Glow discharge in a gas flow

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Usp. Fiz. Nauk **137**, 117–150 (May 1982)

The status of research on glow discharges in a gas flow, used in pumping fast-flow lasers, is reviewed. Systematic study of this discharge began about 10 years ago. This discharge form, according to a number of properties (current flow mechanism, nature of the development of instabilities, etc.), differs considerably from the well-studied glow discharge in tubes. One of the distinguishing features of such a discharge is the negligibly small role of ionization in a large part of the positive column, so that narrow regions near the electrodes contribute most of the positive ions and electrons. Negative ions, which compensate the charge of the positive column, are generated in its volume. The discharge turns out to be weakly inhomogeneous in the direction from the cathode to the anode and the ion currents can form an appreciable part of the total current. These facts have not yet been sufficiently widely discussed in reviews and monographs. In this review, results of experimental investigations of the mechanism of current flow, energy balance, plasmochemical processes, and discharge instabilities are presented, the mathematical models used in their analysis are analyzed, and the possibilities for increasing the stability and efficiency of the discharge in fast-flow lasers are examined.

PACS numbers: 51.50. + v, 47.20. + m, 52.80.Hc, 42.55.Hq

CONTENTS

1. INTRODUCTION

In the last few years, in connection with the development of fast-flow electrical discharge CO_2 and CO lasers, interest has increased in the glow-type discharge, existing in a stationary state in a gas flow at pressures of 10–760 Torr. This discharge, according to a number of properties (current flow mechanism, nature of the development of instabilities, and others), differs considerably from the usual glow discharge in tubes (see, for example, Refs. 1-3 and others). The well-known mechanism of current flow in a glow discharge consists of the fact that the charge carriers (positive and negative ions and electrons) are created in the main volume of the discharge and disappear by recombination or ambipolar diffusion.

In the discharge being examined, charge carriers (positive ions and electrons) are generated primarily in regions near the electrodes and then are carried into the main discharge volume by drifting motion in an electric field, so that in this volume the discharge is not an independent process for low values of the electric field intensity. For this reason, the development of instabilities in the discharge (striations, current filaments) begins in the regions near the electrodes, after which the corresponding inhomogeneities, depending on the experimental conditions, do or do not have the time to encompass the main discharge volume. In view of the absence of a generally accepted terminology, we shall call this discharge form a glow discharge in a gas flow (GDF).[1)]

Just as in a glow discharge in tubes, GDF is characterized by a highly nonequilibrium plasma and a quite

[1)] In the literature, there is no single terminology for this discharge: glow,[4-7] diffuse,[8,9] high-voltage,[10] high-voltage diffuse,[11,12] volume,[13,14] homogeneous,[15], self-sustaining,[16-18] uncontracted,[19,20] discharge in a flow,[21-23] discharge in molecular gases,[24-26] and so on. Each name reflects some property of the GDF.

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high value of the "reduced" electric field intensity (E/N) near the positive column, which in the case of a discharge in molecular gases leads to a high efficiency of transformation of electrical energy into energy stored in the vibrational levels of molecules. In contrast to a discharge, cooled and stabilized by the walls of the tube, GDF is cooled and stabilized due to convective outflow of gas from the zone occupied by the discharge, which, as demonstrated experimentally, permits realizing a stationary uncontracted high-power discharge at high pressures. It is these properties of GDF that determine its practical application in the technology of powerful fast-flow lasers, in plasmochemical reactors, and so on.

The first reports on GDF[8,10,27,28] appeared in connection with investigations of a discharge in gas flows for wind tunnels, MHD generators, and so on. Specific investigations of GDF were begun in the 1970s with the appearance of fast-flow gas discharge lasers.[29-32,39-40]

Most publications on fast-flow lasers, including reviews,[33,34,35] are primarily concerned with describing the technical parameters of laser assemblies and laser characteristics of active media; at the same time, the experimental facts and the theoretical representations of processes occurring in GDF (primarily concerning instabilities of the discharge[3,24,25,36-38]) began to be systemized. Existing experimental information permits regarding as an established fact the considerable inhomogeneity in the GDF along the current, which is emphasized in the present review of the status of research on the mechanism of the discharge and its instabilities.

2. EXPERIMENTAL CONDITIONS

A GDF is realized in gas-discharge chambers (GDC) both with transverse and longitudinal, relative to the average electric current, gas flow (so called transverse and longitudinal discharges). The gas flow velocity constitutes $V = 10^3 - 5 \cdot 10^4$ cm·s^{-1}, its temperature is $T = 100-700$ K, and the total pressure of the gas mixture falls in the range $P = 10-760$ Torr. The main components in the GDF investigated are nitrogen, oxygen, helium, carbon dioxide, carbon monoxide, and argon. Small admixtures of water, oil vapors, hydrogen, plasmochemical reaction products, and others could also be present in the gas mixtures.

In order to increase the volume inhomogeneity of the discharge, the electrodes (as a rule, cathodes) are sectioned and are equipped with individual ballast resistances (Fig. 1). The average current density in the discharge volume is $j \sim 3-30$ mA/cm^2, the current density on the cathode surface $j_c \sim 10^{-1}-10$ A/cm^2 corresponds to the normal current density in a glow discharge. The interelectrode gap in a transverse discharge is usually $h = 1-10$ cm and in a longitudinal discharge $h = 5-100$ cm. Due to the sectioning of the electrodes, the size of the transverse discharge zone along the flow can attain values of $L = 100$ cm and greater.[42]

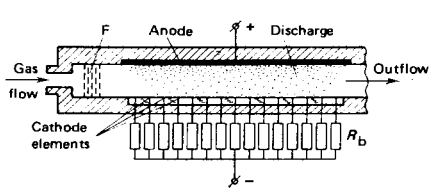

FIG. 1. Diagram of the gas-discharge chamber with transverse discharge and sectioned cathode, consisting of elements, flush-mounted in the cathode plate. F is the device for forming the current; R_b is the ballast resistance.

The characteristic time of flow of the gas through the discharge zone is $\tau_0 = 10^{-4}-10^{-2}$ s, so that some processes in GDF can be investigated with the help of a quasistationary discharge without a gas flow with a current pulse duration $\sim \tau_0$.[43-46]

Present diagnostic capabilities for low-temperature plasma do not permit determining from direct measurements most of the GDF parameters. Part of the GDF parameters can be found by comparing the physical phenomena in the discharge computed on a computer with the measured integral characteristics. Most published papers on investigations of GDF are limited to measuring its current-voltage (I–V) characteristics and determining the limiting energy inputs, corresponding to the transition of the discharge into a contracted state. In separate investigations, the electric field distribution in the discharge was measured using electrostatic probes,[6,8,43,47-50,56] and the volume distribution of heat liberation was measured using an interferometer.[44] The relative negative ion concentrations were estimated by analyzing the I–V curves of the probe.[51] However, the use of probe methods is complicated by the presence of different types of inhomogeneities in the discharge, giving rise to oscillations in the plasma potential, and the error in these measurements can be considerable. Spectroscopic measurement permit, at the present time, measuring under certain conditions only the vibrational temperature of nitrogen (according to the 2^+ band of nitrogen[52]), the ozone concentration (from the absorption of light in the UV region of the spectrum), and the relative population of the upper laser level of the CO_2 molecule (according to the amplification of the weak IR light signal at wavelength 10 μm). The application of other spectroscopic methods (Raman light scattering,[53] intraresonator spectroscopy,[54] measurement of E/N from bremmstrahlung,[55] and others) have not yet provided significant new information for studying GDF. There are practically no papers on the application of mass spectrometry to studying GDF. The basic information on the instability of GDF was obtained from analyzing image converter tube traces and from measurements of current and voltage oscillations on the electrodes (Refs. 5, 41, 164 and others.)

3. DISCHARGE MECHANISM

The discharge mechanism is understood to mean the relation between elementary processes, determining the balance of the number of charged particles, and macroscopic properties of the discharge: the I–V curve, as well as the spatial distribution of the current density j and of the electric field E in the discharge. This relationship is self-consistent, since the

rate constants of many elementary processes depend sharply on the electric field intensity and, in addition, the rates of separate processes can depend in a nonlinear manner on the current density.

In a widely used model of the positive column of the discharge (Refs. 3, 5, 25, and others), it is assumed that the plasma is homogeneous along the current, quasineutral, and the balance of the number of charged particles consists of local equality between the production and loss rates in the volume (ionization, attachment and detachment of ions, recombination, and others). However, the results following from the use of this model do not agree satisfactorily with the experimental investigations of the discharge: the measured values of E/N are less than the theoretical values, the I–V characteristics of the discharge usually do not depend on the magnitude of the energy input to the discharge (i.e., on the concentration of "detachers"), the anode drop increases with increasing distance between the electrodes, the heating of the gas in the discharge is nonuniform, and so on. The model of the inhomogeneous quasineutral plasma discussed for the first time in this review, proposed in Refs. 11, 12, and 47, takes into account the concentration gradients of the charged particles and electric fields along the current; this model, as shown in what follows, agrees well with the experimental data. In a plasma with electronegative impurities, i.e., in real laser mixtures, gradients of the concentrations of positive and negative ions and electrons can exist without destroying quasineutrality in the presence of a comparatively small gradient in the electric field.

The characteristic dimensions of inhomogeneities in the charged particle concentrations are of the order of their drifting lengths in an electric field with respect to their loss mechanism-attachment in the case of electrons and recombination in the case ions. Estimates give for electrons

$$l_a \sim V_e/\nu_a \sim \frac{5\cdot 10^6}{10^4-10^6} \sim 5-500 \text{ cm},$$

and for ions

$$l_r \sim \frac{V_+}{k_r n_-}\frac{n_+}{n_e} \sim \frac{2\cdot 10^4}{10^{-7}\cdot(10^9-10^{10})} \sim 20-200 \text{ cm} \quad (n_+, n_- \gg n_e),$$

which is much greater than the dimensions h of the positive column along the current.

In view of the high mobility of electrons, the magnitude of the electron concentration gradient is usually insignificant. The concentration of negative ions increases away from the cathode region, where it is natural to assume that it is low, and toward the anode due to attachment. Positive ions are generated in a narrow region near the anode and enter into the main volume of the plasma of the inhomogeneous positive column due to drifting motion in the electric field. The positive ion current, due to recombination in the positive column, drops from the anode toward the cathode. The quantity E/N in the positive column corresponds to equality of concentrations (and concentration gradients) of the positive and negative charged particles, which is determined mainly by the rates of recombination of positive ions and of formation of negative ions. Thus, in the main volume of the positive column, the discharge is not an independent process, and the balance of the number of charged particles is maintained due to the input of positive ions from the anode region and electrons from the cathode region, while ionization in the volume of the positive column plays a negligible role.

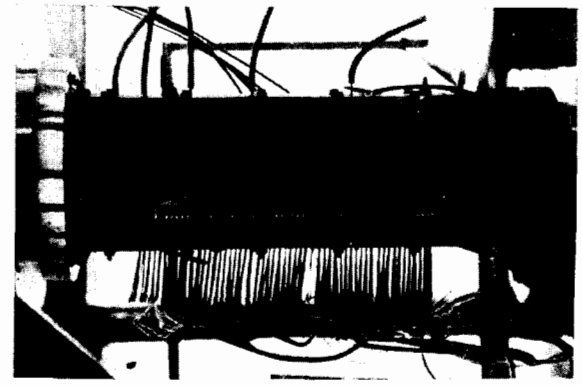

FIG. 2. Photograph of a transverse discharge in the gas-discharge chamber with sectioned cathode and anode in the form of a continuous shaped plate. $h=5$ cm; $V=200$ m/s; $P=60$ Torr; $j=8$ mA/cm^2, air. Flow is from left to right; cathode is at the bottom.

a) Results of experimental investigations

1) *External appearance of the discharge.* Visually, the GDF consists of narrow, with thickness less than 1 mm, luminescing regions at the electrodes: a bright cathode region and a less bright anode region and a weakly luminescing diffuse region in the space between them, traditionally called the positive column (Fig. 2). There is a tendency for the luminescence of the positive column to increase from the cathode to the anode, independent of the direction of flow.

2) *Current-voltage characteristics* (I–V *curve*). In contrast to the glow discharge in tubes, the I–V curves of the GDF, as a rule, are increasing (Fig. 3) (Refs. 18, 21, 22, 41, 42, 56–61, and others). The slope of the I–V curve and the quantity E/P in a transverse discharge in an air flow increase with increasing P (Fig. 4).

3) *Effect of the flow velocity on the burning voltage of the discharge.* In a transverse discharge from a single pair of electrodes, an increase in the flow velocity leads to an increase in the discharge voltage U (Fig. 5).

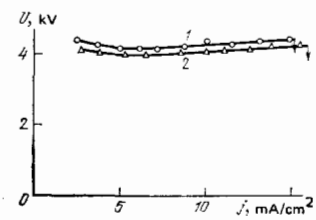

FIG. 3. Typical I-V curve of a GDF for molecular gases.[59] Commercial-grade nitrogen (~2% O_2), $V\approx 100$ m/s, $h=3$ cm, $N=2.8\cdot 10^{18}$ cm^{-3}, 1) $T=230$ K, 2) $T=330$ K. Arrows mark the transition current J^*.

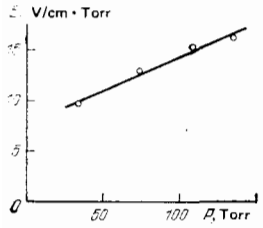

FIG. 4. The P dependence of $\langle E/P\rangle = (U-500)/Ph$ in the positive column for atmospheric air. $h=3$ cm. $V=100$ m/s. $J=70$ mA, cathode area $S_c=0.4\times40$ mm^2, the anode is a continuous plate.

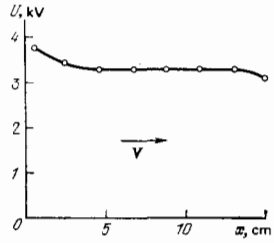

FIG. 6. Voltage distribution on the cathode elements along the direction of the air flow.[42] $P=60$ Torr, $J=0.9$ A, $V=150$ m/s, $h=3$ cm; step between plate cathodes ($S_c=0.2\times40$ mm^2) $\delta=20$ mm.

In the case of long gas discharge chambers ($L \gg h$) with sectioned electrodes, U is observed to increase only for the upstream, relative to the gas flow, electrodes (Fig. 6).[4,42]

4) *Effect of turbulence of the flow and of the velocity profile on the I–V curve.* This effect is insignificant, as is the gas temperature with the gas density remaining constant.[59,62]

5) *Critical discharge current.* When the discharge current J exceeds some critical magnitude J^*, the GDF transforms into a contracted state, visually manifested as brightly luminescing "sections" downstream from the electrodes along the gas flow and accompanied by strong current and voltage pulsations. The specific volume power of the discharge, corresponding to the transition current, in conventionally called the critical volume discharge power $(jE)^*$, while the limiting power of the GDF, referred to the gas flow rate G through the discharge zone, is called the limiting energy input $W^* \equiv J^*U/G$. Usually, in GDF, $(jE)^* = (1-100)\,\mathrm{W\cdot cm^{-3}}$, $W^* = 10-10^3\ \mathrm{J\cdot g^{-1}} \approx 0.003-0.3$ eV/molecule.

6) *Cathode region.* The values of U_c, j_c, and the thickness of the cathode region in the GDF[60,63] are approximately the same as in a normal glow discharge in tubes[1,2] (i.e., $U_c \approx 20-400$ V).

In a transverse gas flow with $P \lesssim 30$ Torr, in a GDF, corresponding to the normal current density law (for sufficiently large cathode surface area), the area of the cathode covered by the luminescence, increases proportionally to the current. For $P > 30$ Torr a nonuniformity appears in j_c in the direction of the flow, increasing with increasing pressure and gas flow velocity, so that the cathode luminescence begins to occupy only part of the cathode surface. The dependence of the magnitude U_c of the anomalous cathode drop on the parameter j_c/P^2 for different gases under GDF conditions is presented in Fig. 7. In GDF, the quantity $j_c^N \sim 0.1-10$ A/cm^2 ($j \sim 10^{-3}-10^{-1}$ A/cm^2), so that the discharge is shaped like a cone, whose apex is located at the cathode.

We note that in a dependent nonself-sustaining discharge, in contrast to GDF, the current density at the cathode can be much less than the normal density. In addition, according to Engel and Steenbeck's theory (see Ref. 2) U_c increases and reaches several kV,[63] and the thickness of the cathode region increases appreciably. In this case, spots, in which the current density equals the normal density[64] j_c^N, can form on the cathode.

7) *Anode region.* Processes in this region, studied in Refs. 47–49, 65, and 66, determine to a large extent the mechanism and stability of the discharge.

Measurements of the distribution of the electric potential near the anode show that the size of the anode region ($10^{-1}-1$ cm) greatly exceeds both the characteristic size of the region in which quasineutrality of the plasma breaks down (~10^{-2} cm) and the thickness of the cathode region. The magnitude of U_a, obtained from these measurements, can amount to hundreds of volts,[47] while in a glow discharge in tubes, it does not exceed 10–20 V.[1,2] It increases both with increasing pressure and with increasing distance between the electrodes (Fig. 8). The I–V curves $U_a(j)$ of the anode region in air and nitrogen, obtained by measuring the heat fluxes into the anode (Fig. 9), are decreasing. This could be the reason for the formation of anode spots; there exist observations showing that the cleanliness of the anode

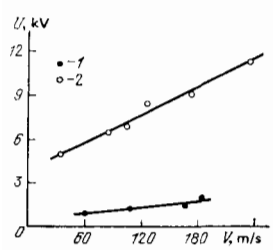

FIG. 5. Voltage on a transverse discharge between the plate (cathode) and the plane (anode) as a function of the air flow velocity. 1) $P=23$ Torr; 2) $P=110$ Torr.

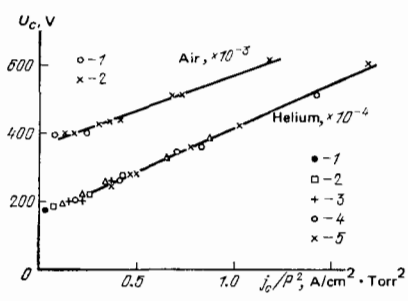

FIG. 7. Cathode voltage drop U_c as a function of the parameter j_c/P^2 in air and helium. Air: 1) $P=80$ Torr; 2) $P=24$ Torr; Helium: 1) $P=455$ Torr; 2) $P=300$ Torr; 3) $P=105$ Torr, 4) $P=80$ Torr, 5) $P=60$ Torr.

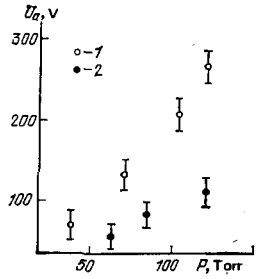

FIG. 8. The magnitude of the voltage drop at the anode U_a in air as a function of P and h with $V=150$ m/s, $j=15$ mA/cm^2.[47] 1) $h=30$ mm; 2) $h=15$ mm.

surface plays an important role here.[58]

Measurements of the current density in the anode spots in nitrogen and air[66] showed that on the anode there also exists a normal current density j_a^N ($j_a^N = 4.2\cdot 10^{-4}$ A·cm^{-2}·Torr^{-2} in the case of nitrogen). In this case, the magnitude of U_a is 10–30 V and increases with increasing P.

8) *Positive column of the discharge.* The typical distribution of the electrical potential in the GDF is shown in Fig. 10. At the cathode, there is a low field region with a low value of E/N, usually having an extent of several millimeters, and beyond a weakly inhomogeneous region with a small increase in E/N extends to the anode. The magnitude of E/N (in nitrogen and air) usually constitutes 20–60 T_d (7–20 V·cm·Torr).

The addition of inert gases (helium) somewhat decreases the magnitude of E/N in the positive column. In contrast to pulsed discharges with UV preionization,[73,74] easily ionizable impurities have practically no effect on the magnitude of E/N.[61,67-72]

Estimates of the electron concentration n_e in the positive column, obtained from measurements of the total corrent J and the cross section of the discharge S, $J/S \approx j \approx e\mu_e E n_e$ (μ_e is the electron mobility), give $n_e \approx 10^9 - 10^{10}$ cm^{-3}.

In a transverse discharge, the gas flow slightly displaces the positive column region[14,31,60] downstream along the flow. The displacement in the positive column can be easily compensated by applying an external magnetic field, perpendicular to the flow velocity and electric current vectors (Refs. 31, 60 and others). With total compensation of the displacement, the magnitude of E/N in the positive column is minimum (Fig. 11).

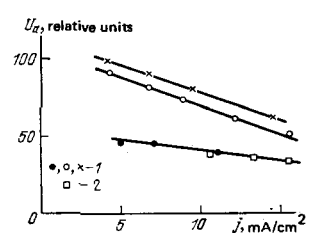

FIG. 9. The dependence $U_a(j)$ for air (1 is for $P=40$, 60, 80 Torr) and commercial-grade nitrogen (2 is for $P=40$ Torr).[49]

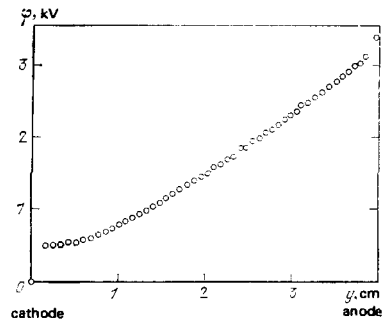

FIG. 10. Typical distribution of the electrical potential between the cathode and the anode in a transverse discharge in an air flow with $P=50$ Torr, $V=100$ m/s, $\langle j\rangle \approx 50$ mA/cm^2, $h=4$ cm.

b) Basic processes in a glow discharge in a gas flow (GDF)

Under the conditions of a nonuniform discharge, *transport processes* play an important role in the balance of the number of charged particles, described by equations of the type $\partial n_i/\partial t + \mathrm{div}(n_i V_i) = A_i$, together with their volume production and loss processes, characterized by the rates A_i; in view of the high values of E/N and E, drift transport in an electric field dominates diffusion transport. Indeed, the ratio of the ambipolar diffusion drift velocity V_i^D to the drift velocity in an electric field V_i^E for ions constitutes $V_{+,-}^D/V_{+,-}^E \sim T_e/hE$ (T_e is the average electron energy) and for electrons $V_e^D/V_e^E \sim (\mu_{+,-}/\mu_e)(T_e/hE)$. For characteristic values $T_e \sim 2V$, $h \sim 3$ cm, $E/N \sim 30\,T_d$, $N \sim 10^{18}$ cm^{-3}, $\mu_{+,-}/\mu_e \sim 10^{-3}$,[83,84] we have $V_{+,-}^D/V_{+,-}^E \sim 10^{-3}$ and $V_e^D/V_e^E \sim 10^{-6}$.

The motion of the gas has an appreciable effect on the motion of ions, since the flow velocity of the gas (10^3–10^4 cm/s) and the drift velocity of ions in the electric field $V_{+,-}$ are comparable. The gas flow has practically no direct effect on the motion of electrons. However, due to the coupling between the electrons and ions through the ambipolar field, the electron trajectories correspond to a field distribution in the discharge that takes into account the removal of ions by the gas flow.

The rates of volume *processes involving electrons* (ionization, attachment, electron-ion recombination) are determined by the form of the energy distribution function of the electrons (EDF), which under typical, for GDF, conditions does not depend on the electron concentration. The time for establishing the EDF is of the

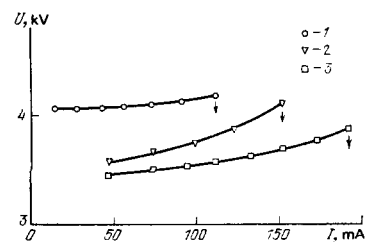

FIG. 11. I-V curve for GDF in a transverse air flow with transverse magnetic field with intensity B.[60] $P=60$ Torr, $V=135$ m/s, $h=4$ cm. 1) $B=0$; 2) $B=3.3$ kG; 3) $B=6.5$ kG. The arrows indicate the value of J^*.[60]

order of $\tau_T \sim n_e T_e/\sigma E^2 \sim 10^{-8}$–$10^{-10}$ s (σ is the plasma conductivity) and is much less than the characteristic times of kinetic processes ($10^{-3} - 10^{-5}$ s).[75-80] Everywhere where the characteristic size of the inhomogeneities exceeds $l_T \approx V_e \tau_T \sim 10^{-3} - 10^{-1}$ cm, it may be assumed that the EDF and the rate constants of elementary processes involving electrons are uniquely determined by the local magnitude of E/N and the gas composition.

The following processes play a basic role in *the balance of the number of electrons* in GDF: direct electron impact ionization of neutral molecules; both dissociative and three body electron attachment to electronegative impurities; detachment of electrons from negative ions with associative reactions or collisions with excited particles and dissociative electron-ion recombination [see Eq. (1a) in what follows]. In many cases, it is necessary to take into account other processes as well, for example step, associative, Penning, and photoionization, ionization by external sources (nonself-sustaining discharge), detachment of electrons from negative ions in collisions with neutral particles due to the excess energy of the negative ions, and photodetachment.

The average energy of ions in the positive column differs appreciably from the average energy of neutral particles [over the mean free path, an ion acquires an energy $\varepsilon_i \approx e\,(E/N)\,1/\sigma_{ia} \sim (2/3)\,M(\mu_i E)^2 \sim 30 - 100$ K, M is the average mass of the interacting particles].[85] Since some rate constants involving ions depend strongly on their energy (ion-ion recombination, detachment, and so on), in addition to taking into account the effect of gas temperature on them, it is also necessary to take into account the effect of the electric field.

Ionization, electron-ion, and ion-ion recombination play a basic role in the balance of the number of *positive ions* together with drift transport. The change in the ion composition occurring with ion-molecular reactions[2)] involves a change in the effective recombination coefficient and ion mobility, which can affect the characteristics of the discharge.

Attachment, detachment, and ion recombination processes also play an important role in the balance of the number of *negative ions* together with transport in an electric field.

The system of equations, describing the GDF, in the one dimensional ($\mathbf{V} \| \mathbf{E} \| y$) stationary case of a weakly conducting plasma, consisting of electrons and positive and negative ions, can be represented in the following form (the origin of coordinates, $y = 0$, is at the cathode):

$$\operatorname{div}(n_-\mathbf{V}_- + n_-\mathbf{V}) = \frac{\mathrm{d}\,(n_-\mu_-^{\mathrm{eff}}E)}{\mathrm{d}y} = k_a n_e N - k_r n_+ n_- - k_d n_- N_d \equiv A_-, \quad (1a)$$

$$n\frac{\mathrm{d}E}{\mathrm{d}y} + E\frac{\mathrm{d}n}{\mathrm{d}y} + (n_+\hat{\mu}_+^{\mathrm{eff}} - n_-\hat{\mu}_-^{\mathrm{eff}} - n_e\hat{\mu}_e)\frac{\mathrm{d}E}{\mathrm{d}y} = -\frac{A_+}{\mu_+^{\mathrm{eff}}} - \frac{A_-}{\mu_-^{\mathrm{eff}}} - \frac{A_e}{\mu_e}, \quad (1b)$$

$$\operatorname{div}\mathbf{E} = \frac{\mathrm{d}E}{\mathrm{d}y} = -4\pi e\,(n_+ - n_e - n_-) \equiv -4\pi e n, \quad (1c)$$

$$e\,(\mu_+^{\mathrm{eff}}n_+ + \mu_-^{\mathrm{eff}}n_- + \mu_e n_e)\,E = j \qquad \left(j = \frac{U_n - U}{R_b} - \mathrm{const}\right), \quad (1d)$$

where $\mu_+^{\mathrm{eff}} \equiv \mu_+ - \frac{V}{E}$, $\mu_-^{\mathrm{eff}} \equiv \mu_- + \frac{V}{E}$, $\hat{\mu} \equiv \frac{\partial \ln \mu}{\partial \ln E}$, $A_e \equiv k_i n_e N - k_a n_e N - k_e n_e n_+ + k_d n_- N_d + a$, $A_+ = A_e + A_-$, a is the external ionization rate, U_n is the supply voltage, R_b is the external ballast resistance per unit area of the discharge.

Equation (1b) follows from the equations of balance of the number of positive ions $\operatorname{div}(n_+\mu_+^{\mathrm{eff}}E) = -A_+$, of electrons $\operatorname{div}(n_e\mu_e E) = A_e$, and Eq. (1d).

The boundary conditions are:

$$n_-|_{y=0} = 0; \quad j_e|_{y=0} = \gamma j_+|_{y=0} \quad \text{(at the cathode)},$$
$$n_+|_{y=h} = 0 \quad \text{(at the anode)}.$$

The equations of balance of charged particles and the equations for the electric field (1c) and current (1d) adequately describe the GDF, if it is possible to neglect heating of the gas, as well as the accumulation of excited particles and plasmochemical reaction products. The gas dynamic flow parameters ($\mathbf{V}, N, T$) and the chemical composition of the gas can usually be assumed to be given everywhere in the volume of the discharge, if the magnitude of the energy input W (see Sec. 4) is small compared to the total enthalpy of the gas flow (in practice, for $W < 100$ J/g). The minimum characteristic scale in the GDF in this analysis is the size of the region in which quasineutrality of the plasma breaks down: $l_\sigma \approx E/4\pi e n_+ \sim 10^{-2} - 10^{-1}$ cm. In view of the boundary conditions, the breakdown of quasineutrality occurs in the regions near the electrodes, characterized by a very sharp gradient in the electric field (1c). Outside these regions, in a stationary plasma, such sharp gradients do not occur (Fig. 12), the plasma is quasineutral (by definition, this is a positive column), and Eq. (1c) is replaced by the algebraic relation[86]

$$n \equiv n_+ - n_e - n_- \approx 0. \quad (1c')$$

For this reason, for typical conditions in the positive column of the GDF, the first two terms on the left side of (1b) can be neglected.

The largest characteristic size (in electronegative gases)[3)] occurs for an inhomogeneity caused by a de-

[2)] In the low-temperature plasma of molecular gases, there is a wide variety of types of charged particles, owing to the multicomponent nature of the gas mixture (and also including the effect of uncontrolled impurities) and large number of possible ion-molecular reactions. The number of types of ions can amount to 10–10^2.[75,77,81,82]

[3)] If the effective mobilities (μ_+^{eff}, μ_-^{eff}, μ_e) of charged particles depend on the electric field, then an inhomogeneity with characteristic dimensions of the order of $l_\mu \approx |\hat{\mu}_i^{\mathrm{eff}}|\mu_i^{\mathrm{eff}}En_+/A_i \sim 10^{-1} - 1$ cm can appear in the positive column. The outflow of fast electrons from the narrow cathode region into the region of the positive column with high electric fields can create on the boundary of this region, due to intense ionization, a region with high conductivity, where the electric field E_0, necessary for the given current to flow, is low due to the condition $j = \sigma E = \mathrm{const}$ (the conductivity can be increased in this zone also as a result, for example, of diffusion of excited particles from the cathode region, photoionization and so on). It is not difficult to show that in the electropositive gas, if $\mu_e = a + (b/E)$ and $V = 0$, near the cathode, according to (1b), $E \approx (jk_e/eb\mu_+)y + E_0$. The size of this inhomogeneous region l_μ is determined by the distance at which the ionization is "switched on." For electronegative gases, the size l_μ is appreciably smaller, since it will be determined by the time at which the attachment is "switched on," which begins at lower electric fields.

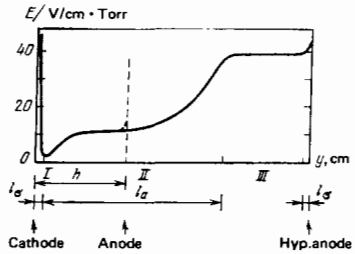

FIG. 12. Distribution of electric fields in GDF according to the system of equations (1) for air with large interelectrode separation.[12] There are near-electrode regions of charged plasma I and IV with dimensions of the order of l_σ and a region with quasineutral inhomogeneous (II, dimention l_a) and homogeneous (III) plasma. However, in reality, in a self-sustaining discharge the characteristic size of the inhomogeneity l_a, which depends on the current density and the gas composition is much larger than the interelectrode distance h, and for this reason region III and right side of region II are absent.

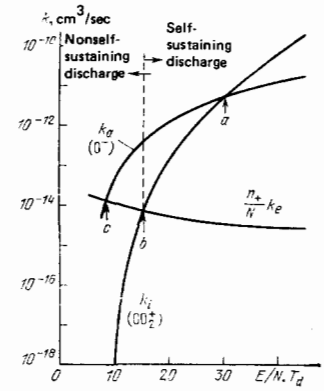

FIG. 13. Illustration of the mechanism of current flow in a homogeneous positive column of a GDF for the mixture N_2:He:CO_2.[25] Positive column regimes: a) no electron detachment, $n_-/n_e \ll 1$; b) strong detachment, $n_-/n_e \ll 1$.

crease in the electron and an increase in the ion currents from the cathode to the anode. The characteristic size of this inhomogeneity is $l_a \sim \mu_e E/k_a N \sim \mu_+ E/k_r n_+ \sim 10 - 10^3$ cm. In the case $l_a > h$ the GDF is adequately described only by the model of an inhomogeneous quasineutral plasma,[11,12,87] taking into account drift transport of ions along the current.

c) Models of the positive column

1) *The diffusion model*, which describes well a low pressure glow discharge in tubes,[1] is constructed for the positive column of a GDF in Refs. 21 and 88–90. In this model, it is assumed that volume ionization is balanced by ambipolar diffusion. Although experiments agree qualitatively with the results of this model (increase in U in the transverse discharge with increasing gas velocity and current density, displacement of the discharge by the gas flow, and so on), this model is inapplicable for $P > 10$ Torr. Indeed, both the recombination time $\tau_e \sim (k_e n_e)^{-1} \sim [10^{-7} \cdot (10^9 - 10^{10})]^{-1} \sim 10^{-3} - 10^{-2}$ s, and the flight time of ions $\tau^E \sim h/\mu_i \cdot E \sim 10/10^4 \sim 10^{-3}$ s and electrons $\tau_e^E \sim 10/10^6 \sim 10^{-5}$ s are much less than the diffusion time $\tau_D \sim h^2/D_a \sim 10/10^2 \sim 10^{-1}$ s. Taking into account turbulent diffusion[87-95] cannot explain the existence of a quasistationary discharge without a gas flow[43,44,96,97] or a discharge in a laminar flow.[65,97]

2) *Homogeneous quasineutral plasma model.* In this model of the positive column, the balance of charged particles is determined exclusively by the rate of elementary processes at a given point in the volume,[3,5,25,45,46,80] the motion of charged particles is neglected, and $V_i = 0$ in the equations of balance of the number of charged particles [i.e., the left sides of Eqs. (1a) and (1b) are set equal to zero]. For a low detachment rate, electrons are lost as a result of attachment, the negative ions formed recombine, and the quantity E/N for the stationary state is obtained from the condition $k_i \approx k_a$, since $k_a \gg (n_+/N)k_e$ (Fig. 13). Attachment greatly increases the magnitude of E/N in the positive column. Estimates[3,98] show that in air the condition $k_i \approx k_a$ is satisfied with $E/P \approx 40$ V/cm · Torr, which is much greater than the magnitudes of E/P observed experimentally in stationary discharges.

When detachment almost completely compensates attachment, the quantity n_-/n_e is small and the discharge must exist for lower values of E/N, which are obtained from the condition $k_i \approx (n_+/N)k_e$ (point b in Fig. 13). According to this model, GDF can exist in a region of values of E/P between the points a and b. Here, ionization dominates electron-ion recombination. An estimate of the concentration of "detacher" particles N_d, necessary in order for detachment to be significant gives $N_d > v_a n_e/k_d n_- \sim 10^{15}$ cm^{-3} with $v_a = 10^5$ s^{-1} and $k_d \approx 10^{-10}$ cm^3 · s^{-1}.

The main detachment channel involves metastable particles and radicals.[76] For these particles to form, energy must be expended, and this energy can be an appreciable fraction of the overall balance of energy in the GDF. The small role of detachment processes under the conditions of GDF with moderate energy inputs was demonstrated experimentally in Refs. 44 and 46.

The basic difficulties of the model of homogeneous GDF are as follows.

The measured values of E/N in the positive column in electronegative gases are small and cannot provide sufficient rate of direct electron impact ionization. Other ionization mechanisms (photoionization, Penning, and associative ionization), which could explain the low values of E/N, are not effective enough under the conditions of the current densities in GDF (photoionization) and with vibrational temperatures below 2500 K (associative ionization[99]).

As the energy input into the discharge increases, the rate of detachment must increase and, therefore, the quantity E/N must decrease, which is not confirmed experimentally in stationary discharges.

The experimentally observed stability of the discharge relative to the formation of striations (see Sec. 5), for values of E/N when dissociative attachment is known to dominate over three body attachment, is not explained.[5,24,25]

Analysis shows that the model of a homogeneous plas-

ma in the positive column of the GDF usually turns out to be inapplicable, with the exception of the case of a nonself-sustaining discharge, controlled by an electron beam.[12,38]

3) *Inhomogeneous quasineutral plasma model.* Neglecting a small region of size l_μ near the cathode, the following relation follows from (1b):

$$a\mu_- + (\mu_- k_i + \mu_+ k_a)\, n_e N = (\mu_+ + \mu_-)\, k_r n_+ n_- + k_e n_+ n_e \mu_- + k_d n_- N_d \mu_+, \quad (2)$$

which describes the dependence $E = E(j_e, j_+, j_-)$ in the positive column. For the case $a = 0, k_d N_d = 0$, taking into account the fact that $k_a \gg k_i$ and $\mu_+ \approx \mu_-$ for values of E/N characteristic for the positive column it follows from (2) that

$$k_a n_e N \approx 2k_r n_+ n_- + k_e n_+ n_e. \quad (2')$$

Relation (2′) together with (1a), (1c), (1d), represented in the form

$$\frac{d(\mu_- n_- E)}{dy} = k_a n_e N - k_r n_+ n_-, \quad (\mu_e n_e + \mu_+ n_+ + \mu_- n_-) E = j_0, \quad (3)$$
$$n_+ = n_e + n_-,$$

determine the I–V curve of the positive column, as well as the variation in the ion currents and the electric field from the cathode to the anode. The boundary condition at the cathode can be taken as $n_- E \approx 0$, since in the greater part of the comparatively narrow cathode region, the ionization rate greatly exceeds the attachment rate.

The basic parameters of the inhomogeneous positive column can be estimated by, for example, representing Eqs. (2′) and (3) in the form

$$k_a \frac{E}{N} \approx \frac{2k_r \mu_e}{N^2 \mu_+^2} \frac{j_+ j_-}{j_e} + \frac{k_e}{\mu_+ N^2} j_+, \quad (2'')$$

$$\frac{dj_-}{dy} \approx \frac{k_r j_+ j_-}{\mu_+^2 E^2} + \frac{k_e j_e j_+}{\mu_+ \mu_e E^2}. \quad (3')$$

It is evident (2″) that in the positive column near the cathode, with high gas density N and in the presence of three body attachment, when k_a is a weak function of E/N, the magnitude of the reduced electric field, due to the smallness of the ion currents [right side of (2″)] can be very small. As the ion currents increase from the cathode to the anode (3′) E/N increases (2″) quite rapidly: $(\hat{k}_a + 1)\partial \ln(E/N)/\partial y \approx 2\partial \ln j_-/\partial y$, $\hat{k}_a^T \equiv \partial \ln k_a^T / \partial \ln E \sim 0$ dissociative attachment with a sharp dependence $k_a(E/N)$ enters the picture: $\hat{k}_a^D \sim 5$. Then, the growth of the electric field toward the anode sharply slows down, and the magnitude of the field in the remaining part of the positive column remains almost constant. The size of the low-field region at the cathode $\Delta y \sim (k_a^D j_0)^{-1/2}$ under the conditions of the GDF is usually less than 1 cm and decreases slightly with increasing current and gas density.

As the current density increases, the gradient of the ion current densities (3′) and their contribution to the charge transport increases. For this reason, the I–V curve of the positive column, according to (2″), turns out to be weakly increasing. These results agree with the results of detailed computer calculations[12] and with the known experimental data. Comparison of the computer calculations with the experimental data permitted refining a number of rate constants of elementary processes (ion-ion recombination, dissociative attachment) and constructing a physicomathematical model of the current flow in the positive column, which describes with good quantitative accuracy the nonuniform heating of the gas by ion currents, the electric field distribution, the I–V curve of the discharge, and so on[44] and reproduces a number of parameters, for example, the distribution of the charged particle concentration along the field, whose direct measurement is not presently possible. The quantitative agreement between the calculations and the experiment is illustrated, for example, in Figs. 14 and 18.

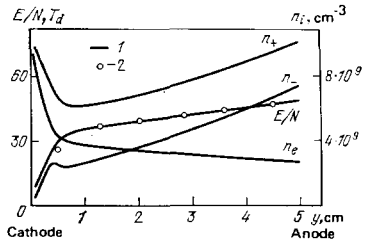

FIG. 14. The distribution of E/N, n_+, n_-, and n_e in the positive column. Dry air, $N = 1.5 \cdot 10^{18}$ cm^{-3}, $j = 4$ mA/cm^3. 1) Calculation according to refined ionic recombination and dissociation attachment constants,[44] 2) experiment. The small values of E/N near the cathode are explained by three-body attachment.

Comparison of the computational results with experiment shows that, apparently, the positive column in known experiments with a stationary discharge was inhomogeneous.

d) Some properties of the GDF

1) *The ionization front* (or the inlet region of the discharge) was examined in Ref. 91, 93–95. These papers concentrated on heat conduction and diffusion (ambipolar or turbulent). However, such models cannot explain, for example, the stationary nature of the discharge in laminar flows or at supersonic velocities. The leading edge of the GDF can be explained by the development of ionization in the quasineutral plasma zone, taking into account the fact that the "seed" electrons in front of the leading ionization edge enter into the gas volume from the region near the cathode as a result of their drifting motion in the electric field, existing in front of the inlet to the zone of the quasineutral discharge plasma. Here, seed electrons can accumulate with concentration $n_{e1} \sim 10^8$ cm^{-3}. In the inlet zone of the discharge, whose size along the flow is $\Delta x \sim h$, there is an exponential ionization growth of the electron concentration to a magnitude n_{e0}:

$$\frac{k_i N}{V} \Delta x \approx \ln \frac{n_{e0}}{n_{e1}}.$$

It is evident that with a given size of the inlet (ionization) zone, the magnitude of E_{in}, due to the sharp dependence of $k_i(E)$, depends very weakly on the degree of preionization n_{e1}/n_{e0}. The magnitude of E_{in} exceeds the value of E_0 in the stationary discharge zone due to the additional energy expenditures on ionization in this zone. The estimates presented correspond to two-dimensional calculations of a discharge in a transverse

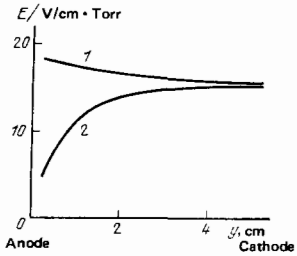

FIG. 15. The distribution of E/P in the positive column near the anode in the absence of negative ions in the presence of ion-molecular reactions[101] (positive ions of type 1 are converted into ions of type 2 with rate constant k_c): $P=30$ Torr, $\mu=1.5\cdot10^3/P\cdot\text{cm}^3/B\cdot\text{s}$, $j=3$ mA/cm^2, $k_c=10^4$ s^{-1}, $k_{e1}=k_{e2}=10^{-7}$ cm^3/s, 1) $\mu_1=0.5\mu_0$, $\mu_2=1.5\mu_0$; 2) $\mu_1=1.5\mu_0$, $\mu_2=0.5\mu_0$.

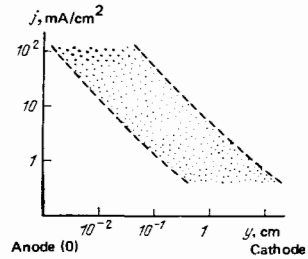

FIG. 16. The region of GDF near the anode with locally decreasing dependence $E(j)$ (calculation[49]).

nitrogen flow[7,100] and to experimental data.[4,42]

2) *Effect of ion-molecular reactions.* The plasma in a real discharge, due to ion-molecular reactions, contains many kinds of both positive and negative ions with different recombination and detachment rate constants and different mobilities. Uncontrolled impurities, for example water, hydrogen, vapors of organic compounds, and so on, whose direct participation in the elementary processes examined in the GDF models (part c of Sec. 3) is negligibly small, can play a large role in ion-molecular reactions. As shown in Ref. 101, impurities with concentration $N_{im}\approx10^{10}-10^{16}$ cm^{-3} can have an appreciable effect on the I–V curve and on the homogeneity of the positive column (Fig. 15) Thus, if the effective recombination coefficient (due to changes in the type of ions in the conversion process) depends on the current density, then anomalies should be expected in the I–V characteristic. If the effective mobilities or recombination coefficient (also due to changes in the type of ions) vary along the current, then the positive column will be inhomogeneous. It is possible that the observed spread in the results of measurements of the I–V characteristics in different experiments, in which there were no quantitative diagnostics of the composition of the impurities, is related to the uncontrolled impurities.

3) *Discharge regions near the electrodes.* The cathode region of the GDF, located deep in the gas-dynamic boundary layer, is practically the same as that in a glow discharge at high pressure.[1,2,102] The mechanism for current flow into the anode region was examined in Refs. 43, 49, and 103. The theoretical analysis shows[49] that the I–V characteristic of the section closest to the anode is always positive (the field intensity directly at the anode surface E_a increases with increasing j). In the case of nitrogen, $E_a\sim j^{1/5}$, near the anode $E(y)=E_a-(8\pi j/\mu_e E_a)y$, i.e., at some distance $y>y_1$ from the anode the function $E(j)$ becomes a decreasing function. The experimentally observed decreasing I–V characteristic of the anode region is explained by the decrease in the dimensions of the high field region at the anode with increasing current density.

Calculations[49] show that the size of the anode region considerably exceeds the dimensions that follow from estimates based only on Poisson equation and depends on the form of $k_i(E/N)$. For low currents, the anode region can actually occupy the entire interelectrode space (Fig. 16). In this case, a decrease in the I–V characteristic is possible for the entire discharge (which is in fact observed in experiments with low currents).

4. ENERGY BALANCE AND PLASMOCHEMICAL PROCESSES IN GDF

a) Energy distribution in GDF

The electrical power jE, liberated per unit volume of the positive column of the discharge, is consumed in the following basic channels: heating of the gas (specific volume power of this process is Q_T, the efficiency is $\eta_T=Q_T/jE$); excitation of molecular vibrations (Q_V, η_V); excitation of electronic molecular states, including ionization (Q_{el}, η_{el}); formation of active radicals, expenditure on chemical reactions, and so on (Q_{ch}, η_{ch}), so that $\eta_T+\eta_V+\eta_{el}+\eta_{ch}=1$. Due to the inhomogeneity of the discharge, the relation of the components in the energy balance is different at different points in the discharge volume. Theoretical investigations of the energy balance in a homogeneous discharge with different E/N were carried out by solving the kinetic equations for the electrons and vibrationally excited particles in many papers,[104-110] and the results are illustrated in Fig. 17. According to these calculations the vibrational efficiency of a self-sustaining discharge ($E/N=30-50$ T_d) is very high ($\eta_V\sim0.8-0.9$).

The quantity η_T is determined by the following: direct heating of molecules by elastic electron collisions;

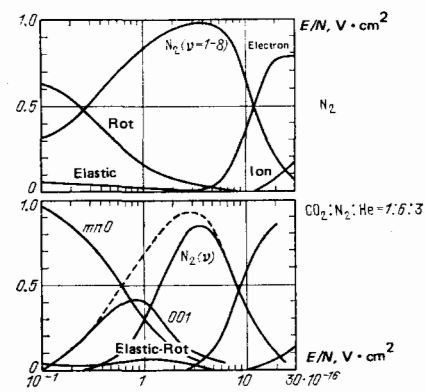

FIG. 17. Balance of electron energy in different gases (calculation[105]).

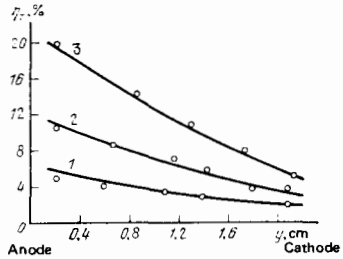

FIG. 18. The distribution in the positive column of GDF of the fraction of the power going into direct heating of dry air with $j = 25$ mA/cm^2 (Ref. 44). 1) $P = 30$ Torr, 2) $P = 60$ Torr, 3) $P = 100$ Torr. Calculation according to refined rate constants and experiment.

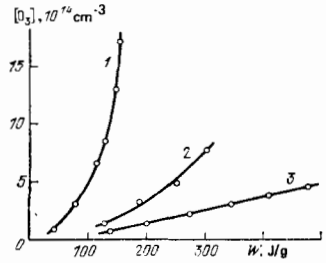

FIG. 19. The dependence of the concentration of ozone on the energy input for dry air at $T_{in} = 10$°C.[120] 1) $P = 125$ Torr, 2) $P = 81$ Torr, 3) $P = 65$ Torr.

heating by ion currents; relaxation of vibrations into heat; electron excitation of the rotational molecular states, whose energy relaxes into heat at gas kinetic rates; the corresponding fraction η_T^R increases with decreasing E/N.[111] For a discharge in nitrogen with very low admixture of electronegative gases (O_2, CO_2, CO, H_2O, and others) the experimentally measured magnitude of η_T usually constitutes 3–10%.[111-113] Interferometry of the discharge zone in the prescence of these impurities showed an increase in the quantity η_T in the direction toward the anode[44] (Fig. 18), which is explained by the increase in the fraction of ion currents in this direction (in accordance with the inhomogeneous plasma model), and direct heating of the gas by these currents.

In a quasistationary discharge in pure and commercial-grade (i.e., containing 1–2% O_2) nitrogen, an anomalously high effective rate of relaxation of vibrational energy into heat was observed: $P\tau_{VT} \approx 3.5 \cdot 10^{-3}$ absolute atmospheres · s (commercial grade nitrogen N_2),[113] which increases η_T in discharge chambers that are long in the direction along the flow. This anomaly for commercial-grade nitrogen, probably, is related to the formation of ozone in the discharge, having a large quenching cross section for vibrationally excited nitrogen molecules.[114] The increase in the effective rate of vibrational relaxation could also be related to the non-Boltzmann distribution of the populations of vibrational levels with high energy inputs.[115]

The experimental determination of the quantity η_V showed[52,117] that with a discharge in commercial-grade nitrogen with helium the quantity $\eta_V = 0.5$–0.9; depending on the dimensions of the chamber and on the gas pressure in dry air ($P = 50$–150 Torr) $\eta_V = 0.5$–0.8. The quantity η_V decreases with increasing specific mass energy input W. An indirect determination of the quantity $\eta_{el} + \eta_{ch} = 1 - \eta_T - \eta_V$ showed that $\eta_{el} + \eta_{ch} \lesssim 10$–15%.[52,116-120]

b) Plasmochemical processes in GDF

In the presence of collisions between high-energy electrons and molecules in GDF, radicals and excited particles, initiating chemical reactions in the gas, form. This initiation requires certain energy expenditures; on the other hand, the plasmochemical reaction products can change both the balance of the charged particle concentrations in the discharge and the effective rate of relaxation of excited molecules. For example, associative detachment of electrons from simple negative ions proceeds efficiently on the radicals (O, H, OH, and others), while the rate constants for attachment to nitrogen oxides (N_2O and NO_2) are two to three orders of magnitude greater than the corresponding constant for oxygen.[121,122] The rate constant for vibrational relaxation of nitrogen by ozone molecules is two to three orders of magnitude greater than the corresponding rate by water molecules.[114]

Since the number of active particles increases with increasing energy input into the discharge, for high-energy inputs ($W \gtrsim 10^{-2}$ eV/molecule) in many cases, in order to explain the discharge mechanism and its instabilities, it is necessary to take into account the contribution of the plasmochemical reaction products.

Plasmochemical processes occurring in air and commercial-grade nitrogen have been studied in greatest detail. Under the conditions of GDF, due to the low dissociation energy of oxygen, the main final product of plasmochemical reactions is ozone.[114,120,123,124]

The basic results of these measurements are presented in Fig. 19. The concentration of ozone $[O_3]$ increases sharply with increasing current and gas pressure ($[O_3]$ can attain a value of 10^{15} cm^{-3}) and decreases with increasing temperature and with the addition of H_2 or H_2O. Analysis shows that the formation of O_3 proceeds via the reaction $O + O_2 + M \rightarrow O_3 + M$, whose reaction constant decreases with increasing temperature, while destruction occurs practically only by H atoms, which are formed in the discharge with the dissociation of H_2O or H_2.[125-127] O atoms are formed as a result of dissociation through electronically excited states of the O_2 molecule, having thresholds ~8 eV and 6 eV for the transitions $^3\Sigma_g^- \rightarrow {}^3\Sigma_u^-$ and $^3\Sigma_g^- \rightarrow {}^3\Sigma_u^+$, respectively. Due to the dissociation of O_2, the quantity η_{ch} can constitute several percent.

Oxygen and ozone atoms actively interact with the dissociation products of hydrogen and water. The most important process for loss of oxygen and ozone atoms is the chain mechanism $O_3 + H \rightarrow OH + O_2$ and $O + OH \rightarrow O_2 + H$. Very insignificant quantities of H and OH are required (~10^{13}–10^{14} cm^{-3}), for these reactions to compete with the ozone forming reactions. Taking into account the comparatively fast association reactions of these radicals with the participation of a third mole-

cule, it can be shown that their concentration must decrease inversely proportional to the gas pressure. Taking this fact into account and the pressure dependence of the rates of dissociation of oxygen and of the ozone forming reaction the ozone yield must, with the discharge parameters remaining unchanged, increase as P^{3-4}, which agrees with the experimental results.[120]

The radicals formed as a result of plasmochemical reactions have an appreciable effect on the properties of the discharge, in particular, on the ionic composition and on the quantity E/N. Analysis of plasmochemical processes under the conditions of GDF shows that although the characteristic energy expenditures on them are not large, with high energy inputs, under certain conditions, they can have an appreciable effect both on the distribution of electric fields in the discharge (and its stability) and on the effective energy balance.

5. INSTABILITIES OF GDF

The state of the GDF examined above, under certain threshold conditions, becomes unstable. Striations (or domains), transverse to the direction of the current, as well as filaments parallel to the current, which can stimulate arc breakdown of the interelectrode gap, arise in the discharge.

a) Attachment instability

Striation (or domain) type inhomogeneities[25,36,37,128-133] are regions of quasineutral plasma, whose conductivity differs from the average conductivity, whose dimensions are less than the interelectrode distance, and which are situated across the current. Striations (domains) can appear when for a given current the conductivity is not single-valued. Under the conditions of GDF, this can occur under two circumstances: either when the drift velocity of electrons is a nonmonotonic function of the electric field or with a change in the ratio of the fractions of electron and ion currents. The first case[131] is observed in mixtures of inert and molecular gases with a composition of the gas mixture such that the magnitude of the average electron energy T_e (~1 eV) is determined by the losses to vibrational excitation of molecules, while the magnitude of the electron mobility μ_e is determined by elastic scattering of electrons by inert gas atoms. With an increase in E/N, accompanied by an increase in T_e, due to the Ramsauer effect, V_e can decrease. Thus, the same current can exist under different values of the electric field intensity. If the discharge voltage U is given, then the positive column will consist of regions with different electric field intensities E_1 and E_2, moving from the cathode to the anode with the drift velocity of the electrons (Fig. 20).

The second case is realized in the GDF, containing electronegative molecules; the instability is caused by dissociative attachment. A positive fluctuation of E leads, due to dissociative attachment, to a sharp increase in n_-. If, at the same time, the increase in the ionization rate and together with it of the quantities n_+ and n_e will be less than the increase in the attachment rate, i.e., an increase in n_- and decrease in n_e, then

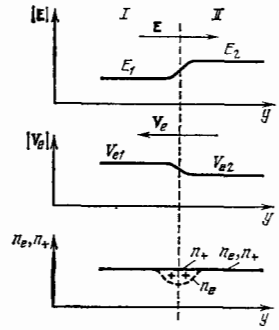

FIG. 20. Diagram illustrating the development of a step in the electric field with $\partial v_e/\partial E < 0$ in a system of coordinates moving with the average drift velocity of electrons. If regions I and II with electric field $E_1 < E_2$ are present in the positive column and if it turns out that $V_{e1} > V_{e2}$, then on the boundary separating these regions due to the motion of electrons, the volume charge, causing the stop in E will intensify, until the drift velocities V_{e1} and V_{e2} become equal. The characteristic time of this process is of the order of $\tau \sim l_0/(V_{e1} - V_{e2}) \sim E/4\pi e n_e V_e \approx 1/4\pi\sigma \sim 10^{-7} - 10^{-10}$ s, much less than the time for the separation boundary ($\sim h/V_e$) to move from the cathode to the anode.

due to local decrease in the conductivity of the quasineutral plasma, as a result of the condition $j = \sigma E$ = const fluctuations in E will be amplified (Fig. 21). The condition for the appearance of the instability in a homogeneous plasma, neglecting the drift motion of charged particles, is: $\hat{k}_a \hat{k}_a > \hat{k}_i k_i$.[25] In order to describe the formation and motion of inhomogeneities in this approximation the analogy of this phenomenon to the Gunn effect involving the formation of domains in semiconductors is often used (Refs. 5, 37, 132, 133 and others). In order for striations to form in an electronegative gas, attachment is important, so that the corresponding instability is called the attachment instability.[3] It was investigated experimentally in Refs. 5 and 41 in flows of air and the mixtures N_2+CO_2, air $+CO_2$, both in longitudinal and transverse discharges with $P = 10-100$ Torr and velocities $V = 30-150$ m/s.

Visually, the region of the positive column in the sta-

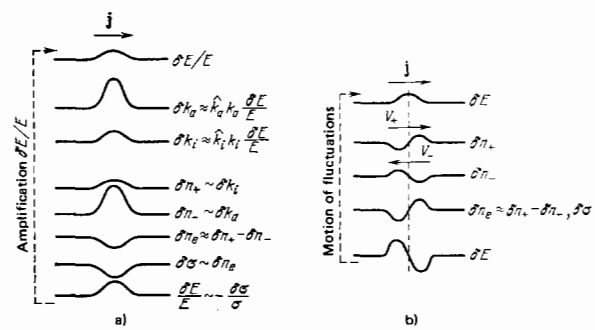

FIG. 21. a) The development of the attachment instability [if with a positive fluctuation δE the attachment rate exceeds the fluctuation in the ionization rate ($\delta k_a > \delta k_i$), then the given inhomogeneity will intensity; the instability increment, evidently, is of the order of the attachment rate $k_a N$, while the boundary of occurrence is $\hat{k}_a k_a \hat{k}_i k_i$]; b) mechanism for motion of the inhomogeneities due to drift motion of charged particles: the inhomogeneities move from the cathode to the anode with velocities comparable to the drift velocities of ions and electrons.

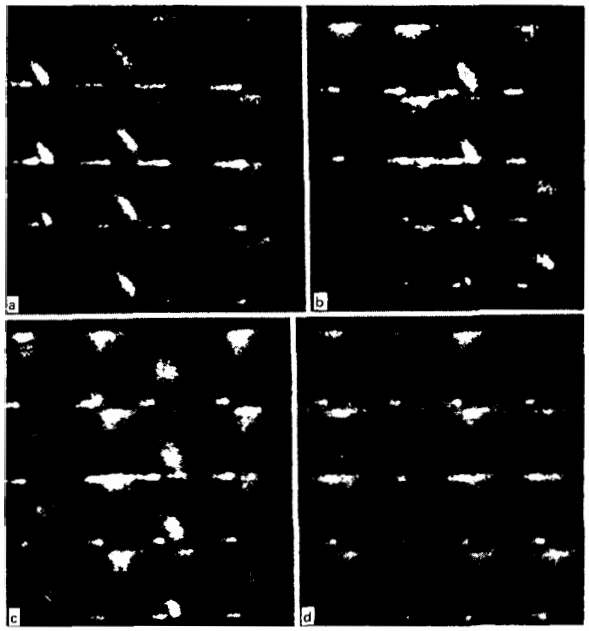

FIG. 22. Domains in a transverse discharge.[41] Air, $h=40$ mm, $J=0.1$ A, $V=100$ m/s. Exposure time 10^{-7} s, interval between frames is $3\cdot10^{-7}$ s. The cathode is at the bottom of the frame and the anode is at the top. The frames are read from the bottom to top and left to right. The direction of flow is from left to right. a) $P=40$ Torr; b) $P=60$ Torr; c) $P=80$ Torr; d) $P=100$ Torr.

ble state of the GDS practically does not luminesce. With the appearance of the attachment instability, the space between the electrodes begins to glow brightly, which is related to the fast motion of the glowing domains from the cathode to the anode. An example of the topology of the domains and the dynamics of their motion for different pressures is shown in Fig. 22. The onset of the instability is accompanied by the appearance of regular oscillations in the current and discharge voltage, whose frequency (10^5–10^6 Hz) increases approximately proportionally to pressure, while the amplitude of the current and voltage oscillations (with a relative magnitude of several percent) decreases with increasing pressure. A decrease in the current corresponds to the phase of formation and motion of domains from the cathode to the anode, while an increase in current occurs during the "entrance" of the domain into the anode. No more than one quite extended domain was observed at any one time.

The velocity of the domain, determined by high-speed photography, increases as the anode is approached, attaining a magnitude of $(1.5–2)\cdot10^6$ cm/s; this velocity increases with increasing pressure.

The investigation of the region of existence of domains as a function of the air pressure, flow velocity, average magnitude of the discharge current, and the interelectrode gap revealed its quite complicated form (Fig. 23). There exists a lower threshold value of the flow velocity (~50 m/s) and lower threshold value of the pressure (~30 Torr). No effect of the current density on the boundary for the appearance of the instability with $P>40$ Torr was observed.[41] Recently, the appearance of domains was observed with high energy inputs (Fig. 24).[164]

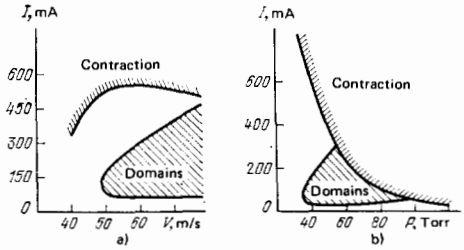

FIG. 23. Regions of existence of domains (dashed line) and boundary of instability in GDF relative to contraction in a gas-discharge chamber that is short along the flow ($L\sim h\approx h\sim 3.5$ cm).

We note that domains were also observed in a quasi-stationary discharge in air at the stage of current growth (with the discharge in a steady state[96]), in a combined discharge with low electric fields[134] after application of an ionizing pulse, in an alternating current discharge with frequency 10 kHz,[135] as well as in a non-self-sustaining gas discharge after switching off the current of an ionizing electron beam.[46]

Mechanism for attachment in inhomogeneous GDF. The domain is generated in the region near the cathode of the positive column with a sharp growth in the discharge current, caused, in particular, by the departure from the interelectrode gap of the high field region localized in the domain. Due to the absence of ionization in the volume, the conductivity of the plasma does not

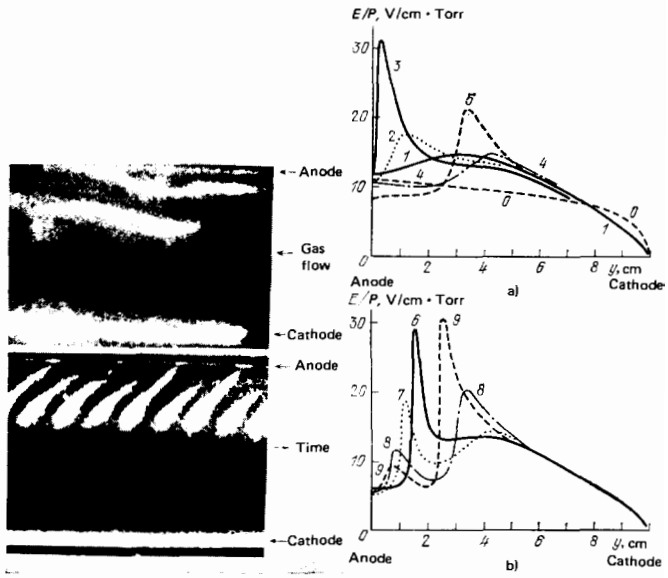

FIG. 24. Stratification in GDF with high levels of energy input into dry air. $P=30$ Torr, $h=10$ cm, $W\approx250$ J/g, $L\approx40$ cm, transverse discharge. Left: photograph of striations in the discharge (last third of the discharge chamber), exposure time $3\cdot10^{-7}$ s; a) linear scan of the luminescence of the positive column of the GDF across the chamber; b) calculation of the distribution of electric fields in the positive column of the GDF with accumulation of "detachers" N_d at different times. Curve 0 corresponds to the absence of "detachers" ($u=0$); $t(\mu s)=1036$ (1), 1042 (2), 1044 (3), 1053 (4), 1056 (5), 1064 (6), 1067 (7), 1071 (8), and 1074 (9).

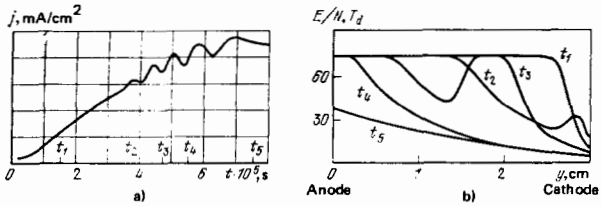

FIG. 25. Formation of domains. a) Oscillogram of the current in a quasistationary discharge in air with the presence of domains[95] (air, $N \approx 2 \cdot 10^{18}$ cm^{-3}); b) calculation of the distribution of fields at the stage of a steady state current under conditions (Ref. 136) close to those in the experiment.[96]

have time to increase sharply and the current jump occurs due to an increase in E/N, attaining maximum magnitude in the region near the cathode, which positive ions, generated in the region near the anode, do not have time to reach within the short time of the jump. Due to the jump in E/N, the attachment instability develops in the region near the cathode: the quantity n_-/η_e increases (Fig. 25).[4)]

The velocity of the domain formed can be found from the nonstationary equations of balance of the number of charged particles in the approximation of a quasineutral plasma:

$$\left.\begin{aligned} &\frac{\partial n_e}{\partial t}+\frac{\partial}{\partial y}\left(-\mu_e n_e \frac{j}{\sigma}+n_e V\right)=(k_1-k_a)\,n_e N-k_e n_e n_+ +k_d n_- N_d+a,\\ &\frac{\partial n_-}{\partial t}+\frac{\partial}{\partial y}\left(-\mu_- n_- \frac{j}{\sigma}+n_- V\right)=k_a n_e N-k_r n_+ n_- -k_d n_- N_d,\\ &n_+ \approx n_e+n_-, \quad \operatorname{div} j=0. \end{aligned}\right\} \tag{4}$$

This system of equations is a hyperbolic type system[87] and describes two waves, one of which corresponds to the perturbation, removed by the gas flow with velocity V, while the other propagates with velocity

$$\mathbf{V}_s=\mathbf{V}-\left|\frac{j_+ +j_-}{j_0}\right|\mu_e \mathbf{E}=\mathbf{V}+\frac{j_1}{j_0}\mathbf{V}_e. \tag{5}$$

If the removal by the gas flow is neglected, then small perturbations in the positive column propagate from the cathode to the anode and, in addition, for $n_- \ll n_e$, $V_s \approx V_- \sim 10^4$ cm/s, while for $n_- \gg n_e$, $V_s \approx V_e \sim 10^6$ cm/s.

In the homogeneous quasineutral plasma model,[5,37] it has been shown that $V_s^{\text{hom}} \approx V_e \nu_a [\tau_\varepsilon + (1/4\pi\sigma)] \sim 10^3$ cm/s (for air with $P \approx 50$ torr), which is two to three orders of magnitude smaller than the observed velocity of domains. This estimate shows that the influence of diffusion transport processes, taken into account in Ref. 37, can be neglected compared to the contribution of the drifting motion of charged particles.

The order of magnitude of the velocity of domains, determined experimentally, as well as the increase in the velocity of domains with an increase in pressure[41] and when the domain approaches the anode agree both with (5) and with the fact that the discharge is inhomogeneous along the electric current. For small perturbations, the velocity of the domains, according to (5), does not depend explicitly on the magnitudes of the rate constants of elementary processes of production and loss of charged particles in the volume of the positive column and is determined uniquely by the quantities V, V_e, and j_1/j_0. It is evident form (5) that the positive column of the discharge is dispersive with respect to concentration waves (V_s increases with increasing n_-/n_e). For this reason, with the motion of waves with $\delta(n_-/n_e) > 0$, the slope of its front will increase until a "shock" appears. The distance over which this steepening occurs depends on the wavelength and amplitude. Such a shock cannot form on the front of a wave with $\delta(n_-/n_e) < 0$ (a good analogy here is the formation of shocks in gas dynamics with the motion of compression and rarefaction waves). The partial (ion and electron) currents are discontinuous, while the normal component of the total current is continuous on the shock. In a two component plasma ($n_- = 0$) with constant charged particle mobility, the shocks under consideration are impossible due to breakdown of quasineutrality. An examination of the conditions for the continuity of currents on both sides of the shock shows[87] that the shock can move only from the cathode to the anode and, in addition, the region with high ion currents is located on the cathode side and for a wave with finite amplitude the velocity of propagation of the shock relative to the stationary medium turns out to be equal to

$$V_s=-\sqrt{V_{s1}V_{s2}}\frac{j}{|j|}, \tag{6}$$

where V_{s1} and V_{s2} are the velocities of propagation of small perturbations on different sides of the shock. Estimates of the velocity of propagation of a domain according to (6) agree well quantitatively with experimental data. The jumps in the partial currents on the shock must be accompanied by a jump in the normal component of the electric field, so that quasineutrality breaks down and volume charges appear on the shock. The thickness of the shock is of the order of the characteristic dimension of the breakdown in quasineutrality $l_\sigma \sim V_e/4\pi\sigma$ and is much less than the characteristic dimensions of the positive column. An estimate of the magnitude of the dissipative dimension l_D, owing to ambipolar diffusion, shows that $l_D < l_\sigma$.

The picture of the motion of domains in an inhomogeneous plasma examined above explains the following: the magnitude of the velocity and direction of motion of domains, including also the case with a finite domain amplitude, the reasons for the appearance of regular oscillations and the conditions for their appearance, the role of the direction of flow velocity and the magnitude

[4)] Another mechanism, causing local growth in E/N and the appearance of the attachment instability, can be, as recently shown in Ref. 164, the process of accumulation of "detachers" in the inhomogeneous discharge with high energy inputs. Due to the inhomogeneous distribution of "detachers," which consist of radicals and excited particles and whose rate of formation increases sharply with increasing electric field, i.e. from the cathode to the anode, a maximum can appear in the ion current density with sufficiently high energy inputs into the positive column. But, an increase in the positive ion current from the anode to the cathode requires switching on ionization, i.e., high electric fields. This, due to the attachment instability mechanism described above, also initiates growth of inhomogeneities, which move toward the anode (Fig. 24). In these experiments, the number of simultaneously observed striations was sometimes greater than unity.

of the flow velocity for self excitation of regular oscillations; the local nature of the formation of domains in GDF. These conclusions are confirmed by the results of calculations.[136,137,164]

b) Instabilities, accompanied by filamentary inhomogeneities

The ionization-heating mechanism for filamentation, discussed in Refs. 24–26, 33–38, 89–92, and 159–162, consists of the fact that due to heating of the gas in regions extended along the current, with increasing gas temperature its density decreases which increases E/N and leads to an exponential increase in the ionization rate, conductivity, and Joule heating and, as a result, to further intensification of the inhomogeneity. The characteristic time τ_i for the development of the ionization-heating instability is given by the approximate[37] equations

$$\tau_i \approx \left(1+\frac{\partial \ln \sigma}{\partial \ln (E/N)}\right)^{-1} \frac{\gamma}{\gamma-1}\frac{P}{\eta_T E} \tag{7a}$$

for $P/jE < \tau_{VT}$,

$$\tau_i \approx \sqrt{\tau_{VT}\left(\frac{\partial \ln k_{VT}}{\partial \ln T}\right)^{-1}\frac{P}{jE}} \tag{7b}$$

for $P/jE < \tau_{VT}$, where τ_{VT} and k_{VT} are, respectively, the time and rate constant for V–T relaxation.

A necessary condition for the formation of filaments can be approximately taken as the smallness of the time for the development of the instability compared to the passage time of the gas through the discharge zone $\tau_i < L/V$ or to the time for turbulent or diffusive dissipation $\tau_i < L^2/(D_T + D)$, if it is less than the passage time.

If the ionization rate depends on the magnitude of the energy input, for example, through its dependence on the concentration of electronic metastable species or vibrationally excited particles, then the ionization instability, likewise leading to the formation of filaments, can develop. The processes that increase the total rate of ionization with constant E/N are as follows: step ionization of electronic metastable species; increase in the concentration of fast electrons with an increase in the degree of vibrational excitation of molecules[161]; associative ionization of highly vibrationally excited molecules.[99]

Due to the nonuniform distribution of electric fields and the specific volume energy inputs in different zones of the GDF (positive column, anode region), these zones are not equally sensitive to the development of ionization and ionization-heating instabilities.

The decreasing I–V curves for the regions near the electrodes in regimes with current densities less than normal lead to nonuniform distribution of current density near their electrodes, which in its turn can be a quite strong perturbation for the development of contraction.[66,163]

On the whole, the process of contraction of GDF is a complex and insufficiently studied phenomenon, so that based on theoretical models, it is not yet possible to

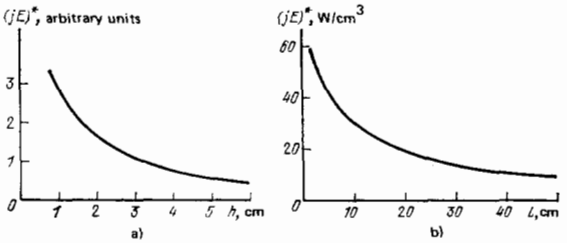

FIG. 26. Limiting volume power of GDF $(jE)^*$ as a function of[42]: a) the interelectrode distance h (longitudinal and transverse discharges); b) length of the discharge chamber along the gas flow L (transverse discharge).

determine the threshold values of the GDF parameters (P, jE, W), corresponding to the appearance of filaments and breakdown of the interelectrode gap. At the present time these parameters are determined only experimentally.

1) *Experimental investigations of threshold conditions for transition of GDF into a contracted discharge (CD).* The transition to a CD is determined by the "limiting characteristics" of the discharge:

a) J^*, the current for transition of GDF into CD; since in GDF, the quantity E depends weakly on J, J^* is proportional to the power of the discharge;

b) $(jE)^*$, the limiting volume power of the GDF $(W \cdot cm^{-3})$;

c) W^*, the limiting energy input into the discharge $(J \cdot g^{-1})$.

The limiting characteristics of the GDF depend on the geometry of the discharge chamber, the flow parameters, the composition of the gas mixture, and so on, and they can be changed by electromagnetic, gas-dynamic and other actions on the discharge.

2) *Effect of discharge geometry.* The quantities J^*/L and $(jE)^*$ decrease with increasing interelectrode gap h and length L of the discharge chamber along the flow (Fig. 26).[42,138,139] The quantities J^* and $(jE)^*$ greatly depend on the construction, geometrical dimensions, and cleanliness of the electrode surfaces.[58,60,61]

The quantity $(jE)^*$ begins to decrease appreciably due to the gas-dynamic inhomogeneities of the flow, inhomogeneity of the state of the electrode surfaces, and so on, when the size of the cathode across the flow l begins to exceed h.[58,62] With careful working of the electrodes and special equalization of the gas flow velocities along l, it is possible to obtain high energy inputs on long (~1 m) electrodes as well.[58,62]

The contraction of the discharge visually in the case of wide plate-like cathodes occurs by irregular volume formation of small arcs, removed by the flow, which are not necessarily accompanied by the formation of a stationary cathode spot. With narrow plate-like cathodes, contraction occurs with the formation of a cathode spot, which then initiates the filamentation of the plasma column.[60]

3) *Effect of flow parameters.* With an increase in

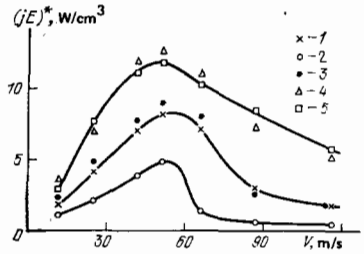

FIG. 27. $(jE)^*$ as a function of the flow velocity in a longitudinal discharge with different diameters of openings in the turbulence-creating grids.[142] 1) ∞, 2) 4, 3) 8, 4) 17, and 4) 24 mm.

pressure P, the limiting characteristics of the discharge decrease (Fig. 23). The characteristic magnitude of P (~30–150 Torr), for which the energy characteristics of the discharge drop sharply, depends strongly on the construction of the gas discharge chamber.

In the case of a discharge in dry air and commercial-grade nitrogen, there exists a critical temperature T^*, which depends on the gas density, below which the GDF cannot exist.[59] As the gas density increases, in the range $N=(1.4-6\ 4)\cdot 10^{18}$ cm^{-3} T^* increases from 120 to 380 K. As the flow velocity V increases, the quantity $J^*(V)$ goes through a maximum (Figs. 23 and 27) (V_{max} ~30–300 m/s), whose position and magnitude are determined, in particular, by the geometry of the discharge chamber.[42,117] For low velocities, the quantity J^* increases approximately linearly with increasing V; in this case, the value of W^* in the gas flow corresponds to the value of W^* of a quasistationary discharge, for which the time of existence of the latter equals the passage time of the gas through the discharge zone.[97]

The velocity profile of the flow has a strong effect on the limiting characteristics of the discharge.[60] The influence of turbulence, as experiments show,[140-142] is not single-valued (Fig. 27). As the degree of turbulence of E increases, $(jE)^*$ first decreases and, beginning with some value of E, $(jE)^*$ increases and then saturates.

In a number of papers,[9,19,10,141-146] it is noted that the increase in the degree of turbulence has a positive effect on the limiting characteristics of the discharge; at the same time, in some cases,[62,97,140] it is noted that turbulence can have a negative effect on the stability of the discharge, initiating the starting perturbations of the plasma density.

4) *Effect of gas composition.* An increase in the fraction of He in the gas mixture permits greatly increasing the working pressure of the GDF (up to atmospheric) (Refs. 16, 19, 145, 147, and others). As a result of plasmochemical reactions in the discharge, different chemical compounds can form; impurities were also specially introduced in order to study their influence on the discharge characteristics. As a rule, impurities ($NO_2, N_2O, CO, CO_2, SF_6, CCl_4$) have a negative action on the stability of the GDF.[56,61,67,68,71,72] A discharge in atmospheric air, as a rule, is more stable than in pure nitrogen or dry air.

5) *Effect of an external transverse magnetic field.* When the removal of ions is compensated by a magnetic field, the discharge voltage is minimum, while J^* increases appreciably (Fig. 11).[60]

6) *Effect of preionization.* Preionization can be carried out both at the inlet to the discharge chamber and in its entire volume. In the latter case, it can be pulsed (ultraviolet,[73,74] periodic short-time independent discharge either with a high-voltage pulse[119,148,149] or at the voltage maximum in an alternating current discharge with frequency 10^4 Hz,[118] pulsed electron beam,[150] and others) or stationary (electron beam,[38,63] HF discharge[151]). In the case of preionization at the inlet to the discharge chamber or pulsed volume ionization, the primary energy input occurs with a nonself-sustaining discharge in the decaying plasma, which increases the stability of the discharge at high pressures. A combination of preionization with low gas density in a supersonic nozzle and subsequent energy input into the plasma, decaying in a diffuser, greatly increases the stability of the discharge and raises the working pressure at the discharge chamber outlet.[117] With stationary volume preionization, the charged particle losses in the volume of the positive column are compensated by ionization from an external source, which greatly increases $(jE)^*$.[38]

7) *The dynamics of a contracting GDF* were investigated in air and N_2 flows at $P=20-100$ Torr, $V=20-200$ m/s, so that the discharge parameters varied over the following intervals: $j=5-50$ mA/s^2, $E/N=15-60$ T_d, n_e

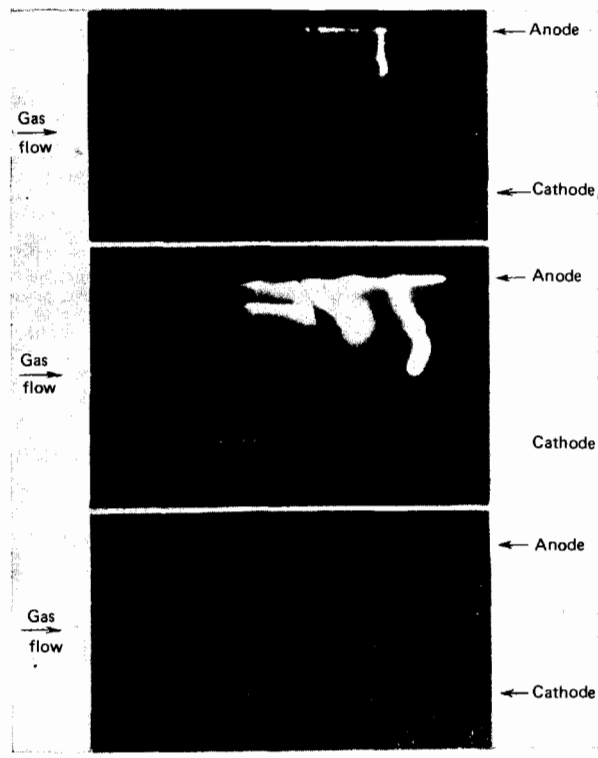

FIG. 28. Filamentary instability in different phases of development. Exposure time 10^{-6} s. Air, $h=10$ cm, $P=35$ Torr, $V=100$ m/s. Flow is from left to right, anode is at the top of the photographs.

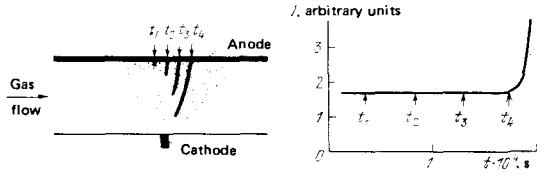

FIG. 29. Diagram of the development of the filamentation instability and contraction of GDF. The sharp increase in discharge current occurs as the top of the filament approaches the cathode.

$=10^9-10^{10}$ cm^{-3}.[152,153]

Photographs of the discharge made with the help of an image converter tube with an exposure time ~10^{-6} s show that as the discharge power increases [$jE-(jE)^*$], thin weakly luminescing filaments, extended along the current (Fig. 28), appear near the anode region of the discharge. The size of these filaments and their rate of appearance increase with increasing current; at a certain current density, arcing appears in the discharge gap. Contraction occurs in two stages: at the first stage, lasting several hundreds μsec after application of the overvoltage pulse, a bright inhomogeneity is generated near the anode and, at the second stage, this inhomogeneity extends to the cathode. At low pressures ($P<30$ Torr), the size of this inhomogeneity is large (~h), it is shaped like a pyramid, narrowing toward the cathode. For $P>30$ Torr, the inhomogeneity has the form of a narrow (diameter 2–4 mm) filament, whose diameter remains constant with motion toward the cathode. After the tip of the filament reaches the cathode at a distance of the order of its diameter there is a sharp decrease in discharge voltage and a significant increase in the current and brightness of the filament (Fig. 29).

The rate of growth of the filament drops as its tip approaches the cathode (Fig. 30a), which correlates with the decrease in the magnitude of E/N at the cathode. With the flow oriented from the cathode to the anode, the magnitude of the velocities of creation and motion of the filament increases, which is related, apparently, to the presence of domains in this regime (within the domains, the magnitude of E is greater than in the rest of the positive column).

The rate of growth of the filament V_f increases with

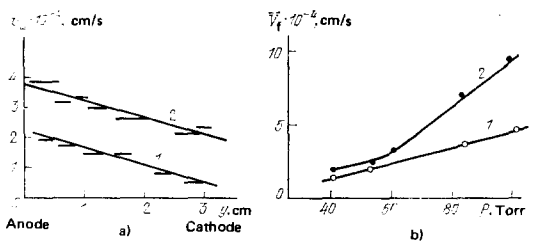

FIG. 30. a) Measurements of the velocity of the filament tip in the interelectrode gap for a discharge in a longitudinal air flow with $P=80$ Torr, $V=40$ m/s [direction of flow: 1) from anode to cathode; 2) from cathode to anode][152]; b) average velocity of the top of a filament as a function of gas pressure (1 domains are absent; 2 domains are present).[152]

gas pressure (Fig. 30b). In the regime without the domains (curve 1), the increase in V_f with pressure is related, apparently, to the increase in the magnitude of E/N. In the regime with domains (curve 2), V_f grows more strongly, the higher the pressure.

In the case of a nonself-sustaining discharge (including an alternating current discharge) or a discharge of short duration, the filamentary instability begins to develop at the cathode[154-157] or immediately in the entire volume of the positive column.[158] The velocity of the filament tips in this case is about 10^7 cm/s.[155] In many cases, an oppositely moving flament begins to move away from the anode.[157]

8) *Mechanism for filamentation in an inhomogeneous discharge.* When current flows in the GDF, perturbations of the conductivity, oriented preferentially along the current, can develop, in accordance with the instability mechanisms described above. Perturbations can develop in the volume of the positive column, as in the nonself-sustaining discharge, according to the heating mechanism; without ionization amplification, since there practically no ionization is produced. In the anode region, the discharge, on the other hand, is self-sustaining and for this reason, the instability increment is much greater here than in the positive column. At high ($P>30$ Torr) pressures, the minimum size of the perturbation transverse to the current, determined by ambipolar diffusion, is less than the thickness of the anode region. The filament originating in the anode region will grow toward the cathode at a velocity determined by the drift of ions and by ionization and heating processes near the tip of the filament. As it approaches the cathode region, the current moves along the channel of the filament, shunting the discharge gap. At low pressures ($P<30$ Torr), the minimum size of the perturbation, transverse to the current, usually exceeds the thickness of the anode region. In this case, a filament is not formed and the instability develops in the volume of the GDF according to one of the ionization-heating mechanisms.

The qualitative picture of the development of the filament instability described above takes into account the following destabilizing factors that affect the development of contraction: increase in the quantity $(jE/P)L/V$, increase in W, decrease in the role of ambipolar diffusion with increasing P, increase in the rate of relaxation with increasing P and T, formation of anode spots due to the decreasing I–V curve of the anode region of the GDF, pulsations in the plasma density due to gas-dynamic turbulence (especially at the anode), which can generate perturbations of the conductivity; stabilizing factors are: positive I–V characteristic of the positive column, low rate of ionization in the positive column, presence of preionization, and ambipolar and turbulent diffusion.

We note that, generally speaking, the mechanism of contraction through the formation of filamentary inhomogeneities at the anode, described above, does not exhaust all possibilities for the GDF. Thus, the decreasing dependence of the parameter $(k_a \cdot E)$ on E leads[12] to the appearance of an unstable phase of the

positive column of the discharge with a sharply decreasing I–V curve and high ion currents, which, apparently, were observed in discharges with SF_6, CCl_4, and other impurities, as well as in discharges with low gas temperatures.[59]

For high flow velocities, the motion of positive ions toward the cathode (in a transverse discharge) partially occurs along the boundary layer, where the gas velocity is low. The concentration of current in the boundary layer leads to its overheating and development of the heating instability.

Thus, although qualitatively the problem of the mechanism of contraction of an inhomogeneous discharge can be analyzed so as to agree with experiment, there are practically no quantitative analyses of it. In order to construct quantitative models of the contraction of GDF, it is necessary to develop further numerical methods for solving the given problem as well as to determine quite completely the experimental conditions under which the instability develops.

In conclusion, we can summarize that the described form of the glow discharge in the flow of a molecular gas differs considerably according to its mechanism from the well-known low-pressure glow discharge in tubes: on the whole, the self-sustaining discharge in the flow is essentially inhomogeneous along the lines of electric current and is locally nonself-sustaining in a large part of the volume. This characteristic of the discharge mechanism has a positive effect on the energy balance and stability of the discharge.

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Translated by M. E. Alferieff