

REVIEWS OF TOPICAL PROBLEMS

PACS numbers: **42.55.–f**, 52.20.Hv, **52.75.–d**, **52.80.–s**

Vortices in a gas-discharge plasma

A R Aramyan, G A Galechyan

DOI: 10.1070/PU2007v050n11ABEH006400

Contents

Abstract. Processes of vortex generation in a weakly ionized gas are reviewed in circumstances where a high-speed flow propagates along the gas discharge and acoustic waves interact with a positive column. Results on the effect of longitudinal gas flow on the positive-column properties are presented. It is shown that in certain conditions the gas flow in the positive column gives rise to vortices that cause the plasma to mix radially, producing a uniformly excited gas at high pressures. Results concerning the interaction of acoustic waves with low-temperature plasma are reviewed, and the acoustic-stimulated formation of vortex motion leading to an uncontracted discharge at elevated pressures is discussed. Also examined are flashes of superluminescence in an argon discharge caused by an abrupt transition of a positive column containing acoustic vortices from the uncontracted state to the contracted one at heightened pressures; this transition is understood to occur because of the turbulent-to-laminar transition in the acoustic flow. Finally, a gas-discharge acoustically induced laser is described.

1. Introduction

The origin of this work lies in the years when quantum electronics was only beginning to develop, when the problem of building a carbon dioxide laser with high specific lasing power had been correctly formulated, i.e., gas lasers at elevated pressures were being designed. This period began with intensive studies of discharges in a longitudinal gas flow, and the goals of these studies were to prevent discharge pinching from occurring when the gas pressure was raised, investigate the possibilities of removing heat produced by electric current in the discharge area from the tube, and generate a homogeneous, uncontracted positive column at high pressures.

In the first studies conducted by Cottingham and Buchsbaum [1] and Gentle et al. [2] and dealing with the effect of flowing gas on the longitudinal electric field strength, it was found that when the flow goes from laminar to turbulent, i.e., when vortices begin to form in the positive column, there is a sudden surge of electric power being absorbed by the discharge, which then gradually increases with gas velocity. This phenomenon is caused by a large loss of charged particles at the tube's wall due to turbulent diffusion which is much stronger than the classical ambipolar diffusion of charges in a plasma [3]. The increase in the recombination rate of charged particles at the tube wall leads to an increase in the ionization rate and, correspondingly, in the longitudinal electric field strength. Granatstein et al. [4–7] examined the fluctuation in the electron concentration in the discharge caused by turbulent flows of gas along a positive column. Later on, Chebotaev [8] pointed out that the diameter of the plasma column depends on the rate of gas flow. Diagrams representing the dependence of the diameter of the positive column on flow rate and gas pressure, obtained through experiments, can be found in Refs [9, 10]. The researchers found that at low pressures and flow rates, when the Reynolds number is smaller than a certain critical value, an increase in gas velocity within the laminar-flow limits leads to contraction of the positive column, an increase in the concentration of charged particles at the discharge axis, and a drop in electron temperature. However, when the Reynolds number becomes larger than the critical value, an increase in

A R Aramyan, G A Galechyan Institute of Applied Problems of Physics, National Academy of Sciences of the Republic of Armenia,
25, Hr. Nersessian Street, 375014 Yerevan, Republic of Armenia
Tel. (37410) 24 10 59. Fax (37410) 28 18 61. E-mail: ara@iapp.sci.am, galechian@web.am

Received 23 April 2007, revised 1 August 2007
Uspekhi Fizicheskikh Nauk **177** (11) 1207 – 1230 (2007)
10.3367/UFNr.0177.200711c.1207
Translated by E Yankovsky; edited by A Radzig

gas velocity leads to forming vortices in the flow and increasing the diameter of the plasma column. Paper [10] reports on the results of an investigation into ionization waves in a gas flow; it was shown that a rise in the flow rate causes an increase in the diameter of the column and an elongation of striations, i.e., their merging and total removing of transverse and longitudinal gas inhomogeneities from the discharge. The authors analyzed the mechanisms of influence of a gas flow on the properties of a plasma column. They revealed that the discharge current and all other parameters of the discharge are modulated with the gas pressure and velocity as the gas flow propagates along a positive column. The dependence of the amplitude and frequency of the oscillations generated by a gas flow in the positive column on the flow parameters was examined in Ref. [11].

Studies of the interaction between acoustic waves and a plasma have revealed that a number of processes running in a discharge with sound are similar to the phenomena occurring in a gas-flow discharge. Raising the intensity of the acoustic wave above a certain value leads to contraction of the positive column and a drop in electron temperature. A further increase in sound intensity results in an increase in the diameter of the plasma column and the formation of a homogeneous, uncontracted discharge at high gas pressures. A drop in the gas temperature and a rise in the electron energy in the plasma [12–14] accompany this. The similarities of the phenomena occurring in a gas-flow discharge and in the field of an acoustic wave have been studied in Ref. [15]

An intense acoustic wave in the discharge tube forms an acoustic flow which generates vortex motion in the discharge that mixes the plasma in the radial direction, leads to decontraction of the positive column, and forms a homogeneous stabilized discharge. If the acoustic wave in a homogeneous, depinched positive column under elevated gas pressure is switched off, the discharge is pinched back into a narrow filament, which causes a sharp drop in electron concentration at the tube's periphery. This in turn leads, as a result of recombination and relaxation, to population inversion of the levels, which produces a flash of superluminescent radiation [16–18]. This prompted a study of the physical mechanism of the flashes of superluminescence, which is related to the transition of the discharge from the uncontracted state to the contracted. This was then used to describe the processes in a laser, which were induced by an acoustic wave.

2. The plasma column in a longitudinal gas flow

The main purpose for gas flowing along a discharge is to decontract a pinched positive column at high pressures, to remove the heat released by the electric current in the positive column, and to increase the energy deposition into the discharge.

A gas flowing along the positive column is widely used to suppress transverse (pinching) and longitudinal (striating and domenizing) instabilities in the discharge.

Studies of discharges in a longitudinal gas flow have revealed that an increase in the gas-flow rate that remains within laminar limits (with the current and gas pressure remaining constant) reduces the diameter of the discharge, the electron temperature, and the longitudinal electric field strength, but elevates the current density in the near-axis region of the plasma column [19, 42]. Raising the gas-flow rate in a pinched discharge above a certain value in the positive column leads to the formation of vortices, in view of which the plasma gets mixed in the radial direction. The diameter of the discharge increases in the process, and the discharge fills the inner volume of the discharge tube. As the flow becomes turbulent, the electric power absorbed by the discharge increases and from then on it grows monotonically with increasing the gas-flow rate. Gentle et al. [2] explained this phenomenon by the exceptionally high loss of charged particles at the tube's wall caused by turbulent diffusion which is much stronger than the classical ambipolar diffusion of charged particles in a discharge.

Plasma density fluctuations in the discharge caused by a longitudinal turbulent flow became a subject of investigation in the works of Cottingham and Buchsbaum [20], Bugnolo [21], Granatstein and Buchsbaum [22, 24], and Niemeyer and Ragaller [23]. Moreover, the plasma column in a turbulent flow became a model for studying the scattering of electromagnetic waves by plasma fluctuations. Granatstein [25], Feinstein and Granatstein [26], Granatstein and Buchsbaum [27], and Granatstein and Philips [28] have studied various aspects of such scattering. For instance, Granatstein and Buchsbaum [27] found that as the Reynolds number increases within laminar limits ($0 < \mathrm{Re} < 1600$), the signal produced by the plasma-scattered wave remains at a low level. With the onset of forming turbulent motion in a flow ($1600 < \mathrm{Re} < 6000$), the intensity of the wave scattered by the plasma abruptly increases twentyfold.

Discharges with a high-speed gas flow are used in high-power compact convective carbon dioxide lasers with a high specific lasing power [29–37]. Deutsch et al. [30] reported that, thanks to the high-speed circulation of a gas mixture through the discharge region, continuous induced emission from a carbon dioxide laser with a power of 140 W was achieved (the discharge tube was 1.35 cm in diameter, and 10 cm long). The specific lasing power amounted up to 9 W cm^{-3}, while without circulation the mean value was 0.25 W cm^{-3}. The length of the carbon dioxide lasers built earlier for generation of laser radiation with a specific power of several kilowatts amounted to hundreds of meters. For instance, Patel [29] reported that 10.6-μm (8.8-kW) laser radiation had been generated with the use of a 200-m long discharge region.

Brown and Devis [32] described a gas-discharge carbon dioxide laser with gas-mixture circulation that emitted 27.2-kW radiation (244 cm long, 6.3 cm wide, and 53 cm height) with 17.2% efficiency. A review of high-power continuous carbon dioxide lasers can be found in Ref. [33].

Most papers published at the beginning of the 1970s and the 1980s and dealt with questions concerning the building of convective carbon dioxide lasers were devoted to paving the ways for the researchers to avoid contraction of discharges as the gas pressure rises, to elevate the electric power deposition to a discharge, and to achieve homogeneous excitation of the gas at high mixture densities in the laser's active region.

Subsequently, gas-flow discharges were used in other applications, such as plasmachemical reactors, plasmatrons, and arc discharges, to achieve high current densities.

Later, the various aspects of the gas-flow discharges became problems in their own right due to the fact that such a type of discharge had been studied only scantily and is rich in various physical phenomena at the juncture of low-temperature plasma physics and gasdynamics. The discharges considered were those with gas flows along the positive column in cylindrical tubes or chambers with

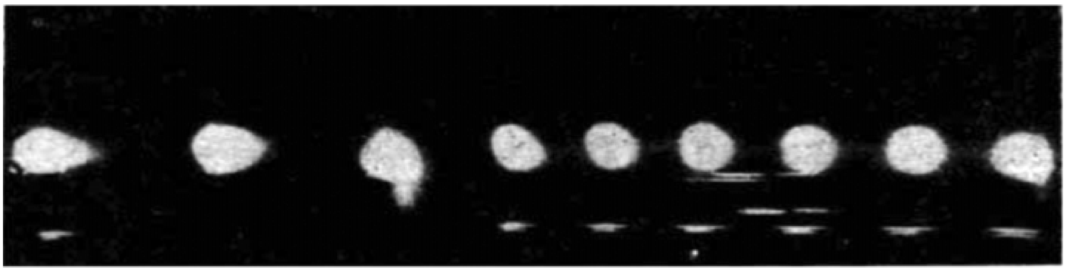


Figure 1. Photograph of striations in a helium flow inside a tube 1 cm in diameter. The direction of flow was from left to right (from cathode to anode), $p = 14$ mmHg, and the current was 20 mA. Near the first three striations the gas velocity $V = 250$ m s^{-1}, and near the next six striations $V = 100$ m s^{-1} [10].

rectangular cross sections and, more than that, with gas flowing at right angles to the plasma column. The review by Velikhov et al. [38] gives the results of studies on gas-flow glow discharges with sectioned cathodes.

In the present section we discuss the various features of the positive column of a glow discharge in a longitudinal gas flow with a cylindrical configuration. We analyze the different aspects of the gas circulation effect on the parameters of the plasma column within the laminar flow mode and in the transition region from laminar flow to turbulent flow, where the discharge parameters undergo oscillations caused by the vortex motion of the plasma.

2.1 Laminar gas flow along the plasma column

Laminar flow along a tube is subjected to certain perturbations that emerge, for instance, because of the conditions at the tube's entrance or because of the presence of a boundary layer on the streamline body (roughness of the wall or nonuniformity of the external flow). Each theory tended to follow the development of the perturbations with time, which are superimposed on the main flow, with the shape of these perturbations being defined in each case individually. The main question was: Do the perturbations die out with the passage of time or do they become stronger? The damping of the perturbations with time would mean that the main flow is stable, but if they become stronger, the main flow is unstable and a transition to turbulent flow is possible. Following this line of reasoning, researchers tried to build a theory of stability of laminar flow that would enable theoretically determining the Reynolds number for a given laminar flow [39, 40].

The distribution of the gas velocity over the tube's radius in the case of laminar flow is parabolic and can be described by the following formula

$$V = V_0(1 - \rho^2)\,, \tag{1}$$

where V_0 is the gas velocity along the tube's axis, and $\rho = r/R$, with R being the inner diameter of the tube, and r the radial coordinate.

Such a distribution of the gas velocity over the cross section of the tube sets in because the gas is viscous and the tube has walls. According to the definition of viscosity [41], the velocity gradient of directed motion in a gas, $\mathrm{d}v/\mathrm{d}\rho$, induces a force acting on the gas along the velocity gradient, which in our case is directed along the radius of the tube from walls to axis:

$$F_{\mathrm{r}} = -\eta\,\frac{\mathrm{d}v}{\mathrm{d}\rho}\,. \tag{2}$$

This force is similar to pressure, and in a plasma with a gas flow it is transferred radially from neutral particles to ions and electrons in collisions involving these particles. However, since the mass of an ion is many times greater than the electron mass, the force F_{r} mainly acts on ions, causing them to be displaced in the radial direction, which leads to a more squeezed distribution of ions over the radius of the positive column than in the absence of a gas flow. The plasma quasineutrality condition implies that the radial distribution of the electron concentration correlates with the ion distribution.

Figure 1 shows a photograph of a contracted, striated positive column of a glow discharge in a longitudinal laminar flow of gas inside a tube 1 cm in diameter. The flow's direction is from left to right (from cathode to anode) with a helium pressure $p = 14$ mmHg, and an electric current $I_{\mathrm{d}} = 20$ mA. The visible limit of the diameter of immobile striations in the plasma column in the laminar flow is about 0.5 cm, which is roughly half the inner diameter of the discharge tube. In the region of the first three striations, the flow rate $V = 250$ m s^{-1}, and in the region of the next six striations $V = 100$ m s^{-1} [10]. After the third striation (from the left), the gas is exhausted by the first pump. After the tenth striation it is exhausted by the second pump, which means that in a single tube, simultaneously, and under the same pressure, immobile striations are formed with different laminar flow rates, and since the first three striations exist at velocities much higher than the next six, the first two striations have a pronounced aerodynamic shape (with a tail). The third striation is somewhat distorted because of the hole through which the gas is exhausted by the first pump. It should also be noted that this photograph shows very distinctly that the distance between the striations formed in the positive column of the glow discharge depends on the gas flow rate. A theory of ionization waves in a longitudinal laminar gas flow in a glow discharge that is in good agreement with the experimental results can be found in Refs [10, 42].

To study the effect of longitudinal laminar flow on the parameters of the positive column from the quantitative angle, we present expressions for the radial fluxes of electrons and ions in a steady glow discharge of electropositive gas with longitudinal circulation.

The gas flows from cathode to anode, in which case one finds

$$\Gamma_{\mathrm{e}} = -D_{\mathrm{e}}\nabla n_{\mathrm{e}} - \mu_{\mathrm{e}} n_{\mathrm{e}} E_{\mathrm{r}} - \frac{\mu_{\mathrm{e}} n_{\mathrm{e}}}{e}\,\eta_{\mathrm{e}}\nabla V\,, \tag{3}$$

$$\Gamma_{+} = -D_{+}\nabla n_{+} + \mu_{+} n_{+} E_{\mathrm{r}} + \frac{\mu_{+} n_{+}}{e}\,\eta_{+}\nabla V\,, \tag{4}$$

where Γ is the flux density of the charged particles, D is the diffusion coefficient, μ is the mobility, E_r is the strength of the radial self-consistent electric field, η is the viscosity coefficient, V is the velocity of the laminar gas flow, and the subscripts 'e' and '+' stand for electrons and positive ions, respectively. Equating the radial flux densities of electrons and ions at the periphery of the discharge, viz.

$$\Gamma_+ = \Gamma_e \,, \tag{5}$$

and using the quasineutrality condition of the plasma, viz.

$$n_+ \approx n_e = n \,, \tag{6}$$

we obtain from Eqns (3)–(6) the formula for the self-consistent electric field strength:

$$E_r = \frac{D_+ - D_e}{\mu_+ + \mu_e} \frac{\nabla n}{n} - \frac{\nabla V}{e} \frac{\mu_e \eta_e + \mu_+ \eta_+}{\mu_e + \mu_+} \,. \tag{7}$$

Substituting formula (7) into Eqns (3) and (4), we get

$$\Gamma = -D_a \nabla n + Bn \nabla V \,, \tag{8}$$

$$D_a = \frac{D_e \mu_+ + D_+ \mu_e}{\mu_+ + \mu_e} \,, \tag{9}$$

$$B = \frac{\mu_+ \mu_e}{\mu_+ + \mu_e} \frac{\eta_+ - \eta_e}{e} \,. \tag{10}$$

Bearing in mind that $D_e \gg D_+$ and $\mu_e \gg \mu_+$, we can simplify formulas (7) and (8):

$$E_r = -\frac{kT_e}{e} \frac{\nabla n}{n} - \frac{\nabla V}{V} \left(\eta_e + \eta_+ \frac{\mu_+}{\mu_e} \right) , \tag{7'}$$

$$\Gamma = -D_+ (1 + \gamma) \nabla n + \mu_+ \frac{\eta_+ - \eta_e}{e} n \nabla V \,, \tag{8'}$$

where T_e is the electron temperature, and $\gamma = T_e / T_+$, with T_+ being the ion temperature. Formula (7) for the radial self-consistent electric field consists of two terms: the first term gives the discharge field in the absence of a gas flow [43], and the second term is related only to gas circulation and at $V = 0$ vanishes.

From Eqn (7) it follows that E_r in the positive column with longitudinal laminar flow increases with gas velocity. This increase in the self-consistent electric field strength E_r is much larger at the periphery of the discharge, where the gas velocity gradient is higher.

To determine the concentration distribution of charged particles over the radius of the positive column, we write out the ionization–diffusion equation subjected to the condition that ionization occurs primarily by direct electron impact, while these particles disappear through diffusion to the tube's wall:

$$\operatorname{div} \Gamma = K_{\text{ion}} n \,, \tag{11}$$

where K_{ion} is the ionization rate.

In Eqn (11), the allowance for laminar gas flow is contained in expression (8) for the flux density of the charged particles (in the second term).

Substituting formula (8) into Eqn (11) and passing to circular cylindrical coordinates, we arrive at an equation for the concentration distribution of charged particles over the radius of the positive column for different values of V_0:

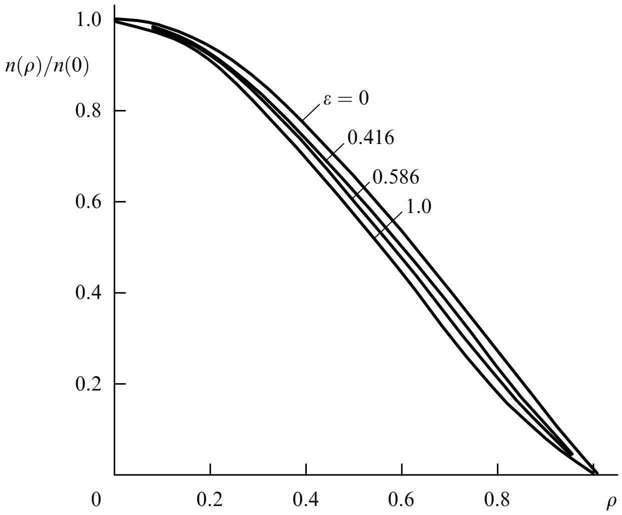


Figure 2. Diagrams representing the distributions of the relative concentration of charged particles over the radius of the positive column for different values of ε ($\varepsilon = V_0 B / D_a$) in a laminar gas flow directed along the discharge tube [19, 42].

$$\frac{d^2 n}{d\rho^2} + \left(\frac{1}{\rho} + \frac{2 V_0 B}{D_a} \rho \right) \frac{dn}{d\rho} + \left(\frac{4 V_0}{D_a / R^2} + A^2 \right) n = 0 \,, \tag{12}$$

where $A^2 = K_{\text{ion}} R^2 / D_a$. At $V = 0$, equation (12) transforms to the Schottky equation [43] corresponding to a positive column without gas flow. The solution of Eqn (12) that satisfies the homogeneous boundary conditions

$$\frac{dn(0)}{d\rho} = 0 \,, \qquad n(1) = 0 \tag{13}$$

is written down as

$$n(\rho) = n(0) \exp(-\varepsilon \rho^2) \, F_a(\alpha; 1; \varepsilon \rho^2) \,, \tag{14}$$

where F_a is a confluent hypergeometric function [44], and

$$\varepsilon = \frac{V_0 B}{D_a} \,, \tag{15}$$

$$\alpha = 1 - \frac{A^2}{4\varepsilon} \,. \tag{16}$$

Figure 2 shows the distributions of the relative electron concentration over the radius of the positive column, calculated by formula (14) for different values of ε.

At $\varepsilon = 0$, i.e., $V = 0$, formula (14) goes over into the solution for the distribution of electron concentration n_e over the cross section of the discharge in the absence of a gas flow: $n(\rho) = n(0) J_0(2.405\rho)$.

At $\varepsilon = 1$ and $\alpha = -1$, we have $n(\rho) = n(0) \exp(-\rho^2) \times F_a(-1; 1; \rho^2)$.

From Fig. 2 it follows that as the rate of laminar gas circulation increases, the distribution of the charged particles narrows.

The results of an experimental study of the effect of laminar flow on the parameters of the positive column of a glow discharge can be found in Ref. [42]. Measurements were done using a discharge tube 50 cm long and 10 mm in diameter with hollow cylindrical electrodes at both ends.

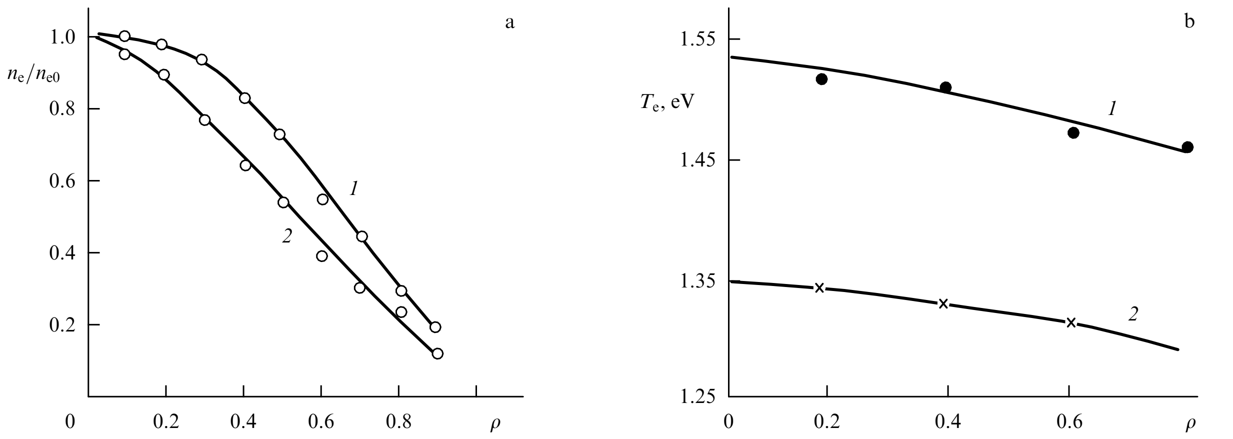


Figure 3. Distributions of the relative concentration of charged particles (a) and the electron temperature (b) over the radius of the positive column in argon at the pressure $p = 5$ mmHg inside a tube 1 cm in diameter and 50 cm long, and the current $I = 40$ mA: *1* — with no gas flowing, and *2* — with the gas flowing with the velocity $V = 10$ m s^{-1} [42].

The double electric probe technique was employed to determine the electron concentration and temperature distributions over the radius of the positive column in discharges both with laminar helium flow and without it.

Figure 3a displays the experimental curves for the dependence of the relative electron concentration on the radius of the positive column in argon at a pressure of 5 mmHg and a discharge current of 40 mA. Curve *1* represents the radial distribution of the electron number density in a discharge in the absence of a gas flow, and curve *2* represents a similar distribution but with a laminar gas flow with a rate of 10 m s^{-1}. The diagrams show that the distribution of electron concentration over the radius of the plasma column in a laminar flow is more abrupt than in the case without such flow. Longitudinal laminar circulation of the gas brings about the contraction of the positive column toward the axis. This results in a rise in the current density in the near-axis region of the discharge and a drop in electron temperature. Figure 3b depicts diagrams for the variation in the electron temperature along the radius of the positive column. We see that the electron temperature drops in the presence of a gas flow. The electron concentration at the axis increases with the rate of the laminar flow, so that at $V = 10$ m s^{-1} we have $n_{e0} = 1.77 \times 10^{10}$ cm^{-3}, while at $V = 0$ we have $n_{e0} = 1.5 \times 10^{10}$ cm^{-3}. It should also be noted that, in the presence of a gas flow along the discharge, the potential difference across the electrodes is smaller ($U_d = 0.5$ kV) than in the absence of such flow ($U_e = 0.65$ kV) in the conditions under study. Similar results have been obtained in experiments involving helium and nitrogen discharges.

Thus, as a result of theoretical and experimental studies it has been established that laminar circulation of gas at constant current and pressure causes contraction of the positive column, just as in thermal contraction [45], and this is accompanied by a drop in the voltage across the electrodes, a lowering of the electron temperature of the plasma, and an increase in electron concentration on the discharge axis. However, in the case at hand there can be no thermal contraction, since pinching occurs as a result of gas circulation (with the flow rate rising within the limits of the laminar mode of flow) which removes the heat produced by the current, and the gas temperature in the contracted column in a gas flow is lower than in the absence of such flow. Therefore, in the case at hand there are all the indications of contraction caused by the force of internal friction between neutrals and charged particles due to a velocity gradient; the contraction sets in when there is laminar flow and it is directed along the tube's radius.

In 1964, Gentle, Ingard, and Bekefi [2] presented the results of their studies of glow discharges in a longitudinal flow of argon inside tube 0.6 cm in diameter at $p = 20$ mmHg and a current of 60 mA. What they observed was that, under constant pressure and current in the tube, a rise in gas velocity from zero to $V = 40$ m s^{-1} leads to a drop in the electric field strength E from 3.6 to 2.8 V cm^{-1}. The researchers noted that they did not understand the mechanism that led to such a drop in E as the gas velocity grew within the limits of low circulation rates.

The results of studies of the effect of laminar flow on the parameters of the plasma column, given in Refs [19, 42], made it clear that the decrease in the longitudinal electric field strength with an increase in the argon velocity from zero to 40 m s^{-1} in Ref. [2] is related to the contraction of the positive column under laminar gas flow.

In his paper [33], DeMaria described how the phenomenon in which the diameter of the positive column diminishes as the gas velocity rises within the limits of laminar flow can easily be observed by using a longitudinal-flow cw carbon dioxide laser with laminar flow of the gas along the positive column. In such a laser, the heat released in the discharge is effectively removed through gas convection, and the temperature of the gas mixture in the active zone of the laser differs little from room temperature. Hence, the profile of the gain of the generated wave is independent of the gas temperature and is determined chiefly by the distribution of the electron concentration over the tube's radius. Having generated laser radiation at low circulation rates and low gas pressures, one should carefully monitor the size of the laser spot on the luminescent screen. An increase in the gas velocity gradually decreases the diameter of the laser spot. This effect can be observed within the ranges of those pressures and velocities of the gas at which there can be no sudden pinching of the discharge [45].

In a discharge with longitudinal laminar gas flow, a rise in the gas velocity leads to contraction of the positive column, which is accompanied by a drop in the longitudinal electric field strength, a rise in electron concentration in the near-axis

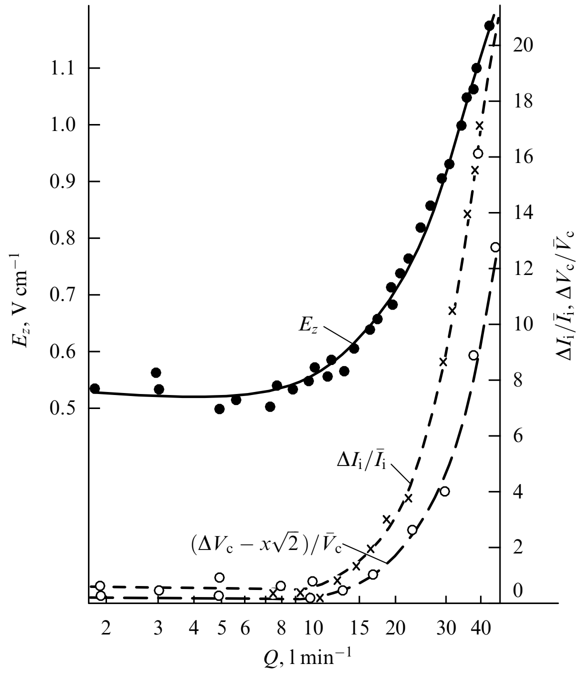


Figure 4. Diagram illustrating the effect of a gas flow on the longitudinal electric field strength and on the intensity of plasma fluctuations directed along the positive column inside a tube with a diameter of 2.2 cm at argon pressure $p = 5$ mmHg, discharge current $I = 1.5$ A, and electron temperature $T_e = 1$ eV [5].

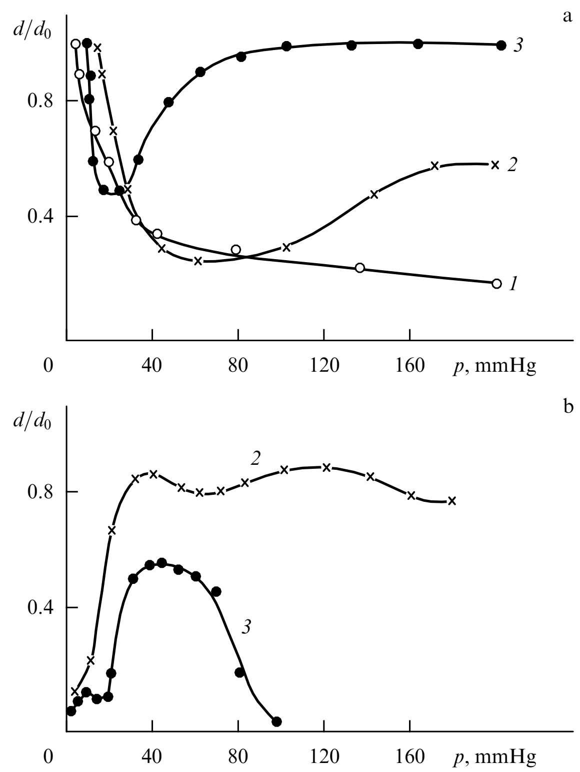


Figure 5. Diagrams illustrating the dependence of the diameter of the visible boundary of the positive column (a) and the amplitude of oscillations of the discharge current (b) on helium pressure inside a 30-cm long tube 1 cm in diameter at a discharge current of 30 mA for different values of flow rate [9, 10].

region of the plasma column, and a drop in electron temperature.

2.2 The effect of transition processes on the properties of the plasma column

A transition of a gas flow from laminar to turbulent mode occurs when, instead of dying out, oscillations build up in the flow. A specific feature of such a transition is the double nature of this motion. The transition can be characterized as a phenomenon in which the laminar flow becomes turbulent. In his article [46], Betchov noted that the flow in its transition from laminar to turbulent mode has lost its well-ordered structure but has not yet become completely disordered. Hinze [47] called such motion pseudoturbulent, since it is periodic in both space and time. Schlichting et al. [39] remarked that, as the transition point is approached, nearly sinusoidal oscillations appear in the tube. This transition is the least studied topic in the mechanics of fluids and gases, despite it having a history of more than a century. The situation with transition theory is well described in Refs [39, 46–48].

In this section we analyze the results of experimental studies of the effect of a flowing gas in the transition mode on the properties of a weakly ionized plasma column. But before we begin to describe the results of such studies, we would like to note that any oscillations that emerge in the gas flow manifest themselves in the discharge current in the form of modulation of the current's parameters which can be analyzed and from which one can extract information about the processes taking place in the gas flow. Electric probes immersed in the plasma also detect these oscillations. Furthermore, an antenna placed outside the discharge tube can be used to glean information about oscillations in the flow.

Figure 4 presents diagrams exhibiting the effect of a gas flow on the longitudinal electric field strength and on the intensity of plasma fluctuations directed along the plasma column inside a tube 2.2 cm in diameter at the argon pressure $p = 670$ Pa and the discharge current $I = 1.5$ A, with $T_e = 1$ eV [5]. What the diagrams show is that a rise in flow rate above a certain value leads to an increase in the longitudinal electric field strength. This rise in E_z is caused by vortex formation in the argon flow, a fact corroborated by the lower curve which characterizes the intensity of plasma fluctuations in the flow measured by a Langmuir probe (I_i is the mean value of the ion saturation current, and ΔI represents the fluctuating component).

The lowest curve characterizes the level of the wave (2.95 GHz) reflected from the positive column. The reflected wave travelled to the open end of a waveguide located opposite the tube. Figure 4 shows that a rise in fluctuations in the plasma begins at the same value of the flow rate at which the longitudinal electric field strength increases.

Now we turn to two papers [9, 10] published in the mid-1970s that present the results of studies of the effect of gas flow on the parameters of the positive column of a glow discharge. Such studies involved varying the gas pressure inside the tube at constant flow rate and discharge current.

Figure 5a depicts curves representing the dependence of the visible boundary of the diameter of the positive column on helium pressure inside the tube. The experiment was done inside a 30-cm long tube with an inner diameter of 1 cm, and the discharge current was 30 mA. The direction of gas flowing coincided with that of the electric current. Finally, the

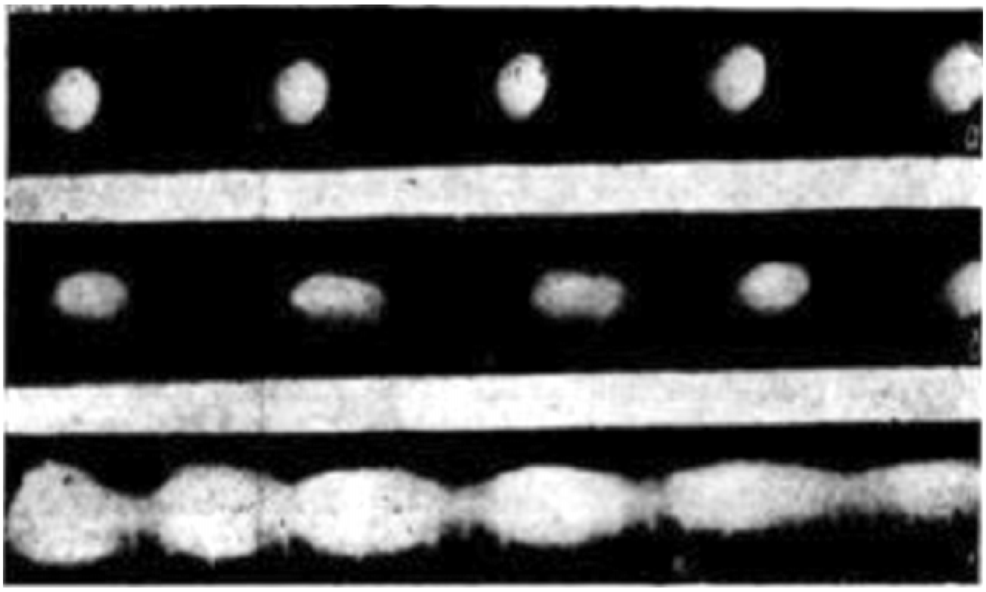


Figure 6. Photographs of contracted striations in a longitudinal helium flow inside a tube with an inner diameter of 1.0 cm, a discharge current of 20 mA, and a gas velocity of 240 m s^{-1} at various pressures: (a) 14 mmHg, (b) 27 mmHg, and (c) 32 mmHg [10].

diameter of the positive column was assumed equal to the diameter of the visible boundary of that column.

Let us analyze the curve corresponding to $V = 250$ m s^{-1}. Gas breakdown was achieved at a pressure of 0.01 mmHg. Up to 10 mmHg, the diameter of the positive column was equal to the inner diameter of the tube (diffusive discharge). At $p = 10$ mmHg, the discharge underwent contraction and the diameter of the positive column dropped rapidly to 5 mm. This process was accompanied by a decrease in the longitudinal electric field strength [49], the occurrence of modulation in the discharge current, and the generation of oscillations on the electric probes immersed in the plasma. Figure 5b shows the amplitudes of oscillations generated in the discharge as a result of a change in the flow modes along the positive column. An antenna placed outside the tube detected these oscillations. The occurrence of oscillations in the tube ($\sim$ 5 kHz) was accompanied by contraction of the discharge. In the process, vortices with diameters equaling that of the tube emerged, which corresponds to a pseudoturbulent mode of gas flowing. It was found that raising the gas pressure in the discharge leads to an increase in the diameter of the plasma column and a reduction in the oscillation amplitude. Here, one observes an increase in the Reynolds number, the splitting of large vortices into smaller ones, and a decrease in the oscillation amplitude. A further rise in pressure results in an increase in the discharge diameter, in complete decontraction of the discharge, and in its filling the entire volume of the tube. The oscillation amplitude decreases, the frequency grows to a value of about 800 kHz, and a region of well-developed turbulence establishes itself in the flow. Figure 5a also displays a diagram for a flow rate of 40 m s^{-1}. In this case, the diameter of the positive column in the helium flow after contraction and minor decontraction does not exceed $0.6d/d_0$ as the pressure is raised to 752 mmHg, $\mathrm{Re} = 3300$. The oscillation amplitude in the plasma does not decrease in the process (Fig. 5b) and remains the same as at $p = 23$ mmHg. Hence, the large Reynolds number of the flow in the plasma column does not guarantee the production of a homogeneous, stabilized decontracted discharge — high circulation rates are needed. For comparison purposes, we show in Fig. 5a the diagram for the dependence of the visible boundary of the diameter of the positive column on gas pressure in the absence of a flow. At a pressure of about 180 mmHg, the relative value of the discharge diameter is $0.2d/d_0$.

To clearly demonstrate how the decontraction of a discharge by a gas flow at high pressures actually develops, we display in Fig. 6 photographs of a discharge in a longitudinal helium flow inside a tube with an inner diameter of 1 cm, a current of 20 mA, and a gas velocity of 250 m s^{-1} [10, 42]. Figure 6a depicts standing striations in a contracted positive column in a flow directed from cathode to anode at a pressure of 14 mmHg (the diameter of the striations is 0.5 cm). It also shows the transverse and longitudinal inhomogeneities in gas excitation inside the discharge volume. In Fig. 6b we see that as the pressure grows to 27 mmHg, the striations get longer. A further rise in pressure to 32 mmHg leads to the boundaries of the striations becoming smeared, and the striations merge (i.e., destriation occurs). Moreover, the diameter of the positive column increases (decontraction), after which a homogeneous discharge sets in both in longitudinal and transverse directions.

Now let us turn to Fig. 7 which can provide us with information about the conditions in which vortices are generated in a flow [9, 10]. Figure 7 shows the dependence of the pressure difference Δp between the entrance and the exit of a 20-cm long tube with a diameter of 1 cm (the pressure difference Δp was measured by a U-type oil manometer) on the static pressure in the middle of the tube with the helium flow rate being 250 m s^{-1}. The curve has a kink at 20 mmHg, which coincides with the minimum of the curve representing the function $d/d_0 = f(p)$ in Fig. 5a at $V = 250$ m s^{-1}. The kink is an indication that at this gas pressure the nature of the flow changes. At 20 mmHg, the flow loses its stability. Immediately after this a new turbulent gas flow sets in. The curve $\Delta p = f(p)$ becomes less steep, since a part of the energy of the laminar (directional) flow is transformed into the energy of vortices which mix the gas transversely.

In the initial stage of the transition, in which the discharge becomes contracted, large-scale low-frequency vortices

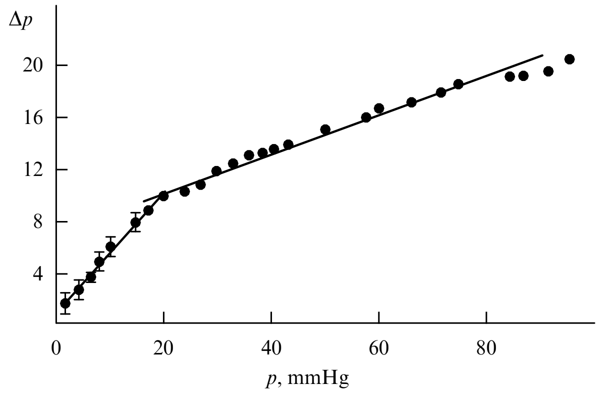


Figure 7. The pressure difference Δp between the entrance and the exit of a 20-cm long discharge tube with a diameter of 1.0 cm as a function of the static pressure in the middle of the tube [9, 10].

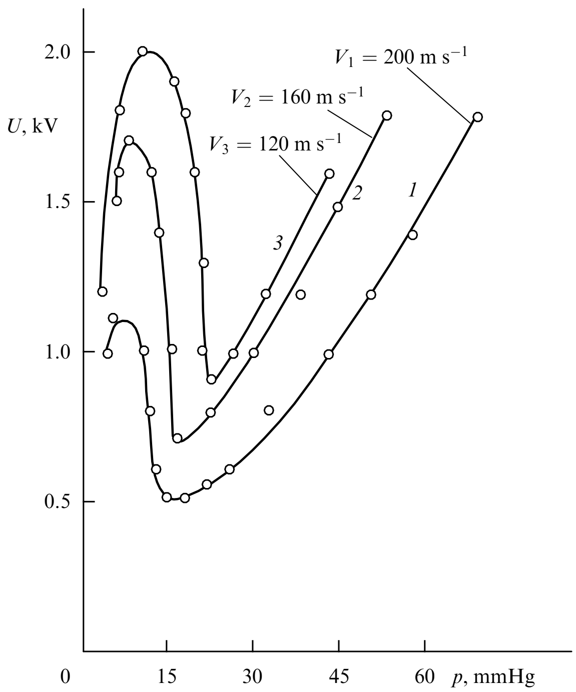


Figure 8. The voltage across the electrodes of a discharge tube as a function of the helium pressure in the tube (the direction of flow is from cathode to anode, and the tube's diameter is 1.0 cm). Curve *1*, $V_1 = 200$ m s^{-1}; curve *2*, $V_2 = 160$ m s^{-1}, and curve *3*, $V_3 = 120$ m s^{-1}.

emerge in the flow. These vortices set the entire positive column into oscillation, and the discharge may disintegrate into separate oscillating plasma channels. Such a mode of discharge burning was also observed by Chebotaev [8], who described a discharge sustaining mode in which the positive column oscillates as a whole, like a broom. As the gas density or the flow rate grows, i.e., the Reynolds number increases, large vortices split into small ones, and the flow goes over into a mode of small-scale high-frequency vortices which lead to complete decontraction of the discharge.

We will now examine a contraction of a discharge in a longitudinal gas flow [50], being caused by the flow's transition from the laminar mode to the turbulent. Figure 8 depicts the curves representing the dependence of the potential difference across the electrodes of the discharge tube (30 cm long and 1 cm in diameter) on helium pressure for various values of the flow rate.

The discharge's contraction is accompanied by substantial reduction of the potential difference at which oscillations on the electric probes immersed in the positive column are detected; modulations of the discharge current also occur and the diameter of the plasma column is reduced. For instance, curve *1* corresponds to a flow rate $V_1 = 200$ m s^{-1}, with contraction occurring at $p_1 = 12$ mmHg; curve *2* corresponds to $V_2 = 160$ m s^{-1}, and contraction happens at $p_2 = 15$ mmHg, and, finally, curve *3* corresponds to $V_3 = 120$ m s^{-1}, with contraction occurring at $p_3 = 20$ mmHg — that is, $p_1 V_1 = p_2 V_2 = p_3 V_3 = pV = \text{const} \cong \text{Re} = 300$.

Experiments with the discharge in a longitudinal argon flow produced similar results. Since at different flow rates contraction occurs at the same Reynolds number and is accompanied by modulation of the discharge current, harmonic oscillations of substantial amplitude are generated on the probe, which is proof that the flow mode has changed. Thus, we can sum up by saying that pinching is caused by vortex motion which emerges when laminar flow goes over to turbulent flow. What speaks in favor of such development is the fact that the experiments were carried out at low current densities at which the gas temperature differed little from room temperature. The heat liberated by the current in the discharge is effectively removed by the flow and the radial gradient of the gas temperature in the conditions under study is low, with the result that there is no reason for thermal contraction as well. Various aspects of contraction of the positive column in glow discharges are discussed in Refs [45, 51].

Hence, contraction of the positive column in a longitudinal gas flow occurs, provided that the heat liberated by the discharge current is effectively removed, as the laminar mode of gas flow goes over to the pseudoturbulent mode (the mode in which turbulence is undeveloped). This happens because the stability of the laminar mode of gas flow is violated and large-scale low-frequency pulsations are formed, leading to the development of instability. This conclusion coincides with the results of Akishev and Napartovich [52], Bondarenko et al. [53], and Vysikailo [54], who examined how vortices (turbulence) that emerge in the discharge affect the stability of the positive column in the gas flow in a channel with a rectangular cross section. The researchers found that, in addition to the stabilizing effect of turbulence on the stability of the discharge, the introduction by the flow into the positive column of additional inhomogeneities capable of developing instabilities has a destabilizing effect [55, 56].

It should be noted that the thermal contraction can also manifest itself in a discharge tube with gas flow. Such a situation may occur when the current density becomes higher and flow rate is low, i.e., when the heat liberated by the current is removed by gas circulation and the temperature gradient over the radius of the positive column has established itself.

Let us examine the mechanism of discharge contraction in a gas flow when the laminar flow conditions are replaced with the turbulent ones. As is known (see Ref. [19]), the distribution of the gas flow velocity over the tube's cross section in laminar flow is parabolic. A rise in the mean flow rate is accompanied by a rise in the gas velocity on the tube's axis and an increase in the velocity gradient near the wall. Laminar flow along the tube is subjected to some perturbations, e.g., because of the conditions that exist at the entrance to the tube and because of the roughness of the wall or inhomogeneities in the external flow, which lead to boundary-layer separation. At a certain value of gas velocity (or the Reynolds number), the perturbations emerging on the boundary layer begin to increase with the passage of time, and this increase signals that the main flow is unstable and so a transition to turbulent flow becomes possible [36, 46–48]. The steady laminar flow ceases to exist, and large-scale pulsations are generated, which lead to the development of instabilities. In the initial stage of this transition, low-frequency, pseudoturbulent, periodic oscillations form in the tube [39, 46, 47], with the frequency of these oscillations being on the order of tube's diameter. The positive column oscillates together with the flow, and the regime of radial ambipolar diffusion of charged particles becomes violated, which leads to discharge contraction.

The results of studies on the behavior of the positive column in a gas flow can be found in Refs [16, 42]. It was found that inside a tube 1 cm in diameter the flow becomes unstable in the initial stage of transition from the laminar mode to the turbulent mode. This leads to the generation of oscillations with a frequency of about 5 kHz, which are accompanied by contraction of the plasma column (the visible boundary of the diameter of the discharge is reduced by a factor of two) and by an abrupt drop in electric field strength [42]. This may serve as proof that the contraction of the gas-flow discharge is caused solely by oscillations generated in the flow at the very beginning of the mode transition and is gasdynamic in nature. Oscillations in a plasma can easily be detected by various methods (by a Langmuir probe, a coil placed outside the tube, a photoelectric multiplier irradiated by the light from the discharge, etc.). After the discharge has contracted, undeveloped turbulence sets in (in the low-frequency range). As the gas pressure (or the gas velocity) is increased, the Reynolds number also grows, and large vortices split into small ones [39, 46, 47]. This is accompanied by a rise in the frequency of oscillations in the discharge (Fig. 5b), thus intensifying transfer processes which effect an increase in the diameter of the discharge (the vortices mix the plasma in the radial direction and reduce the radial temperature gradient). At a pressure of about 80–100 Torr, the discharge becomes completely decontracted: the visible boundary of the diameter of the positive column becomes equal to the inner diameter of the tube, and the oscillation frequency amounts to about 800 kHz (well-developed turbulence).

2.3 Discharge in a turbulent flow

The main reason for using gas flows that circulate along the positive column of a glow discharge is to stabilize the discharge, produce a homogeneous, uncontracted, uniform excitation over the entire volume of the gas at high pressures, and remove the heat liberated by the current in the plasma column. In the transition mode, large-scale low-frequency oscillations are generated in the discharge, and the frequency of these oscillations varies from 10 to 20 kHz, depending on the tube's diameter, with the oscillations easily detected by Langmuir probes. Gas flows are widely used to suppress instabilities that appear in the discharge. As the flow rate is increased, the frequency of the oscillations generated by the flow in the plasma column rises, and this is accompanied by an increase in the diameter of the discharge. At sufficiently

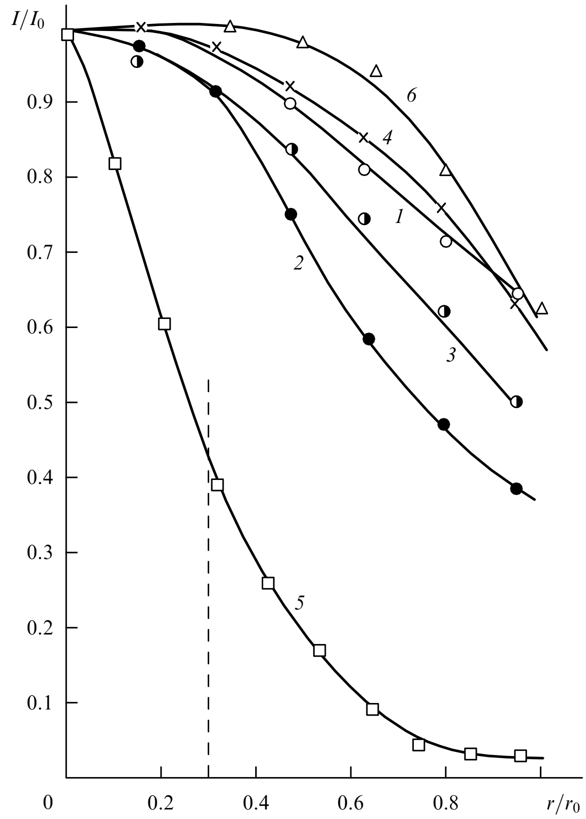


Figure 9. Distributions of the relative probe saturation current in double electric probes over the radius of the positive column of a glow discharge in a longitudinal helium flow: curve *1*, for a diffusive discharge at a pressure $p = 3$ mmHg and a flow rate $V = 250$ m s^{-1}; curves *2* and *3*, for contracted discharges at 22 and 56 mmHg, respectively, with $V = 250$ m s^{-1}; curve *4*, for a decontracted discharge at $p = 78$ mmHg and $V = 250$ m s^{-1}, and curve *5*, for a contracted discharge in helium without any flow at $p = 50$ mmHg. The vertical dashed line marks the diameter of the visible boundary of the plasma filament. Curve *6* represent the current distribution for a decontracted discharge at $V = 450$ m s^{-1} and $p = 55$ mmHg [42].

high flow rates and at elevated pressures, in the discharge there sets in a concentration distribution of charged particles over the column's radius that is flatter than in the case of a diffusive positive column at low pressures. This is especially clear if one looks at Fig. 9 which shows the results of radial probe measurements of the current in a plasma column in a gas flow at various pressures, with the gas velocity being $V = 250$ and $V = 450$ m s^{-1} [10, 42].

The distribution of the probe saturation current over the radius of a diffusive column at a low pressure (curve *1*) is parabolic, in accordance with Schottky's theory. In the contracted column at $p = 22$ mmHg, the current distribution is steeper (curve *2*). In the decontracted column (curve *4*) at $p = 75$ mmHg, the distribution of the probe current over the radius of the plasma column becomes the same as at a low pressure of 3 mmHg. Figure 9 also depicts the distribution of the probe current over the radius of a contracted discharge in helium (curve *5*) in the absence of any flow, and this distribution is in good agreement with the well-known bell-shaped distribution of the concentration of charged particles over the radius of the positive column in the absence of gas flow [57]. The vertical dashed line (intersecting curve *5*) in Fig. 9 marks the visible boundary of the diameter of the plasma filament. The fact that this dashed line intersects curve *5* has been corroborated by the data listed in Ref. [57]. Also in Fig. 9 one can see the distribution of the saturation current in double electric probes over the discharge's radius, with the gas flow rate being 450 m s^{-1} and helium pressure $p = 55$ mmHg (Re = 3000). Under these conditions, a radial distribution of the current density (curve *6*) that is more uniform than in the case of a diffusive positive column at helium pressure of 3 mmHg (curve *1*) sets in.

As a result of experiments on stabilizing discharges by turbulent flows, discussed in this section, we can draw the following conclusion. The positive column in a gas flow is subjected to contraction caused by the emergence of large-scale low-frequency oscillations that appear in the flow when the laminar mode goes over to the turbulent one. However, a further increase in pressure or velocity of the gas results in the flow exhibiting small-scale well-developed turbulence combined with the formation of a uniform positive column filling the entire volume of the tube. As the flow rate rises, the plasma column gets a distribution of the current density over the radius of the positive column that is more homogeneous than at low pressures in the case of a diffusive discharge.

Shwartz and Lavie [58] and Ziganshin et al. [59] calculated the concentration profiles of charged particles in the positive column in a developed turbulent flow on the assumption that electrons and ions diffuse toward the tube walls, and found that they are formed in the near-axis zone of the discharge by direct electron ionization.

What is more, the calculations were done on the assumption that the gas pressure and temperature, as well as the electron temperature, are homogeneous over the cross section of the discharge and that characteristics of the turbulence of the neutral and ion gases are correlated. Ziganshin et al. [59] obtained, through calculations, the distributions of the relative concentration of the charged particles over the radius of the positive column, and these coincide with the measurement data presented in Fig. 9.

Garosi et al. [60] performed experiments in which they studied the effects of vortex motion in an argon discharge inside a tube 2.2 cm in diameter with a current of 1.8 A and a gas pressure of 3.325 kPa. They measured the longitudinal electric field strengths, the electron temperature, and the ionization rate as functions of the gas flow rate and the Reynolds number. The researchers found that as the Reynolds number was raised from 0 to 6300, the ionization rate increased by a factor of ten, the electric field strength rose by a factor of approximately two, and the electron temperature rose by 10%. In the process, the plasma column became wider and filled the entire volume of a discharge tube. The concentration profiles of the charged particles broadened and evened out.

The dependences of the electron temperature, the longitudinal electric field strength, and the ionization rate on the Reynolds number calculated by Ziganshin et al. [59] are compared with the available experimental dependences in Ref. [60]. The difference in the electron temperature is about 2–3%, in the ionization rate 10–15%, and in the longitudinal electric field strength 50–100%.

As a result of their experiments, Gentle et al. [2] also found that the rise in the gas flow rate from approximately 10 to 70 m s^{-1} in an argon glow discharge at a pressure of 2.66 kPa leads to a rise in the electron temperature in the positive column by 5–15%.

Due to disruption of laminar flow in the tube, oscillations are generated in a discharge with longitudinal (flow-through) gas circulation. The reasons why such a flow are disrupted may be protrusions and roughness on the inner surface of the tube, which result, as the Reynolds number rises, in the streamlines being bent and, subsequently, vortices being formed. Other reasons may be the perturbations created by the flow at the point where the gas enters the tube, the presence of openings in the wall of the tube needed for plasma diagnostics, etc. At first, oscillations are generated whose frequency is assigned by the tube's diameter (the region of undeveloped turbulence). As the gas pressure or velocity rises, the amplitude of the oscillations grows, and so does the frequency. Figure 5b depicts curves representing the dependence of the current oscillation amplitude on the gas pressure at a constant mean helium-flow rate of 250 m s^{-1}. The simplest way to detect oscillations caused by flowing gas is to analyze the electric signal from the resistor brought into the electric circuit including the discharge tube. In this way, one can observe on the screen of an oscilloscope or a computer monitor the modulation of the discharge current caused by gas circulation and draw conclusions concerning the processes running in the flow. The oscillations of the charge particle number density can be detected with an electric probe and a photoelectric multiplier irradiated by the light from the discharge by monitoring the oscillations of the density of excited atoms in the plasma. A small coil placed outside the tube also detects the oscillations generated in the discharge as the flow goes over from laminar mode to turbulent. Granatstein et al. [7] used an anemometer with a heated filament to measure the fluctuations in the gas velocity in the flow circulating along the discharge, while a probing laser beam was employed to determine the spectrum of the gas density oscillations. In the same experiment, Granatstein et al. [7] employed an electric probe to measure plasma density fluctuations in a contracted positive column whose diameter was half the inner diameter of the tube. The researchers found that the scale of turbulence of the neutral gas is twice the scale of turbulence in the plasma filament.

The first to detect the oscillations in a discharge caused by flowing gas through probe measurements were Gentle et al. [2]. The researchers note that the noise spectrum of the oscillations corresponding to a frequency range extending from 0.5 to 3 kHz was detected by a Langmuir probe with the gas flowing from anode to cathode. However, when the gas was flowing from cathode to anode in an argon discharge, the signal was periodic with a characteristic frequency ranging from 0.8 to 2 kHz, which is related to the flow rate, the gas pressure, and the discharge current. These effects were observed in a 10-cm long tube with a diameter of 0.6 cm at argon flow rates ranging from 10 to 70 m s^{-1} (the region of undeveloped turbulence), a pressure $p = 2.66$ kPa, and discharge currents up to 0.2 A.

Similar results of studies upon plasma density oscillations in a 30-cm long discharge tube with a diameter of 1 cm in a helium flow have been reported in Ref. [11]. The gas flow was directed from cathode to anode, and a Langmuir probe was utilized to measure the periodic oscillations whose frequency varied from 2 to 36 kHz as the discharge current was varied from 5 to 100 mA at a pressure up to 15 kPa and the helium flow rate ranging from 0 to 300 m s^{-1}. The researchers found the oscillation amplitude of the discharge current (the variable part) as a function of the helium flow rate for various fixed values of pressure. They established that there were practically no oscillations at gas velocities close to zero for any pressure. As the gas velocity was increased, the oscillation amplitude increased, too, and reached its maximum value at 80 m s^{-1} for the pressures considered. The oscillation amplitude was also found to increase with pressure, reaching its saturation value at 16 kPa, with the maximum oscillation amplitude of the discharge current (the modulation percentage) approaching 16 mA. Hence, the variable component of the discharge current caused by the gas flow amounts to more than 50% of the current (30 mA) settled in the laminar flow in the absence of oscillations. A rise in the flow velocity up to 80 m s^{-1} reduces the oscillation amplitude and increases the visible boundary of the discharge diameter. The higher the pressure, the steeper the dependence of the oscillation amplitude on the velocity, and the lower the rates at which the discharge is decontracted by the gas flow. The latter is due to the fact that with the diameter of the tube remaining the same the decontraction of the positive column at a higher pressure is achieved at a lower gas velocity. Thus, it has been verified through experiments that decontraction of a discharge by a gas flow at elevated pressures depends on the Reynolds number, namely, at a value of the Reynolds number at which the gas flow goes over to the region of well-developed turbulence.

The results of studies on the plasma density fluctuations in a discharge in a well-developed turbulent flow can be found in Refs [5, 6, 60]. The researchers studied the lifetime of a vortex in a steady flow and found that it is longer than the time that is needed for the vortex to pass through a stationary probe. Turbulent motion is related to viscous dissipation of energy in the vortex. The flow frequency spectrum unites (reflects) three laws of variation. These variations are related to the Kolmogorov subband where the vortices are neither gained nor damped and acquire energy from the larger vortices and transfer it to the smaller ones. The central region is a system in which the diffusion coefficient (the classical coefficient of ambipolar diffusion of the plasma) is much larger than the kinematic viscosity coefficient. In this case, the size of the plasma density dissipates and resides in the inertial subband. This implies that there is a range of wave numbers or vortex sizes within which the motions of charged and neutral particles are correlated. The good agreement between the measured spectrum and the theory [5, 6] corroborates the fact that the small scale of turbulence is homogeneous and isotropic. This reveals that the spectrum is free from various types of plasma instabilities, such as striations and oscillation relaxation [61].

Spectral measurements at lower values of the flow parameters show that fully developed turbulence sets in at Reynolds numbers of the order of 4000.

Today, high-speed gas flows in discharges are widely used in various areas of science and technology, in particular, for auxiliary plasma ignition, for maintaining and monitoring flame parameters, and for increasing the efficiency of burning combustible mixtures [62].

A turbulent flow pumped through the positive column noticeably broadens the multitude of properties of a glow gas discharge and raises the possibilities of its use in various areas of science and technology.

3. Controlling plasma parameters by acoustic waves

A gas glow discharge is a self-regulating, self-consistent plasma entity. In the positive column, the gas temperature, the spatial distribution of the electric current density, the electron energy, and the nature of the variation of the neutral particle temperature in space depend on the gas pressure, the magnitude of the discharge current, the diameter of the discharge tube, and the nature of the gas.

At low pressures (up to several mmHg), the shape of the electron concentration distribution over the radius of the plasma column is a parabola (in accordance with Schottky's theory [43]), and the temperatures of electrons and neutral particles for all practical purposes are constant over the entire radius of the tube. As the gas pressure is raised (above 5–10 mmHg, depending on the nature of the gas and diameter of the tube), the discharge contracts, i.e., the positive column undergoes pinching which results in the shape of the spatial distribution of the electron concentration over the tube's radius changing from parabolic to bell-shaped, strong gradients in temperature and current density emerging, and the gas temperature on the axis of the positive column rising. Such parameters of the discharge may not correspond to the necessary conditions for building a specific device under development.

Today, gas glow discharges are widely used in engineering for methodical purposes as well. Often in the use of such discharges there appears the need to alter the self-consistent plasma entity and correct it somewhat, i.e., create a discharge with the parameters needed for a specific purpose. For instance, building a carbon dioxide laser with high specific lasing power required forming a homogeneous uncontracted discharge at an elevated pressure with a gas temperature in the positive column no higher than 500 K, since at temperatures above 600 K population inversion disappeared. To solve this problem, researchers pumped gas with a high velocity through the discharge area, as a result of which the heat released by the current in the positive column was carried away by the turbulent flow, while the vortices that appeared in the plasma column mixed the gas in the radial direction and created a homogeneous discharge at an elevated pressure.

Subsequently, an uncontracted homogeneous discharge at a high pressure was generated using an intense acoustic wave directed along the positive column. The acoustic vortices that emerge in the discharge mix the gas in the radial direction, carry away the heat from the near-axis region of the plasma column to the tube's wall, and create a homogeneous discharge. In addition, an acoustic wave can be applied to gradually (and easily) vary the electron energy and the longitudinal electric field strength, and to reduce the radial temperature gradient in the positive column.

The remarkable result is that in its influence on the properties of a gas discharge (and on the parameters of the discharge) an acoustic wave is an analog of a gas flow directed along the positive column. Just as a flow, an acoustic wave causes the discharge to contract as the intensity of the wave increases, i.e., when acoustic vortices are generated in the tube.

It is more convenient to control the parameters of a gas discharge by an acoustic wave than by a high-speed gas flow, which requires the use of bulky and noisy pumps. Furthermore, an acoustic wave brings to life new, very interesting effects in a plasma column, which we discuss below.

Note that one of the first questions in the problem of the interaction of acoustic waves with plasma, which came to the foreground as a result of studies of acoustic instabilities in a thermodynamically nonequilibrium, low-temperature non-Maxwellian plasma [55, 61, 63], was the question of how to reinforce acoustic waves in a weakly ionized gas.

The most general mechanism of amplification of acoustic waves in plasmas is related to bulk heat release which depends on the charged particle number density. Tsendin [64] and Ingard and Schulz [65, 66] analyzed a thermal mechanism based on the hydrodynamic approach. Another mechanism of sound amplification related to negative viscosity was studied by Molevich and Oraevskii [67] and Osipov and Uvarov [68]. The results of studies on the amplification of acoustic waves generated by an external source and propagating along the positive column of a glow discharge in inert gases can be found in Refs [69 – 73].

The gain anisotropy as a function of the direction of propagation of a traveling acoustic wave with respect to electron drift has been studied in Refs [72, 74, 75]. The mechanism of formation of sound amplification anisotropy in a gas-discharge plasma has been studied in Ref. [74]. Aleksandrov et al. [76] and Zavershinskii et al. [77] analyzed a mechanism of amplification of an acoustic wave in a nonself-sustained discharge, which is related to the friction between electrons and the neutral gas.

An acoustic wave can be amplified in a molecular gas due to transformation of the vibrational energy of excited molecules into the energy of the acoustic wave. Bauer and Bass [78], Kogan and Mal'nev [79], and Osipov and Uvarov [80] developed a linear theory of an acoustic wave amplification as the wave propagates in a molecular gas; the theory takes into account the interaction between sound and the amplifying medium. Kogan and Molevich [81] and Eletskii and Stepanov [82] described the results of studies on a nonlinear theory of acoustic wave amplification in a molecular-gas plasma. Aleksandrov et al. [72] measured the amplification coefficient of an acoustic wave in both the inert-gas discharges and molecular-gas discharges (nitrogen, air, and a mixture of the air nitrogen and argon) at low pressures (from 6 to 18 mmHg) in the discharge. The results of experimental work on the amplification of acoustic waves in a vibrationally nonequilibrium molecular gas (nitrogen) at a pressure of 78 mmHg can be found in Ref. [83]. In a steady diffusive nitrogen discharge, the amplification was found to agree with the linear theory, while in a contracted discharge the gain abruptly increases in accordance with the nonlinear theory of sound amplification in a vibrationally nonequilibrium gas. Torosyan and Mkrtchyan [84], Schulz and Ingard [85], and Kaw [86] examined a theory of acoustic instability and the behavior of the phase velocity of acoustic waves in plasma.

A number of articles deal with studies of the stratification of the positive column in a gas discharge, caused by acoustic waves [87 – 89]. The first to experiment with sound-stimulated discharge stratification was Šubertová [87], and the results of theoretical investigations on this phenomenon can be found in Refs [88, 89]. One way for an acoustic wave to influence a gas discharge is to take advantage of the strong dependence of the ionization rate constant on the ratio of the electric field strength to the number density of the plasma's neutral component, E/N, which can be directly modulated with sound. This modulation can be reinforced when there is parametric interaction of the acoustic modes with one of the eigenmodes of the discharge or a discharge circuit at a proper ratio between frequencies. As a result of such modulation, the effective ionization rate in the plasma may increase, which creates the necessary conditions for the development of one type of ionization instabilities, where the choice of type depends on the properties of the discharge and the structure of perturbations. The nonlinear stage in the development of these instabilities usually leads to the formation of a new structure of discharge — there occurs either stratification [90, 91] or contraction [12, 89]. The stratification of the positive column by an acoustic wave takes place when in the rarefaction zone there sets in an electron concentration higher than that in the absence of the acoustic wave. The frequency range within which stratification may come about depends on the mechanism of loss of charged particles.

Now let us briefly discuss another phenomenon that occurs in discharges in the presence of an acoustic wave. The propagation of sound through the positive column invokes modulation in the plasma parameters (the magnitude of the discharge current, the electric field strength, the concentrations of electrons and ions, etc.). As a result, a phase shift is set up in the plasma between the oscillations of the various plasma components and the acoustic wave [92, 93]. The authors of these works presented the results of measurements of the phase shifts between the oscillations of the discharge current, the electron and ion concentrations, and the acoustic wave as functions of sound intensity and frequency, the gas pressure, and the discharge current. The smallest phase shifts set in at the resonance frequencies of the acoustic wave (20 to 40 degrees of arc), and the phase shift decreases as sound intensity grows.

We will analyze in the next two sections the processes related to the positive column contraction induced by an acoustic wave and the discharge decontraction by intense vortex motion in the discharge. Also, we will examine the influence of sound intensity on the gas temperature and the longitudinal electric field in the positive column.

3.1 The effect of sound on the longitudinal electric field in a positive column

In the positive column of a glow discharge, the longitudinal electric field strength is determined by the ionization, plasmachemical, kinetic, and thermophysical processes. The behavior of an electric field in a plasma in the absence of any external action has been scrutinized in Refs [51, 57]. The information about changes in the electric field in the plasma column makes it possible to draw a conclusion concerning the processes that take place in the discharge. When the positive column is pinched with the current maintained constant, the current density in the near-axis region increases and the longitudinal electric field weakens, while expansion of the discharge leads to an opposite result, i.e., the electric field strength increases.

Let us examine the effect of the acoustic wave frequency on the magnitude of the discharge current and the electric field strength. Measurements were done in a 100-cm long quartz discharge tube 6 cm in diameter with electrodes attached to the lateral wall at a distance of 85 cm from each other [12].

An electrodynamic acoustic radiator was hermetically attached to one of the ends of the tube. Sinusoidal electric oscillations from an audio-frequency generator were fed to the radiator through an amplifier.

Variations in the longitudinal electric field caused by variations in the frequency of the acoustic wave (with the gas pressure in the tube remaining constant) are usually accompanied by variations in the discharge current.

Figure 10 shows diagrams representing the dependence of the discharge current and the voltage across the electrodes on the frequency of the acoustic wave in the range extending

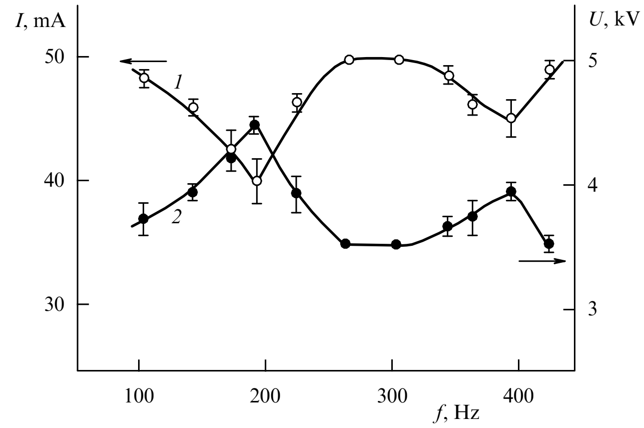


Figure 10. Diagrams of the dependence of the discharge current (curve *1*) and the electric voltage across the electrodes (curve *2*) in a 100-cm long tube with an inner diameter of 6 cm on the frequency of an acoustic wave with an intensity of 83 dB at an argon pressure of 110 mmHg. The largest deviation of the quantities in question caused by the acoustic wave is observed at resonance frequencies of 190 and 380 Hz, at which standing waves are formed.

from 100 to 420 Hz in argon at a pressure of 110 mmHg and a constant intensity of the acoustic wave equal to 83 dB. In the absence of sound and with a voltage of 3.5 kV across the electrodes, the discharge current amounted to 50 mA.

It was found that generating an acoustic wave in the discharge and varying its frequency under constant pressure in the tube lead to the largest deviation of the quantities at the resonance frequencies of 190 and 380 Hz. The length of the tube (100 cm) was half the wavelength at a frequency of 190 Hz in argon, and it corresponded to one wavelength at a frequency of 380 Hz.

At 190 Hz, the electric current drops to 40 mA, and the discharge voltage rises to 4.5 kV. Raising the frequency of the acoustic vibrations above the resonance frequency of 190 Hz leads to an increase in current strength and a decrease in discharge voltage, while at 250 Hz the current reaches 50 mA and the voltage drops to 3.5 kV. For all practical purposes, at frequencies within the 250 – 320-Hz range, the discharge current and the voltage across the electrodes become equal to the respective values in the absence of an acoustic wave. Raising the frequency above 320 Hz causes the current to decrease, reaching its minimum value at the resonance frequency of 380 Hz, but this value is larger than the one at 190 Hz, while the voltage is higher. The resistance of the discharge gap (at constant gas pressure and input electric power) at 190 Hz is 1.6 times higher than in the absence of an acoustic wave, while at 380 Hz the resistance is 1.26 times higher. If the voltage across the electrodes is raised at the resonance frequencies to a value corresponding to a 50-mA current (which existed when there was no acoustic wave), the energy deposition to the discharge increases by a factor of approximately 1.6, which is extremely important for a number of applications, e.g., in building gas lasers.

The variations in the electrical parameters of the discharge caused by acoustic waves were accompanied by an increase in the diameter of the positive column from 2 to 6 cm. In the process, the gas temperature on the axis of the plasma column dropped from 432 to 390 K, while at the wall it grew from 305 to 335 K. Thus, the radial gradient of the gas temperature in the discharge fell from 127 to 55 K, i.e., by a factor of more than two.

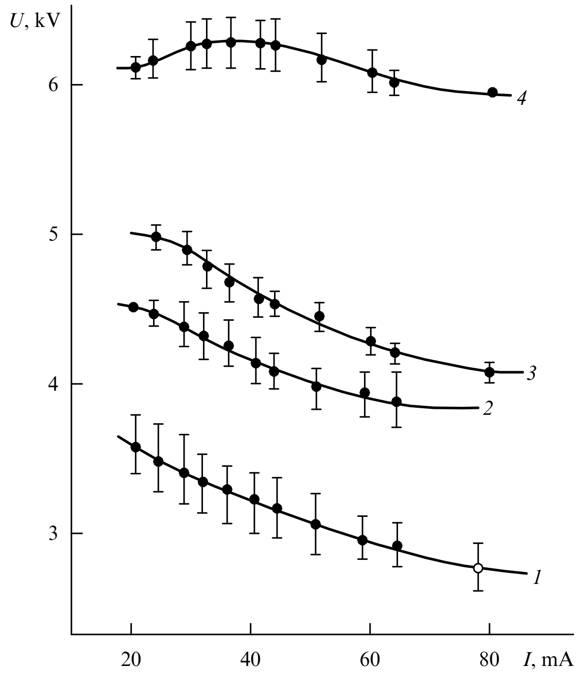


Figure 11. Current – voltage characteristics of a discharge at argon pressure of 110 mmHg for different intensities of acoustic waves with a frequency of 190 Hz in a 100-cm long tube 6 cm in diameter, with the electrode spacing being 85 cm: curve *1*, in the absence of sound; curve *2*, at 70 dB; curve *3*, at 74 dB, and curve *4*, at 83 dB.

It was shown in Ref. [94] that at low acoustic-wave intensities of about 70 dB (argon pressure in the discharge was 110 mmHg), an increase in sound intensity leads to a drop in the longitudinal electric field strength from 60 to 40 V cm^{-1}, which is analogous to a discharge in a longitudinal gas flow [19] (described in Section 2.2), where an increase in the gas flow rate within the laminar mode of gas flow along the discharge causes pinching of the positive column and a decrease in the electric field strength.

However, when the intensity of the acoustic wave of resonance frequency is raised above 70 dB, the longitudinal electric field gets stronger.

Figure 11 shows the current – voltage characteristics of a discharge at a pressure of 110 mmHg (inside a 100-cm long tube 6 cm in diameter) for different intensities of a standing acoustic wave with a frequency of 190 Hz that sets in along the plasma column. Curve *1* was obtained in the absence of an acoustic wave and is a typical example of a descending current – voltage characteristic. Curve *2* represents the current – voltage characteristic with an acoustic wave of 70-dB intensity, curve *3* with an acoustic wave of 74-dB intensity, and curve *4* with an acoustic wave of 83-dB intensity. These diagrams demonstrate that under constant gas pressure and discharge current an increase in the acoustic-wave intensity leads to a sizable increase in the voltage across the electrodes, so that as sound intensity increases to 83 dB the voltage increases greater than twice the magnitude, when there is no acoustic wave.

Let us now analyze the effects of acoustic waves on the rise in the longitudinal electric field strength in the positive column of a glow discharge. As is known, contraction of a discharge is characterized by an abrupt decrease in the cross-section area of the current pinch, a decrease accompanied by a rise in the gas temperature on the axis of the plasma column

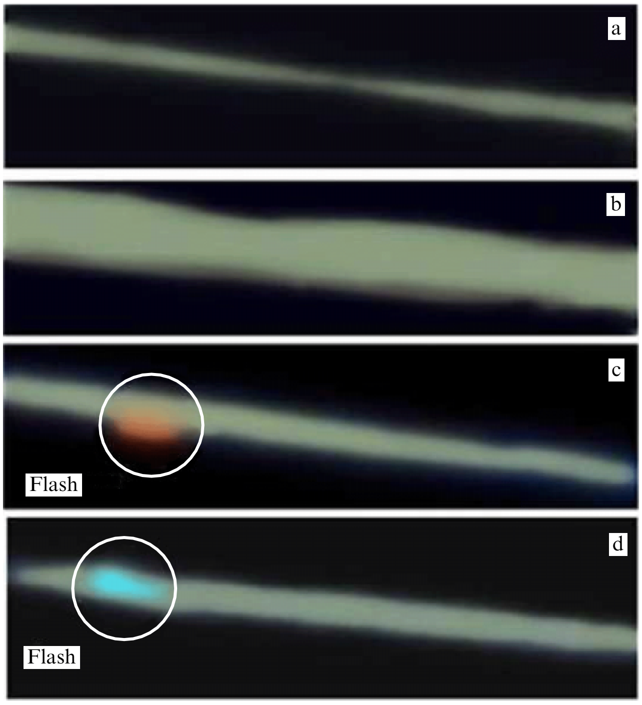


Figure 12. Photographs of the positive column of a glow discharge at an argon pressure of 110 mmHg and a current of 50 mA in the presence of an acoustic wave with a resonance frequency of 190 Hz: (a) a contracted discharge in the absence of an acoustic wave, (b) a decontracted positive column in the presence of an acoustic wave with an intensity higher than 83 dB, and (c, d) a plasma column in the presence of an acoustic wave whose intensity is below 83 dB.

and a decrease in the longitudinal electric field strength [45, 57]. In the above results of experimental studies, the opposite situation is realized: the longitudinal electric field strength increases, which indicates discharge depinching.

The increase in the diameter of the positive column has been observed visually. Figure 12a depicts a photograph of a contracted discharge: the diameter of the visible boundary was about 1 cm in a tube 6 cm in diameter at an argon pressure of 110 mmHg with a current of 50 mA in the absence of an acoustic wave. Figure 12b displays a photograph of a decontracted positive column in the presence of an acoustic wave with its intensity higher than 83 dB and a frequency of 190 Hz at the same gas pressure and current (the diameter of the visible boundary is equal to the inner diameter of the tube, or 6 cm).

Thermocouple measurements in gas discharges have shown that an increase in sound intensity above 82 dB is accompanied by a drop in the gas temperature on the discharge axis and an increase in the gas temperature at the tube's wall, in view of which the temperature drop between the axis and wall decreases.

A decrease in the radial gas-temperature gradient in the gas discharge can be explained as follows. In the field of the acoustic wave there may be oscillations near the tube's hard wall that are the cause of vortex flow. Vortex motion manifests itself most distinctly in the field of a standing acoustic wave (the phenomenon is known as acoustic flow [40]).

Generation of an intense standing acoustic wave in a medium with a sizable temperature drop gives rise to the formation of a vortex acoustic flow [40, 95].

An acoustic field in a thermodynamically inhomogeneous medium has a velocity component directed along the radius. Steady convective flows that have a velocity component along the radius may emerge either because of acoustic flows in the field of a standing wave or because of the excitation of turbulent vortex motion due to the high vibrational velocities of the acoustic field and the presence of a boundary layer. What is important for the vortex motion to manifest itself is the presence of inhomogeneities in the acoustic field and the existence of a transverse profile in the standing wave. Inhomogeneities in the acoustic field in a discharge tube exist, first, because there is a boundary layer near the tube's wall where the velocity of motion decreases from values in the acoustic wave in the middle of the tube to zero at the tube's wall, and, second, because of a sizable temperature gradient along the tube's radius.

Nonlinear acoustic flow is capable of significantly contributing to transfer processes, but for this to happen the size a of the inhomogeneities in the acoustic field must be much larger than $\delta = \sqrt{\eta/\pi f}$, where δ is the size of the boundary layer, and η is the viscosity coefficient. Thus, only strong temperature inhomogeneity over the entire radius of the tube can be responsible for the occurrence of acoustic flows having any effect on transfer processes [96]. Such strong temperature inhomogeneity in the experiments in question may be present in a pinched discharge in the absence of an acoustic wave.

Vortex motion within the tube manifests itself in the form of pulsations in the discharge current. The presence of such motion results in the gas temperature being evened out along the tube's radius, which is accompanied by an increase in the diameter of the visible boundary of the positive column.

Acoustic vortices generated in a discharge may lead to a situation in which radial turbulent diffusion of the charged particles establishes itself in the plasma, and this diffusion is stronger than the classical ambipolar diffusion in the absence of sound, i.e., decontraction of the discharge by an acoustic wave tends to intensify the loss of charged particles on the tube's wall. To balance such elevated neutralization of electrons and ions by the agency of an intense acoustic wave, the ionization rate must be increased. This can be done only if the longitudinal electric field gets stronger.

In addition to this mechanism, there is another process giving rise to decontraction of the positive column by an acoustic wave. This phenomenon is related to an increase in heat conductivity in the radial direction and the equalization of the radial temperature drop by vortex motion in which the heat released by the electric current in the near-axis region of the plasma column is effectively removed toward the tube's wall via turbulent mixing. Because of this process, the gas temperature in the middle of the discharge reduces, while on the tube's wall it grows, so that the radial temperature gradient that sets in is much smaller than the one in a contracted discharge. In such a plasma column, the distribution of the ionization rate over the tube's radius is more homogeneous and the discharge becomes depinched.

In a gas discharge with an acoustic wave directed along the positive column, an increase in sound intensity up to 70 dB at constant current and gas pressure leads to pinching of the plasma filament and a decrease in the longitudinal electric field strength. A further increase in sound intensity, accompanied by the formation of a well-developed turbulent flow, causes the plasma filament to expand and the longitudinal electric field strength to grow, inflicting additional loss of charged particles on the tube's wall.

3.2 The effect of sound on the gas temperature in a plasma

The gas temperature in a weakly ionized plasma is one of the basic parameters and is determined by the balance between energy release in the discharge and heat-removal processes. The spatial distribution of the gas temperature depends on the shape of the electron concentration distribution over the plasma column and is very sensitive to variations in this concentration, and vice versa. An experiment is known to have been conducted in which the wall of the tube was heated, with the result that the plasma filament displaced and propagated along the heated area.

Thermal inhomogeneity in the positive column is the most general physical cause of pinching [97]. Due to the temperature difference between the axis and wall of the discharge tube, the gas density proves to be inhomogeneous along the radius. Hence, the parameter E/N determining the main characteristics of a discharge proves to be a rapidly decreasing function of the radial coordinate (E is the longitudinal electric field strength, and N is the gas-particle number density in a plasma). The sharpest dependence on E/N is a characteristic feature of the rate constant for ionization of neutral particles by electron impact [45].

In view of this dependence, when the radial temperature drop is abrupt, the ionization rate also proves to be a rapidly decreasing function along the radius, with the result that the main ionization processes are localized in the near-axis area of the discharge, and the positive column undergoes pinching.

Detailed studies of the gas temperature in a glow discharge and the respective gas-temperature spatial profile that are based on the solution to the heat conduction equation and the balance equation for the electron number density, with invoking the results of measurements in a discharge in the absence of an acoustic wave, have been discussed by Eletskii [45].

A number of applications that employ gas discharge require a homogeneous, uncontracted positive column with a fairly low gas temperature in the plasma. In particular, it must be noted that the efficiency of a carbon dioxide laser depends to a great extent on the gas temperature in the plasma. To maintain a high degree of population inversion in the active region of a carbon dioxide laser, the gas temperature in the positive column must be sufficiently low [98].

To suppress discharge contraction and reduce the gas temperature in the discharge, high-speed turbulent gas circulation is successfully used. Turbulent mixing of the plasma in the radial direction lowers the gas temperature on an axis of the plasma column, reduces the radial temperature gradient, assists in the decontraction of the discharge, and helps form a homogeneous positive column at high gas pressures [9, 10].

Research has shown (see Refs [12, 13, 99–101]) that the gas temperature in the plasma of a glow discharge can be controlled quite successfully by an acoustic wave directed along its positive column. Sound initiates the formation of vortices in the discharge, and these vortices remove heat from the near-axis area of the plasma column to the tube's wall (with the current and gas pressure in the tube remaining constant), reduce the gas temperature in the plasma column, and allow this temperature to reach a value necessary for a specific applied task to be performed or a relevant experiment to be carried out.

Let us look at the results of experiments in which the effects of an acoustic wave on the gas temperature in a discharge were studied. The measurements involved using a 100-cm long quartz tube 6 cm in diameter. The separation between the electrodes attached to the tube's wall in the form of branch pieces was 85 cm. The acoustic wave in the discharge tube was generated by an electrodynamic radiator attached to one end of the tube. A microphone used to monitor the parameters of the acoustic wave was attached to the opposite end. Two thermocouple sensors with quartz protective coating measured the gas temperature in the discharge. One of these was placed on an axis of the positive column, and the other at the tube's wall at the same distance from the electrode.

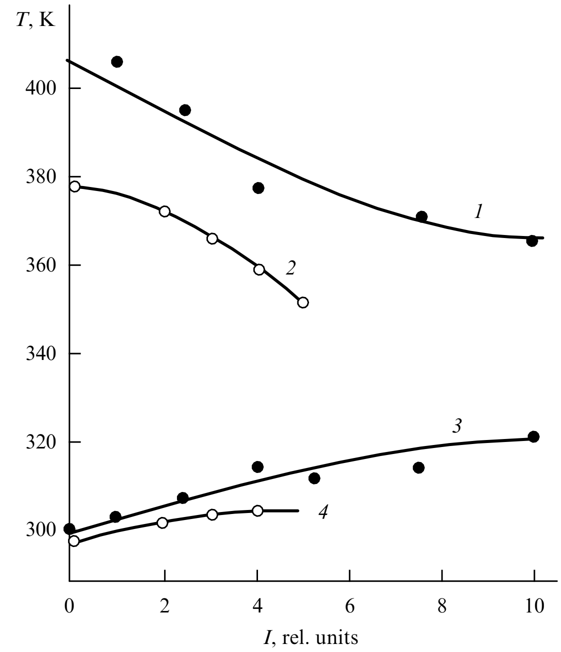


Figure 13. Curves representing the dependence of the gas temperature on the intensity of the acoustic wave with the first resonance frequency of 190 Hz (at which the tube's length is equal to half the wavelength) in an argon discharge at a current of 60 mA: curves *1* and *2*, on the discharge axis; curves *3* and *4*, on the tube's wall; curves *1* and *3*, at an argon pressure of 110 mmHg, and curves *2* and *4*, at 60 mmHg. The tube was 100 cm long and 6 cm in diameter.

Figure 13 depicts the curves representing the dependence of the gas temperature on the intensity of sound with the first resonance frequency of 190 Hz (at which the length of the tube is half the wavelength) in an argon discharge at a current of 60 mA: curves *1* and *2* show these dependences for the gas temperature on the axis, and curves *3* and *4* for the temperature on the wall. Curves *1* and *3* correspond to an argon pressure of 110 mmHg, and curves *2* and *4* to an argon pressure of 60 mmHg.

At 110 mmHg, the sound intensity of 1.2 rel. units in the diagram corresponds to 74 dB, and that of 10 rel. units to 85 dB. We see that as the sound intensity rises from 74 to 85 dB, the gas temperature on the axis of the positive column drops from 407 to 365 K, while on the wall it rises by 20 K, with the result that the temperature drop between the discharge's axis and the tube's wall decreases from 105 to 43 K. Comparing the diagrams obtained at 110 and 60 mmHg, we notice that the gas temperature in the middle of the discharge at the greater pressure is higher, and that the influence of an acoustic wave on the gas temperature at a higher pressure is more effective.

The gas temperature in the plasma on an axis of the positive column of a gas discharge at the resonance frequency depends on sound intensity. The gas temperature decreases with rising sound intensity. As the gas pressure rises, gas cooling in the plasma by an acoustic wave becomes more pronounced, provided that the discharge current and sound intensity remain constant, but the effect weakens at constant gas pressure as the discharge current increases.

In contrast to the processes that run on an axis of the positive column, a rise in sound intensity drives the gas temperature at the tube's wall up. At fixed current and gas pressure, a rise in the gas temperature on the tube's wall is achieved at the resonance frequency. As the sound intensity and the gas pressure rise, the effect of temperature rising on the tube's wall is more pronounced (at a fixed discharge current).

Let us discuss the mechanism by which acoustic waves affect the gas temperature in the plasma and its radial gradient. From the data gathered on this effect we can conclude that the strongest influence is achieved at resonance frequencies, when standing acoustic waves are generated.

The reason why the gas temperature on an axis of the positive column drops and that on the tube's wall rises as sound intensity grows is that in a field of a standing acoustic wave in the presence of a hard wall steady vortex flows may emerge [33]. This type of flow manifests itself most vividly when the size of the region occupied by vortices is smaller than the acoustic wavelength $\delta = \sqrt{\eta/(\pi f)}$ (η is the viscosity coefficient, and f is the frequency of the acoustic wave). Within the region of such motion there exists a narrow boundary layer (called the acoustic boundary layer) in which the gas velocity drops from its value on the axis in the acoustic wave to zero on the hard wall. Outside the boundary layer there appears a steady vortex flow whose rate is independent of the gas viscosity [42]. The condition $\lambda > R > \delta$ (where λ is the acoustic wavelength; for the first resonance frequency $f = 190$ Hz, $\lambda = 200$ cm) is met fairly well in the experiment in question. In the case of a pinched discharge, a strong gradient of the gas temperature sets in along the radius of the tube, which must result in the phase velocity depending on the radial coordinate. Here, the velocity with which the gas particles move in the acoustic wave also depends on the radial velocity. In view of the fact that $v \sim c$ (where v is the velocity with which the particles vibrate in the acoustic wave, and c is the velocity of sound), as the gas particles get closer to the wall, their velocity decreases. If the condition $\lambda \gg R \gg \delta$ is met, then the particle velocity drops to zero within a narrow boundary layer, i.e., a steady vortex motion emerges within the tube, and this is what is actually observed.

The presence of vortices gives rise to gas mixing and to equalization of the gas-temperature gradient along the radius of the discharge tube. A rise in gas pressure and sound intensity creates more favorable conditions for the propagation of these vortices in the discharge, which leads to further equalization of the gas-temperature gradient along the tube's radius.

In a gas glow discharge with an acoustic wave directed along the positive column, a rise in sound intensity reduces the gas temperature in the middle of the tube and the radial temperature gradient in the plasma thanks to the vortex acoustic flow generated in the plasma column. This is accompanied by an increase in the diameter of the pinched discharge.

4. Acoustically induced superluminescent radiation in an argon plasma

The study of the processes involved in the interaction of plasma with external actions has always been an important factor since, in addition to establishing new physical mechanisms, the results obtained in such studies made it possible to use them for various applications.

In the last 50 years, the physics of the gas discharge has developed along these lines. After the various mechanisms of positive-column contraction had been exposed [45] there was posed the problem of overcoming discharge pinching and of forming an uncontracted plasma column at elevated gas pressures. Here, the researchers used electromagnetic waves, electron and ion beams, circulation of turbulent gas flow through the discharge region, etc. Many reviews and monographs have been devoted to these studies [51, 98].

One of the ways of influencing the discharge parameters and producing homogeneous excitation of a gas at high pressures is to employ the vortex motion of acoustic waves to affect the properties of the positive column.

In this section we examine the effect of acoustic vortex motion on the spectrum of optical radiation emitted by an argon discharge at relatively high pressures, analyze the processes accompanying the changes in atomic excitation levels that are caused by an acoustic wave, and study the conditions needed for the generation of flashes of monochromatic radiation in the plasma with diminishing sound intensity. According to fairly recent reports [16–18], a new phenomenon has been discovered in which an acoustic wave acting on the gas-discharge plasma brings about a rapid change in its emission spectra. A few seconds after the acoustic wave is switched off, light flashes (over the course of several minutes) are observed in various parts of the gas-discharge tube. Later, it was revealed that this radiation is monochromatic and superluminescent in its nature [16–18].

We also present the results of experimental studies dealing with the generation of a flash of superluminescence in the positive column of an argon plasma as the intensity of sound in an uncontracted discharge decreases at an elevated gas pressure, with the flash being caused by a transition of the acoustic flow from turbulent to laminar.

4.1 Observing monochromatic radiation in an argon plasma

The study of the optical radiation emitted by an argon discharge was done using a test bench consisting of a 100-cm long gas-discharge tube with an inner diameter of 6 cm. The distance between the electrodes attached to the tube's wall in the form of branch pieces was 85 cm. An electrodynamic radiator of acoustic waves was hermetically attached to one end of the tube. The optical radiation emitted by the plasma was extracted through the opposite end of the tube and was focused by a lens onto the entrance slit of a spectrograph.

Let us follow the experimental procedure. First, a discharge in argon at 110 mmHg and an electric current of 50 mA is produced in the absence of an acoustic wave. A contracted positive column sets in (Fig. 12a), and we take a spectrogram of the optical radiation emitted by the plasma, shown in Fig. 14a. Next, we introduce an acoustic wave with intensity higher than 82 dB and a resonance frequency of 190 Hz into the discharge. The acoustic vortex motion that emerges in the tube results in the depinching of the decontracted discharge (Fig. 12b). The spectrogram of the radiation

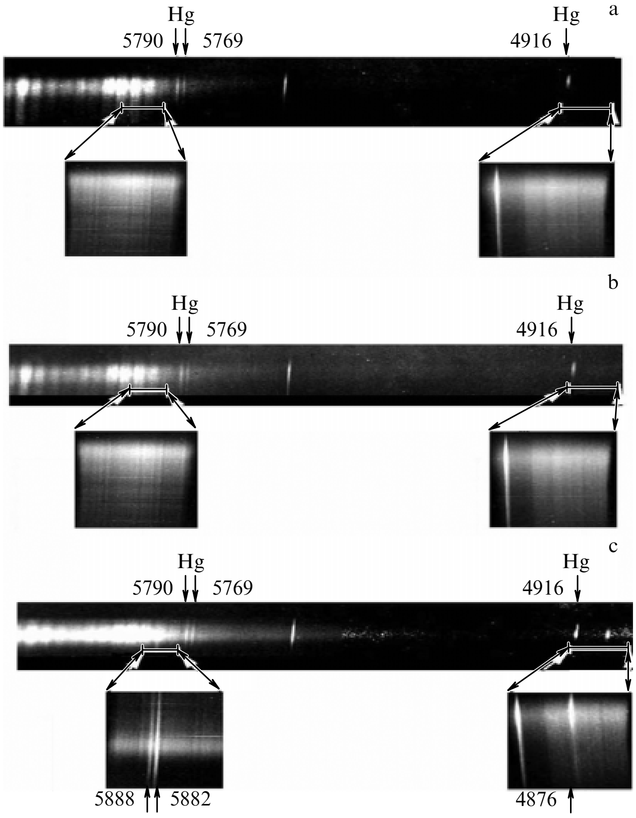


Figure 14. Emission spectra of argon plasma in a 100-cm long discharge tube 6 cm in diameter at a pressure of 110 mmHg and a current of 50 mA: (a) the emission spectrum from a contracted positive column in the absence of acoustic waves; (b) the emission spectrum from a uniformly decontracted discharge subjected to the action of resonant acoustic waves with a frequency of 190 Hz and with intensities higher than 82 dB, and (c) the emission spectrum from a contracted plasma column several seconds after acoustic waves with intensities below 82 dB ceased to act.

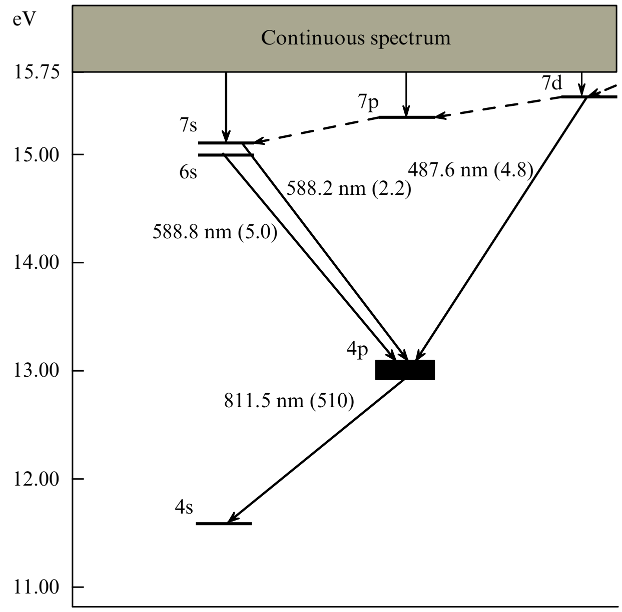


Figure 15. The energy level diagram of some optical transitions in atomic argon.

emitted by such a discharge is shown in Fig. 14b. We reduce the intensity of sound in the positive column below 82 dB. The acoustic flow in the discharge transforms from turbulent to laminar, the positive column gets contracted (Fig. 12c), and the visible boundary of the diameter of the plasma column reduces from 6 to 1.5 cm. Figure 14c displays the emission spectrum of the argon plasma after discharge contraction (roughly 2 to 3 s). The reference lines in all three figures (Figs 14a – c) are indicated at the top of the spectrograms. Clearly visible in the last spectrogram of the discharge emission spectrum are three intense spectral lines with wavelengths $\lambda = 5888$ Å, $\lambda = 5882$ Å, and $\lambda = 4876$ Å.

These lines are observed in the discharge as intense flashes 15 – 20 ms long. The flashes are seen for a fairly long time (2 – 3 min) after the sound intensity is reduced. Basically, they appear at the periphery of the discharge at the boundary of the plasma filament (near the tube's wall), where the electron concentration drops considerably after the sound intensity is reduced and the positive column is pinched [12, 96, 99]. As the discharge contracts, one can detect three flashes in the radiation emitted by the plasma column: two orange (5888 Å and 5882 Å) and one blue (4876 Å). Note that the flashes appear in the discharge independently of one another. They emerge inside the discharge, but the orange flashes also appear on the outer side of the visible boundary of the plasma filament, while the blue flashes occur only inside the discharge.

Analysis of the spectral composition of the emission in the form of flashes shows that they correspond to three transitions between the energy levels of atomic argon:

$$7\mathrm{d}-4\mathrm{p}\,, \quad \lambda = 4876\ \text{Å}\,,$$

$$7\mathrm{s}-4\mathrm{p}\,, \quad \lambda = 5882\ \text{Å}\,,$$

$$6\mathrm{s}-4\mathrm{p} \quad \lambda = 5888\ \text{Å}\,.$$

Figure 15 shows the energy level diagram for the above transitions in argon. Since the oscillator strength of the 4p – 4s transition is approximately 100 times greater than that of any of the above transitions, the 4p level is rapidly depleted. In view of this, population inversion between each of the three levels 7d, 7s, and 6s, on the one hand, and the 4p level, on the other, may emerge. Such population inversion is the reason behind the observed flashes of radiation.

Flashes of superluminescence appear in an argon discharge at elevated pressures, when the intensity of the acoustic wave decreases, and are accompanied by contraction of the positive column.

4.2 Studying sound-induced processes of the generation of superluminescent flashes in a plasma

Let us examine the conditions that must be met for generating flashes of monochromatic radiation in an argon discharge at an elevated pressure under the effect of acoustic waves. The variations in the intensity of a spectral line caused by variations in sound intensity were studied with the aid of a monochromator. The radiation emerging from one end of a 100-cm long discharge tube 6 cm in diameter was sent to the entrance slit of a monochromator and then to a photoelectric multiplier. Then, the signal from the photomultiplier proceeded to an oscilloscope [17, 18].

The diagram representing the dependence of the radiation intensity of the 6s – 4p emission line for an argon atom on the intensity of an acoustic wave at a frequency of 190 Hz is shown in Fig. 16, and the curve is clearly of a hysteresis nature. From the diagram it follows that the intensity of the acoustic wave at the resonance frequency of 190 Hz grows

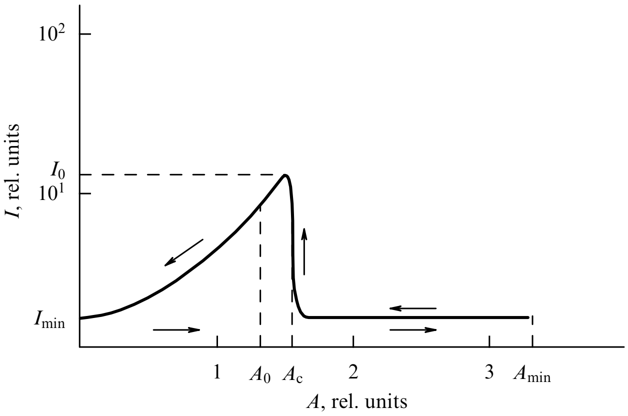


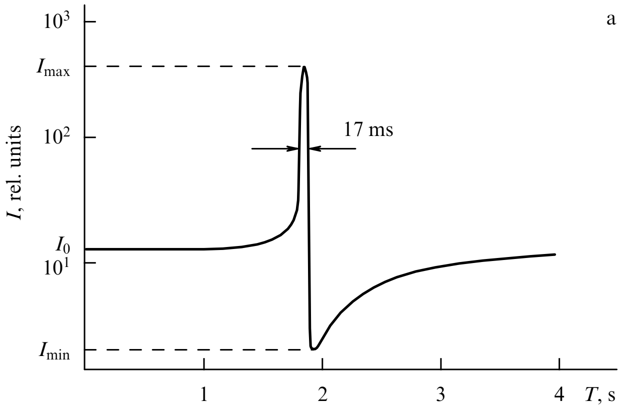
Figure 16. Intensity of the 6s–4p emission line for atomic argon as a function of the intensity of a resonant acoustic wave with a frequency of 190 Hz.

from zero to A_{max} which corresponds to an intensity of 90 dB. In the process, the pinched discharge becomes completely decontracted by vortex motion in the plasma, i.e., the diameter of the visible boundary of the positive column increases and becomes equal to the inner diameter of the tube at an argon pressure of 110 mmHg.

As the sound intensity drops from A_{max} to A_c, the spectral-line intensity remains unchanged. However, at A_c it suddenly increases by a factor of approximately 100, and a light flash occurs (this can be visually observed). Simultaneously, the diameter of the plasma column rapidly decreases and the discharge contracts, i.e., the flash of superluminescence occurs immediately after pinching of the positive column. The intensity of the acoustic wave A_c, at which the discharge contracted and the flash occurred, corresponds to 82 dB. At this critical value of sound intensity, whereat the charge becomes contracted, the acoustic flow transforms from turbulent to laminar. Further reduction of the acoustic-wave intensity is accompanied by a gradual decrease in the intensity of the spectral line.

To determine the relation that exists between the constant enhancement of the intensity of a spectral line and the onset of flash, we constructed a diagram reflecting the time dependence of the intensity of emission produced by the 6s–4p transition (Fig. 17). Figure 17a shows the time dependence of the intensity of the spectral line corresponding to the 6s–4p transition in an argon discharge at a constant intensity A_0 of the acoustic wave, which is lower than A_c and equals 80 dB. In the absence of flashes, the intensity of the spectral line corresponding to the 6s–4p transition has a constant value I_0. At the time of the flash, the intensity of the spectral line enhances considerably (by a factor of 100) to I_{max}. After the flash (whose duration is about 15–20 ms), the intensity of the spectral line drops to its minimum value I_{min} which is simply the line intensity in the absence of an acoustic wave.

The time it takes the radiation intensity to rise from I_{min} to I_0 is rather long (about 1 s). Figure 17b shows the time dependence of the radiation intensity from the 6s–4p transition after the acoustic wave has been switched off. After this happens, the intensity of the spectral line over the course of several seconds (~ 2 s) remains at its minimum value I_{min}. After a time interval t_0, the intensity of the spectral line reaches I_0 and then gradually drops to I_{min} over the course of 15–20 ms. The shape of the flashes is the same as in the previous case (Fig. 17a).



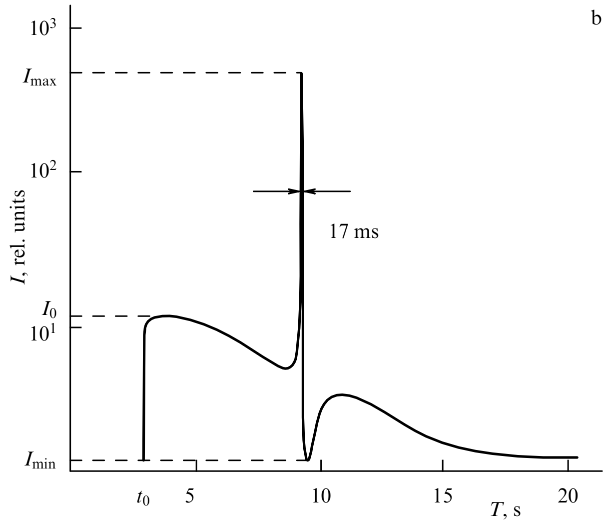


Figure 17. Time dependence of the intensity of emission produced by the 6s–4p transition in argon: (a) as a resonant acoustic wave of a frequency of 190 Hz and an intensity of 80 dB acts permanently on the discharge, and (b) after weakening the action of an acoustic wave of a resonance frequency of 190 Hz and an intensity of 90 dB.

A flash of superluminescence is formed after the discharge under an elevated pressure (and stabilized by acoustic vortices) goes over from the uncontracted state (as sound intensity decreases) into the pinched state. In the process, the radiation intensity increases by a factor of approximately 100.

4.3 A mechanism of superluminescent flash generation in an argon discharge

We now examine the processes that take place in an argon discharge as sound intensity decreases from A_{max} to A_{min} (see Fig. 16). At A_c, the discharge goes over from the decontracted state (Fig. 12b) into the pinched state (Fig. 12c), and the radiation intensity rises very rapidly.

An analysis of how a gas flow and an acoustic wave both directed along the positive column affect the discharge has been conducted in Refs [14, 15, 102], where the researchers also established a similarity in the way these two factors act on the plasma parameters. They found, in particular, that if in a glow discharge with a longitudinal laminar flow oscillations are set up when the gas velocity or pressure is increased, they may get stronger, initiate vortex motion, and cause sudden contraction of the positive column. This has also been established in experiments, whose results have been reported in Refs [11, 42]. The oscillations induced in the positive column can easily be detected, and the oscillogram of the discharge current reveals the presence of modulation with the respective frequency. The gas flow with large-scale vortices is known as the pseudoturbulent gas flow [39, 47]. A further increase in gas velocity or density raises the Reynolds number and leads to decontraction of the discharge by the intense turbulent flow. Similar processes were observed when acoustic waves interacted with a glow discharge plasma. An enhancement in sound intensity gives rise to contraction of the positive column, while a further enhancement in sound intensity is accompanied by an increase in the discharge diameter [12, 15]. Hence, the inverse process is also possible, i.e., a decrease in the gas velocity directed along the positive column brings about an abrupt transition of the discharge from the decontracted state (stabilized by turbulent flow) to the contracted, with the gas flow becoming laminar in the process. Thus, we may conclude that at an intensity of the acoustic wave equal to $A_{\max}$ (see Fig. 16), the discharge carries an acoustic flow with turbulent motion. A decrease in the sound intensity results in a situation in which the positive column at A_c abruptly becomes contracted, since the acoustic flow in the discharge transforms from turbulent to laminar and the visible boundary of the diameter of the positive column drops from 6 to 1.5 cm.

We will now analyze the experimental findings.

Obviously, the low-frequency background cannot influence the transitions between electron energy levels and emission processes, so that we may conclude that the processes running in the discharge are related to the hydrodynamic flows which can influence the stability and configuration of the plasma cloud and, through them, the ionization and recombination processes.

Let us assume that there is an intense standing acoustic wave acting on the positive column of a gas discharge. The discharge current flows along the z-axis, and the temperature gradient is directed along the x-axis. As shown in Refs [12, 95, 96], the profile of the standing wave in a medium with an inhomogeneous temperature distribution depends on the temperature profile. Due to deformation of the phase planes, the vibrational velocity in a longitudinal acoustic mode acquires a transverse component [96]:

$$\begin{aligned} v_{az} &= v_a(x)\sin kx \sin\omega t\,, \\ v_{ax} &= \frac{\mathrm{d}v_a'(x)}{\mathrm{d}x}\cos kz \sin\omega t\,, \end{aligned} \tag{17}$$

where

$$v_a = \frac{\delta P}{\rho_0 c_0}\left[1 + \frac{\alpha\omega^2}{c_0^2}\,x^2\left(1 + \frac{x^2}{2R^2}\right)\right]$$

is the parameter characterizing the temperature inhomogeneity of the medium, $T(x) = T(0)(1 + \alpha x^2/R^2)$, R is the tube's radius, α is the size of the inhomogeneity in the acoustic field, ρ_0 is the gas density, ω is the frequency of the acoustic wave, c_0 is the speed at which the acoustic wave travels in an undistorted medium, and δP is the stationary pressure of the acoustic vibrations in the tube [96].

The general physical reason for contracting the gas discharge is the temperature inhomogeneity of the gas perpendicular to the current [45]. Decontraction by an acoustic field is the result of an intensification of transfer processes along the tube's radius, removal of heat from the plasma filament, reduction in the radial gradient of the gas temperature, an increase in the diameter of the positive column, and an increase in diffusion losses of charged particles on the tube's wall.

An acoustic field in a thermally inhomogeneous medium has a component of vibrational velocity directed along the tube's radius. The effect of the radial vibrational velocity on transfer processes has been evaluated by Zavershinskii et al. [104]. The researchers used a method developed by Isachenko et al. [105], who reported that the effect of convective vortex flows on thermal conduction can be taken into account by introducing an effective heat conductivity. We believe that this method does not guarantee correct results, since the radial velocity of an acoustic wave (in a thermodynamically inhomogeneous medium) is of a vibrational origin and is not constant. Constant convective flows with velocity components directed along the tube's radius may develop either because of acoustic flows in a standing-wave field or because of mixing by vortex motion with substantial vibrational velocities of the acoustic field in the presence of a boundary layer.

Let us discuss the contribution of acoustic flows to an increase in the transport coefficients.

In addition to rapid acoustic vibrations in a standing-wave field there can be slow constant flows, or acoustic flows [95], whose driving force is the acoustic analog of the Miller force. This force arises due to the inhomogeneity of averaged acoustic vibrations. If the standing acoustic wave were to have no transverse configuration, the Miller force would still exist, but the field would be homogeneous. Such a field would only lead to a redistribution of the gas in the tube and to the development of a pressure gradient, but no constant vortex motion would be set in. Vortices are formed when the acoustic field is nonuniform, i.e., there exists a transverse configuration of the standing wave. An acoustic wave inside a tube is nonuniform, first, because of the boundary layer near the tube's wall, where the velocity drops from its value in the acoustic wave to zero at the wall and, second, because of the large temperature gradient along the radius of the discharge tube. Later on, we will see that a linear acoustic flow cannot noticeably change the transfer processes in the tube. A nonlinear acoustic flow is capable of providing a large contribution to the transfer processes, but such a flow can exist only when the size α of the inhomogeneity in the acoustic field is much larger than the size δ of the boundary layer, i.e., $\alpha \gg \delta$. Thus, only a strong temperature nonuniformity along the tube's radius can be responsible for the generation of large acoustic flows acting on the transport processes.

As shown in Ref. [96], acoustic vortices are generated in the field of a constant acoustic wave (17), and their velocity field can be represented as follows:

$$\begin{aligned} u_x &= -\frac{v_a^2}{10c}\,\frac{R^2}{\delta^2}\,\frac{x}{\lambda}\left(1 - \frac{x^2}{R^2}\right)\cos 2kz\,, \\ u_z &= \frac{v_a^2}{c}\,\frac{\alpha}{120}\,\frac{R^2}{\delta^2}\,\frac{x}{\lambda}\left(1 - \frac{x^2}{R^2}\right)\left(1 - \frac{5x^2}{R^2}\right)\sin 2kz\,. \end{aligned} \tag{18}$$

A diagram of the velocity field (18) of acoustic vortices is depicted schematically in Fig. 18. We see that two symmetric vortices are generated on a quarter of the wavelength.

Let us estimate the lower limit to the effect of acoustic flows on the transport coefficients. From Ref. [96] it follows that convective vortex flows in a medium intensify the transport processes, which can be approximately described by the diffusion equation with an effective diffusion coeffi-

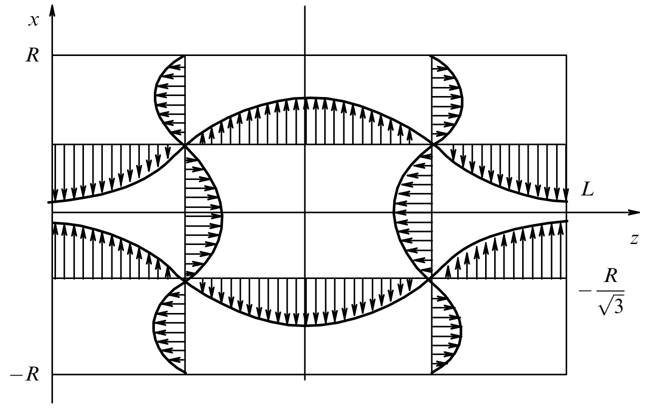


Figure 18. Diagram of the velocity field of acoustic vortices in an acoustic flow, where R is the tube's radius, and L is the tube's length.

cient

$$D_{\text{eff}} = D_0(1 + ru)\,, \tag{19}$$

where D_0 is the diffusion coefficient for a medium without convective flows, r is the mean vortex radius, and u is the mean velocity of vortex motion.

Then, the estimates give

$$\frac{\Delta D}{D_0} \approx \frac{ru}{l v_T}\,,$$

where D_0 is the initial diffusion coefficient (see above), ΔD is the change in the diffusion coefficient caused by acoustic flows, l is the mean free path, and v_T is the thermal velocity. In one experiment (see Ref. [12]), a standing acoustic wave with the intensity $I = 83$ dB was generated in a discharge tube of radius $R = 3$ cm with argon plasma under a pressure of 110 mmHg, and with the gas temperature on the tube's axis being 400 K. In these conditions, $u \sim 0.2$ cm s^{-1} and $\Delta D/D_0 \sim 0.1$. This was also corroborated in the experiment described in Ref. [12], where the discharge was decontracted by high-intensity (> 82 dB) acoustic waves. And it was also found that the radial temperature gradient substantially diminished in the process.

It is also known that at sufficiently high pressures ($p > 10$ mmHg) actually the only process of bulk neutralization of a charged particle in a gas-discharge plasma that can compete with diffusion is the dissociative recombination of electrons and molecular ions [106]. In inert-gas discharges at high pressures ($p > 10$ mmHg) and relatively low gas temperatures ($T < 1000$ K), molecular ions dominate. Thus, it may be assumed that in the experimental conditions under examination the following processes proceed:

$$\mathrm{Ar}^+ + 2\mathrm{Ar} \to \mathrm{Ar}_2^+ + \mathrm{Ar}\,,$$

$$\mathrm{Ar}_2^+ + \mathrm{e} \to \mathrm{Ar}^* + \mathrm{Ar}\,.$$

These processes run at a high rate and lead to the effective formation of highly excited atoms of the inert gas. What is also known is that highly excited atoms can be produced via dissociation of molecules by electron impact [107, 108]. This process was widely used in the early studies (in the 1960s) of Rydberg atoms.

Quantum theory predicts that atomic energy levels with large quantum numbers ($n \gg 1$) possess long radiative lifetimes. The mean lifetime t_n depends on the principal quantum number n as $t_n \sim n^4$.

Taking into account the aforesaid, we can make the following assumptions: the formed flows (see Fig. 18) are directed at some points inside the tube toward the tube's wall, and at other points to the center. These flows move the charged particles from the discharge area to the wall, but they also move the cold neutral particles from the wall toward the discharge axis. Hence, in the first case the hot electrons rapidly cool off, primarily because of elastic collisions with cold atoms. There is intense recombination of electrons with ions, basically with molecular ions. A similar intense recombination also takes place at the sites where the acoustic flows are directed toward the center of the tube, where the particles of the cold gas enter the middle of the discharge and cause intense recombination. It occurs that in such recombination processes, i.e., in the course of dissociative recombination, highly excited long-lived atoms are rapidly produced. This is the way in which highly excited atoms collect at the specified sites.

Let us examine the decay of such a highly excited long-lived atom as a result of its collisions with atoms and molecules.

In accordance with the theory of atomic collisions [109, 110], the probability of a transition between two energy levels rigorously depends on the Massey parameter ξ [the probability is proportional to $\sim \exp(-\xi)$]. We estimate the value of the Massey parameter for the $nl - n'l'$ transition, where $n' = n - 1$. The energy difference between the levels involved in this transition equals

$$\Delta\varepsilon \sim \frac{\delta_l - \delta_{l'}}{n^3}\,,$$

where δ_l is the quantum defect, and n is the principal quantum number. The Massey parameter [109, 110] is defined as

$$\xi = \frac{\Delta\varepsilon a}{v_{\text{a}}} \sim \frac{\delta_l}{n v_{\text{a}}}\,,$$

where a is the size of the excited atom, and v_{a} is the velocity at which the atomic nucleus moves. For $n, l \gg 1$, the Massey parameter is small due to the smallness of the quantum defect δ_l, and the probability of the respective transitions is high. This situation changes when the highly excited levels have a small orbital angular momentum $l \geqslant 0$. In such a case and for moderate values of n, the Massey parameter $\xi \gg 1$. Then, the probability of electron transitions related to collisions is much lower than in the previous case.

Due to quenching of the highly excited levels caused by collisions with atoms and molecules, energy levels with $n, l \gg 1$ are rapidly depleted, while the levels with $n \gg 1$ and $l \geqslant 0$ are intensely populated. In the experiment, the 7s, 6s, and 7d levels of an argon atom are populated, and because of this an enhancement in the intensity of the emission from the transitions 7s $\to$ 4p, 6s $\to$ 4p, and 7d $\to$ 4p is observed. As for flashes and the places where they form, the observed superluminescent radiation is probably formed when the threshold of overpopulation for the superradiation is overcome.

The blue flash from the 7d $\to$ 4p transition originates only inside the plasma filament, while the orange flashes (7s $\to$ 4p and 6s $\to$ 4p) occur both inside and outside the plasma filament. The reason is that the concentration of charged particles is much higher inside the plasma filament than outside it, and the recombination of the charged particles inside the filament is much more intense (because of the acoustic flows) than outside the radial boundary of the plasma filament. For the same reason, the concentration of highly excited atoms inside the filament is much higher and the threshold of overpopulation between the levels in 7d $\rightarrow$ 4p transition can easily be overcome, which ends up in superluminescence — the cause of the observed blue flashes. Levels 7s and 6s (orange flashes) become heavily populated both inside and outside the plasma filament, but the probability of these levels being quenched through collisions with atoms and molecules is much lower than it is for the level 7d. For this reason, orange flashes are observed both inside and outside the plasma filament.

Figure 17 shows that after the flashes of superluminescence (with duration 15 to 20 ms) have subsided, the intensity of the observed spectral lines is reduced to a minimum, and it takes a fairly long time (about 1 s) for the intensity to restore itself to its initial value. Apparently, the rate of the acoustic flow determines this period. Under the conditions specified in Ref. [17] (the tube's radius $R = 3$ cm, the sound's wavelength $l = 200$ cm, $T = 400$ K, $p = 100$ mmHg, and the sound intensity $I = 83$ dB), the acoustic-flow rate $u \sim 0.1-0.2$ cm s^{-1}. Charged particles traveling with such velocity cover the distance from the center of the discharge (the discharge diameter is 2 to 3 cm, roughly) to the tube's wall in approximately 1 s. Hence, after superluminescent radiation (i.e., stimulated depletion of the 7s, 6s, and 7d levels) it takes approximately 1 s for the depleted levels to restore their population to a value that existed prior to optical luminescence.

The hysteresis nature of the dependence of the intensity of the above-mentioned spectral lines on sound intensity is probably related to the effect of initiation of the spatial harmonics of the principal acoustic vortex [95].

At this point, we would like to note that the observed effect, i.e., superluminescent radiation emitted by an argon discharge at elevated pressure, can be realized by other means as well. The same effect can be brought about by vortices generated by a turbulent gas flow directed along the positive column. A high-speed gas flow will lead to a marked decrease in the radial temperature gradient in the gas and to decontraction of the pinched discharge. After that, one should reduce the gas flow rate to a value at which the discharge contracts [42], and this is followed by the emission of a superluminescent flash.

4.4 An acoustically induced gas-discharge laser

Quantum electronics is developing because new ways of producing population inversion appear all the time. This makes possible the building of new lasers based on these new approaches. Among the main methods by which population inversion can be achieved are optical pumping, inversion produced in a gas discharge where electrons collide with neutral particles (the He–Ne laser, the carbon dioxide laser, etc.), inversion produced in a gasdynamic flow (gasdynamic lasers), chemical excitation, and photodissociation. Population inversion has also been produced in a gas (argon) discharge through controlling the plasma configuration by acoustic waves (see Refs [16–18]).

This new way of producing overpopulation of atomic energy levels in the positive column is related to generating a uniformly excited gas in an argon discharge under elevated pressure with the aid of acoustic vortices. Interrupting the

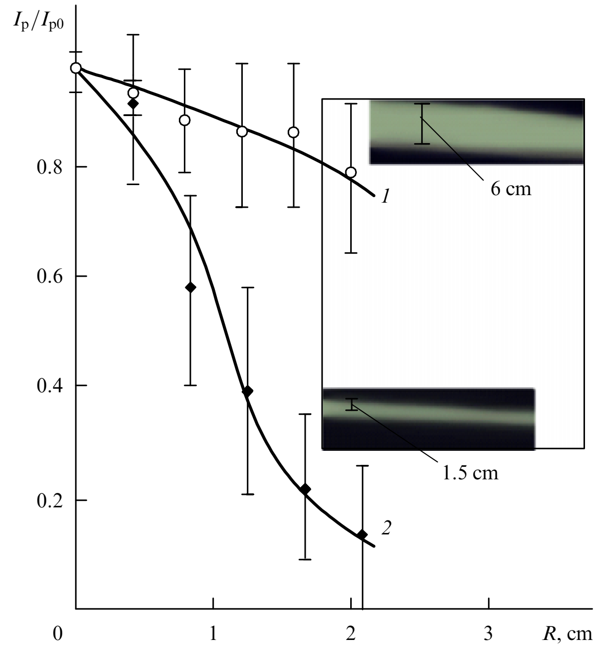


Figure 19. Distributions of the relative electron saturation current in double electric probes over the radius of a discharge tube with an inner diameter of 6 cm at a pressure of 110 mmHg and a current of 75 mA; the acoustic wave had a resonance frequency of 190 Hz and its intensity was 85 dB. Curve *1*, with sound, and curve *2*, without sound.

sound or radically reducing the intensity of the acoustic wave in such a positive column gives rise to discharge contraction. As a result, the plasma column is pinched into a thin bright filament, at the periphery of which the electron concentration abruptly drops (Fig. 19). In view of a number of recombination and relaxation processes (described earlier), population inversion sets in inside the gas-discharge tube with such a plasma filament, and this is followed by a flash of superluminescence. As the flash propagates in the optical cavity, feedback is established, and we arrive at a gas-discharge laser.

Figure 20 displays a block diagram of an acoustically induced gas-discharge laser which consists of a 100-cm long discharge tube (*1*) 6 cm in diameter, two electrodes (*2*) placed 85 cm apart, a high-voltage power source (*3*), an electrodynamic radiator of acoustic waves (*5*) hermetically attached

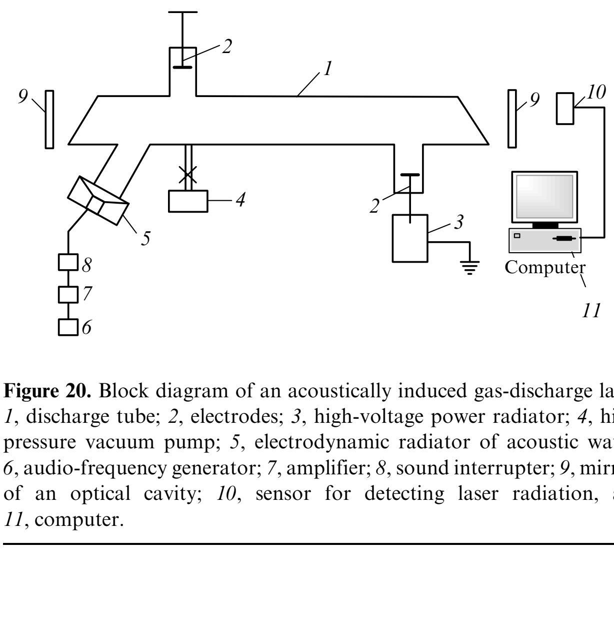


Figure 20. Block diagram of an acoustically induced gas-discharge laser: *1*, discharge tube; *2*, electrodes; *3*, high-voltage power radiator; *4*, high-pressure vacuum pump; *5*, electrodynamic radiator of acoustic waves; *6*, audio-frequency generator; *7*, amplifier; *8*, sound interrupter; *9*, mirrors of an optical cavity; *10*, sensor for detecting laser radiation, and *11*, computer.

to one of the tube's ends at an angle of 30° to the tube's axis, an audio-frequency generator (*6*) with an amplifier (*7*) and a sound interrupter (*8*), and an optical cavity (*9*).

Acoustic waves of 84 dB intensity generated by the radiator produced a homogeneous uncontracted positive column in an argon discharge at a pressure of 110 mmHg and a current of 50 mA. Reduction of the sound intensity to a value below 82 dB leads to discharge contraction followed by the generation of a pulse of laser radiation at three wavelengths: 5888, 5882, and 4876 Å. An acoustically induced gas-discharge laser can operate both in the pulsed mode and in the pulse-periodic mode.

5. Conclusion

Vortex motion that emerges in a weakly ionized gas in response to a gas flow or acoustic waves directed along the positive column affects the properties of the discharge in different ways, depending on the scale of vortices, which is related to the Reynolds number. These vortices bring about changes in the longitudinal electric field at constant current and gas pressure in the discharge, in the magnitude of the electron energy, in the temperature of the neutral gas and its radial gradient, in the modulation of the discharge current, and in all other plasma parameters. They also lead to contraction and depinching of the positive column.

Weakly ionized gases with vortex oscillations are being used more and more in various areas of science and technology [62]. One of the latest applications of this kind is the acoustically induced gas-discharge laser [111] and a laser controlled by a gas flow [112].

When an acoustic wave of resonance frequency with an intensity higher than I_{cr} is directed along a contracted positive column of a glow discharge at elevated pressures, the result is the turbulent mixing of the plasma in the radial direction and the emergence of a homogeneous uncontracted plasma column filling the entire volume of the tube. Subsequent reduction in the intensity of the acoustic wave to values below I_{cr} leads to an abrupt transition of the discharge from the uncontracted, homogeneous state to the contracted. Several seconds after the plasma column has contracted, during which period various recombination and relaxation processes (described above) in argon take place, population inversion sets in and a train of the flashes of superluminescence (with intensity higher by a factor of approximately 100) are emitted.

Tuning the optical cavity to such a discharge ensures feedback and, eventually, lasing.

Acoustic waves in a discharge tube initiate the change in plasma configuration from a homogeneous, uncontracted plasma column to a contracted column, which leads to reaching population inversion in the argon discharge followed by emission of superluminescent radiation. Similar processes take place in an uncontracted discharge with a turbulent gas flow directed along the positive column at an elevated pressure. If the flow rate is reduced to a value at which the discharge abruptly becomes contracted, i.e., a pinched positive column is formed, population inversion develops in the argon discharge, and this is followed by a flash of superluminescence. By attaching an optical cavity to such a discharge tube one can build a gas-discharge laser controlled by a gas flow. Such a laser was recently described in Ref. [112].

References

1. Cottingham W B, Buchsbaum S J *Bull. Am. Phys. Soc.* **8** 424 (1963)
2. Gentle K W, Ingard U, Bekefi G *Nature* **203** 1369 (1964)
3. Cottingham W B, Buchsbaum S J *J. Appl. Phys.* **36** 2075 (1965)
4. Granatstein V L, Buchsbaum S J *Appl. Phys. Lett.* **7** 285 (1965)
5. Granatstein V L, Buchsbaum S J, Bugnolo D S *Phys. Rev. Lett.* **16** 504 (1966)
6. Granatstein V L *Phys. Fluids* **10** 1236 (1967)
7. Granatstein V L, Levine A M, Subramanian M *Phys. Fluids* **14** 2581 (1971)
8. Chebotaev V P *Dokl. Akad. Nauk SSSR* **206** 334 (1972) [*Sov. Phys. Dokl.* **17** 923 (1973)]
9. Galechyan G A, Petrosyan S I *Prikl. Mekh. Tekh. Fiz.* (6) 9 (1975) [*J. Appl. Mech. Tech. Phys.* **16** 844 (1975)]
10. Galechyan G A, Petrosyan S I *Teplofiz. Vys. Temp.* **14** 931 (1976)
11. Galechyan G A, Petrosyan S I *Teplofiz. Vys. Temp.* **16** 677 (1978)
12. Aramyan A R, Galechyan G A, Mkrtchyan A R *Akust. Zh.* **37** 213 (1991) [*Sov. Phys. Acoust.* **37** 107 (1991)]
13. Aramyan A R, Galechyan G A, Mkrtchyan A R *Pis'ma Zh. Tekh. Fiz.* **17** 12 (1991) [*Sov. Tech. Phys. Lett.* **17** 4 (1991)]
14. Galechyan G A *Usp. Fiz. Nauk* **165** 1357 (1995) [*Phys. Usp.* **38** 1309 (1995)]
15. Galechyan G A *Laser Phys.* **4** 23 (1994)
16. Aramyan A R *Pis'ma Zh. Eksp. Teor. Fiz.* **69** 355 (1999) [*JETP Lett.* **69** 383 (1999)]
17. Aramyan A R *Phys. Rev. Lett.* **91** 155002 (2003); *Pis'ma Zh. Eksp. Teor. Fiz.* **77** 326 (2003) [*JETP Lett.* **77** 276 (2003)]
18. Aramyan A R, in *Advances in Plasma Physics Research* Vol. 5 (Ed. F Gerard) (New York: Nova Sci. Publ., 2006) Ch. 5, p. 133
19. Arutyunyan G G, Galechyan G A, Tavakalyan L B *Izv. Akad. Nauk Arm. SSR Ser. Fiz.* **15** 286 (1980)
20. Cottingham W B, Buchsbaum S J *Phys. Rev.* **130** 1002 (1963)
21. Bugnolo D S *J. Geophys. Res.* **70** 3721 (1965)
22. Granatstein V L, Buchsbaum S J, in *Turbulence of Fluids, Proc.* (Microwave Research Institute Symposia Ser., Vol. 18, Ed. J Fox) (Brooklyn, NY: Polytechnic Press, 1969) p. 231
23. Niemeyer L, Ragaller K *Z. Naturforsch. A* **28** 1281 (1973)
24. Granatstein V L, Buchsbaum S J *Bull. Am. Phys. Soc.* **11** 463 (1966)
25. Granatstein V L *Appl. Phys. Lett.* **13** 37 (1968)
26. Feinstein D L, Granatstein V L *Phys. Fluids* **12** 2658 (1969)
27. Granatstein V L, Buchsbaum S J *Phys. Fluids* **10** 1851 (1967)
28. Granatstein V L, Philips T O *Phys. Fluids* **13** 2810 (1970)
29. Patel C K N *Sci. Am.* **219** (2) 22 (1968) [Translated into Russian in *Usp. Fiz. Nauk* **97** 697 (1969)]
30. Deutsch T F, Horrigan F A, Rudko R I *Appl. Phys. Lett.* **15** 88 (1969)
31. Hill A E *Appl. Phys. Lett.* **18** 194 (1971)
32. Brown C O, Devis J W *Appl. Phys. Lett.* **21** 480 (1972)
33. DeMaria A J *Proc. IEEE* **61** 731 (1973)
34. Brown C O *Appl. Phys. Lett.* **17** 388 (1970)
35. McLeary R, Gibbs W *IEEE J. Quantum Electron.* **QE-9** 828 (1973)
36. Artamonov A V et al. *Kvantovaya Elektron.* **4** 581 (1977) [*Sov. J. Quantum Electron.* **7** 323 (1977)]
37. Abel'siitov G A et al. *Kvantovaya Elektron.* **7** 2467 (1980) [*Sov. J. Quantum Electron.* **10** 1436 (1980)]
38. Velikhov E P, Golubev V S, Pashkin S V *Usp. Fiz. Nauk* **137** 117 (1982) [*Sov. Phys. Usp.* **25** 340 (1982)]
39. Schlichting H *Grenzschich-Theorie* (Karlsruhe: G. Braun, 1958) [Translated into English: *Boundary-Layer Theory* (New York: McGraw-Hill, 1968); translated into Russian (Moscow: Nauka, 1974)]
40. Landau L D, Lifshitz E M *Gidrodinamika* (Fluid Mechanics) (Moscow: Nauka, 1986) [Translated into English (Oxford: Pergamon Press, 1987)]
41. Eletskii A V, Palkina L A, Smirnov B M *Yavleniya Perenosa v Slaboionizovannoi Plazme* (Transport Phenomena in Weakly Ionized Plasma) (Moscow: Atomizdat, 1975)
42. Galechyan G A, in *Khimiya Plazmy* (Plasma Chemistry) Issue 10 (Ed. B M Smirnov) (Moscow: Energoatomizdat, 1983) p. 73
43. Schottky W *Phys. Z.* **25** 342 (1924)

44. Madelung E *Die Mathematischen Hilfsmittel des Physikers* (Berlin: Springer, 1964) [Translated into Russian: 2nd ed. (Moscow: Nauka, 1968)]
45. Eletskii A V, in *Khimiya Plazmy* (Plasma Chemistry) Issue 9 (Ed. B M Smirnov) (Moscow: Energoatomizdat, 1982) p. 151
46. Betchov R "Transition", in *Handbook of Turbulence* Vol. 1 *Fundamentals and Applications* (Eds W Frost, T H Moulden) (New York: Plenum Press, 1977) p. 147 [Translated into Russian (Moscow: Mir, 1980) p. 164]
47. Hinze J O *Turbulence*: *An Introduction to Its Mechanism and Theory* (New York: McGraw-Hill, 1959) [Translated into Russian (Moscow: Fizmatgiz, 1963)]
48. Loitsyanskiy L G *Mekhanika Zhidkosti i Gaza* (Mechanics of Liquids and Gases) (Moscow: Nauka, 1978) [Translated into English (New York: Begel House, 1995)]
49. Bradshaw P (Ed.) *Turbulence* (Topics in Applied Physics, Vol. 12) (Berlin: Springer-Verlag, 1978) [Translated into Russian (Moscow: Mashinostroenie, 1980)]
50. Galechyan G A *Teplofiz. Vys. Temp.* **20** 379 (1982)
51. Raizer Yu P *Fizika Gazovogo Razryada* (Gas Discharge Physics) (Moscow: Nauka, 1987) [Translated into English (Berlin: Springer-Verlag, 1991)]
52. Akishev Yu S, Napartovich A P *Fiz. Plazmy* **4** 1146 (1978) [*Sov. J. Plasma Phys.* **4** 641 (1978)]
53. Bondarenko A V et al. *Fiz. Plazmy* **5** 687 (1979) [*Sov. J. Plasma Phys.* **5** 386 (1979)]
54. Vysikailo F I *Teplofiz. Vys. Temp.* **24** 657 (1986)
55. Nedospasov A V, Khait V D *Kolebaniya i Neustoichivosti Nizkotemperaturnoi Plazmy* (Oscillations and Instabilities in Low-Temperature Plasma) (Moscow: Nauka, 1979)
56. Eletskii A V, Rakhimov A T, in *Khimiya Plazmy* (Plasma Chemistry) Issue 4 (Ed. B M Smirnov) (Moscow: Atomizdat, 1977) p. 123
57. Granovskii V L *Elektricheskii Tok v Gaze. Ustanovivshiisya Tok* (Electrical Current in Gas. Steady Current) (Moscow: Nauka, 1971)
58. Shwartz J, Lavie Y *AIAA J.* **13** 647 (1975) [Translated into Russian: *Raket. Tekh. Kosmonavtika* **13** (5) 137 (1975)]
59. Ziganshin R R, Ismagilov R Kh, Minushev M A *Inzh.-Fiz. Zh.* **39** 636 (1980) [*J. Eng. Phys.* **39** 1074 (1981)]
60. Garosi G A, Bekefi G, Schulz M *Phys. Fluids* **13** 2795 (1970)
61. Napartovich A P, Starostin A N, in *Khimiya Plazmy* (Plasma Chemistry) Issue 6 (Ed. B M Smirnov) (Moscow: Atomizdat, 1979) p. 159
62. Leonov S B et al., in *44th AIAA Aerospace Sciences Meeting and Exhibit, 9–12 January 2006, Reno, Nevada* (Reston, VA: AIAA, 2006) AIAA 2006-563
63. Velikhov E P et al. *Impul'snye CO_2-Lazery i Ikh Primenenie dlya Razdeleniya Izotopov* (Pulsed CO_2 Lasers and Their Application for Isotope Separation) (Executive Ed. B M Smirnov) (Moscow: Nauka, 1983)
64. Tsendin L D *Zh. Tekh. Fiz.* **35** 1972 (1965) [*Sov. Phys. Tech. Phys.* **10** 1514 (1966)]
65. Ingard U *Phys. Rev.* **145** 41 (1966)
66. Ingard U, Schulz M *Phys. Rev.* **158** 106 (1967)
67. Molevich N E, Oraevskii A N *Zh. Eksp. Teor. Fiz.* **94** (3) 128 (1988) [*Sov. Phys. JETP* **67** 504 (1988)]
68. Osipov A I, Uvarov A V *Usp. Fiz. Nauk* **162** (11) 1 (1992) [*Sov. Phys. Usp.* **35** 903 (1992)]
69. Hasegawa M *J. Phys. Soc. Jpn.* **37** 193 (1974)
70. Fitaire M, Mantei T D *Phys. Fluids* **15** 464 (1972)
71. Galechyan G A, Divanyan É G, Mkrtchyan A R *Akust. Zh.* **36** 364 (1990) [*Sov. Phys. Acoust.* **36** 200 (1990)]
72. Aleksandrov N L et al. *Fiz. Plazmy* **16** 862 (1990) [*Sov. J. Plasma Phys.* **16** 502 (1990)]
73. Galechyan G A *Priroda* (7) 74 (1996)
74. Galechyan G A et al., Preprint No. 1 (Yerevan: Institute of Applied Problems of Physics, National Acad. of Sci. of Armenia, 1991)
75. Zavershinskii I P, Kogan E Ya, Molevich N E *Akust. Zh.* **38** 702 (1992) [*Sov. Phys. Acoust.* **38** 387 (1992)]
76. Aleksandrov N L et al. *Zh. Eksp. Teor. Fiz.* **95** 1614 (1989) [*Sov. Phys. JETP* **68** 933 (1989)]
77. Zavershinskii I P, Kogan E Ya, Molevich N E *Zh. Eksp. Teor. Fiz.* **100** 422 (1991) [*Sov. Phys. JETP* **73** 231 (1991)]
78. Bauer H-J, Bass H E *Phys. Fluids* **16** 988 (1973)
79. Kogan E Ya, Mal'nev V N *Zh. Tekh. Fiz.* **47** 653 (1977) [*Sov. Phys. Tech. Phys.* **22** 391 (1977)]
80. Osipov A I, Uvarov A V *Khim. Fiz.* **6** 385 (1987)
81. Kogan E Ya, Molevich N E *Zh. Tekh. Fiz.* **56** 941 (1986) [*Sov. Phys. Tech. Fiz.* **31** 573 (1986)]
82. Eletskii A V, Stepanov E V *Khim. Fiz.* **8** 1247 (1989)
83. Galechyan G A, Mkrtchyan A R *Pis'ma Zh. Tekh. Fiz.* **27** (14) 68 (2001) [*Tech. Phys. Lett.* **27** 605 (2001)]; *Akust. Zh.* **48** 314 (2002) [*Acoust. Phys.* **48** 268 (2002)]
84. Torosyan O S, Mkrtchyan A R *Fiz. Plazmy* **29** 376 (2003) [*Plasma Phys. Rep.* **29** 346 (2003)]
85. Schulz M, Ingard U *Phys. Fluids* **10** 1031 (1967)
86. Kaw P *Phys. Rev.* **188** 506 (1969)
87. Šubertová S *Czech. J. Phys.* **15** 701 (1965)
88. Mkrtchyan A R et al. *Acustica* **69** 124 (1989)
89. Zavershinskii I P, Kogan E Ya *Fiz. Plazmy* **20** 933 (1994) [*Plasma Phys. Rep.* **20** 838 (1994)]
90. Landa P S *Avtokolebaniya v Raspredelennykh Sistemakh* (Self-oscillations in Distributed Systems) (Moscow: Nauka, 1983)
91. Golubovskii Yu B, Nekuchaev V Yu *Zh. Tekh. Fiz.* **53** 482 (1983) [*Sov. Phys. Tech. Phys.* **28** 301 (1983)]
92. Antinyan M A et al. *Akust. Zh.* **38** 391 (1992) [*Sov. Phys. Acoust.* **38** 215 (1992)]
93. Antinyan M A, Galechyan G A, Tavakalyan L B *Zh. Tekh. Phys.* **63** 197 (1993) [*Tech. Phys.* **38** 53 (1993)]
94. Galechyan G A, Karapetyan D M, Tavakalyan L B *Pis'ma Zh. Tekh. Phys.* **18** (1) 44 (1992) [*Sov. Tech. Phys. Lett.* **18** 17 (1992)]
95. Rudenko O V, Soluyan S I *Teoreticheskie Osnovy Nelineinoi Akustiki* (Theoretical Foundations of Nonlinear Acoustics) (Moscow: Nauka, 1975) [Translated into English (New York: Consultants Bureau, 1977)]
96. Hatsagortsyan K Z, Galechyan G A *Laser Phys.* **4** 502 (1994)
97. Eletskii A V, Smirnov B M *Zh. Tekh. Fiz.* **40** 1682 (1970) [*Sov. Phys. Tech. Phys.* **15** 1308 (1971)]
98. Eletskii A V, Smirnov B M *Fizicheskie Protsessy v Gazovykh Lazerakh* (Physical Processes in Gas Lasers) (Moscow: Energoatomizdat, 1985) [Translated into English in *J. Russ. Laser Res.* **7** (3) 203 (1986)]
99. Galechyan G A, Karapetyan D M, Tavakalyan L B *Teplofiz. Vys. Temp.* **31** 698 (1993) [*High Temp.* **31** 642 (1993)]
100. Antinyan M A et al. *Acustica* **82** 619 (1996)
101. Galechyan G A *Priroda* (3) 65 (1994)
102. Galechyan G A, Mkrtchyan A R *Akustoplazma* (Acoustically Induced Plasma) (Yerevan: Apaga, 2005)
103. Antinyan M A et al. *Laser Phys.* **2** 685 (1992)
104. Zavershinskii I P, Kogan E Ya, Molevich N E, in *Tezisy Dokl. 2-go Vsesoyuz. Seminara 'Vzaimodeistviya Akusticheskikh Voln s Plazmoi'* (Abstracts of Reports Delivered at the 2nd All-Union Workshop 'Interactions of Acoustic Waves with Plasma') (Yerevan, 1991) p. 35
105. Isachenko M B et al. *Zh. Eksp. Teor. Fiz.* **98** 919 (1990) [*Sov. Phys. JETP* **71** 512 (1990)]
106. Eletskii A V, Smirnov B M *Usp. Fiz. Nauk* **136** 25 (1982) [*Sov. Phys. Usp.* **25** 13 (1982)]
107. Kupriyanov S E *Zh. Eksp. Teor. Fiz.* **55** 460 (1968) [*Sov. Phys. JETP* **28** 240 (1969)]
108. Freund R S *J. Chem. Phys.* **54** 3125 (1971)
109. Mott N F, Massey H S W *The Theory of Atomic Collisions* 3rd ed. (Oxford: Clarendon Press, 1965) [Translated into Russian (Moscow: Mir, 1969)]
110. Smirnov B M *Vozbuzhdennye Atomy* (Excited Atoms) (Moscow: Energoizdat, 1982)
111. Aramyan A R, Galechyan G A, Manukyan G V *Laser Phys.* **17** 1129 (2007)
112. Galechyan G A *Laser Phys.* **17** 1209 (2007)