LOW-TEMPERATURE NONEQUILIBRIUM-IONIZATION INERT-GAS PLASMA AND MHD-GENERATORS*

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The main results of theoretical and experimental studies of low-temperature magnetized ($\beta > 1$) nonequilibrium-ionization plasma properties are reported. Such plasma is found to be more stable as compared to the equilibrium-ionization one. Development of ionization instability in such plasma results in the formation of striae oriented perpendicularly to the plasma velocity and not decreasing its effective electric conductivity. Thus, the possibility exists of designing an effective MHD-generator operating with the inert-gas plasma without admixtures in closed-cycle installations.

The notion of nonequilibrium plasma in magnetic gas dynamics is used to describe two-temperature equilibrium-ionization plasma. An example of such plasma is a mixture of inert gases with alkali vapors. Such plasma properties have been thoroughly investigated in connection with the problem of designing a closed-cycle MHD-generator [1]. It has been theoretically and experimentally shown that due to development of ionization instability the efficiency of energy conversion considerably deteriorates as a result of decreasing the effective electric conductivity σ_{ef} of the plasma [2]. In this case, the instability develops sufficiently quickly ($\tau_i \simeq 10^{-6}$ sec), while the effective electric conductivity of the inhomogeneously ionized plasma is inversely proportional to the magnitude of a magnetic field ($\sigma_{ef} \sim 1/B$).

A specific feature of low-temperature pure inert gas plasma (at $T_e \leq 1$ eV and ionization degrees $\alpha = 10^{-5}$-10^{-4}) is the relatively small value of ionization and recombination rates. Consequently, nonequilibrium-ionization states in such plasma are sufficiently simple to realize. For instance, at quick plasma cooling or Joule heating, the recombined plasma $\alpha_0/\alpha_r > 1$ is generated in the former case and the ionized plasma $\alpha_0/\alpha_{eq} < 1$ is generated in the latter case.

The present work is an attempt to generalize the results of research studies of supersonic MHD-flows of inert-gas nonequilibrium-ionization plasma conducted during 15 years [3-11] and representing, in essence, a new trend in the physics of low-temperature plasma and magnetic gas dynamics, namely, MHD-interaction of a relaxing plasma.

Comprehensive investigations included experiments and theoretical studies. The experiments were conducted in MHD-channels of cylindrical, disc and linear geometry installed in gas shock-wave tubes. We investigated the argon, xenon plasma flows produced either by a transmitted or incident shock wave. In the latter case, the MHD-channels were installed in the end section of the shock-wave tubes. In experiments, we measured the plasma flow velocity and pressure, electron concentrations n_e and temperature T_e. Along with local spectrographic measurements of plasma parameters (n_e, T_e) by a high-speed ZhLV photorecorder and UMI-95 electrooptical transducer of the LV-01 device, a space–time structure of plasma inhomogeneities was recorded [4]. We used sweep and frame-by-frame photography with an exposure time $\tau_e = 0.1$ μsec. When investigating operation conditions of MHD-generator models, in addition to total power we measured potential and current distributions with respect to channel length. The Hall parameter was varied within $\beta = 0.1$-20.

Theoretically, we studied the linear stage of instability by the method of a local dispersion equation (LDE). The expressions obtained for the critical Hall parameter β_{cr} were analyzed numerically in the general case.

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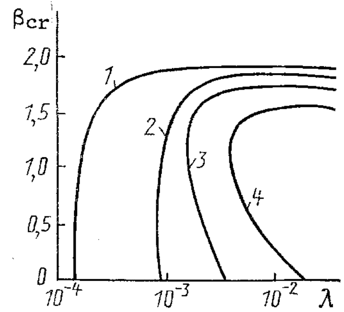

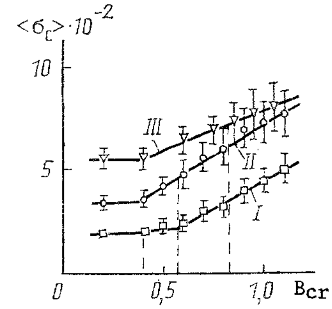

Fig. 1 Fig. 2

Fig. 1. Critical Hall parameter β_{cr} as a function of a disturbance wavelength (X_e, $n_{xe} = 2 \cdot 10^{24}$ m^{-3}, T_g = 300 K): 1) $T_e = 10 \cdot 10^3$ K; 2) $8 \cdot 10^3$; 3) $7 \cdot 10^3$; 4) $6 \cdot 10^3$. λ, m.

Fig. 2. Mean electric conductivity (cm/m) versus magnetic induction (T) for three regimes: I) B_{cr} = 0.4 T (β_{cr} = 3.5); II) B_{cr} = 0.5 T (β_{cr} = 2.2); III) B_{cr} = 0.8 T (β_{cr} = 1.5) (X_e, n_{xe} = $2 \cdot 10^{24}$ m^{-3}; u = $1.2 \cdot 10^3$ m/sec).

The results of investigations have shown that ionization instability development in the nonequilibrium-ionization plasma is accompanied by a number of unexpected effects connected with both the ionization nonequilibrium state and the interaction of plasma and gas dynamic inhomogeneities [5-8]. As an example, Fig. 1 (X_e, $n_{xe} = 2 \cdot 10^{24}$ m^{-3}, T_g = 3000 K) shows one of the distinguishing features of the ionization instability development in a relaxing plasma: the critical Hall parameter β_{cr} depends on the disturbance wavelength λ. Some values of λ_b (b = boundary value) exist when at $\lambda < \lambda_b$ the instability develops at any smallest β. Also, it is established that the recombined plasma is more stable than the ionized plasma. The time of instability development in a relaxing plasma is essentially longer than in the equilibrium-ionization counterpart. No plasma inhomogeneities have been experimentally found at $\tau_i > \tau_f$ (where τ_f = L/u is the time of flight).

In the nonlinear stage, the instability may develop not only due to volume disturbances. Inhomogeneities generated by near electrode processes were experimentally discovered. In both cases, striae oriented perpendicular to a plasma flow velocity arise.

The absence of alkali admixtures in a plasma whose complete ionization at an increase of T_e restricts local electroconductivity growth and the absence of Joule heating in an inhomogeneous plasma may, under certain conditions, lead to an increase of effective electrical conductivity. Such regimes have been experimentally found in MHD-channels of linear and disc geometry at $\beta > \beta_{cr}$. Figure 2 is illustrative of the effective conduction as a function of the magnitude of a magnetic field for a disc-geometry channel (X_e, $n_{Xe} = 2 \cdot 10^{24}$ m^{-3} u = $1.2 \cdot 10^3$ m/sec). Dashed lines show the critical magnitude of a magnetic field B_{cr}.The main conclusion, basically distinguishing a relaxing plasma from an equilibrium-ionized counterpart, lies in the fact that at $B > B_{cr}$ the effective conduction does not decrease but increases with B. To describe MHD-interaction of the plasma flowing in channels, we used the quasi-one-dimensional model of a two-fluid nonequilibrium plasma [9, 10]. In calculations of linearly divergent channels with sectionalized electrodes, we additionally took account in the one-dimensional approximation of friction and heat transfer as well as near-electrode losses. Also, to attain satisfactory agreement with experiment, a procedure to allow for the Hall leakage current was suggested [10].

The results obtained allow formulation of a new conception of MHD-generators using the plasma of pure inert gases. Two types of generators are possible. The first type: an MHD-generator with a preionizer generating periodic impulses, an MHD-channel operates on a stable-ionization recombining plasma. In the second type, an MHD-generator uses ploys a continuous-operation preionizer, an MHD-channel operates on the developed ionization instability plasma flow.

Table 1 lists the calculation results for the Faraday disc-geometry MHD-generator. In MHD-channel calculations, it has been assumed that the effective conduction in the channel is constant and equal to the conduction at the channel inlet. Estimates have shown the energy consumed for gas preionization to be ~1%. Relative heat losses due to heat transfer towards a wall are 0.2%, relative pressure losses because of friction are 1%.

The performed calculations of MHD-generator characteristics have demonstrated that their enthalpy conversion coefficients are higher than the values of MHD-generators with alkali metal additives under design. This is a convincing reason for continuation of research studies in the field of MHD-interaction of a relaxing plasma.

TABLE 1. Basic Parameters of the Faraday Disc-Geometry MHD-Channel

Magnetic induction	6T	Mach number at the inlet	1.9
		Mach number at the outlet	1.3
Enthalpy at the channel inlet	447 MW	Effective azimuthal conduction	10 cm/m
Stagnation temperature	2000 K	Azimuthal current	4.6 kA
Stagnation pressure	0.33 MPa	Mean azimuthal current density	1.0 A/cm²
Gas flow rate	447 kg/s	Mean azimuthal Faraday's field	40 V/cm
Initial radius	1.2 m	Power density	40 MW/m³
Height at the inlet	0.25 m	Load factor	0.8
Finite radius	2.34 m	Enthalpy conversion coefficient	45%
Wall temperature	600 K		
Electron temperature	10500-11000 K		

NOTATION

n_e, electron concentration; T_e, electron temperature; T_g, gas temperature; α_{eq}, equilibrium degree of ionization; α_0, local degree of ionization; β, Hall parameter; β_c, critical Hall parameter; τ_i, time of development of ionization instability; σ_{ef}, effective electric conductivity (conduction); λ, disturbance wavelength; u, plasma flow velocity.

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