Physics – Uspekhi **38** (12) 1309 – 1330 (1995)

PACS numbers: 52.35.Dm; 51.40.+p

Acoustic waves in plasma

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Contents

Abstract. This is a review of studies of the interaction of acoustic waves and plasma. It is shown that the variation of parameters of an acoustic wave directed along the positive column of a gaseous discharge makes it possible to adjust continuously the plasma properties — in particular, to increase or decrease the gas and electron temperatures and the electric field intensity over a wide range. The issues considered are how sonic waves affect the compression (contraction) and expansion (decontraction) of the plasma column, and also the accompanying abrupt increases in wave amplitude and discharge current modulation. The mechanisms of the phenomena listed are examined. Analogies between processes which occur in plasma when sonic waves propagate in it and when gas flows through it are discussed. The results of studies of the combined effect of a sonic wave and a gas flow on the parameters of a gaseous discharge are presented.

1. Introduction

The low-temperature plasma is a partially ionised state of gas, which responds actively to the slightest external stimulus. Insignificant heating of a wall of the plasma chamber gives rise to a noticeable redistribution of the densities of charged particles over the plasma column cross-section. The weak laminar pumping of gas along the plasma column results in the contraction of the column and in the drop of the electron temperature near the axis of the discharge. The fast gas flow along the contracted positive discharge brings about an increase in the diameter of the discharge, buildup of the electric field in plasma, increase in the electron temperature, and other phenomena.

Study of properties of the plasma and of how it responds to external actions has always been a topical issue because the results of these studies have revealed new physical mechanisms and rapidly found their way into practical applications. The influence of electromagnetic waves, and electron, ion, and neutral beams on plasma properties has been studied thoroughly. There are many reviews and monographs on this theme. However, the influence of acoustic waves on plasma parameters has not been studied as thoroughly. In the last few years this issue has aroused heated attention, promising results have been obtained, and a great number of papers have been published. So the time has come to write a review and summarise the data. Let me first list several phenomena which occur in plasma when a sonic wave propagates through it.

An increase in intensity of a standing sonic wave directed along the positive column of a gaseous discharge brings about a drop in the gas temperature in plasma, reduction of the radial gradient of the gas temperature, increase of the longitudinal electric field intensity, increase in the electron temperature, and formation of a homogeneous stabilised noncontracted discharge at a high gas pressure. In addition, the sonic wave causes the stratifica-

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Received 25 November 1994, revised 16 June 1995
Uspekhi Fizicheskikh Nauk **165** (12) 1357–1379 (1995)
Translated by D Kh Gan'zha; edited by L Dwivedi

tion of the positive column, modulations of the discharge current and electric field, and changes in the electron temperature and density.

In low-temperature plasma, owing to the difference in temperatures of electrons and heavy particles and because of a non-Maxwellian energy distribution of electrons, a thermodynamically nonequilibrium state is realised such that the sonic wave can be amplified in the plasma in which it propagates [1]. Fluctuations of gas-dynamic parameters of the medium may cause an acoustic instability to develop in plasma [1]. The most general mechanism of sonic wave amplification in plasma is related to the spatial heat release depending on the density of charge particles. The mechanism of sound amplification, related to negative viscosity, is considered in Refs [4, 5]. The thermal mechanism is examined within the framework of gas dynamics in Refs [6 – 8]. The amplification of sonic waves emitted by an external source and propagating along the positive column of the glow discharge in inert gases is studied in Refs [9 – 12].

In Refs [12, 13] the anisotropy of the gain is considered depending on the direction of propagation of the travelling sonic wave relative to the drift of electrons. The mechanism of formation of anisotropy of the sound gain in gas-discharge plasma is studied in Ref. [13]. In a vibrationally nonequilibrium molecular gas, the amplification of sound is possible because of transformation of the extra vibrational energy into the energy of the sonic wave. In Refs [15 – 17], the authors develop the linear theory of propagation of a sonic wave in a molecular gas, though it does not account for the reciprocal action of the amplitude of the sonic wave and the amplifying medium. In Ref. [18] the nonlinear theory of propagation of a sonic wave in a molecular gas is constructed with account being taken of the above effects. In Ref. [12] the amplification of sound is measured in discharges of inert and molecular gases (nitrogen, air, and nitrogen – argon mixture). However, in Ref. [12] the studies were conducted at relatively low pressures in discharge (6 to 18 torr). The study of sonic waves in the nitrogen – oxygen discharge was conducted at 78 torr in Refs [19, 20]. The amplitude of sound is found to change abruptly with a contraction of the positive column in molecular gases. In Ref. [14] the influence of sonic waves on the properties of the positive column was studied experimentally for the first time; a homogeneous positive column is shown to become stratified under the action of a sonic wave directed along the discharge.

This incomplete list of phenomena occurring in plasma when acoustic waves propagate in it shows that a new line of inquiry which has theoretical as well as applied significance has been formed at the junction of the fields of acoustics and plasma physics. Nearly all the parameters of plasma in discharge may be controlled by waves.

In this review the main emphasis will be on the influence of acoustic waves on plasma parameters in a glow discharge since the amplification of sonic waves in plasma has already been examined [5]. We shall describe the influence of acoustic waves on the gas temperature in plasma, on the electric field in discharge, on the electron temperature and electron density, and also consider the effects of gas pumping and sonic waves on the properties of the positive column and expound the issues of the combined action of sound and gas flow on the parameters of a gaseous discharge.

2. Influence of a sonic wave on the parameters of plasma in a glow discharge

The glow discharge is the simplest and most thoroughly studied plasma phenomenon. The applied electric field ionises a low-pressure gas in the gap between two electrodes located at the opposite ends of a tube and thus creates a glow discharge with a positively charged plasma column. The plasma is in a nonequilibrium state because the electron energy significantly exceeds the ion energy. The gas is ionised mainly when electrons collide with atoms and molecules.

The gaseous discharge is widely used in numerous instruments and devices — in particular, in neon lamps, magneto-hydrodynamic and plasmochemical generators, etc. Therefore, it is important to control the plasma parameters independently in order to bring the devices to the optimal operational condition. Also it is equally important, useful, and interesting to study physical processes when plasma parameters change under the influence of acoustic waves. In this respect, the influence of sound on the electrical parameters of the glow discharge, on the gas temperature in plasma, and on the electron density and electron temperature are considered in this section.

2.1 Electrical parameters of a discharge in the field of an acoustic wave

The electric field governs kinetic, plasmochemical, and thermal processes in plasma. The study of the electric field gives an insight into the kinetics of birth and decay of charged particles and the processes of compression and expansion of the plasma column in response to external actions. When the positive column of the discharge is compressed at a constant gas pressure, the current density increases near the axis and the longitudinal electric field strength decreases; when the discharge expands, the opposite phenomena take place.

The electric field in plasma, in the absence of an external action, is considered in Refs [21, 22]. Here we shall examine the results of experiments on the influence of acoustic waves on the electric field in a plasma column at various intensities and frequencies of the sonic wave [23, 24], compare them with the data about the action of a gas flow on the electric field in discharge [25], and then consider physical mechanisms responsible for these processes.

The influence of sonic waves on the electric field in the positive column was measured in the testing unit with a fixed quartz tube (mounted upright), 9.8 cm in inner diameter and 52 cm in length [33]. The ring wire-gauze electrodes were separated by 27 cm. Electrical power was supplied by a high-voltage dc-current source. To one of the ends of the gas-discharge tube an electrodynamic radiator of sonic waves was hermetically fastened. At the opposite end of the tube (behind the anode) a microphone was attached to the flange to control the parameters of the sonic wave. The frequency of sound was varied by a low-frequency generator of sinusoidal oscillations, and the amplitude by an amplifier. The signal from the microphone came to the double-beam oscilloscope. The value of the permanent component of the longitudinal electric field intensity in the plasma column was evaluated by the compensation method described in Ref. [26]. The two electrical probes were placed at a distance of 1 cm from each other on the axis of the discharge and could be moved with the use of a special device along the positive column of discharge between the anode and cathode over a distance up to 11 cm. The electric field intensity was also determined by a single probe. The values of the electric field measured by the two methods were found to be in good agreement.

The gas temperature in the discharge was measured by two thermocouple sensors with quartz protective coatings. One of the sensors was on the axis of the positive column at a distance of 8 cm from the anode and the second was on the wall of the tube at the same distance from the anode. The flange to which the microphone was fastened had a cavity with a diameter greater than the inner diameter of the tube. The acoustic resonator of this design is similar to a cylindrical resonator with one open end. The theoretical considerations show [27] that the natural frequencies of this resonator may be calculated by means of the formula

$$f_k = \frac{ck}{4(L + 0.8R)} , \tag{1}$$

where c is the speed of sound, $k = 1, 3, 5, \ldots, L$ is the tube length, and R is the tube radius. At resonance, an odd number of quarter wavelengths falls within the tube length or, more precisely, within the length $L + 0.8R$. Only these resonant frequencies were observed in the cited experiment in the standing sonic wave regime.

Let us consider the results of measurements of the longitudinal electric field E in the positive column over the range of frequencies of sound f from 130 to 200 Hz, taken in the nitrogen–oxygen discharge at the pressure 40 torr, current 40 mA, and intensities 95 and 98 dB [28] (Fig. 1).

The peak values of the field were reached near the first resonance $f = 170$ Hz in nitrogen and $f = 155$ Hz in oxygen. In the nitrogen discharge, the electric field was 105 W in the absence of sound, and 138 W at the sound intensity 98 dB with the frequency 170 Hz; in oxygen it was, respectively, 55 W without sound, and 78 W in the presence of sound with the resonant frequency $f = 155$ Hz. It follows from the cited results that the emission of a sonic wave along the positive discharge causes the longitudinal electric field to build up. Moreover, the greatest buildup of the field occurs at the resonant frequency of sound. An increase in the sonic wave intensity at a constant frequency causes the electric field to build up.

The comparison of the dependences of electric field intensity on the frequency (curves *1* and *2* versus *3* and *4* in Fig. 1) shows that the dependence is sharper for oxygen than for nitrogen.

The buildup of the electric field with an increase in the sonic wave intensity is accompanied by a drop in the gas temperature in plasma, an increase in the electron energy, and a diametric expansion of the visible boundary of the plasma column. In the oxygen discharge, the gas temperature $T_0 = 589$ K on the discharge axis in the absence of sound at 40 torr and 40 mA. The emission of a sonic wave of intensity 95 dB causes the temperature to drop to 548 K. The maximum drop of T_0 is observed at the resonant frequency. Simultaneously, the temperature rises on the tube wall, i.e. in plasma the radial gradient of the gas temperature diminishes under the action of a sonic wave propagating along the positive column of the gaseous discharge.

The change in the longitidinal electric field in discharge with variation of the sonic wave frequency (at a fixed gas pressure in the tube) should be accompanied by an appropriate change in the current. Let us consider changes in the discharge current and in the difference of electric field intensities at electrodes depending on the sonic wave frequency over the range from 100 to 420 Hz in argon at the pressure of 110 torr and fixed intensity 83 dB in a tube of length 100 cm and inner diameter 6 cm with electrodes separated by 85 cm [23]. In the absence of sound, the discharge current is 50 mA and the electric field intensity is 3.5 kW.

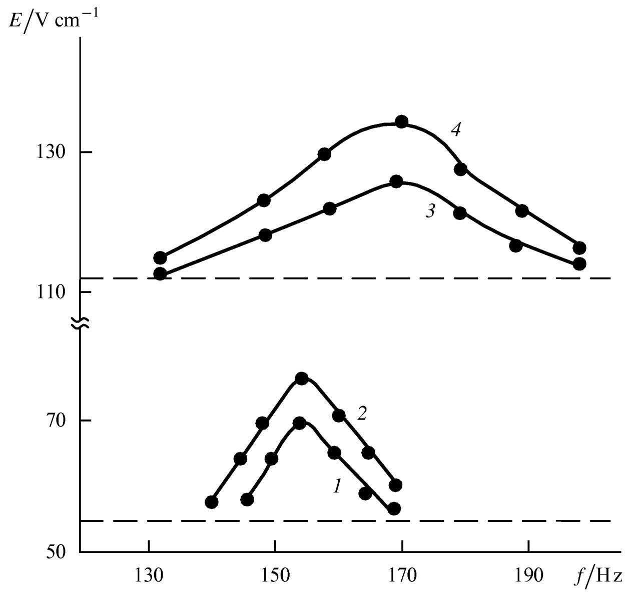

Figure 1. Dependence of the longitudinal electric field intensity on the frequency near the first resonance of the sonic wave at 40 torr and 40 mA: discharge in oxygen (*1*, *2*); discharge in nitrogen (*3*, *4*) (*1*, *3* — at the sound intensity 95 dB; *2*, *4* — at 98 dB). The discharge tube was 9.8 cm in diameter and 52 cm in length, and the wire-gauze electrodes were separated by 27 cm. The dashed curves represent the values of the field in discharge in the absence of a sonic wave.

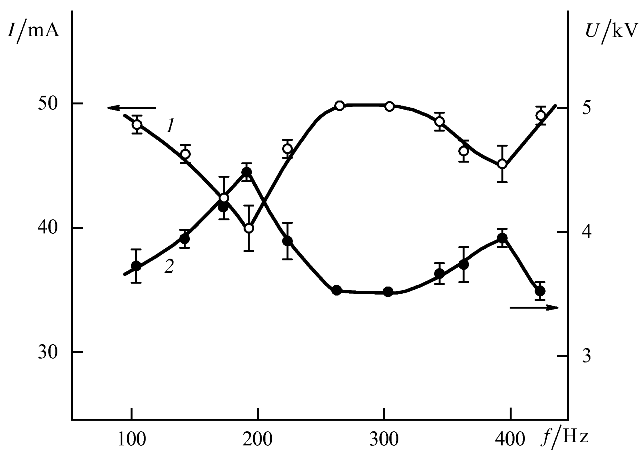

Figure 2. Dependences of the discharge current (curve *1*) and the electric voltage of the electrodes (curve *2*) on the sound frequency in the tube of length 100 cm and inner diameter 6 cm at the intensity 83 dB and argon pressure 110 torr. The quantities deviate most under the influence of a sonic wave at the resonant frequencies 190 and 380 Hz, at which a standing wave develops in the tube.

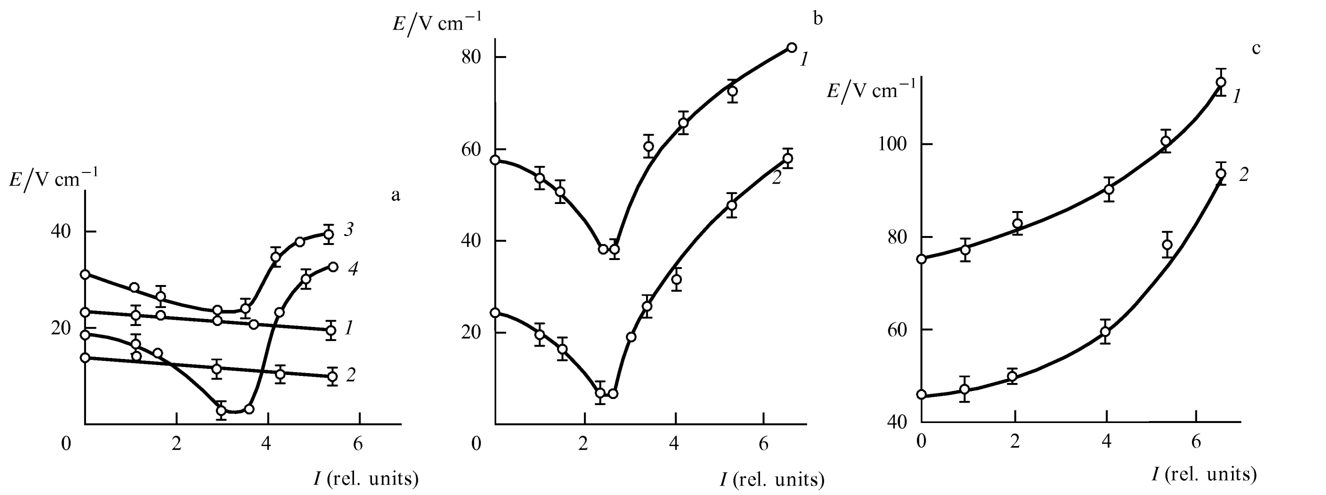

Figure 3. Dependences of the longitudinal electric field intensity on the sonic wave intensity in an argon discharge ($f = 150$ Hz) at different pressures in the tube of diameter 9.8 cm and length 52 cm. (a) $p = 48$ torr (curves *1* and *2*), $p = 54$ torr (curves *3* and *4*); $j_p = 40$ mA (curves *1* and *3*), $j_p = 100$ mA (curves *2* and *4*). (b) $p = 110$ torr; $j_p = 40$ mA (curve *1*), $j_p = 100$ mA (curve *2*). (c) $p = 180$ torr; $j_p = 40$ mA (curve *1*), $j_p = 100$ mA (curve *2*).

With the emission of a sonic wave and a change in the frequency, the maximum deviations are observed at the resonant frequencies 190 and 380 Hz, at which standing waves develop (Fig. 2). At 190 Hz the electric current drops to 40 mA and the discharge intensity increases to 4.5 kW. An increase in the frequency of sound oscillations above the resonant frequency of 190 Hz results in an increase in current and a decrease in the discharge intensity; at 250 Hz the current amounts to 50 mA and the electric field intensity diminishes to 3.5 kW. At 250–320 Hz the current and discharge intensities are practically the same as those in the absence of sound. An increase in frequency above 320 Hz results in a decrease in current, which reaches a minimum at the resonant frequency 380 Hz. At 190 Hz the resistance of the discharge gap (at fixed pressure and electric power supply) is 1.6 times that in the absence of a sonic wave.

The changes in electric parameters under the action of an acoustic wave were accompanied by an expansion of the positive column from 2 cm to 6 cm in diameter. The gas temperature dropped from 432 to 390 K on the discharge axis and increased from 305 to 335 K on the tube wall. Thus, the radial gradient of the gas temperature diminished from 127 to 55 K, i.e. by more than half.

Before analysing the cited experimental data, let us examine changes in the electric field over a wide range of sound intensities — from 70 to 92 dB in the argon discharge at various pressures in a tube 9.8 cm in diameter and 52 cm in length [29], and at the first resonant frequency, which is 150 Hz in these conditions. In the experiment, pure gaseous argon was used: the argon content was no less than 99.95%, of nitrogen no more than 0.01%, of oxygen no more than 0.0017 %, and of moisture no more than 0.03 g m^{-3}.

In the argon discharge, the longitudinal electric field intensity was measured by the compensation method at various gas pressures. At 48 torr in the tube (straight lines *1* and *2* in Fig. 3a), the emission of sound and increase in its intensity from *I* to 88 dB was accompanied by a slight decrease in the field strength *E*. The emission of a low-intensity sonic wave (from 70 to 80 dB, 1 rel. unit in Fig. 3 corresponds to 74 dB, 5.2 to 88 dB, 6.5 to 92 dB) at 54 torr (curves *3* and *4* in Fig. 3a) and at 110 torr (curves *1* and *2* in Fig. 3b) brings about a sharper decrease in the field strength *E*; over the range of intensities more than 82 dB–84 dB the sharp buildup of the longitudinal electric field is observed. At 180 torr (curves *1*, *2* in Fig. 3b), the buildup of *E* is accompanied by the increase of the longitudinal electric field intensity in the charge over the entire range of the sonic wave intensity studied. Note that at 54 torr (curves *3* and *4* in Fig. 3a) and 110 torr (curves *1* and *2* in Fig. 3b), the decrease in the electric field strength *E* is accompanied by the contraction of the positive column and the increase in the radial gas temperature gradient; at the intensities at which the field builds up, the discharge experiences a decontraction and the radial gradient diminishes. The pattern of changes in the electric field in discharge with variation of the sonic wave intensity over the range of pressures from 54 to 110 torr (Fig. 3a, b) is similar to the axial electric field dependence on the gas flow velocity in discharge, as obtained in Ref. [25].

I shall now cite the results of studies described in Ref. [25]. The measurements were made in a tube of diameter 0.6 cm and length 10 cm. The gas (argon) was supplied axially to the tube. The longitudinal electric field intensity in the positive column was measured from the difference of potentials at two electrical probes located at a fixed distance from each other along the discharge in the gas flow. The increase in the gas flow from zero to 40 m s^{-1} at the fixed pressure of 20 torr and the discharge current of 60 mA brings about the decrease in the longitudinal electric field *E* from 3.6 to 2.8 W cm^{-1} (Fig. 4), which remains nearly constant for the gas velocity v up to 120 m s^{-1} and then (for $v \sim 120$ m s^{-1}) increases abruptly. The value of velocity at which the buildup of the field occurs does not depend on the flow direction, nor on the discharge current; it is inversely proportional to the gas pressure. The Reynolds number Re, at which *E* begins to build up, is approximately equal to 1800. This is the value at which the gas flow in the tube goes into the turbulent regime.

The buildup of the electric field with an increase in the sound intensity or the gas flow is accompanied by the visible expansion in diameter of the positive column. In particular,

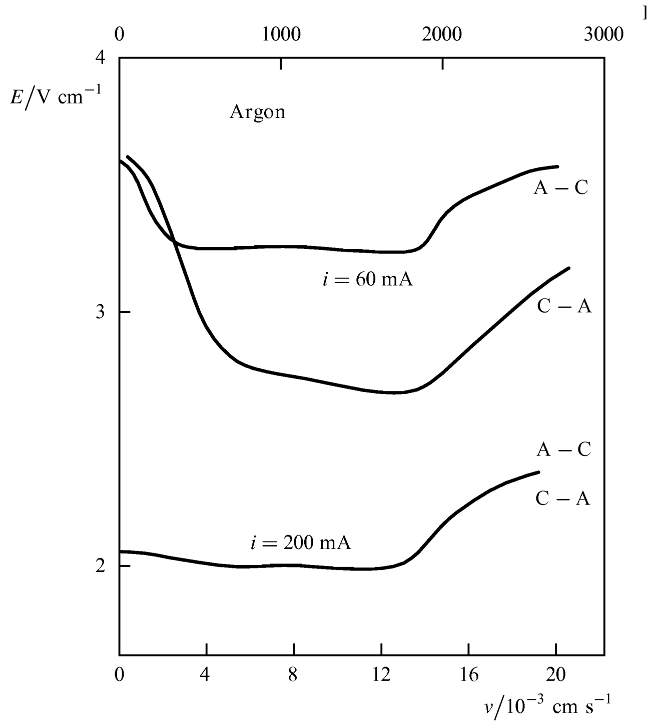

Figure 4. Dependence of the longitudinal electric field on the velocity of gas in an argon discharge when the gas flows from anode to cathode (A − C) and from cathode to anode (C − A) in the tube of inner diameter 0.6 cm at 20 torr.

it was established experimentally that, in the tube of length 100 cm and inner diameter 6 cm with electrodes separated by 85 cm, the emission of the sonic wave of intensity 83 dB caused the stepping-up of the discharge voltage on electrodes from 2.8 to 6 kV at the pressure of argon 100 torr, i.e. more than two times [23]. The experiment was performed at the first resonant frequency of 190 Hz. In this case, the visible boundary of discharge expanded in diameter from 2 to 6 cm and the positive column experienced the full decontraction.

We shall discuss the mechanisms of influence of sonic waves on the increase in the longitudinal electric field intensity in the discharge. It is known that the contraction of a discharge is characterised by an abrupt shrinkage of the area of the current cord and it is accompanied by a rise in the gas temperature on the axis of the positive column and a decrease in the longitudinal electric field intensity [32]. In the experiments cited, the opposite situation was realised, i.e. all indications show that the discharge is unraveled. The expansion of the plasma discharge in diameter was observed visually; the visible boundary of the cord expanded approximately by a factor of 1.5 to 2.5 with an increase in the sound intensity. Thermocouple measurements showed that the increase in the sonic wave intensity over 82 dB is accompanied by a drop in the gas temperature on the discharge axis and a rise in the temperature on the tube wall and, as a result, a reduction of the temperature difference between the axis and the wall.

The reduction of the radial gradient of the gas temperature in the discharge may be explained as follows. In a sonic field, a steady-state vortex flow can develop within solid walls. This vortex flow is most pronounced in the field of a standing sonic wave (the so-called acoustic flow [34]). The vortex motion in the tube is observed as pulsations of the discharge column. The existence of the motion results in the radial mixing of the gas and the radial alignment of the gas temperature difference in the tube. This latter effect is accompanied by an expansion in diameter of the visible boundary of the positive column. The acoustic vortices in discharge can bring about the radial turbulent diffusion of charged particles in plasma. It exceeds the value of the classical ambipolar diffusion, i.e. the sound-induced decontraction of the discharge results in the greater rate of decay of charged particles on the tube wall. To compensate for the increased neutralisation of electrons and ions caused by an intense sonic wave, the ionisation rate should be increased. This is possible when the longitudinal electric field builds up.

It seems that in parallel with this mechanism another process causes the gaseous discharge to unravel by a sound or by a turbulent gas flow. This phenomenon is related to an increase in the heat conductivity in the radial direction and to the alignment of the radial difference of the gas temperature because of the vortex motion whereby the heat released by the turbulent mixing near the axis is carried away efficiently to the tube wall. As a result, the gas temperature drops near the axis of the positive column and rises at the tube wall; the radial temperature gradient settles at a much lower value than that in the contracted discharge. In such a column, the distribution of the radial ionisation rate is more homogeneous and the discharge is more decontracted.

To reveal the mechanism which tends to decrease the longitudinal electric field in discharge on an increase in the intensity of a sonic wave directed along the positive column, we shall consider the effect of the laminar flow on the parameters of the plasma column, as described in Ref. [30]. The study was performed in a discharge tube of length 50 cm and inner diameter 50 mm with hollow cylindrical electrodes at the ends. The radial electron density and temperature distributions in the positive column with and without a laminar flow were determined by two electrical probes. The gas flows from cathode to anode. The probe was situated 20 cm away from the cathode. The measure-

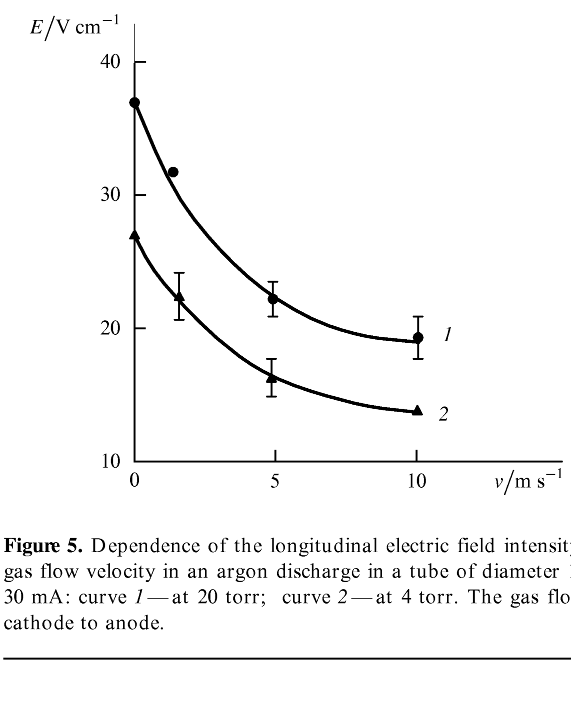

Figure 5. Dependence of the longitudinal electric field intensity on the gas flow velocity in an argon discharge in a tube of diameter 10 cm at 30 mA: curve *1* — at 20 torr; curve *2* — at 4 torr. The gas flows from cathode to anode.

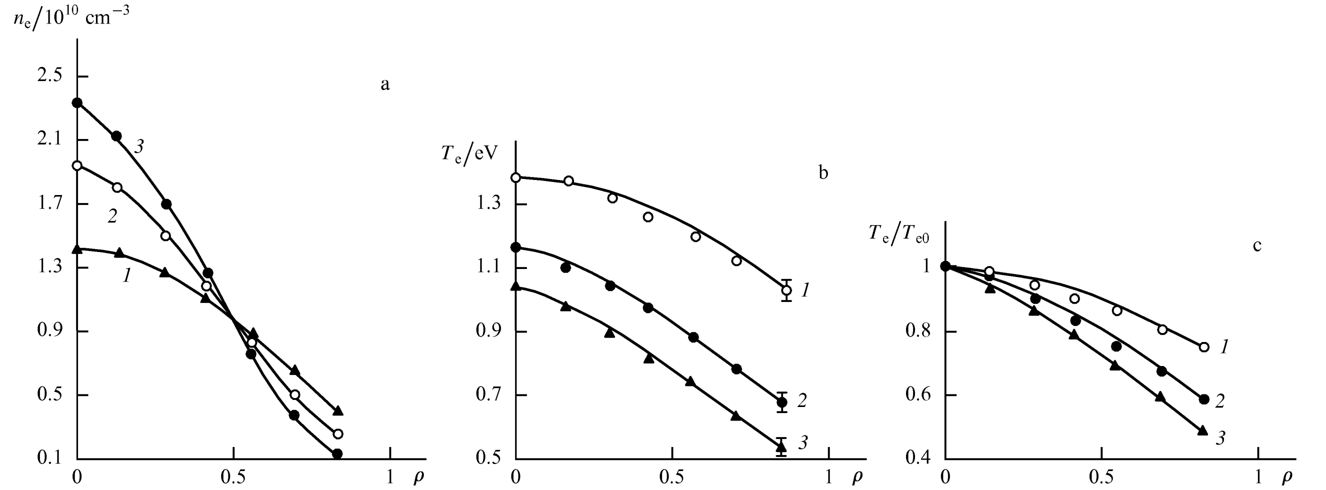

Figure 6. Radial distributions of (a) electron density, (b) electron temperature, (c) relative electron temperature in an argon discharge at 4 torr and 30 mA: curve *1* — in the absence of a flow; curve *2* — in a flow with $v = 5$ m s^{-1}; curve *3* — in a flow with $v = 10$ m s^{-1}.

ments were made in the argon discharge at 30 mA and at 20 and 4 torr. The increase of the gas flow velocity from 0 to 10 m s^{-1} brings about the decrease of the longitudinal electric field intensity from 37 to 20 V cm^{-1} at the gas pressure 20 torr (Fig. 5, curve *1*). This result is qualitatively consistent with the analogous dependences in Ref. [25] (see Fig. 4) and with the decrease in the electric field on an increase in the sonic wave intensity at a low value of the field (see Fig. 3)

An increase in the gas flow velocity within the laminar flow regime brings about a compression of the positive column and a drop in the electron temperature in the plasma. The radial electron density distributions in the positive column in an argon discharge were measured at various rates of pumping, from which it followed that the electron distribution over the discharge cross-section became steeper with an increase in the gas velocity (Fig. 6a) and the value of the velocity increased along the axis of the positive column, i.e. if in the absence of the gas flow the value of the electron density n_e is 1.4×10^{10} cm^{-3}, then $n_e = 1.9 \times 10^{10}$ cm^{-3} for $v = 5$ m s^{-1}, and $n_e = 2.35 \times 10^{10}$ cm^{-3} for $v = 10$ m s^{-1}.

The compression of the discharge with an increase in the gas flow velocity within the laminar flow regime is accompanied by a drop in the electron temperature on the axis of the positive column and an increase in its radial gradient. With the argon flow velocity 5 m s^{-1} along the discharge, the electron temperature drops from 1.38 to 1.16 eV on the axis of the positive column. A further increase in the flow velocity to 10 m s^{-1} brings about the drop in the electron temperature to 1.05 eV (Fig. 6b). An increase in the gas flow velocity brings about an increase in the radial gradient T_e in addition to the drop in the electron temperature. So, if there is no flow $T_e/T_{e0} = 0.9$ (T_{e0} is the electron temperature on the axis of the plasma column) for $\rho = r/R = 0.5$ (where R is the tube radius and r is the radial coordinate), and $T_e/T_{e0} = 0.7$ for the argon velocity $v = 10$ m s^{-1}.

The compression of the plasma column with an increase in the laminar flow velocity at a fixed current and at a fixed gas pressure in the tube means in fact that the current density increases near the axis of the discharge and decreases at the periphery. As a consequence of an increase in the electron density on the axis of the positive column, the frequency of collisions between electrons and neutral particles increases and, as a result, the gas temperature rises at the centre of the discharge and drops near the wall, i.e. the radial temperature gradient in the discharge increases with the gas velocity.

We shall consider the mechanism of growth of the gas temperature gradient in the discharge with an increase in the flow velocity within the laminar flow regime. The time for which argon is pumped (the distances from the cathode to probes are $L = 20$ cm for the mean flow velocity $v = 10$ m s^{-1}) is $\tau = L/2v = 10^{-2}$ s. In this time, argon atoms drift radially from the axis over a distance of about 0.1 cm (the value of the diffusion coefficient for atoms was calculated with the use of Ref. [29]). Consequently, the heat that the current releases near the discharge axis, where the current density peaks, has no time to propagate radially because it is carried away faster with the gas flow in the longitudinal direction.

This conclusion has been validated in experiment through the measurement of the tube wall temperature by a thermocouple sensor in the sustained steady-state regime of discharge at the argon pressure of 4 torr and the current 30 mA. The result is that the tube wall temperature T is 51 °C if there is no flow, $T = 41$ °C for $v = 5$ m s^{-1}, and $T = 36$ °C for $v = 10$ m s^{-1}. The drop in the gas temperature on the periphery of the positive column with an increase in the flow velocity results in a decrease in the density of atoms N and this causes a decrease in the radial flow of charged particles and tends to make the radial electron density distribution steeper in the plasma column

The compression of the discharge with an increase in the flow velocity, accompanied by a drop in the rate of decay of charged particles on the tube wall, should tend to lower the ionisation rate near the axis of the column and, as a result, decrease the longitudinal electric field. It appears that similar processes will occur in the discharge on an increase in the intensity of a sonic wave directed along the positive column over the low-intensity range. In this case, with the increase in the sound intensity to 80 dB, the electric field intensity drops from 32 to 22 V cm^{-1} (curve *3* in Fig. 3a), the gas on the axis of the column heats up, the gas temperature on the wall drops, and the radial temperature gradient rises from 85 to 125 °C. In addition, the positive column contracts [29].

2.2 Gas temperature in plasma

The gas temperature is one of the main parameters of a partially ionised plasma. It depends on the balance of the energy release and heat removal. The spatial gas temperature distribution in the plasma column depends on the electron density distribution and is very sensitive to a change in this distribution. Comprehensive studies of the gas temperature and its spatial distribution based on the heat conduction equation and on the balance equation for the electron density with regard for measurements in the discharge in the absence of an acoustic wave are presented in Ref. [32].

We shall consider processes related to the effects of a sonic wave on the gas temperature and its spatial distribution, determine the temperature as a function of intensity and of frequency of sound for various discharge currents and at various gas pressures, and examine the accompanying processes [33]. The study was conducted in a quartz discharge tube, of diameter 9.8 cm and length 52 cm, with ring wire-gauze electrodes separated by 27 cm. The sonic wave was supplied to the discharge by an electrodynamic radiator fastened hermetically to an end of the tube; to the opposite end the microphone for measuring sound parameters was fastened. The gas temperature was measured by two thermocouple sensors. One was located on the tube wall at 8 cm from the anode, the second on the axis of the positive column at the same distance from the anode. The temperature could be measured simultaneously at these two points in the adopted scheme of measurements. Experiments were conducted at pressure $p = 10-60$ torr and discharge current 40–90 mA. The sound intensity was varied from 70 to 95 dB. Industrial nitrogen was used: the contents of nitrogen were not less than 99.5 %, of oxygen not more than 0.5%, and of steam not more than 0.07%.

The measurements of the gas temperature on the axis of the discharge as a function of the sonic wave frequency were taken over the frequency range from 120 to 200 Hz about the first resonant frequency $f = 170$ Hz at the pressure of nitrogen 40 torr, discharge current 40 mA, and various intensities of sound. In the absence of a sonic wave, the gas temperature on the axis of the plasma column was 395 °C. At the sound frequency 120 Hz and intensity 90 dB, the gas temperature was 395 °C. With an increase in frequency (at fixed values of current and gas pressure in the tube), the temperature on the axis of the discharge dropped and at the resonant frequency 170 Hz reached the minimum value of 380 °C (Fig. 7). A further increase in the frequency of sound caused a rise in temperature and at 200 Hz it became equal again to 395 °C. An increase in the sonic wave intensity (at fixed current and pressure of nitrogen in discharge) caused further cooling of gas, and at 95 dB ($f = 170$ Hz) the gas temperature became equal to 355 °C. On an increase in the gas pressure in the tube, the sound-induced cooling of gas at a fixed value of the discharge current became more pronounced and on a rise in the discharge current it became less pronounced.

In contrast to the processes on the axis of the positive column, the gas temperature on the tube wall increased when a sonic wave was emitted into the discharge. At fixed values of current and pressure, the rise of the gas temperature on the tube wall because of sound occured

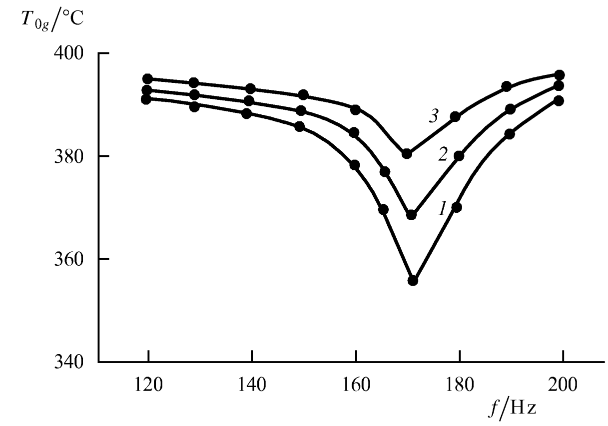

Figure 7. Dependence of the gas temperature along the axis of the positive column on frequency in a nitrogen discharge near the first resonance of the sonic wave ($f = 170$ Hz) at 40 torr, 40 mA, and 95 dB (curve *1*), 93 dB (curve *2*), and 90 dB (curve *3*).

at the resonant frequency. With increases in the sound intensity and gas pressure, the rise of the gas temperature on the tube wall became more pronounced. In the nitrogen discharge in the absence of a sonic wave, a rise in the gas pressure (at a fixed current) caused an increase in the radial temperature difference; thus, at 40 mA and 20 torr the difference was 285 K. The emission of a sonic wave of 95 dB with the resonant frequency at 20 torr caused the difference to settle at 240 K. The rise in gas pressure to 30 torr caused the difference to increase to 260; a further rise in pressure caused the difference to diminish and settle at 235 K at 60 torr.

Thus, in response to an intensive sonic wave at a fixed current the radial temperature difference in the discharge diminished by 45 K at 20 torr and by 125 K at 60 torr, i.e. with a rise in the gas pressure the efficiency of the action of a sonic wave on plasma improved. At 10 torr the sound-induced reduction in the temperature gradient was insignificant.

The stronger effect of a sonic wave at this pressure is related to the necessity of a further increase in the limiting values of the sound intensity. A perceptible change in the temperature gradient was observed at a pressure above 20 torr. An increase in the sonic wave intensity to over 82 dB was accompanied by the reduction of the radial temperature difference between the axis and the tube wall and caused the visible boundary of the positive column to expand.

We shall examine the mechanisms of influence of a sonic wave on the gas temperature in the discharge. At 20 torr in the discharge, the gas temperature distribution in the tube is a parabolic function with the maximum on the axis. With a rise in the discharge current or gas temperature, the radial temperature gradient and gas temperature on the axis of the discharge increased. Even if a sonic wave was initially plane on entry in an axially symmetric chamber, the existence of the radial temperature gradient in the discharge should cause the speed of sound to be a function of the radial coordinate; i.e. the cylindrical modes should appear. In Ref. [9] the modes of sonic waves propagating along the positive discharge column in the tube were experimentally detected. The basic modes of sound oscillations coincided with the cylindrical ones. The radial sonic mode of a wave in the discharge could cause the heat removal to improve in gas, i.e. cause the radial heat conduction to increase in the tube; but we shall dwell on another, stronger mechanism of heat removal, that caused by a sonic wave.

In the case of a column discharge in which the current is localised near the axis, the charged particle distribution along the radius of the tube is bell shaped and the charge particles decay through volume recombination; a strong radial temperature gradient results in the positive column and this should cause the phase speed of sound to be a function of the radial coordinate. The speed of gas particles in the sonic wave should also be a function of the radial coordinate.

An increase in the intensity of the sonic wave directed along the positive column at fixed values of current and gas pressure causes the vibrational speed of particles to enhance in the field of the wave near the axis of the discharge whereas the gas velocity remains zero on the wall. At a specific intensity of the standing sonic wave, pulsations of gas develop near the walls and a steady vortex flow develops (the so-called acoustic flow [34]) and may be observed visually. In the flow there is a narrow boundary layer (the so-called acoustic boundary layer), in which the gas velocity drops from the value in the sonic wave to zero on the solid wall. Outside the boundary layer there is a steady vortex motion, the velocity of which does not depend on viscosity [34].

The existence of a vortex motion in the discharge can bring about gas mixing and alignment of the radial gas temperature gradient in the tube. Increased pressure and sound intensity produce more favourable conditions for turbulent mixing of gas in the discharge and, as a result, the vortex motion should create a stronger alignment of the radial gas temperature difference in the tube. This was verified in the experiments.

2.3 Temperature and density of electrons in plasma

The electron temperature in the discharge reaches the steady state self-consistently and depends on the choice of the gas, pressure, tube diameter, current density, and not on the steady-state parameter N/E in the positive column (where E is the longitudinal electric field, and N is the density of neutral particles). The dependence of the electron tempera-ture on the conditions in the discharge is considered in detail in the absence of external actions in Ref. [22].

The electron temperature in the plasma column depends to a large extent on the shape of the spatial electron density distribution in the discharge, which specifies the rate of decay of charged particles in the positive column, i.e. it specifies whether the radial electron density distribution in the tube has a parabolic (diffusion discharge) or a bell-like (contracted discharge) shape. In the case of a diffusion discharge when the plasma column fills the whole tube, the rate of decay of charged particles on the walls is much greater than that in the contracted discharge and the electron temperature is higher in comparison with the value in the contracted positive column.

The discharge diameter (the shape of the radial electron density distribution in the tube) may be changed by external actions at fixed values of the current and gas pressure in the discharge. It is shown in Ref. [35] that the radial electron density distribution in the discharge can be changed from the bell-like to the parabolic or even to the plane shape by the gas flow parallel to the positive column. A standing sonic wave can act on the diameter of the discharge in a similar manner.

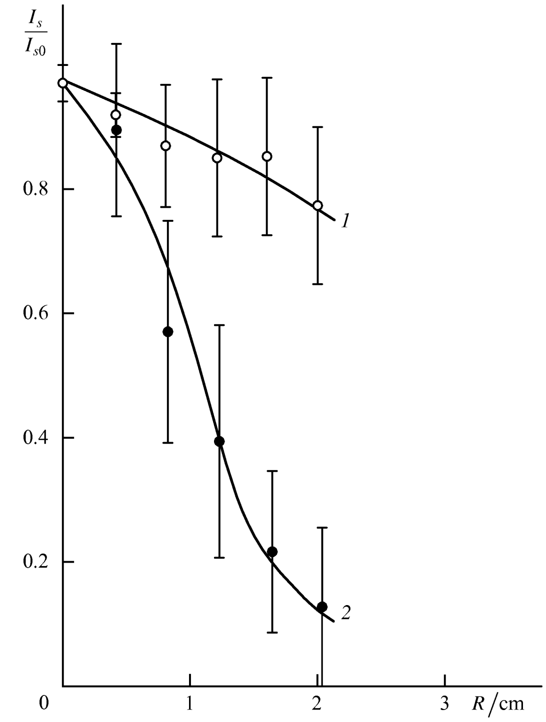

Figure 8. Radial distribution of the relative electron current of saturated dual electric probes in the tube of inner diameter 6 cm at the argon pressure 110 torr, current 75 mA, sound intensity 85 dB, and resonant frequency of sonic wave 190 Hz. Curve *1* — with sound; curve *2* — without sound.

In Ref. [23] the results of measurements of the relative radial electron saturation current distribution for dual electrical probes in the argon discharge, in the absence of sound and with it, in the tube 6 cm in diameter and 100 cm in length with electrodes separated by 85 cm are presented. The measurements were made at the first resonant frequency of 190 Hz for the sonic wave with intensity 85 dB. At the argon pressure of 110 torr in the tube and for the discharge current 75 mA in the absence of sound, the resultant relative radial electron saturation current distribution for dual electric probes in the tube has a bell-like shape with the diameter of the outer boundary being 2 cm (curve *2* in Fig. 8).

The emission of a sonic wave causes the saturation current distribution of the electron probe to take a parabolic shape and the diameter of the visible boundary to become 6 cm, or to equal the inner diameter of the tube; the discharge is fully decontracted (curve *1* in Fig. 8). In this case, the gas temperature drops from 420 to 385 K on the axis of the positive column and rises from 300 to 330 K on the wall, i.e. the radial difference diminishes from 120 to 55 K and the longitudinal electric field builds up. These processes should be accompanied by a rise in the electron temperature in plasma.

The ability to change the electron energy in plasma at fixed values of current and pressure in the discharge, in particular, by acoustic waves, is an important factor because in this way the plasma with a fixed temperature may be produced for accomplishing a particular task. This is especially valuable for gas-discharge lasers [36] in which the value of the electron temperature can be fixed by the use of sonic waves such that the inverse population density is maximum and the laser radiation is optimal.

Results of studies of electron temperature and electron density as functions of intensity and frequency of a sonic wave are described in Refs [37, 38]. The measurements were taken in the testing unit involving a quartz discharge tube of inner diameter 9.8 cm and length 52 cm. Two wire-gauze electrodes separated by 27 cm were used. The electron temperature and density were measured by probes. The probe was 4 cm away from the anode on the axis of the positive column; in the case of a single probe, the anode was used as a bearing electrode. The electron temperature in plasma was determined from the electronic characteristics of the single Langmuir probe. For comparison purposes, the electron temperature was also determined from the voltage – current characteristics of the dual probe. The closer the potential of the negative probe is to the potential of the plasma, the more the electronic characteristics of the single probe differ from an exponent at a pressure above several torr. Therefore, the parts corresponding to high potentials were used to determine the electron temperature from the slope of the characteristic. In these parts the deviations from the exponential curve, related to the small, free path length of the electron at an elevated pressure, can be neglected and the electron temperature may be evaluated by the methods described in Ref. [26].

Under the conditions of the experiment, the electron characteristics do not differ from an exponent near the floating probe potential. In this case, the dual probe method may also be applied [26, 39]. The processed characteristics of single and dual probes showed good quantitative agreement between the electron temperatures evaluated by the two methods. The values of density evaluated agreed to within the experimental error.

This scheme of probe measurements was used to read the averaged characteristics as well as to determine the sound-induced variations of the electron density and temperature. The charged particle density modulation was measured with a single Langmuir probe in the ionic saturation regime and was calculated as a ratio of the amplitude of oscillations of current to probe to the average value with regard for the electron temperature modulation. The oscillations of current to the probe were recorded by a double-beam oscilloscope, along with the sound signal coming from the microphone.

The temperature modulation was determined as follows. For a fixed voltage on the probe, the time dependence of current to the probe was recorded. The family of probe characteristics was constructed to determine the electron temperatures corresponding to different phases of oscillations.

The mean electron temperature was determined from the probe characteristics constructed for the mean value of current to the probe. The construction of the family of probe characteristics for various phases of oscillations of cur- rent showed that over the ranges of parameters of discharge and sound studied the following inequalities hold: $\Delta j_0/j_0 < 1$, $\Delta T_e/T_e < 1$, $\Delta V_s < V_s < 1$, where j_0 is the current to probe; T_e is the electron temperature; V_s is the space potential; Δj_0, ΔT_e, and ΔV_s are deviations of current to probe, electron temperature, and space potential, respectively, from the mean values of these quantities. If $\Delta T_e = 0$, then the electron temperature can be determined from the semilogarithmic dependence of the mean current j_m to the probe on V [39]. In this case, the existence of oscillations of j_0 and V_s causes the probe characteristic to shift without a change in the slope. When $\Delta T_e \neq 0$ the dependence of j_0 on V is not quite linear. However, when $\Delta T_e/T_e < 1$ the deviation from a straight line is insignificant. The experimental relationship $\ln j_0 = f(V)$ agrees well with the linear law near the floating probe potential.

When constructing the probe characteristics pertinent to various phases of oscillations, it is necessary to know the instantaneous value of current to the probe. If the above inequalities for the deviations of the quantities T_e, V_s, and j_0 hold, then the instantaneous value of current to the probe is calculated as the sum of the mean value of current to the probe and its variable component recorded by the oscilloscope. It was pointed out in Ref. [39] that with a rise in pressure the pattern of processes near the probe and the voltage – current characteristics of the probe change, and that the ionic part of the probe characteristic does not exhibit a tendency towards saturation.

In the experimental conditions considered, over the range of pressure of nitrogen in the tube from 10 to 40 torr and at the discharge current in the range from 40 to 90 mA, a clear saturation was reached in the ionic part of the probe characteristic. Near the floating potential probe, the electron characteristics largely follow an exponential law and this makes it possible to evaluate the electron temperature with a high precision. If we want to be rigorous, then the temperature should characterise an equilibrium state of the system. However, the notion of temperature is frequently used in considerations of non-equilibrium distributions of particles in physical systems.

Usually electrons in plasma are assumed to have a Maxwellian velocity distribution and in this case the electron temperature can be measured by Langmuir probes [26]. The existence of the Maxwellian electron distribution in plasma cannot always be established from the shape of the voltage – current characteristics and therefore it is preferable to measure the electron distribution function.

Data exist that show that the electron energy distribution function is not Maxwellian in the discharge plasma of molecular gases even at several torr. The exponential shape of the electron part of the voltage – current characteristics of the probe near the floating potential observed in these experiments suggests that the electron distribution is quasiequilibrium, or that electrons are locally in a thermo-dynamically equilibrium state. Note that to make a more accurate conclusion the experimental data of probe measurements are needed at a higher pressure but, unfortunately, such data do not exist.

The emission of a sonic wave in a discharge increases the mean value of the electron temperature. Thus, it was experimentally established that in the nitrogen discharge at 40 torr and 40 mA the electron temperature was 0.75 eV on the axis of the positive column at the resonant frequency of the sonic wave 170 Hz with intensity 98 dB (Fig. 9, curve *1*), whereas it was 0.5 eV in the absence of sound at the same current and pressure (curve *2*).

The electron temperature increases with the sound intensity. The change in the sonic wave frequency from 170 to 200 Hz at a fixed intensity is accompanied by the drop of the mean electron temperature from 0.75 to 0.55 eV. The mean value of the electron density on the axis of the positive column decreases upon emission of sound in the discharge. The maximum drop in the mean electron density in the discharge because of sound is observed at the resonant frequency of sound (Fig. 9); the

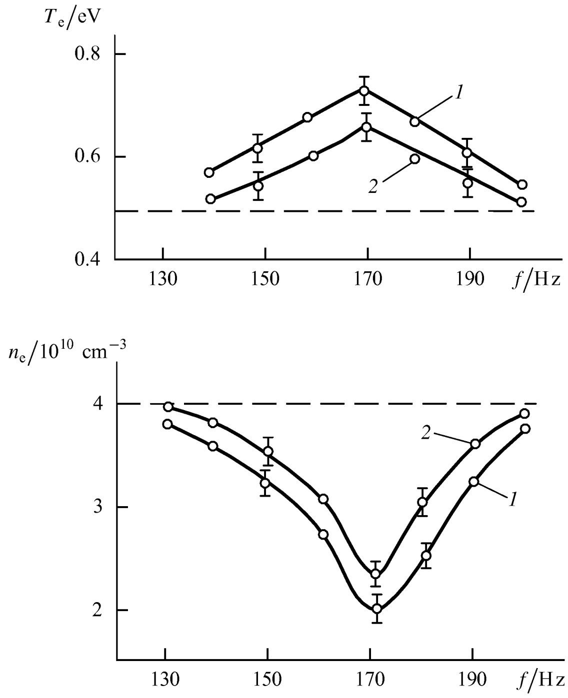

Figure 9. Dependences of the electron temperature and electron density on the sound frequency near the first resonant frequency $f = 170$ Hz at the nitrogen pressure of 40 torr and discharge current 40 mA in the tube of diameter 9.8 cm in diameter with the electrodes spaced at 52 cm. Curves *1* and *2* represent the sound intensities 98 dB and 96 dB, respectively. The dashed curves represent the values of electron temperature and density in the absence of sound.

emission of a sonic wave with intensity 98 dB reduces the electron density by half.

To understand fully the processes in the discharge with sound, we shall consider the behaviours of the longitudinal electric field intensity and gas temperature. Besides a rise in the electron temperature and a drop in the mean electron density, the emission of sound in the discharge increases the longitudinal electric field intensity. The maximum increase in the field is observed at the resonant frequency. The electric field was measured by the compensation method with two probes separated by 1 cm from each other, and by the characteristics of a single probe. A good agreement is obtained between the values of the electric field measured by the two methods (the difference does not exceed 3%). The emission of a sonic wave with intensity 98 dB at the resonant frequency 170 Hz (at 40 mA and 40 torr) causes the increase in the electric field from 115 to 140 V and the reduction of the radial temperature gradient by 70 K.

It was established in electron experiments that the depths of temperature and electron density modulations increase with the sound intensity (at fixed pressure and discharge current). A rise in the gas pressure at fixed current and sound intensity causes the electron temperature and electron density modulation depths to increase. At fixed pressure and sound intensity, an increase in the discharge current is accompanied by a decrease in the depths of modulations of the parameters mentioned above. So, at the pressure 40 torr and sound intensity 96 dB ($f = 170$ Hz) an increase in the discharge current causes the depth of the electron density modulation to decrease from 19 to 6% and that of the temperature modulation from 18.2 to 5%.

The rise in the electron temperature in plasma on an increase in the standing acoustic wave intensity is associated with development of acoustic vortices in discharge [34] and, as a result, a reduction in the radial gas temperature difference in the tube, an expansion of the diameter of the contracted positive column, a buildup of the longitudinal electric field, and a larger parameter E/N. Since the electron temperature is proportional to the ratio E/N, the value of the resonant sound intensity controls its value in the discharge.

3. Contraction of the positive column in the field of an acoustic wave

The contraction of a glow discharge — a well-known phenomenon in the physics of low-temperature plasma — consists of compression of the positive column on an increase in pressure or current flowing through the gas. The contraction of discharge in the tube causes a steeper radial electron density or current density distribution in the positive column (with an abrupt contraction the shape of the electron density distribution over the column cross-section changes from parabolic to bell-like), the longitudinal electric field to decrease, the current density to increase near the axis of the discharge, and the electron temperature to drop. The parameters of the discharge, at which the contraction occurs, do not depend on specific experimental conditions: the choice of gas, content of gas mixture, tube radius, etc.

The principal shortcomings restricting the use of the contracted column in a glow discharge for practical purposes (in gas-discharge lasers, magnetohydrodynamic generators, etc.) are the incomplete utilisation of the chamber, the equilibrium state of the gas-discharge plasma, the increase in the gas temperature near the axis of the discharge tube, the drop in the electron temperature, and also the inhomogeneity of the gas-discharge plasma. The issues concerning the contraction of a glow discharge are covered in Ref. [32]. In addition, we may point out Refs [21, 22], in which the processes of contraction of a positive column are considered. Various mechanisms of contraction of the discharge are determined. We shall briefly outline their peculiarities.

In inert gases the thermal contraction occurs at fairly high values of the electric power of the discharge, at which the radial temperature difference forms in the tube and the ionisation constant exhibits strong variations over the discharge cross-section; charged particles are produced in a narrow axial region and their volume recombination by molecular ions on the periphery of the column dominates over diffusion [41–44].

With a low energy supply to the discharge when the role of the temperature inhomogeneity is insignificant, a non-thermal contraction is possible, related to a strong radial inhomogeneity of the constant of ionisation of atoms by impacts of electrons due to the strong dependence of the electron distribution function on the degree of ionisation [45–50]. In molecular gases, the positive discharge column contracts when the vibrationally excited molecules appearing in the discharge relax in the volume and the major part of the power supplied to the discharge is transformed into heat. The radially inhomogeneous state of the positive column results and brings about the compression of the positive column in the presence of the volume recombination of charged particles at the periphery [51–53]. The contraction of the discharge in an electronegative molecular gas is characterised by generation of electrons near the axis due to the radial temperature gradient in the column (and also due to the ionisation constant dependence on the gas temperature), and by adhesion of electrons to atoms or molecules on the periphery of the discharge with subsequent efficient volume ion–ion recombination [54–56].

The contraction of a discharge and decontraction of a contracted positive column can be induced by external action. In particular, it is shown in Ref. [57] that the discharge experiences an abrupt contraction when the gas flowing along the positive column goes from the laminar to the turbulent regime; also when the turbulence with small-scale vortices develops in the flow, the discharge exhibits decontraction [58]. We shall now consider the influence of a sonic wave on the discharge contraction and the accompanying processes; in particular, the jump of the amplitude of sound on contraction of the positive column in molecular gases [59].

3.1 Influence of a sonic wave on the discharge contraction

To study processes of the action of sound on the contraction of a positive column we shall consider the voltage–current characteristics of the discharge at various sonic wave intensities. The voltage–current characteristics are measured in a quartz discharge tube 9.8 cm in diameter and 52 cm in length. The ring wire-gauze electrodes are spaced at 27 cm. An electrodynamic radiator of sonic waves was fastened to one end and a microphone to control parameters of the sonic wave to the opposite end (behind the anode). The experiments were conducted in nitrogen over the ranges of pressures from 10 to 78 torr and of discharge currents from 40 to 120 mA. The sound intensity varied from 84 to 96 dB. With sound the measurements in the discharge were made at the first resonant frequency of sound $f = 170$ Hz. It was established, by studies in the nitrogen discharge over the range of pressures less than 78 torr, that in the absence of sound the voltage–current characteristics of the discharge have the shape of a smooth incident curve over the range of currents from 40 to 120 mA.

The voltage–current characteristics of the discharge in nitrogen at 78 torr are shown in Fig. 10. On increase of current from 40 to 70 mA in the absence of a sonic wave, the electric field intensity U_p decreases continuously from 7.3 to 6 kV. However, at 70 mA the discharge voltage drops suddenly by approximately 1 kV while the current increases from 70 to 73 mA. Further increase in the current from 73 to 120 mA causes the discharge voltage to decrease continuously. The decrease in current from 120 to 65 mA causes U_p to decrease smoothly; then the voltage jumps suddenly (by 1 kV) while the discharge current falls to 62 mA, i.e. the contraction exhibits a hysteresis behaviour. On an increase in current, the transition of the discharge to the contracted state occurs at a somewhat higher current than the inverse transition on a decrease in current. In the contracted state, a bright luminous cord, the outer boundary of which has a diameter of 0.5 cm, is formed about the axis.

The experiments verify that in the discharge tube with a sonic wave of a relatively low intensity the contraction occurs at higher currents than in the case of discharges without sound. Thus at the sound intensity 84 dB the contraction occurs at 80 mA (curve *2* in Fig. 10a), and at the sound intensity 88 dB the transition to the contracted state occurs at 95 mA (curve *3* in Fig. 10a). The hysteresis area on the voltage–current characteristics of the discharge shrinks with the sound intensity; there is no contraction at the sonic wave intensity 90 dB and the hysteresis on the voltage–current characteristics vanishes completely.

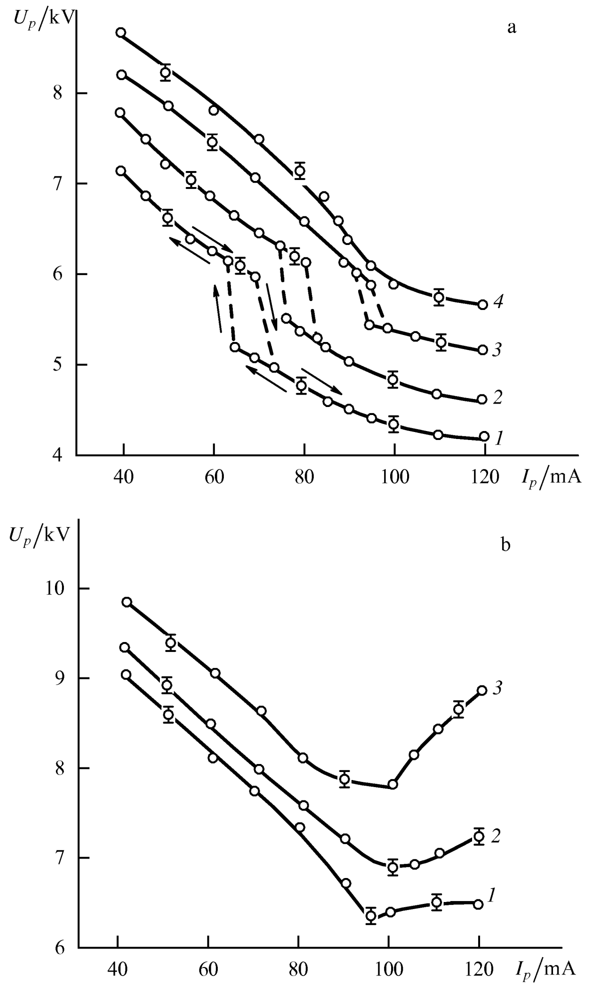

Figure 10. The voltage–current characteristics of the discharge in nitrogen at 78 torr in the tube 9.8 cm in diameter and 52 cm in length. (a) Curve *1* represents the discharge without sound; curves *2–4* represent discharges with sound of 84, 88, and 90 dB, respectively. (b) Discharges with sound of 92, 94, and 96 dB are represented by curves *1–3*.

At the sound intensity 92 dB (curve *1* in Fig. 10b) the voltage–current characteristics of the discharge of the growing part tend to form at large currents. With increase in the sound intensity, i.e. at 94 dB (curve *2* in Fig. 10b) and 96 dB (curve *3* in Fig. 10b), the increase in current from 100 to 120 mA causes a steeper stepping-up of the discharge voltage, i.e. an increase in the input power into the discharge.

The emission of sound in the discharge tube and increase in its intensity causes the diameter d of the visible boundary of the plasma column to extend. So, for example, at 120 mA in the discharge without sound the diameter of the visible boundary of the cord is $d = 0.4$ cm, and in the presence of sound with intensity 96 dB $d = 4.5$ cm, i.e. the diameter of the visible boundary of the positive column extended more than 10 times under the action of the sonic wave.

At the nitrogen pressure of 78 torr the thermocouple measurements were taken. The gas temperatures on the axis of the positive column and on the wall of the discharge tube were measured by two thermocouple sensors 8 cm away from the anode. It was established that in a discharge without sound at 70 mA the gas temperature is 866 K on the axis, and the temperature difference between the axis and the tube wall is 470 K. Upon transition to the contracted state, the temperature on the axis rises and is 933 K at the discharge current of 80 mA; the radial temperature gradient increases by 80 K and becomes equal to 550 K. The increase in the gas temperature gradient was also observed during transition to the contracted state in the discharge with a sonic wave. At 84 dB the temperature gradient increased by 53 K and at 88 dB by 30 K.

At fixed values of gas pressure and discharge current, a further increase in the sound intensity is accompanied by a decrease in the gas temperature on the axis of the positive column; in this case, the radial gas temperature gradient also diminishes. The increase in the sound intensity to 96 dB at 100 mA causes the gas temperature to drop by 100 K on the axis of the positive column and the radial gas temperature gradient to diminish by 135 K. At 100 mA (with the same sound intensity), the temperature drops by 138 K and the temperature gradient by 165 K.

The general physical model of contraction of a discharge is the thermal inhomogeneity of the positive column. This is verified by the results given above which show that the positive column becomes thermally more inhomogeneous with the transition of the discharge to the contracted state. The emission of a sonic wave along the positive column causes the radial gas temperature difference to diminish in plasma and the discharge diameter to increase. At a sound intensity over 90 dB, the plasma column becomes fully decontracted.

3.2 Sound-induced modulation of the discharge current on contraction of a gaseous discharge

As well as taking readings of the voltage–current characteristics of the discharge, we measured the amplitude of oscillations caused by the sonic wave in the discharge current. The modulation depth of the discharge current increases with the sound intensity at fixed pressure and current, and at the sound frequency $f = 170$ Hz. An increase in the pressure of nitrogen at fixed values of discharge current and sound intensity causes an increase in the current modulation depth.

However, at fixed values of nitrogen pressure and sonic wave intensity, the modulation depth of the discharge current falls smoothly with the permanent component of the discharge current. This dependence of the modulation depth on current is observed in the nitrogen discharge in the absence of contraction at 60 torr and 84 dB (Fig. 11a, curve *1*). At a pressure of 78 torr and sonic wave intensity 84 dB, the modulation depth of the discharge current jumps abruptly from 7 to 14% at 80 mA (curve *2* in Fig. 11a). This means that the amplitude of the sonic wave experiences a jump at that value of current. Note that at 80 mA the discharge undergoes a contraction (see Fig. 10a, curve *2*). A further increase in current causes the modulation depth to decrease.

The decrease in the discharge current from 100 to 75 mA results in a larger modulation depth. At 75 mA the modulation depth of the discharge current drops abruptly by half. At this value of current, the discharge undergoes decontraction (see Fig. 10a, curve *2*). The jump of the depth of the sound-induced modulation of discharge current occurs when the value of the sound intensity is smaller than 90 dB. At an intensity over 90 dB, the hysteresis area is totally absent (Fig. 11b). A further increase in the sound intensity causes an expanding area to form at large currents on the curves in Fig. 11c.

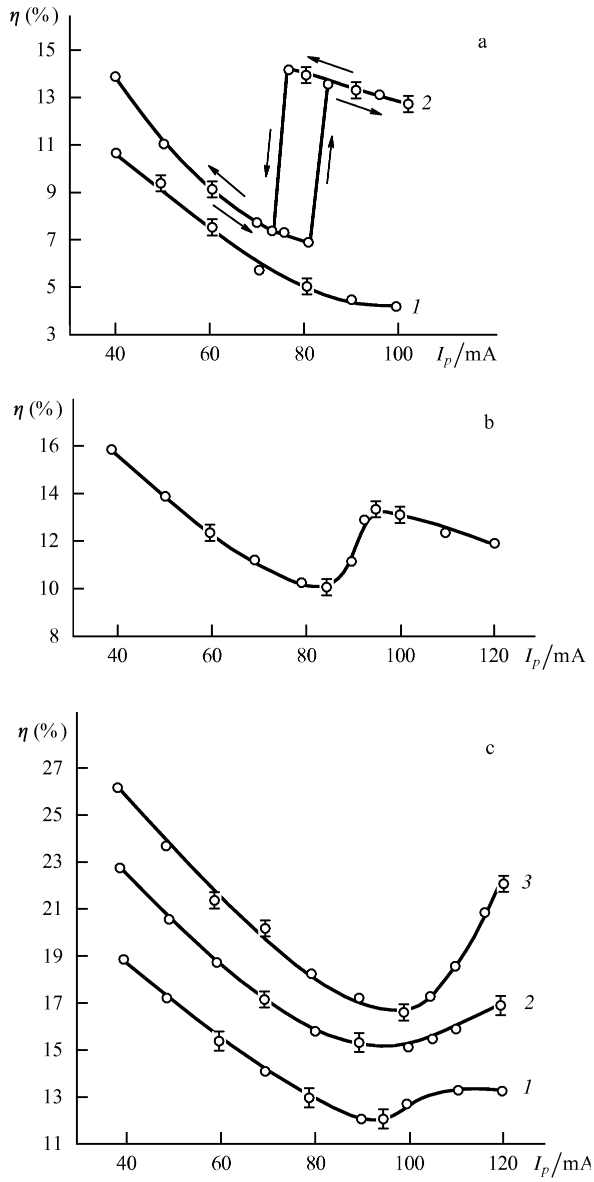

Figure 11. Dependence of the depth of sound-induced modulation of current on the discharge current. (a) Curve *1* is obtained at 60 torr and 84 dB; curve *2* at 78 torr and 84 dB. (b) The curve is obtained at 78 torr and 90 dB. (c) Curves *1* – *3* are obtained at 78 torr and, respectively, 92, 94, and 96 dB.

3.3 Jump of amplitude of a sonic wave on contraction of a gaseous discharge

With the abrupt contraction of gaseous discharge in nitrogen caused by a sonic wave, the current modulation depth increases steeply and the increase is accompanied by a sharp growth in the amplitude of sound. We shall consider the results of the experimental investigations of evolutions of amplitude and sonic wave intensity during the

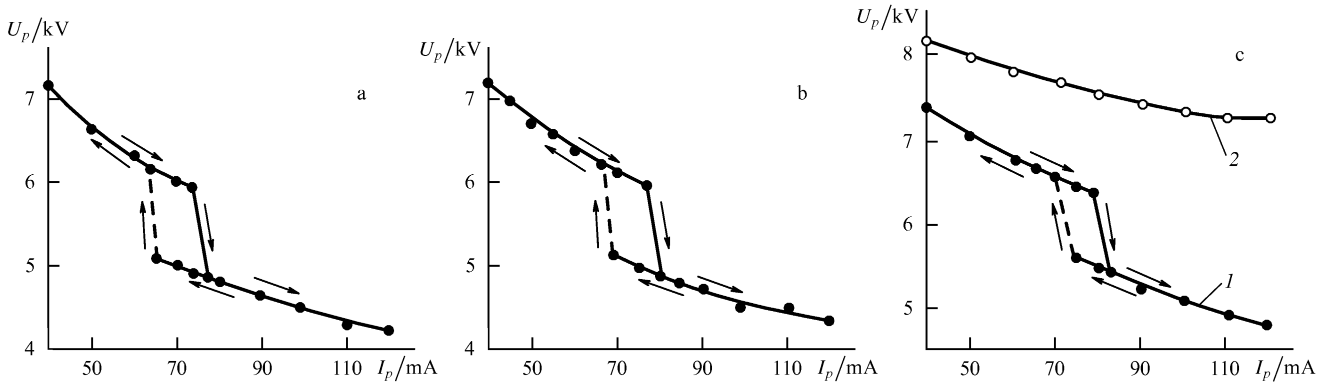

Figure 12. The voltage–current characteristics of the nitrogen discharge with the sonic wave at the first resonant frequency ($f = 170$ Hz) at 78 torr for different sound intensities J_0: (a) $J_0 = 68$ dB, (b) 72 dB, (c) curves *1* and *2* represent, respectively, 76 and 88 dB.

transition of the discharge in molecular gases to the contracted state [19, 20].

The measurements were taken with a testing unit involving a quartz tube of inner diameter 9.8 cm and length 52 cm. The ring wire-gauze electrodes were spaced at 27 cm. The sonic wave in the discharge tube was created with an electrodynamic radiator fastened hermetically to one of the tube ends. To the opposite end (behind the anode) a microphone was fastened to monitor the parameters of the sonic wave. The experimental investigations in the nitrogen discharge were conducted at $p = 78$ torr over the range of discharge currents from 40 to 120 mA at the first resonant frequency $f = 170$ Hz of the sonic wave. The nitrogen used in the experiments contained up to 0.07% of steam and less than 0.4% of oxygen.

At a nitrogen pressure of 78 torr in the discharge without a sonic wave, the abrupt contraction of the positive column with formation of hysteresis was observed (see Fig. 10). The emission of a sonic wave in the discharge tube and growth of its intensity results in a larger energy contribution to the discharge and a shrinkage of the hysteresis area on the voltage–current characteristics of the discharge. For each value of the sound intensity, the readings of the voltage–current characteristics were taken at a fixed intensity, which was artificially sustained in the discharge tube over the entire range of discharge currents from 40 to 120 mA.

In Fig. 12 the voltage–current characteristics of a discharge in nitrogen in the field of the sonic wave are shown. To obtain these characteristics, the sonic intensity was not sustained at a fixed value with a change in current, in contrast to the results shown in Fig. 11. The measurements were taken at different fixed values of the sonic wave coming from an external source. The values of the discharge voltage U_p at each value of current (from 40 to 120 mA) were taken at the sound intensity, which was set up in the discharge tube at the given current upon interaction between the sonic wave and plasma. In the experiment, the intensity J_0 of sound coming from an external source at 40 mA was set to be between 66 and 88 dB depending on the amplitude.

In the nitrogen discharge without a sonic wave, at 78 torr the transition to a contracted state occurred at $I_{p_1} = 70$ mA. The emission of sound results in a slight shift of the value I_{p_1} towards a stronger current. The values of I_{p_1} for different sound intensities J_0 are listed in table 1; the values of I_{p_2} that were set up in the discharge immediately after the contraction are also listed there. The increase in the intensity J_0 is accompanied by a shrinkage of the hysteresis area on the voltage–current characteristics of the discharge; a significant shrinkage occurs at $J_0 > 72$ dB. At $J_0 = 88$ dB the hysteresis area vanishes totally (Fig. 12c) and in this case the discharge is fully decontracted.

Table 1.

J_0/dB	66	68	70	72	76	81	84	88
I_{p_1}/mA	71	73	75	76	78	79	83	—
I_{p_2}/ mA	75	77	79	80	82	82	86	—
J_1/dB	68	70	72	75	79.5	82.5	85	—
J_2/dB	70.5	74	79	83	84.5	85.5	86	—
J_3/dB	71	76	81	84	85	86	88	91

We shall consider the evolution of parameters of a sonic wave directed along the positive column as the current in the nitrogen discharge changes from 40 to 120 mA. The investigations show that in the range of pressure lower than 78 torr an increase in the discharge current is accompanied by a smooth increase in the amplitude of sound. At 78 torr, over the range of intensity J_0 from 66 to 88 dB and for specific values of discharge current, the amplitude of the sonic wave increases abruptly on contraction of the positive column (in Fig. 13 A/A_0 is the relative amplitude of sound, where A_0 is the amplitude of sound at 40 mA).

The comparison of plots in Figs 12 and 13 shows that at these currents the charge goes suddenly to the contracted state. The A/A_0 dependence on current as well as the voltage–current characteristics of discharge (see Figs 12 and 13) exhibit the hysteresis behaviour. It follows from the results of studies that an increase in J_0 from 66 to 72 dB is accompanied by an enhancement of the effect of the abrupt growth of the amplitude of sound. The maximum growth of the amplitude of sound is observed at $J_0 = 72$ dB. The amplitude of the sonic wave at the current immediately after the contraction ($I_p = 80$ mA) is 3.6 times that at the current immediately before contraction ($I_p = 76$ mA). Over the range of intensities $J_0 > 72$ dB, an increase in J_0 is accompanied by a weakening of the effect of abrupt growth of the amplitude of sound. At $J_0 = 88$ dB the hysteresis area in the A/A_0 dependence on the discharge current is eliminated totally (Fig. 13c, curve *2*); in this case, the discharge is decontracted fully by the sonic wave (Fig. 12c).

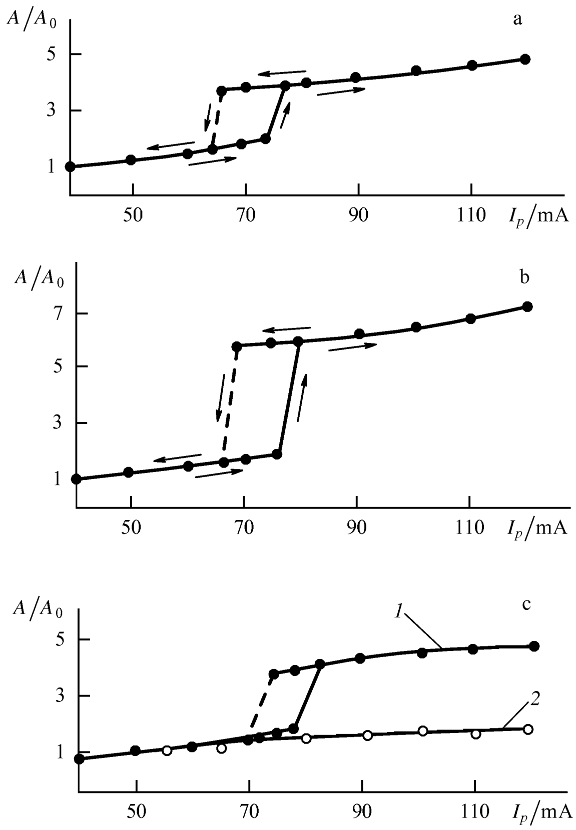

Figure 13. Dependence of the relative amplitude of a sonic wave A/A_0 (where A_0 is the amplitude at 40 mA) on the discharge current in nitrogen at 78 torr for sonic waves with different intensities J_0: (a) $J_0 = 68$ dB, (b) $J_0 = 72$ dB, (c) curves *1* and *2* represent, respectively, $J_0 = 78$ and 88 dB.

For a clearer understanding, in Fig. 14 the dependence of the ratio of the amplitude of sound at I_{p_2} to the amplitude of sound at I_{p_1} on the sound intensity J_0 is examined. In the same figure, the ratio of the amplitude of sound at 120 mA to the amplitude at 40 mA, A_3/A_0, is plotted against J_0, from which it follows that at $J_0 = 72$ dB the increase in current from 40 to 120 mA results in the sevenfold growth in the amplitude of sound.

Simultaneously with the measurement of the amplitude of the sonic wave, the dependence of the sonic wave intensity on the discharge current was recorded. The values of the sound intensity J_1 at currents immediately before contraction and the values J_2 after contraction, and also J_3 at 120 mA for different J_0 are listed in table 1, from which it follows that the largest jump of the sound intensity occurs at $J_0 = 72$ dB accompanied by an increase of 8 dB in the sound intensity. The increase in current from 40 to 120 mA (at $J_0 = 72$ dB) is accompanied by the growth of the sonic wave intensity by 12 dB.

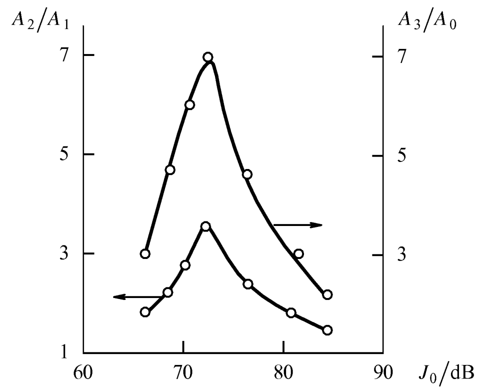

Figure 14. Dependence of the ratio of amplitudes A_2/A_1 immediately after and before the jump on the sound intensity J_0 for a sonic wave directed along the discharge in nitrogen at 120 and 40 mA.

Let us examine the mechanism of the abrupt growth of the amplitude of sound upon transition of the discharge in nitrogen into the contracted state. The propagation of the sonic wave in the plasma column leads to spatial and temporal modulations of temperature and gas density. These modulations bring about the modulation of the intensity of heat released because of the vibrational (V $-$ T) relaxation. In its turn, the last modulation causes the modulation depths of the initial temperature and gas density to increase, i.e. the amplitude of the sonic wave grows. With transition of the discharge to the contracted state, the diameter of the positive column decreases, the current density increases on the axis of the discharge tube and, consequently, the gas temperature rises in the plasma. If, in addition, the V $-$ T relaxation is much less than the period of sound oscillations, then the intensity of heat release caused by this process will be modulated efficiently by the sonic wave and this can result in a substantial growth of the modulation depths of the initial temperature and density and in a jump of amplitude of the sonic wave.

When the pressure of nitrogen is 78 torr, the gas temperature T does not exceed 860 K on the axis; with contraction T rises above 935 K (the gas temperature was measured by a thermocouple sensor located on the axis of the discharge tube at 8 cm from the anode). At $T = 900$ K the gas particle density is $N = p/kT = 8.5 \times 10^{17}$ cm^{-3}. In these conditions in pure nitrogen the V$-$T relaxation constant is $k = 10^{-16}$ cm^3 s^{-1} [58] and the V$-$T relaxation time is $\tau_{\mathrm{VT}} = (k_{\mathrm{VT}} N)^{-1} = 1.1 \times 10^{-2}$ s. The period of sound oscillations is $\tau_s = 6 \times 10^{-3}$ s, i.e. $\tau_{\mathrm{VT}} > \tau_s$ in pure nitrogen. However, the nitrogen used in experiments contained the 0.07% admixture of steam. The vibrational relaxation of molecules of nitrogen is studied comprehensively over the range of temperatures from 300 to 963 K in Ref. [59]. At $T = 900$ K the vibrational relaxation constant for molecules of nitrogen is 10^{-13} cm^3 s^{-1} according to Ref. [59]. The V$-$T relaxation time for the $N_2{-}N_2O$ mixture may be calculated by means of the formula given in Ref. [60]:

$$\frac{1}{\tau_{\mathrm{VT}}} = \frac{1}{\tau_{\mathrm{VT}}^0} \frac{P_0}{P} + \frac{1}{\tau_{\mathrm{VT}}^1} \frac{P_1}{P} ,$$

where P_0 and P_1 are partial pressures of nitrogen and steam, τ_{VT}^0 and τ_{VT}^1 are the times of relaxation of nitrogen by nitrogen and by molecules of water, respectively. In the conditions considered, the partial pressure of water is approximately $P_1 = 0.1$ torr. The cited formula yields $\tau_{\mathrm{VT}} = 5 \times 10^{-3}$ s for nitrogen with the 0.07% admixture of steam. If we also take account of the fact that nitrogen has a 0.4% admixture of oxygen, then the constant of vibrational relaxation of nitrogen by oxygen is greater by two orders of magnitude than that of nitrogen by nitrogen [61]. As a result, τ_{VT} should be even less than 5×10^{-3} s. The jump in the amplitude of the sonic wave is most pronounced at a relatively low sound intensity ($J < 75$ dB).

At $J > 75$ dB the effect weakens because of development of an acoustic flow at this intensity. In these conditions, the vortex flow may be observed visually in the discharge tube. Vortices shrink as the sound intensity increases.

The vortex motion in the discharge tube (of small-scale vortices much smaller than the tube diameter in size) is most pronounced at a sound intensity $J > 88$ dB. In this case, the discharge experiences decontraction in the field of the sonic wave and the process is accompanied by elimination of the jump in the sound amplitude. The existence of the steady vortex motion (acoustic flow [34]) causes remixing of the gas over the tube cross-section and alignment of the radial temperature gradient; as a consequence, the gas temperature T on the discharge axis is lowered. The drop in T causes the V–T relaxation processes to slow down and, with the inequality $\tau_{VT} < \tau_s$ being violated, the modulation of intensity of the heat release caused by V–T relaxation will have a low efficiency; in this case, the amplitude of sound cannot increase significantly. At $J = 85$ dB the gas temperature on the axis drops by more than 100 K, and τ_{VT} amounts to 10^{-2} s, i.e. the inequality $\tau_{VT} < \tau_s$ is violated. Thus, the elimination of the jump in the amplitude of sound, accompanied by decontraction of the discharge, may be explained by the development of the steady vortex flow in the plasma column because of sound waves.

We shall now consider the results of experimental investigations of the abrupt growth of the amplitude of the sonic wave emitted by an external source along the positive column, upon contraction of the discharge in nitrogen–oxygen mixtures. The measurements were taken at 78 torr over the range of discharge currents from 40 to 120 mA [20]. The oxygen content in mixtures varied from 0 to 40%. The investigations show that the abrupt contraction of the positive charge at 78 torr is observed also when oxygen is added to the nitrogen discharge. In this case, the values at which the contraction of the positive column occurs shift towards low currents on an increase in the percentage of oxygen in the mixture.

In a nitrogen discharge without additional oxygen the critical current is 70 mA, with 10% content of oxygen in the mixture it is 65 mA, and with 40% content of oxygen in the mixture it is 55 mA. In the field of a sonic wave (when the sound intensity is maintained constant over the entire range of discharge currents from 40 to 120 mA), with an increase in the sound intensity in the discharge in an oxygen–nitrogen mixture, the abrupt growth of the amplitude of sound on the voltage–current characteristics of the discharge occurs at a higher value of the discharge voltage and is accompanied by a shrinkage of the hysteresis area, as is the case in a nitrogen discharge [19].

In the nitrogen discharge at the sound intensity 90 dB the discharge is fully decontracted in the field of the sonic wave and this process is accompanied by the elimination of the hysteresis area on the voltage–current characteristics of discharge. A further increase in the sound intensity results in a larger energy content in the discharge. In nitrogen–oxygen mixtures with the oxygen content between 0 to 30%, the full decontraction of the discharge occurs also at the sound intensity 90 dB. With the oxygen content of more than 30% in mixture, the discharge is fully decontracted in the field of the sonic wave at a higher sound intensity ($J > 92$ dB).

The study of voltage–current characteristics of discharges in mixtures was conducted at the first resonant frequency of sound. The addition of oxygen to the nitrogen discharge resulted in the downward shift of the resonant frequency ($f = 170$ Hz); with 10% content of oxygen in the mixture the frequency was $f = 167$ Hz, with 20% content it was 165 Hz, and with 40% content it was 162 Hz. With an increase in the percentage of oxygen in the mixture, the jump in the amplitude of sound as a result of the contraction of the positive column becomes greater. So, in the nitrogen discharge the ratio of the amplitude of the sonic wave immediately after the contraction to the amplitude of sound before contraction, A_2/A_1, is 3.6 at the sound intensity of 72 dB. In the mixture with the 10% content of oxygen, $A_2/A_1 = 5$, with the 20% content it is 7, and with the 30% and 40% contents it is 8.8 (Fig. 15). In this case, the intensity of the sonic wave increases by 13 dB. As in nitrogen, in the discharge in an oxygen–nitrogen mixture the discharge undergoes decontraction with the elimination of the jump in the amplitude of sound when the sonic wave intensity increases to over 84 dB.

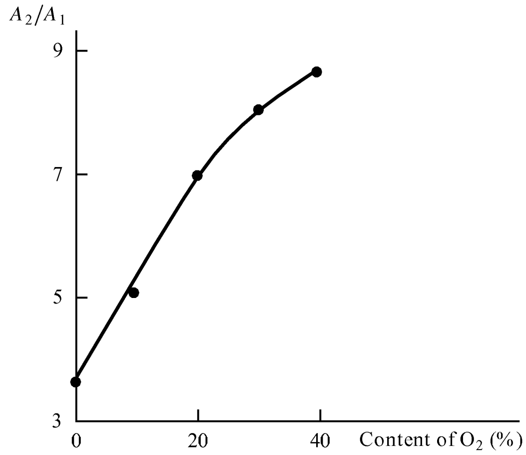

Figure 15. Dependence of the ratio of amplitudes of the sonic wave immediately after the discharge contraction and before the contraction on the percentage of oxygen in a nitrogen–oxygen mixture at the sound intensity 72 dB.

In the course of the study of the effect the sonic waves have on the contraction of the positive column, the characteristic time τ was measured for which the amplitude of sound increased from A_1 at the current immediately before contraction to A_2 settling immediately after contraction of the discharge. An increase in the percentage of oxygen in the mixture is accompanied by a decrease in the characteristic time of growth of the amplitude of sound caused by the contraction of the discharge (Fig. 16). At the sonic wave intensity of 70 dB in the nitrogen discharge $\tau = 2.5$ ms, in the mixture with 10% content of oxygen is $\tau = 1.3$ ms, and in the case of 40% content of oxygen $\tau = 0.4$ ms. The time of growth of the amplitude of sound upon contraction increases with an increase in the sonic wave intensity. One of the mechanisms of the jump of the amplitude of sound upon contraction of the discharge in a molecular gas is related to the strong temperature dependence of the constant of vibrational relaxation of excited molecules. The sharp increase in amplitude is possible if the V–T relaxation time τ_{VT} is less than the period of sound oscillations τ_s [18]. In this case, the intensity of heat released because of V–T relaxation is modulated by the sonic wave and this can result in a significant increase in the amplitude

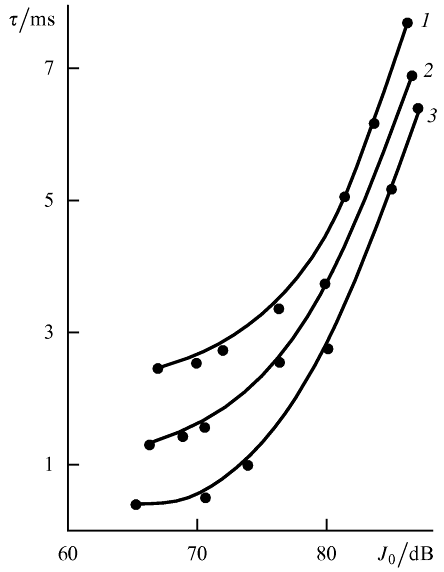

Figure 16. Dependence of the time of growth of the amplitude of a sonic wave caused by the jump of the amplitude on the sonic wave intensity J_0: *1* — in a nitrogen discharge; *2* and *3* — in the discharge in a nitrogen – oxygen mixture. (Curve *2* corresponds to an oxygen content of 10%, and curve *3* to 40%.)

of sound. In pure nitrogen the V–T relaxation constant $k_{VT} = 10^{-16}$ cm^3 s^{-1} at $T = 800$ K [58], and the relaxation time $\tau_{VT} = 1.1 \times 10^{-2}$ s. The period of sound oscillations $\tau_s = 6 \times 10^{-3}$ s, i.e. in pure nitrogen $\tau_{VT} > \tau_s$. However, the nitrogen used in the experiment contained an admixture of water at $T = 900$ K, according to Ref. [60] k_{VT} is 10^{-13} cm^3 s^{-1}. For the $H_2 + H_2O$ mixture at the partial pressure of steam of 0.1 torr (0.07), the V–T relaxation time is $\tau_{VT} = 5 \times 10^{-3}$ s, $\tau_{VT} < \tau_s$. In Ref. [68] the results of studies of sound-induced modulation of the discharge current in nitrogen with the 0.07 % admixture of water are reported. The authors established that at 50 torr and 40 mA in the tube of inner diameter 9.8 cm at the sound intensity 98 dB the current modulation depth is 26%. They showed that this large value of the depth of sound-induced modulation of current stabilised because of the V–T relaxation for $\tau_{VT} < \tau_s$.

The addition of oxygen to nitrogen in the discharge results in a larger current modulation depth and with 40% content of oxygen in the mixture the modulation depth stabilises at 36%. This is related to the fact that the vibrational relaxation of nitrogen by oxygen is two orders of magnitude higher than that of nitrogen by nitrogen [60], i.e. with the increase in the percentage of oxygen in a nitrogen discharge the value of τ_{VT} becomes smaller and the amplitude of sound increases. This fact explains the stronger effect of the abrupt growth of the amplitude of sound upon contraction of the discharge in the nitrogen – oxygen mixture and the behaviour of the A_2/A_1 dependence on the percentage of O_2 in $N_2 + O_2$ (shown in Fig. 15). With the increase of the percentage of oxygen in the mixture, the characteristic time τ, for which the amplitude of the sonic wave increases from A_2 at the current before the contraction to A_2 immediately after contraction of the discharge, becomes smaller.

4. Joint influence of a sonic wave and a gas flow on the parameters of a discharge

The sonic wave propagating along the positive column causes drops in the gas temperature and in the radial gas temperature gradient, changes in the longitudinal electric field, in temperature and electron density, compression and expansion of the plasma column, and stabilisation of the discharge. A longitudinal gas flow has a similar effect on the positive column [35]. With a high rate of pumping and an elevated pressure, the flow provides for the excitation of an homogeneous noncontracted discharge by virtue of the turbulent mixing of gas. In this case, the radial distribution of charged particles in the positive column can be more homogeneous than that in the diffusion discharge at low pressure.

In Ref. [25] the authors established experimentally the intensity dependence of the longitudinal electric field intensity on velocity in the argon discharge with a longitudinal flow. They found that, over the range of gas flow velocities from 0 to 40 m s^{-1}, the longitudinal electric field intensity E decreases with an increase in the rate of pumping; on a further increase in the rate of pumping, the electric field increases sharply. The buildup of the field for a velocity above 120 m s^{-1} is explained by the transition of the gas flow to the turbulent regime [25]. In Refs [30, 62] it was shown experimentally that, in the laminar regime of pumping, a decrease in the longitudinal electric field intensity is accompanied by a drop in the electron temperature and an increase in the radial electron temperature gradient in the discharge. The authors established that the laminar pumping of gas brought about an increase in the electron density on the axis of the positive column and a steeper radial electron density distribution in the plasma column than that in the discharge without a flow. This is because the particles are carried off with the longitudinal flow faster than electrons and ions decay on the tube walls as a consequence of their radial diffusion or of their volume recombination on the periphery of the positive column. The effect of contraction of the profile of the radial electron density distribution in the positive column takes place when the gas is pumped from the cathode to the anode, as well as when it is pumped in the opposite direction.

The experimental investigations reported in Refs [30, 62] were conducted in discharges of electropositive gases: in argon, helium, and nitrogen. In this section we present the results of experiments on the combined influence of a sonic wave and a longitudinal gas flow on the discharge parameters and establish general rules. For this purpose it is sufficient to study how a sonic wave directed along the positive column affects the properties of the discharge [63]. We study the influence of sound on the voltage – current characteristics of the discharge in the gas flow, on the longitudinal electric field intensity, electron temperature, and gas temperature difference between the axis and the discharge tube wall. We shall show that, in the field of a sonic wave at a comparatively large intensity (above a critical one), the positive column is more homogeneous in the transverse direction in discharge with a gas flow than in discharge without a flow. In this case, the power input in the discharge with a flow exceeds the input in the discharge without a flow. The situation is just the opposite when the sound intensity is lower than the critical value.

The experimental measurements were taken in the unit with a quartz discharge tube of inner diameter 9.8 cm and length 52 cm. The ring wire-gauze electrodes were spaced at 27 cm. The sonic wave in the discharge was emitted by an electrodynamic radiator fastened to one of the ends of the discharge tube; to the opposite end (behind the anode) a microphone was fastened to monitor the parameters of the plasma. The gas was pumped by a roughing-down pump along the discharge tube from the anode to cathode. The section-averaged gas flow velocity in the discharge tube was 0.63 m s^{-1}. The experiments were conducted at a pressure of 40 – 60 torr and discharge current 40 – 60 mA. The sonic wave intensity varied from 84 to 98 dB. The measurements were taken at the first resonant frequency of sound, which is 170 Hz in the discharge without pumping. The initiation of pumping brings about a downward shift of the resonant frequency by 15 Hz, i.e. the resonant frequency is 155 Hz in the discharge with a gas flow.

4.1 Sound-induced decontraction of the discharge in a gas flow

In Refs [30, 62] the authors established that the laminar pumping along the discharge in an electropositive gas resulted in a contraction of the positive column. A similar contraction is observed when a sonic wave is emitted along the positive column. We shall compare here the voltage – current characteristics of the discharge in nitrogen at 60 torr over the range of currents from 40 to 90 mA in the absence of sound, in a gas flow, and in the presence of a sonic wave (Fig. 17).

The discharge voltage at 40 mA in the absence of sound and gas flow is $U_0 = 5.2$ kV (curve *1*), and the diameter of the visible boundary of the positive column is about 2 cm in these conditions. Upon creation of a flow U_0 decreases to 4.3 kV (curve *2*) and the diameter to 1.2 cm. Upon the emission of a sonic wave with intensity 88 dB in the discharge with a flow, the voltage settles at $U_0 = 4.8$ kV and the visible boundary of the positive column settles at 2.4 cm. In the case of a discharge with a sonic wave ($J = 88$ dB) but without a flow $U_0 = 5.6$ kV (curve *4*), the discharge diameter $d = 2.4$ cm. In the discharge without a flow at the sonic wave intensity of 98 dB (curve *5*), the discharge voltage increases significantly ($U_0 = 6.8$ kV), and the diameter of the visible boundary of the positive column extends to 6.5 cm at 40 mA. In the case of a discharge with a gas flow in the field of a sonic wave with intensity $J = 98$ dB (curve *6*), the discharge voltage and the diameter increase still further ($U_0 = 8$ kV, and at 40 mA d= 7.5 cm).

The results of measurements show that with the sonic wave of intensity $J < 90$ dB at the resonant frequency the diameter of the positive column and the discharge current are lower with pumping than those in the discharge without a gas flow. At $J > 90$ dB the situation is just the opposite: in the discharge with pumping of gas the values of the discharge voltage and of the diameter of the visible boundary of the positive column become larger than in the case of a discharge without a gas flow (at the same sonic wave frequency).

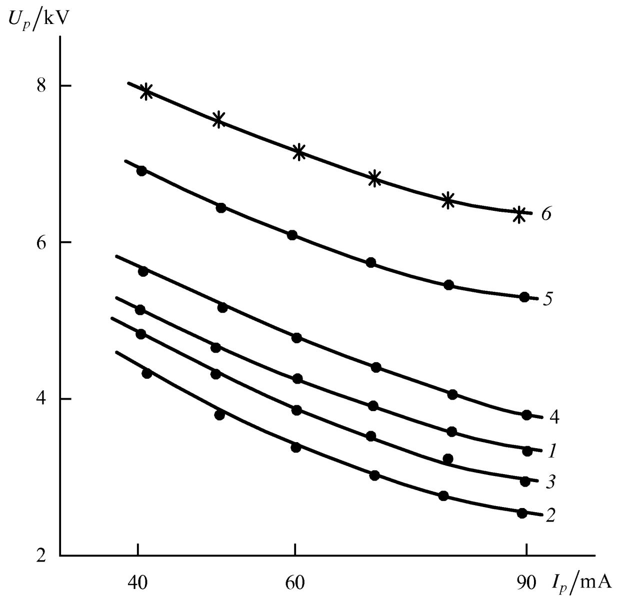

Figure 17. The voltage – current characteristics of the discharge in nitrogen at 60 torr: *1*, *2* (without sound); *3* – *6* (with sound); *1*, *4*, *5* (without pumping); *2*, *3*, *6* (with pumping, $v = 0.63$ m s^{-1}); *4* ($J = 88$ dB), *5*, *6* ($J = 98$ dB).

4.2 Influence of a sonic wave on the electric field in the discharge with a gas flow

As pointed out above, the electric field in the discharge with a gas flow was studied in Refs [30, 62]. It is shown there that the discharge experiences a contraction and the longitudinal electric field intensity decreases as the velocity of the laminar gas flow parallel to the positive column increases. When the flow is turbulent, an increase in the rate of gas pumping results in a larger diameter of the positive column and in a stronger electric field.

We shall examine here how the sonic wave affects the electric field of discharge in the laminar gas flow with the velocity 0.63 m s^{-1}; in fact this means that we shall study the combined influence of a gas flow and a sonic wave on the longitudinal electric field in the positive column. The measurements were taken in the tube of diameter 9.8 cm and length 52 cm. The electrodes were spaced at 27 cm. The electric field was measured by a compensation method (described in Ref. [26]) with two probes spaced at 1 cm on the axis of the positive column and 8 cm away from the anode. The experiments were conducted in the nitrogen discharge at 60 torr and 40 mA. The longitudinal electric field intensity without pumping of gas and in the absence of a sonic wave was 160 V cm^{-1} (Fig. 18, curve *1*). The emission of sound with intensity 88 dB causes the electric field strength to increase to 170 V cm^{-1}; $E = 175$ V cm^{-1} at $J = 90$ dB, and $E = 210$ V cm^{-1} at $J = 98$ dB. The creation of a nitrogen flow along the positive column in the absence of a sonic wave brings about a decrease in the electric field strength; as a result, the field strength stabilises at $E = 133$ V cm^{-1} (Fig. 18, curve 2). At the sound intensity 90 dB in the discharge with a gas flow, in the positive column the electric field becomes equal to 175 V cm^{-1}, i.e. it has the same value as that in the absence of the flow. However, at 98 dB in the gas flow the value of the field stabilises at $E = 240$ V cm^{-1}; it is 30 V cm^{-1} greater than that without pumping of gas. Consequently, the sonic wave causes the longitudinal electric field to build up in the discharge with laminar pumping as well as without it.

A characteristic feature of the electric field dependence on the sound intensity in a gas flow occurs at 90 dB when these two curves intersect. At $J < 90$ dB the value of the

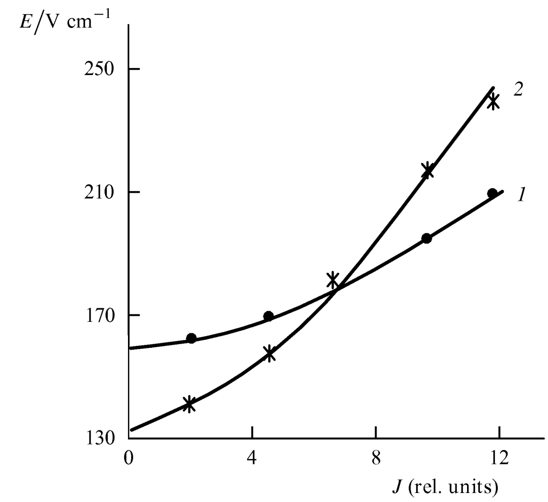

Figure 18. Dependence of the longitudinal electric field intensity on the sonic wave intensity in a nitrogen discharge at 60 torr and 40 mA: curve *1* — without pumping; curve *2* — with pumping, $v = 0.63$ m s^{-1}.

electric field in the discharge with a flow stabilises at a higher value than that in the discharge without pumping (at the same sonic wave intensity). In the case of $J < 90$ dB, the value of the field in the discharge with a flow is less than that in the positive column in the absence of a gas flow.

4.3 Influence of a sonic wave on the temperature gradient in the discharge with a gas flow

For a better understanding of the processes occurring in the discharge with a laminar gas flow in the presence of a sonic wave, we shall examine the dependence of the radial gas temperature gradient on the sound intensity in the positive column with pumping. The temperature was measured by two thermocouple sensors. One was located on the axis of the discharge tube at a distance 8 cm from the anode and the other on the discharge tube wall at the same distance from the anode. In the nitrogen discharge without a flow and in the absence of a sonic wave, at 60 torr and 40 mA the gas temperature on the tube axis settles at $T_0 = 733$ K.

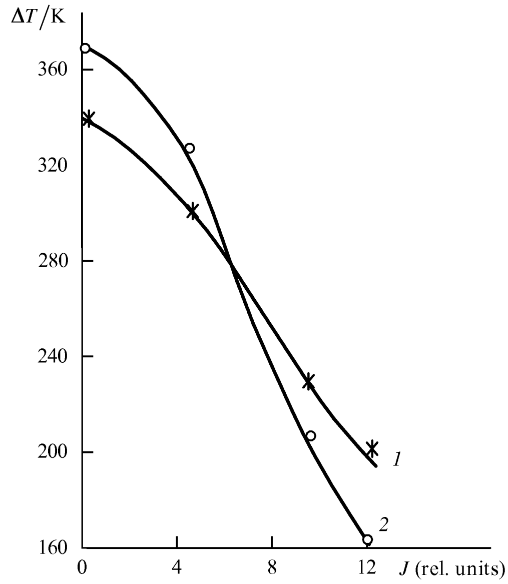

Figure 19. Dependence of the temperature difference between the axis and tube wall on the sound wave intensity in a nitrogen discharge at 60 torr and 40 mA: curve *1* — without pumping; curve *2* — with pumping, $v = 0.63$ m s^{-1}.

The pumping of gas at the rate $v = 0.63$ m s^{-1} brings about a drop in the temperature by approximately 70 K. Although the gas temperature drops on the axis in the discharge with a flow, the radial gas temperature difference T in the discharge with a flow is greater than that in the discharge without pumping (Fig. 19). The emission of a sonic wave brings about a reduction in the radial temperature difference in the discharge with a flow as well as without it. Over the range of sound intensities $J > 90$ dB, the radial difference is less in the discharge with pumping than that in the discharge without a gas flow. In the discharge without pumping of gas, at $J = 98$ dB and 40 mA the gas temperature T_0 on the axis of the positive column settles at 610 K and the radial difference at 200 K; in the discharge with a flow $T_0 = 510$ K and $\Delta T = 165$ K in this case.

4.4 Dependence of the electron temperature on the sonic wave intensity in the discharge with a nitrogen flow

One of the most important tasks for which a gaseous discharge is used in practical applications is to control independently the electron temperature in plasma at fixed values of current and gas pressure in the discharge. The ability to bring the electron temperature in the discharge to the optimal value makes it possible to create conditions in plasma such that peak output parameters of a gas-discharge unit are obtained. Thus the attainment of the optimal electron temperature in a gas-discharge laser results in the peak output power of the laser. It will be shown later that the combined use of a gas flow and a sonic wave to change the electron temperature makes it possible to expand significantly the range of variation of the electron temperature in discharge at fixed values of current and gas pressure in the tube.

The electron temperature was measured by a Langmuir probe. The gas temperature in plasma was measured on the discharge axis and on the tube wall by two thermocouple sensors at a distance of 8 cm from the anode. The measurements were taken in the nitrogen discharge over the range of pressures from 30 to 40 torr and at the electric current 40 mA. The sonic wave intensity at the first resonant frequency $f = 170$ Hz varied from 84 to 98 dB. The laminar gas flow velocity was 0.63 m s^{-1}. The gas was pumped by a roughing-down pump from the anode to the cathode. The electron temperature in the nitrogen discharge, in the absence of a flow and with a sonic wave on the axis of the positive column at 30 torr and 40 mA in the tube 9.8 cm in inner diameter, was 0.5 eV. An increase in the sonic wave intensity raised the electron temperature T_e (Fig. 20, curve *1*). At the sound intensity 84 dB (2 in rel. units) $T_e = 0.53$ eV, at 90 dB (8 in rel. units) $T_e = 0.6$ eV, and at 98 dB (12 in rel. units) $T_e = 0.72$ eV. In this case, the discharge experienced a decontraction, the diameter of the visible bound-ary of the positive column expanded from 2 to 6.5 cm, the gas temperature on the axis dropped from 614 to 574 K, and the radial gas temperature gradient diminished from 310 to 260 K.

As the experiment showed, the pumping of gas in the absence of a sonic wave causes the electron temperature to

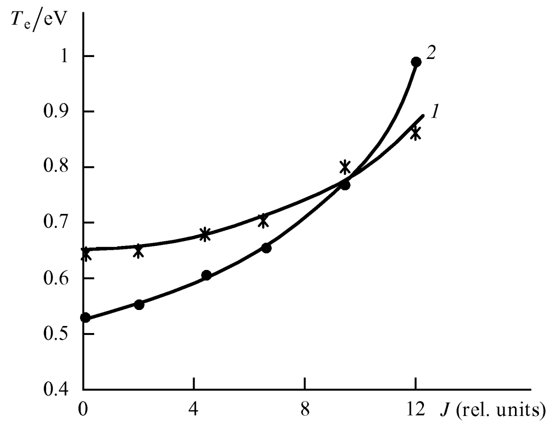

Figure 20. Dependence of the electron temperature on the axis of the positive column on the sonic wave intensity in a nitrogen discharge at 60 torr and 40 mA: curve *1* — without a gas flow (at the first resonant frequency of sound, $f = 170$ Hz); curve *2* — in a gas flow with $v = 0.63$ m s^{-1} ($f = 155$ Hz).

drop from 0.5 to 0.38 eV while the discharge diameter diminishes from 2 to 1.2 cm. In this situation, the longitudinal electric field also decreases. If there is a gas flow, then an increase in the gas intensity brings about a steeper rise in the electron temperature than that in the absence of pumping (see Fig. 20, curve *2*), and T_e amounts to 0.6 eV at 90 dB, i.e. curves *1* and *2* intersect. A further increase in the sonic wave intensity brings about a steeper rise in the electron temperature in the nitrogen flow, and at $J = 98$ dB it amounts to 0.92 cm while the diameter of the positive column expands to 7.75 cm. Thus, it follows from the cited experimental results that, at fixed current and gas pressure in the discharge, the electron temperature in the positive column may be increased 2.5 times by appropriate choice of the gas flow and sonic wave intensity.

Note that at a sonic wave intensity lower than the critical value (in the conditions considered it is $J_{cr} = 90$ dB), the gas flow brings about a drop in the electron temperature, whereas at $J > 90$ dB the pumping of gas causes the electron temperature to settle at a higher value, i.e. at T_e which is higher than the value of T_e in the discharge in the presence of sound but in the absence of a flow.

4.5 Results of experiments

Eaperimental results show that a sonic wave in discharge with a flow as well as without it brings about increases in the longitudinal electric field intensity and in the electron temperature, a reduction in the radial gas temperature difference in the tube, and an expansion of the diameter of the visible boundary of the positive column. In the discharge without a sonic wave but with laminar pumping of gas, the plasma parameters exhibit the opposite behaviour. Sound with intensity $J < 90$ dB causes the longitudinal electric field intensity and electron temperature to settle at higher values and the radial gas temperature difference to settle at a lower value than in discharges with pumping of gas. The diameter of the visible boundary of the positive column with a flow is then smaller than that in the discharge without pumping of gas.

In the range $J > 90$ dB the electric field and electron temperature, and also the diameter of the positive column in discharge with a flow, are larger and the gas temperature gradient is smaller than in discharges without pumping. In the nitrogen discharge at 40 torr a similar change in the behaviour of the discharge parameters is observed at the sonic wave intensity $J = 96$ dB. In Ref. [33] the reduction of the gas temperature difference in the discharge with a sonic wave (without a gas flow) is associated with development of a steady vortex flow in the standing sonic field (so-called acoustic flow [34]).

The reduction of the radial gas temperature difference in the discharge, as a result of the turbulent mixing of gas in the vortex flow, brings about a smoother radial distribution of the E/N parameter in the positive column than in the discharge without a sonic wave. As a result, the radial ionisation rate and electron density distributions are smoother and hence the longitudinal electric field density, electron temperature, and diameter of the positive column are larger.

The vortex flow in the tube may be observed visually in the experiment. The vortex acoustic flow develops subject to the inhomogeneity of the acoustic flow [64]; in the discharge tube the inhomogeneity develops because of the sharp, radial gas temperature difference in the positive column.

The measurements show that, in a discharge with a laminar gas flow (without a sonic wave), the radial gas temperature difference in the positive column is larger than that in a discharge without a flow. This fact can be explained as follows. The time $\tau_s = L/2v$, for which the flow carries gas particles away from the axis of discharge with the section-averaged rate of pumping $v = 0.63$ m s^{-1} for $L = 13.5$ cm (the centre of the tube), is 0.1 s. At 60 torr and 40 mA in the discharge with a flow, in the absence of a sonic wave the gas temperature on the axis of the plasma column is 660 K. For nitrogen molecules the diffusion coefficient D calculated with the use of data cited in Ref. [65] is 25 cm^2 s^{-1} in this case, and the characteristic time of diffusion to the wall is $\tau_D = R^2/D = 0.7$ s. It follows that the time for which the flow carries gas particles away from the discharge zone is much less than the characteristic time of diffusion to the wall and, as a result, the radial distribution of neutral particles in the positive column is more inhomogeneous and the radial gas temperature difference is greater in the discharge with a laminar flow.

The acoustic flow shows up in the discharge without pumping as well as in the discharge with a gas flow. However, at a relatively high sonic wave intensity (at $P = 80$ torr and $J_{cr} > 90$ dB) the stronger radial temperature inhomogeneity of the discharge with a gas flow encourages a stronger development of the acoustic flow than that in the discharge without a gas flow and, as a result, the plasma parameters experience greater quantitative changes in the discharge with a flow in the field of a sonic wave.

In a discharge with a gas flow in the field of a sonic wave over the range of the sound intensity $J_{cr} > 96-90$ dB (J_{cr} changes from 96 to 90 dB as the pressure of nitrogen increases from 40 to 60 torr), the size of vortices is less than that in the discharge without pumping of gas (at the same sonic wave intensity) and the discharge is more homogeneous in the transverse direction than in the case without pumping. The situation is just the opposite in the range of sound intensities $J < J_{cr}$. The gas-dynamic effects caused by a gas flow and a sonic wave in discharge at an intensity $J > J_{cr}$ are added.

5. Mechanisms of interaction of sound and gas-discharge plasma

The theoretical considerations of how acoustic waves affect the parameters of a gaseous discharge may be found in Refs [67, 69, 75]. In Ref. [67] the processes that cause the decontraction of a gaseous discharge because of a sonic wave are analysed theoretically. The authors point out that, because the discharge current flows along the tube axis and there is a radial temperature gradient in the positive column, in such temperature-inhomogeneous media the standing sonic wave assumes a profile related to the temperature gradient profile [66]. In the tube, the longitudinal standing mode is excited. Because of deformation of the phase planes, the vibrational velocity in the longitudinal acoustic mode acquires a transverse component. In the discharge tube, in addition, the inhomogeneity of the acoustic field develops because of the existence of a strong radial temperature gradient in the tube and also because of the boundary layer near the walls, where the velocity of motion of the medium drops from the value in the sonic wave on the axis of the positive column to zero at the walls.

Because of the inhomogeneity of the acoustic field, the vortex acoustic flow develops in the standing sonic wave [64]. This flow enhances the radial transfer processes in the tube. As a result, heat conductivity increases and this brings about a drop in the gas temperature on the axis of the plasma column and a reduction in the radial gas temperature gradient, a greater diffusion loss of charged particles on the wall, and unraveling of the positive column.

Note that a linear acoustic flow cannot actually affect the transfer processes in the tube, whereas in the field of a standing sonic wave a nonlinear flow can make an appreciable contribution to the transfer processes but the size of inhomogeneities of the acoustic field should be large, $g \gg \delta$ (δ is the thickness of the boundary layer), for the latter flow to exist. The strong radial temperature inhomogeneity in the tube is responsible for development of large acoustic flows which affect the radial transfer processes in the discharge and, hence, for decontraction of the positive column.

In Ref. [69] the theoretical study of how acoustic waves affect the structure of a discharge, i.e. the stratification of the positive column and the contraction of the discharge, is conducted. The sound-stimulated stratification of a discharge was first observed experimentally in Ref. [14] and the sound-induced contraction of a positive column in Ref. [70]. In Ref. [69] the existence of a sharp dependence of the ionisation rate constant k_{i} on the ratio of the electric field intensity to the neutral component density E/N in plasma, modulated directly by sound, is considered to be a link through which the acoustic wave affects the discharge. This modulation can be enhanced by the parametric interaction between acoustic waves and one of the eigenmodes of the discharge or discharge circuit at an appropriate ratio between frequencies. As a result of this modulation, the efficient rate of ionisation in plasma increases and this provides the necessary conditions for one of the ionisation instabilities to develop; the type depends on the properties of the discharge and the structure of perturbations. In the nonlinear stage of development of these instabilities, a new structure of the discharge is normally formed — either stratification [71, 72] or contraction of the discharge [22, 72] occurs. In addition, if E/P, where P is the gas pressure, is large enough, then according to Ref. [73] negative relaxation (second) viscosity which decreases the overall dissipation of sound can develop. The presence of an acoustic field in the positive column renders the discharge unstable at a specific density of energy of acoustic field even if it is stable in the absence of sound. In Ref. [69] an expression for the threshold value of the amplitude of sound is derived and it provides the excitation condition for strata. In addition, a threshold condition is derived from the discharge and energy balance equations. The excess over the threshold leads to the development of the ionisation-overheat instability and, as a result, to a new stable state with the transverse scale lower than the initial one. This means that the sound-stimulated decontraction of discharge occurs.

An acoustic wave directed along the positive column causes a time – space modulation of the neutral component of plasma and, as a result, the parameter E/N, on which the main parameters of the discharge depend, will be larger in the rarefied layers than in the dense layers (in the approximation that the electric field is not constant along the positive column). As a result, the rate of ionisation depends exponentially on the parameter E/N and the rates of birth differ strongly in rarefied and dense layers and eventually this brings about the stratification of the positive column. However, the ionisation waves can develop at a higher rate of ionisation than the acoustic wave frequency. Note that the modulation depth of the electron density in the discharge with a sonic wave is enhanced with intensity [74, 75].

This conclusion based on calculations was verified fully by the results of later experiments [37, 62, 68, 76, 77]. In Ref. [62] the measured values of the modulation depth of the discharge current in nitrogen, nitrogen – argon and nitrogen – helium mixtures are listed versus the sonic wave intensity, gas pressure, and discharge current.

In a nitrogen discharge with a 0.07% admixture of steam at 50 torr and 40 mA (in the tube of inner diameter 9.8 cm) the increase in the sound intensity from 88 to 98 dB at the resonant frequency 170 Hz brings about an increase in the modulation depth of the discharge current from 11.2 to 25%. At fixed values of the permanent components of current and sound intensity, an increase in the gas pressure in the tube brings about an increase in the modulation depth of the discharge current. At the sonic wave intensity of 90 dB an argon or helium addition to nitrogen (at the pressure of mixture 40 torr and current 40 mA) causes the modulation depth to decrease from 10% in nitrogen to 2% in the mixture with the 75% content of argon or helium.

In discharges of molecular gases, the V–T relaxation processes occur and, as a result, the energy is pumped from vibrational degrees of freedom to translational ones. The heat release modulation caused by the vibrational – translational relaxation brings about increases in the modulation depths of the gas parameters [18] and the discharge parameters. In this case, if the V–T relaxation time is less than the period of sound oscillations, then the intensity of release because of this process will be modulated efficiently by the sonic wave and a high value of the discharge current modulation depth can be reached. An argon or helium addition to nitrogen will bring about drops in the partial pressure of nitrogen in the mixture and in the density of the vibrationally excited molecules and, as a result, a decrease in the modulation depth. However, addition of oxygen to nitrogen, on the contrary, will bring about an increase in the depth of sound-induced modulation of current in the discharge [68]. Addition of oxygen to nitrogen (at 50 torr in the mixture with the 40% content of oxygen) at the discharge current 40 mA and the sonic wave intensity 98 dB increases the modulation from 25 to 40%.

The larger depth of the sound-induced modulation of the discharge current with an increase in the percentage of oxygen in the nitrogen discharge is, it appears, related to the fact that the probability of the vibrational relaxation of molecules of nitrogen by oxygen is greater than that of nitrogen by nitrogen. According to Ref. [60] at $T = 288$ K the probability of the vibrational relaxation of nitrogen by oxygen is two orders of magnitude greater than that by nitrogen at a higher temperature ($T = 600$ K). The study of the depth of the sound-induced modulation of electron temperature and electron density in the nitrogen discharge is given in Ref. [37]. The authors showed that at the nitrogen pressure of 40 torr, current 40 mA, and sound intensity 95 dB with the frequency 170 Hz, the modulation depth of the electron temperature is 18% and that of the electron density is 22%, whereas that of the longitudinal electric field in a nitrogen discharge at the same pressure, current, and sound intensity is about 0.5% [24]. This proves that the approximation adopted in Ref. [75] and cited above, i.e. that the electric field along the positive column is constant, is to a large extent correct.

It should be pointed out that this review does not cover some issues which influence the effect of sonic waves on the discharge parameters. These include, for example, the phase shift between oscillations of different components of plasma and sonic waves in a gaseous discharge [8, 11, 78, 79].

6. Conclusion

The results of studies of the influence of acoustic waves and gas flow, and of their combined action on the parameters of a gaseous discharge, make it possible to conclude that there is a deep analogy between the processes in a plasma when sonic waves propagate in it and when gas flows through it. Consequently, instead of the bulky pumping devices needed to create a turbulent gas flow in a plasma column so that a homogeneous excited plasma can be produced at an elevated pressure, by mixing of gas and by attaining the prescribed values of electron temperature and pressure, acoustic radiators with which these parameters can be controlled over a wide range can be used.

The material reviewed shows that the parameters of the gas-discharge plasma change under the action of acoustic oscillations. Thus, a simple and handy method of action on the properties of plasma consists of the use of sound oscillations. There is no doubt that it will occupy a prominent place among the methods used in experimental investigations of gaseous discharge.

References

1. Nedospasov A V, Khait V L *Kolebaniya i Neustoichivosti v Nizkotemperaturnoi Plasme* (Pulsations and Instabilities in a Low-Temperature Plasma) (Moscow: Nauka, 1979)
2. Napartovich A P, Starostin A N, in *Khimiya Plazmy* (Plasma Chemistry) (Moscow: Atomizdat) Issue 6, p. 153
3. Velikhov E P, Baranov Yu V, Letokhov V S et al. *Impul'snye CO-lazery i Ikh Primeneniya dlya Razdeleniya Izotopov* (Pulsed CO-lasers and Their Applications for Isotope Separation) (Moscow: Nauka, 1983)
4. Molevich N E, Oraevskii A N *Zh. Eksp. Teor. Fiz.* **94** (3) 128 (1988) [*Sov. Phys. JETP* **67** 504 (1988)]
5. Osipov A I, Uvarov A V *Usp. Fiz. Nauk* **162** (11) 1 (1992) [*Sov. Phys. Usp.* **35** 903 (1992)]
6. Tsendin L D *Zh. Tekh. Fiz.* **35** 1972 (1965) [*Sov. Phys. Tech. Phys.* **10** 1514 (1966)]
7. Ingard U *Phys. Rev.* **145** 41 (1966)
8. Ingard U, Shulz M *Phys. Rev.* **158** 106 (1967)
9. Hasegawa M *J. Phys. Soc. Jpn.* **37** 193 (1974)
10. Galechyan G A, Divanyan E G, Mkrtchyan A R *Akust. Zh.* **36** 364 (1990) [*Sov. Phys. Acoust.* **36** 200 (1990)]
11. Fitaire M, Mantei T *Phys. Fluids* **15** 464 (1972)
12. Aleksandrov N L, Napartovich A P, Pal' A F, et al. *Fiz. Plazmy* **16** 862 (1990) [*Sov. J. Plasma Phys.* **16** 502 (1990)]
13. Galechyan G A, Zavershinskii I P, Kogan E Ya, et al. Preprint IPPF, Erevan, 1991
14. Subertova S *Czech. J. Phys.* **B 15** 701 (1965)
15. Bauer H, Bass H *Phys. Fluids* **16** 988 (1973)
16. Kogan E Ya, Mal'nev V *Zh. Tekh. Fiz.* **47** 653 (1977) [*Sov. Phys. Tech. Phys.* **22** 391 (1977)]
17. Osipov A I, Uvarov A V *Khim. Fiz.* **16** 385 (1987)
18. Eletskii A V, Stepanov E V *Khim. Fiz.* **18** 1247 (1989)
19. Galechyan G A, Mkrtchyan A R, Tavakalyan L B *Fiz. Plazmy* **19** 1400 (1993) [*Plasma Phys. Rep.* **19** 734 (1993)]
20. Galechyan G A, Mkrtchyan A R, Tavakalyan L B *Fiz. Plazmy* **20** 593 (1994) [*Plasma Phys. Rep.* **20** 533 (1994)]
21. Granovskii V L *Elektricheskii Tok v Gaze* (Electric Current in a Gas) (Moscow: Nauka, 1971)
22. Raizer Yu P *Fizika Gazovogo Razryada* (Physics of Gaseous Discharge) (Moscow: Nauka 1987)
23. Aramyan A R, Galechyan G A, Mkrtchyan A R *Akust. Zh.* **37** 213 (1991) [*Sov. Phys. Acoust.* **37** 107 (1991)]
24. Antilyan M A, Galechyan G A, Tavakalyan L B *Fiz. Plazmy* **17** 1490 (1991) [*Sov. J. Plasma Phys.* **17** 862 (1991)]
25. Gentle K W, Ingard V, Bekefi G *Nature (London)* **203** 1969 (1964)
26. Kozlov O V *Elektricheskii Zond v Plazme* (Electrical Probe in Plasma) (Moscow: Atomizdat, 1969)
27. Avdus' Z I et al. *Praktikum po Obshchei Fizike* (Practical Course in General Physics) (Moscow: Prosveshchenie, 1971) p. 85
28. Galechyan G A, Karapetyan D M, Tavakalyan L B *Teplofiz. Vys. Temp.* **31** 698 (1993) [*High Temp.* **31** 642 (1993)]
29. Galechyan G A, Karapetyan D M, Tavakalyan L B *Fiz. Plazmy* **18** 1084 (1992) [*Sov. J. Plasma Phys.* **18** 565 (1992)]
30. Arutyunyan G G, Galechyan G A, Tavakalyan L B *Izv. Akad. Nauk SSR Fiz.* **19** 42 (1984)
31. Degasov V A, Smirnov B M, Chaivanov B B, in *Khimiya Plasmy* (Plasma Chemistry) (Moscow: Energoatomizdat, 1992) Issue 9, p. 100
32. Eletskii A V in *Khimiya Plazmy* (Plasma Chemistry) (Moscow: Energoatomizdat, 1992) Issue 9, p. 151
33. Antinyan M A, Galechyan G A, Tavakalyan L B *Teplofiz. Vys. Temp.* **29** 1081 (1991) [*High Temp.* **29** 870 (1991)]
34. Landau L D, Lifshitz E M *Fluid Mechanics* (Oxford: Pergamon Press, 1987)
35. Galechyan G A, in *Khimiya Plazmy* (Plasma Chemistry) (Moscow: Energoatomizdat, 1992) Issue 10, p. 73
36. Eletskii A V, Smirnov B M *Fizicheskie Protsessy v Gazovykh Lazerakh* (Physical Processes in Gas Lasers) (Moscow: Energoatomizdat, 1985)
37. Antinyan M A, Galechyan G A, Tavakalyan L B *Fiz. Plazmy* **18** 367 (1992) [*Sov. J. Plasma Phys.* **18** 193 (1992)]
38. Antinyan M A, Galechyan G A, Tavakalyan L B *Laser Phys.* **2** 683 (1992)
39. Akishev Yu S, Napartovich A P *Dokl. Akad. Nauk SSSR* **241** 812 (1978) [*Sov. Phys. Dokl.* **23** 594 (1978)]
40. Ivanov Yu R, Polak L S, Slovetskii D I *Teplofiz. Vys. Temp.* **9** 1151 (1971) [*High Temp.* **9** 1061 (1971)]
41. Baranov V Yu, Ul'yanov K N *Zh. Tekh. Fiz.* **39** 249 (1969) [*Sov. Phys. Tech. Phys.* **14** 176 (1969)]
42. Rakhimov A T, Ulinich K N *Dokl. Akad. Nauk SSSR* **187** 72 (1969) [*Sov. Phys. Dokl.* **14** 655 (1970)]

43. Eletskii A V, Smirnov B M *Zh. Tekh. Fiz.* **40** 1682 (1970) [*Sov. Phys. Tech. Phys.* **15** 1308 (1970)]
44. Bychkov V L, Eletskii A V *Fiz. Plazmy* **48** 1682 (1970)
45. Golubovskii Yu B, Zonenberg R *Zh. Tekh. Fiz.* **49** 295 302 (1979) [*Sov. Phys. Tech. Phys.* **24** 173, 177 (1979)]
46. Golubovskii Yu B, Zinchenko A K, Kogan Yu M *Zh. Tekh. Fiz.* **47** 1478 (1977) [*Sov. Phys. Tech. Phys.* **22** 851 (1977)]
47. Eletskii A V, Chiflikyan R V, in *Khimiya Plazmy* (Plasma Chemistry) (Moscow: Energoatomizdat, 1989) Issue 15, p. 266
48. Eletskii A V, Starostin A N *Fiz. Plazmy* **1** 684 (1975) [*Sov. J. Plasma Phys.* **1** 377 (1975)]
49. Eletskii A V, Starostin A N *Fiz. Plazmy* **2** 838 (1976) [*Sov. J. Plasma Phys.* **2** 466 (1976)]
50. Eletskii A V, Kutvitskii V A *Fiz. Plazmy* **3** 880 (1977) [*Sov. J. Plasma Phys.* **3** 496 (1977)]
51. Pis'mennyi V D, Rakhimov A T *Dokl. Akad. Nauk SSSR* **200** 68 (1971) [*Sov. Phys. Dokl.* **16** 737 (1972)]
52. Arutyunyan G G, Galechyan G A *Zh. Tekh. Fiz.* **48** 631 (1978) [*Sov. Phys. Tech. Phys.* **23** 374 (1978)]
53. Bychkov V L, Eletskii A V *Teplofiz. Vys. Temp.* **17** 1153 (1979) [*High Temp.* **17** 951 (1979)]
54. Galechyan G A, in *Khimiya Plazmy* (Plasma Chemistry) (Moscow: Energoatomizdat, 1989) Issue 7, p. 218
55. Galechyan G A *Teplofiz. Vys. Temp.* **20** 411 (1982) [*High Temp.* **20** (1982)]
56. Galechyan G A, Petrosyan S I *Zh. Prikl. Mekh. Tekh. Fiz.* **16** (6) 9 (1975) [*J. Appl. Mech. Tech. Phys.* **16** 844 (1975)]
57. Antinyan M A, Galechyan G A, Tavakalyan L B *Fiz. Plazmy* **18** 383 (1992) [*Sov. J. Plasma Phys.* **18** 202 (1992)]
58. Lukasik S, Young J *J. Chem. Phys.* **27** 1149 (1957)
59. Whitson M, McNeal R *J. Chem. Phys.* **66** 2969 (1977)
60. Kondrat'ev V N *Kinetika Khimicheskikh Gazovykh Reaktsii* (Moscow: Izd. Akad. Nauk SSSR, 1958)
61. Taylor R, Bitterman S *Rev. Mod. Phys.* **41** 430 (1969)
62. Antinyan G G, Galechyan G A, Tavakalyan L B *Teplofiz. Vys. Temp.* **29** 659 (1991) [*High Temp.* **29** 511 (1991)]
63. Galechyan G A, Tavakalyan L B *Fiz. Plazmy* **19** 420 (1993) [*Plasma Phys. Rep.* **19** 219 (1993)]
64. Rudenko O V, Soulyan S I *Teoreticheskie Osnovy Nelineinoi Akustiki* (Theoretical Foundations of Nonlinear Acoustics) (Moscow: Nauka, 1975)
65. *Tablitsy Fizicheskikh Velichin: Spravochnik* (Tables of Physical Quantities: a Reference Book) (Moscow: Atomizdat, 1976) p. 287
66. Zavershinskii I P, Kogan E F, Molevich N E *II Vsesoyuznyi Seminar "Vzaimodeistvie Akusticheskikh Voln s Plazmoi* (II All-Union Seminar on Interaction of Acoustic Waves and Plasma) (Erevan, 1991) pp 37-39
67. Hatsagortsyan K Z, Galechyan G A *Laser Phys.* **4** 3 (1994)
68. Galechyan G A, Karapetyan D M, Tavakalyan L *Teplofiz. Vys. Temp.* **30** 849 (1992) [*High Temp.* **30** 691 (1992)]
69. Zavershinskii I P, Kogan E Ya *Fiz. Plazmy* **20** 933 (1994) [*Plasma Phys. Rep.* **20** 838 (1994)]
70. Galechyan G A, Karapetyan D M, Tavakalyan L B *Pis'ma Zh. Eksp. Tekh. Fiz.* **18** (1) 44 (1992) [*Sov. Tech. Phys. Lett.* **18** 17 (1992)]
71. Landau P S *Avtokolebaniya v Raspredelennykh Sistemakh* (Self-oscillations in Distributed Systems) (Moscow: Nauka, 1983)
72. Golubovskii Yu B, Nekuchaev V Yu *Zh. Tekh. Fiz.* **53** 482 (1983) [*Sov. Phys. Tech. Phys.* **28** 301 (1983)]
73. Zavershinskii I P, Kogan E Ya, Molevich N E *Vysokochastotnyi Razryad v Volnovykh Polyakh Ch. 1* (High-Frequency Discharge in Wave Fields P. 1) (Samara, Izd. Samarsk. Pedagog. Inst., 1990; 1994) p. 64
74. Mkrtchyan A R, Galechyan G A, Divanyan E G *Izv. Akad. Nauk Arm. SSR Fiz.* **22** 231 (1987) [*Sov. J. Contemp. Phys.* **22** (4) 54 (1987)]
75. Mkrtchyan A R, Hatsagortsian K Z, Galechyan G A, et al. *Acustica* **69** 124 (1989)
76. Galechyan G A, Divanyan R G *Zh. Tekh. Fiz.* **61** (11) 205 (1991) [*Sov. Phys. Tech. Phys.* **36** 1314 (1991)]
77. Antinyan M A, Galechyan G A, Tavakalyan L B *Zh. Tekh. Fiz.* **62** (5) 164 (1992) [*Sov. Phys. Tech. Phys.* **37** 573 (1992)]
78. Antinyan M A, Galechyan G A, Tavakalyan L B *Akust. Zh.* **38** 391 (1992) [*Sov. Phys. Acoust.* **38** 215 (1992)]
79. Antinyan M A, Galechyan G A, Tavakalyan L B *Zh. Tekh. Fiz.* **63** 197 (1993) [*Tech. Phys.* **38** 53 (1993)]