, which places priority on the performance of experimental work. The first works on SWs in a partially ionized gas-discharge plasma were conducted in an electric shock tube (EST) more than 20 years ago [1-3]. However, the broad investigation of this phenomenon was begun much later [4]. At present, a significant number of works have been published on experimental investigations of SWs that are propagating both along and across pulsed and steady discharges, and also in decaying gas-discharge plasmas. In these, various experimental methods were used to measure the SW parameters in the gas-discharge plasma, including probes, mass-spectrometry, interferometry, and the schlieren method. As a result, an entire series of new physical effects has been established, and mechanisms for their realization have been proposed. In our review, we examine the more significant of these effects.

1. SW Acceleration in a Gas-Discharge Plasma. Chutov [2] first established experimentally that a SW is sharply accelerated during passage from a neutral gas into a gas-discharge plasma, in an investigation of SWs in a glass EST with Ø of 1.6 cm, filled with hydrogen at a pressure of 67 Pa. In these experiments, a quasisteady gas-discharge plasma was created during discharge of a capacitor bank C through resistance R, so that $\tau = RC \sim 1.6$ msec (Fig. 1b). Fig. 1a, taken from [2], represents the

T. G. Shevchenko State University, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 62, No. 5, pp. 707-713, May, 1992. Original article submitted November 12, 1991.

 1062-0125/92/6205-0504$12.50