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LOW-TEMPERATURE PLASMA EXPOSED TO EXTERNAL ACOUSTIC DISTURBANCES

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Within the framework of a three-liquid model specific properties of the states of a low-temperature plasma subjected to external acoustic disturbances are assessed.

Introduction. It is known that acoustic effects on a low-temperature plasma are displayed as complex electrophysical manifestations [1], whose mechanism of formation is, however, still not clearly understood [2, 3].

The present work is devoted to elucidation of the general features of the mechanism of the electrophysical manifestations and, as a whole, of the specific properties of the states of a low-temperature plasma under these conditions.

1. STATEMENT OF THE PROBLEM

1.1. General Propositions. In formulating the general propositions concerning the mechanism mentioned above, it is natural to assume that this mechanism is based, first of all, on the development of plasma inhomogeneities in the volume charge distribution. In this case it is expedient to consider a plasma subjected to acoustic disturbances to be a thermodynamically open material system with a variable number of particles in which charging fluctuation, as a consequence of the external disturbances, may occur.

It seems reasonable to assume that some relationships exist between the parameters of the acoustic disturbances and the space-time characteristics of charge inhomogeneities. The approach developed fits the specific features of the quasi-equilibrium three-liquid model, on the basis of which the low-temperature plasma is considered to be a combination of energetically and viscously interacting neutral a, ionic i, and electronic e components, and its local composition is determined integrally by the generally accepted conditions of ionization equilibrium, the viscous interactions between the plasma components, and the dynamic characteristics of the external disturbances.

1.2. Three-Liquid Plasma System. For our considerations we shall introduce a three-liquid plasma model. In terms of the model the local composition of the plasma is determined integrally by the degree of ionization

$$\alpha = \frac{p_i}{p_a^{(0)}} = \frac{n_i\, kT}{n_a^{(0)}\, kT} = \frac{n_i}{n_a^{(0)}} \tag{1}$$

and the relative electron concentration in the medium

$$\eta = \alpha\,(1 - \xi)\,. \tag{2}$$

If n_a^0 is the initial particle concentration of a three-liquid medium, then the equations

$$n_i = \alpha\, n_a^{(0)}\,; \tag{3}$$

$$n_e = \alpha\,(1 - \xi)\, n_a^{(0)} = \eta\, n_a^{(0)}\,; \tag{4}$$

$$n_a = (1 - \alpha)\, n_a^{(0)} \tag{5}$$

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are used to evaluate the particle concentration of its separate components.

Taking into account the assumption of energy equilibrium and Eqs. (1)-(5), we derive expressions for partial pressures

$$p_i = n_i kT = \alpha n_a^{(0)} kT ; \tag{6}$$

$$p_e = n_e kT = \eta n_a^{(0)} kT = \alpha (1 - \xi) n_a^{(0)} kT ; \tag{7}$$

$$p_a = n_a kT = (1 - \alpha) n_a^{(0)} kT , \tag{8}$$

as well as for the total pressure of the medium

$$p_\Sigma = p_e + p_i + p_a = [1 + \alpha (1 - \xi)] n_a^{(0)} kT = (1 + \eta) n_a^{(0)} kT . \tag{9}$$

Finally, the particle concentration of the initial medium is

$$n_a^{(0)} = \frac{p_\Sigma}{[1 + \alpha (1 - \xi)] kT} = \frac{p_\Sigma}{(1 + \eta) kT} . \tag{10}$$

1.3. Description of the Mechanism by a System of Equations. The system describing the state of a plasma subjected to external acoustic disturbances under the assumption of a weak magnetic interaction between the plasma components is the electrogasdynamic one (the EGD-system). This system consists of the equations of motion of the electronic and ionic components

$$n_e m_e \left(\frac{\partial}{\partial t} + \mathbf{U}_e \nabla \right) \mathbf{U}_e + \frac{e n_e}{\mu_e} (\mathbf{U}_e - \mathbf{U}_a) + \nabla p_e - e n_e \mathbf{E} = 0 ; \tag{11}$$

$$n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{U}_i \nabla \right) \mathbf{U}_i + \frac{e n_i}{\mu_i} (\mathbf{U}_i - \mathbf{U}_a) + \nabla p_i + e n_i \mathbf{E} = 0 ; \tag{12}$$

the equation of ionization equilibrium of the medium in the Saha form with account for (1)-(10) and the constants in them:

$$\frac{\alpha \eta}{(1 - \alpha)(1 + \eta)} = 6.666798 \cdot 10^{-2} \frac{T^{5/2}}{p_\Sigma} \exp \left(- \frac{V}{kT} \right) ; \tag{13}$$

the relations for the mean-mass density and velocity

$$\rho_\Sigma = \frac{m_e \eta + m_i \alpha + m_a (1 - \alpha)}{1 + \eta} \frac{p_\Sigma}{kT} ; \tag{14}$$

$$\mathbf{U}_\Sigma = \frac{m_e \mathbf{U}_e \eta + m_i \mathbf{U}_i \alpha + m_a \mathbf{U}_a (1 - \alpha)}{m_e \eta + m_i \alpha + m_a (1 - \alpha)} ; \tag{15}$$

the equation of flow continuity

$$\frac{\partial}{\partial t} \rho_\Sigma + \nabla (\rho_\Sigma \mathbf{U}_\Sigma) = 0 ; \tag{16}$$

the equation of charge conservation

$$\frac{\partial}{\partial t} q + \Delta \vartheta_k = 0 ; \quad (17)$$

the Poisson equation (the electric component of the field)

$$\Delta \mathrm{E} - \frac{1}{\varepsilon_0} q = 0 . \quad (18)$$

Here

$$\mu_e = \frac{e}{m_e Q_{ea}} [\pi m_e/(8kT)]^{0.5} \frac{(1+\eta) kT}{(1-\alpha) P_\Sigma} ; \quad (19)$$

$$\mu_i = \frac{e}{m_i Q_{ia}} [\pi m_i/(8kT)]^{0.5} \frac{(1+\eta) kT}{(1-\alpha) P_\Sigma} \quad (20)$$

are the mobilities of the electronic and ionic components, respectively;

$$q = e \frac{P_\Sigma (\alpha - \eta)}{kT (1+\eta)} \quad (21)$$

is the local density of the uncompensated (excess) charge;

$$\vartheta_k = e (\alpha \mathrm{U}_i - \eta \mathrm{U}_e) \frac{P_\Sigma}{(1+\eta) kT} \quad (22)$$

is the convective component of the electric current density.

With account for Eqs. (1)-(10), (19)-(22) system (11)-(18) is reduced to eight linearly independent relations between ten functions: U_e, U_i,, U_a, ρ_Σ, U_Σ, α, η, E, P_Σ, T. The system is closed by the assumption that the functions P_Σ, T, determining the character of the acoustic effects, are known.

2. PROCEDURE OF INVESTIGATIONS AND RESULTS

2.1. General Conditions. System (11)-(18) was investigated in the one-dimensional representation, permitting the most descriptive interpretation of the results.

It was assumed that

$$P_\Sigma = p_0 \left[1 + c \cos \left(\frac{2\pi n_1 f_0}{a_0} x \right) \sin (2\pi n_1 f_0 t) \right] . \quad (23)$$

To determine the current temperature, we used the dependence

$$T = T_0 \left(\frac{p}{p_0} \right)^{\frac{n-1}{n}} . \quad (24)$$

Here a_0 is the velocity of sound (assumed equal to $1 \cdot 10^3$ m·sec^{-1}).

Taking into consideration the dissipation processes accounted for by the system (see (11), (12)), the current temperature was determined, along with (24), by the relation

$$T = T_0 \left[1 + c \cos \left(\frac{2\pi n_1 f_0}{a_0} x \right) \sin (2\pi n_1 f_0 t) \right] . \quad (25)$$

The problem was reduced to integration of (11)-(18) in the domain

$$x \in [0\,,\ m_x x_f]\,,\quad t \in [0\,,\ m_\tau \tau_f] \quad (x_f = a_0/(n_1 f_0)\,,\quad \tau_f = 1/(n_1 f_0))$$

under the following initial conditions corresponding to the physic sense:

$$x = 0 \vee t = 0:\ U_e = U_i = U_a = U_\Sigma = 0\,,\quad E = 0\,.$$

Here m_x, $m_\tau = 1, 2, \ldots$ are integers that determine the multiplicity of integration from the conditions of obtaining a stationary solution.

In integrating, a difference grid was formed by dividing the intervals $[0, x_f]$, $[0, t_f]$ into $(Z-1)$ subintervals so that

$$x_j = (k_x - 1)\, x_f + (j - 1)\, h_x\,;\quad t_i = (k_\tau - 1)\, t_f + (i - 1)\, h_t$$

$k_x = 1, \ldots, m_x$; $k_\tau = 1, \ldots, m_\tau$ are the current multiplicities of integration over x and t, respectively; $i, j = 1, \ldots Z$; $h_x = x_f/(Z - 1)$, $h_t = t_f/(Z - 1)$ are the distances between the nodes.

For the characteristic points p, T (see (23), (25)) to be at the nodes, $(Z - 1)$ was chosen to be a multiple of to 4. As the basic value, at which most results were obtained, $Z = 41$ was assumed.

In solutions, in addition to the grid fucntions, we also evaluated other parameters of the state. The dependences

$$\Omega_{ij} = - \sum_{2}^{j} (E_{i,j-1} + E_{ij}) \frac{h_x}{2}\,, \tag{26}$$

$$J_{k_{ij}} = (\alpha_{ij} U_{i_{ij}} - \eta_{ij} U_{e_{ij}}) \frac{eP_{\Sigma_{ij}}}{(1 + \eta_{ij})\, kT} \tag{27}$$

were used to determine the electrostatic potential of space and the longitudinal current component corresponding to the node ij. We also evaluated some other parameters that make the space-time picture of the plasma states more clear.

In our investigations the basic values of the pressure, the temperature, and the potential of medium ionization ranged as follows: $p_0 \in (0.05;\ 3.5)$ MPa, $T_0 \in (1000;\ 3500)$ K, $V \in (7;\ 16)$ V. The coefficients c, n_1 were prescribed as 0.01, 0.05, 0.10, 0.15, 0.20, 0.25 and 1, 4, 8, ..., 16, respectively. The quantity f_0 was assumed to be constant and equal to 1000 $\sec^{-1}$. The conventional masses of the ion and the neutral component were assumed to be $4.648585 \cdot 10^{-25}$ and $4.648676 \cdot 10^{-26}$ kg. The cross sections of electronic and ionic collisions were assumed to be equal and to correspond to $Q_{ea} = Q_{ia} = 1.5 \cdot 10^{-19}$ m^2.

2.2. Results of the Investigations and Discussion. The general results of the investigations show that the acoustic disturbances of the low-temperature plasma actually give rise to complicated, in nature, electrophysical phenomena and, first of all, to the fluctuating charge formations in the plasma volume. These charge formations are macroscopic: the extent of their existence in space and time is indicative of links with characteristics of the disturbances as well as with plasma properties, and in each particular it case may exceed substantially the Debye radius corresponding to the plasma and the characteristic times between two neighboring collisions of electrons with heavy particles. In other words, the charge inhomogeneity discovered my also be defined as a charge plasma instability of acoustic origin. It is pertinent to note that the general character of the results is retained independently of whether relation (24) or (25) is taken into account in integration.

Figure 1 shows a typical (among those considered in the investigations) space-time dependence of the acoustic component of the pressure (the primary disturbing action corresponding to a medium pressure of 30 MPa, a relative amplitude of pulsations of 5%, and a frequency of 16,000 Hz), and Fig. 2 gives the corresponding space-time dependences of individual characteristics (the degree of disruption of quasineutrality, electric intensity, electric potential, and current density) of electrophysical manifestations taking place in media of various compositions at $T_0 = 3000$ K.

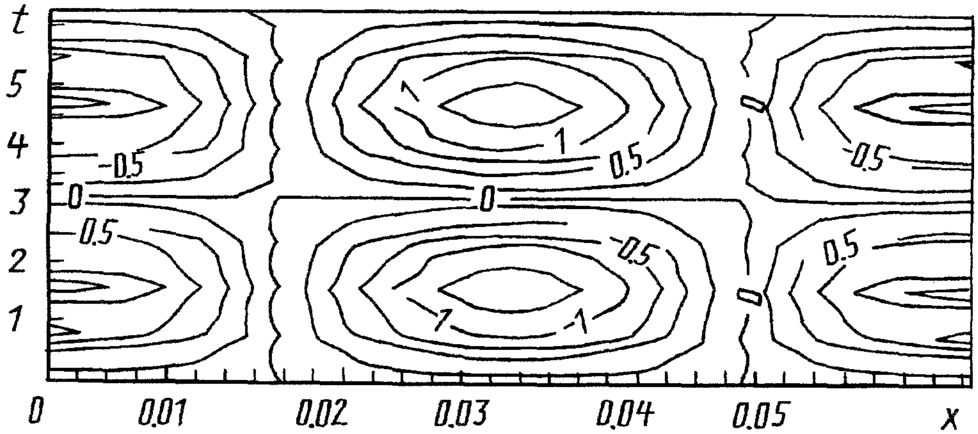

Fig. 1. Space-time dependence of the pulsation component of the pressure $p = f(x, t)$, which is the disturbing acoustic effect. t, sec$\cdot 10^{-5}$; x, m; p, MPa.

The results presented, as w ell as those obtained overall, reveal that the concrete specific features of the characteristics and regimes of development of the charge instabilities depend on various factors, including the medium composition, the basic pressure and temperature, and the parameters of nonstationary effects. However, the diversity of the characteristics and regimes of development of the charge instabilities that is expected as a consequence may be reduced to three typical varieties (groups):

charge instabilities that develop under conditions where the contribution of electric responsive interactions between the plasma components prevails compared to viscous interactions (see, e.g., Fig. 2a);

charge instabilities that develop under conditions where the contribution of viscous responsive interactions between the plasma components is decisive compared to electric interactions (Fig. 2b);

charge instabilities that develop under comparable contributions by electric and viscous responsive interactions between the plasma components (Fig. 2c).

It is established that independently of the specific features of the primary acoustic disturbances their electrophysical manifestations may be found in any of the above groups of charge instabilities. An increase (decrease) in the temperature of the medium as well as a change in its composition toward a decrease (increase) in the ionization potential increases, other conditions being equal, the probability of electrophysical manifestations of the disturbing actions in accordance with the specific features of the charge instabilities of the first (second) group. This is illustrated by the dependences in Figs. 1, 2, which also show general tendencies of the electrophysical manifestations classified above.

The space-time dependences of the electrophysical manifestations occurring in the case of development of charge instabilities of the first group in the plasma (Fig. 2a) display most fully the characterizing features of the primary acoustic disturbances (Fig. 1). Their temporal changes in some fixed region of space are almost harmonic. They are characterized by relatively high amplitudes.

The space-time dependences in Fig. 2b illustrate the specific features of charge instabilities of the second group. It is of interest that for fixed regions of space the formerly sign-alternating (under conditions for instabilities of the first group) electrophysical characteristics are transformed, in essence, into unipolar ones. The cyclic character of the primary actions on the medium is manifested only in specific changes in secondary electrophysical parameters in the unipolar regions (with the exception of the current density).

The electrophysical manifestations of the acoustic disturbances that pertain to the third group of charge instabilities are, other conditions being equal, radically different. They develop at "boundaries of transitions" between charge instabilities of the two first groups, fail to be cyclic, and are "catastrophic," in essence. The parameters estimated by the solutions are extremely high in this case and correspond to conditions close to the stability limit of the difference scheme.

Finally, it should be noted that the plasma parameters in Figs. 1, 2 (as well as the characteristics of the acoustic disturbances) are typical for the conditions in, for example, combustion chambers of various thermal

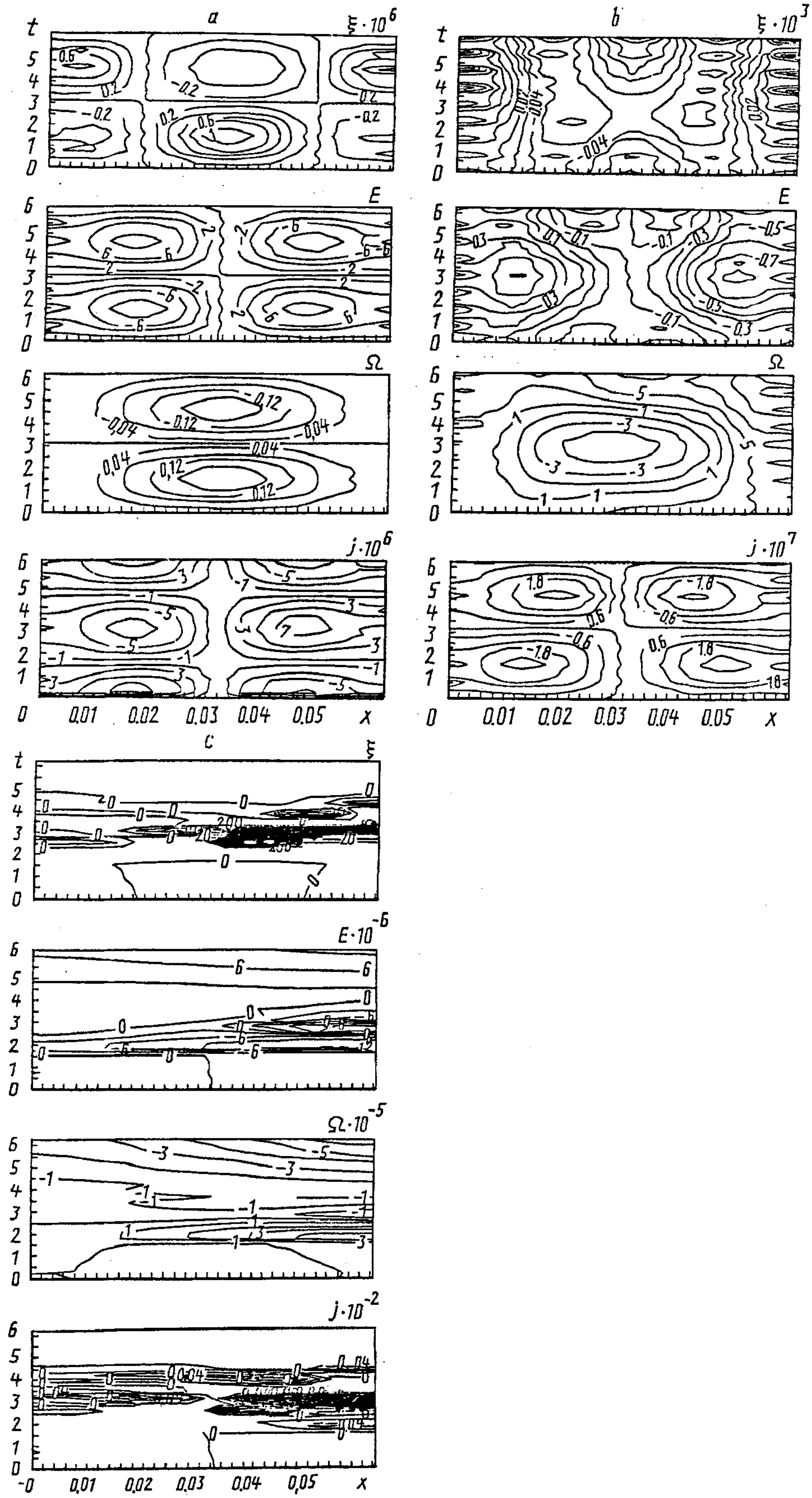

Fig. 2. Space-time characteristics of electrophysical manifestations of acoustic disturbances in a medium of arbitrary composition with the ionization potential $V = 12$ (a), 16 (b), and 14 V (c). t, sec$\cdot 10^{-5}$; E, V$\cdot$m^{-1}.

converters. As applied to the latter, the development of charge instabilities may be considered to be the response of a gaseous material system of combustion products to disturbances of intrachamber origin [2].

This is indicative of the pronounced diagnostic richness of electrophysical information about the working processes of thermal converters and is supported by well known experimental results [3].

Conclusions. Theoretical studies with use of the three-liquid model have allowed us to refine general concepts of the mechanism of electrophysical manifestations of external acoustic disturbances in a low-temperature plasma the specific properties of the states of the plasma induced by these disturbances.

It is established that the mechanism of the electrophysical manifestations under these conditions depends primarily on the instabilities in the electric charge distribution over the volume that develop in the low-temperature plasma (charge instabilities).

The generalized analysis of the results obtained has revealed general features of the characteristics and regimes of development of charge instabilities in accordance with the relationship between the electric and viscous contributions to the response of the medium to a disturbance. Separation of three characteristic groups of charge instabilities based on this principle is substantiated.

The results obtained indicate the pronounced rickness of the electrophysical information describing the processes in the chambers of various thermal converters and are in agreement with well known experimental data.

NOTATION

a, velocity of sound, $\mathrm{m \cdot sec^{-1}}$; e, single electric charge; f, frequency, $\mathrm{sec^{-1}}$; j, current density, $\mathrm{A \cdot m^{-2}}$; h, distance between grid nodes (pitch); k, Boltzmann constant; m, particle mass, kg; n, process index, concentration, $\mathrm{m^{-3}}$; q, excess charge, C; x, linear coordinate, m; t, time, sec; α, degree of ionization; $\xi = (n_i - n_e)/n_i$, extent of quasineutrality disruption; $\eta = \alpha(1 - \xi)$, relative content of the electronic component; μ, mobility, $\mathrm{kg^{-1} \cdot A \cdot sec^{-2}}$; ρ, density, $\mathrm{kg \cdot m^{-3}}$; Ω, electric potential, V; E, electric intensity, $\mathrm{V \cdot m^{-1}}$; Q, collision cross section, $\mathrm{m^2}$; P, p, pressure, Pa; T, temperature, K; U, velocity, $\mathrm{m \cdot sec^{-1}}$; V, ionization potential, V. Subscripts: a, e, i, neutral component, electron, ion; Σ, the entire medium; 0, undisturbed parameter; c, convective; f, final; i, j, components of the node numbering.

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