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Research paper

Numerical study of the ionization process and radiation transport in the channel of plasma accelerator

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ABSTRACT

The study of the axisymmetric ionizing gas flows in a channel of the quasi-steady plasma accelerator is presented. Model is based on the MHD and radiation transport equations. The MHD model for a three-component medium consisting of atoms, ions and electrons takes into account the basic mechanisms of the electrical conductivity and heat transport. The model of the radiation transport includes the basic mechanisms of emission and absorption for the different parts of the spectrum. Results of the numerical studies of ionization process and radiation transport are obtained in the approximation of the local thermodynamic equilibrium.

1. Introduction

One of the illustrative examples of nonlinear sciences refers to the ionization process corresponding to a phase transition from the gaseous state of medium to plasma in the ionizing gas flows in channel of the plasma accelerator.

Relevant theoretical, numerical and experimental studies of dynamics of the ionizing gas and plasma flows constitute one of the scientific directions related with the quasi-steady plasma accelerators (QSPA) and magneto plasma compressors (MPC) [1–6]. For these devices we explore the transonic plasma flows including the presence of an additional longitudinal magnetic field [7,8], the near-electrode processes caused by the Hall effect and leading to the phenomenon of the current crisis [9], the compressible streams, the radiation transport, the dynamics of impurities, as well as the numerical models of the ionization process corresponding to different levels of complexity [1,3,10,11]. Besides the investigations of the ionization processes, the plasma dynamics and radiation transport are connected with a number of other actual branches of science, and a plenty of publications is devoted to them (see e.g. [12–22]).

Simple plasma accelerators consist of two coaxial electrodes connected to the electrical circuit. As a result of the breakdown between electrodes the ionization front corresponding to a transition from one state of matter to another is formed. In the simplest devices the processes occur in the presence of the main azimuthal component of the magnetic field. The azimuthal field is generated by electric current flowing along the inner electrode. In turn the radial plasma current flowing between electrodes and the azimuthal magnetic field provide the acceleration of plasma behind the ionization front due to the Ampere force $\frac{1}{c}\mathbf{j} \times \mathbf{H}$, where $\mathbf{j}$ is the current density in plasma. The ionization process and the preliminary acceleration of plasma occur particularly in the first stage of the two-stage QSPA [2–6]. These multifunctional devices are designed for fusion research, different technological applications, and are of interest for development of the perspective high-power electro-plasma thrusters.

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The properties of the ionizing gas streams are typically studied by means of stationary or rather quasi-stationary flows with the calculated steady-state solution. For steady-state flows the foundations of theory of processes at the ionization front were also developed in [23]. Earlier the ionizing gas flow was considered within the framework of the quasi-one-dimensional approximation in a narrow cylindrical channel (see e.g. [1,10,11]). On the one hand the ionizing gas flow is characterized by a sharp increase in temperature, velocity and degree of ionization, and on the other hand – by a sharp decline in density and magnetic field at the ionization front. This behavior of the flow variables is characteristic for the considered process.

This paper continues the cycle of studies of the ionizing gas flows. Numerical model of the two-dimensional axisymmetric quasi-stationary flows of the ionizing gas is based on approximation of the local thermodynamic equilibrium (LTE) which corresponds to the nonlinear description of ionization process provided an abrupt change of the magnetic viscosity corresponding to the electrical conductivity of the medium.

The present level of experimental and numerical studies allows the simultaneous determination of local values of the macroscopic parameters of plasma and the radiation characteristics. It opens up new opportunities for the integrated research and convergence of the calculation results with possibilities of experimental works [2,4–6]. This work is also dedicated to the construction of the three-dimensional numerical model of radiation transport in the ionizing gas flow. To solve the problem of radiation transport it is necessary to take into account a number of factors associated with accuracy of the geometry description of the radiating volume and the shadow regions, with details of description of the emission spectrum and the basic mechanisms of emission and absorption, as well as to take into account possibilities of the numerical solution methods of the radiation transport equation [15–22].

2. The equations of the radiation plasma dynamics

2.1. The equations of magnetic gas dynamics for the three-component medium

The description of plasma is carried out by means of the kinetic equations or the equations of the magnetic gas dynamics depending on parameters of medium. In turn the MHD description for the dense medium includes various approximations. As a rule the classical set of MHD equations is used. In some cases it is necessary to use the two-fluid MHD model with the Hall effect (see e.g. [1–3,8]), and also the two-fluid MHD model taking into account the inertia of electrons (see e.g. [24,25]).

There are also various ways of description of the ionization process in problems of the nonlinear plasma dynamics (see e.g. [1–3,10,11,13–15]). In this work the MHD model is used within the framework of the LTE approximation including the radiation transport because the density of the radiation energy flux can influence the redistribution of energy in medium.

The MHD model of the self ionizing gas flow is based on the transfer equations for the three-component medium [24] consisting of atoms, ions, and electrons, as well as on the magnetic field diffusion equation which is a consequence of Maxwell's equations and Ohm's law $\mathbf{E} = \frac{\mathbf{j}}{\sigma} - \frac{1}{c}\,[\mathbf{V},\ \mathbf{H}]$ if the inertia of electrons and the displacement current are neglected. The ionization process is studied for hydrogen which is often used in experiments. The masses of atoms and ions are identical $m_a = m_i = m$. It is known from the experimental data that the temperature at the ionization front increases up to 1–3 eV. The concentration of gas entering the channel is supposed to be sufficiently high $n = 10^{17} - 10^{18}\ \mathrm{cm}^{-3}$. It can be assumed for such parameters that a medium is quasi-neutral $n_i = n_e$, and the velocities of the medium components are equal $\mathbf{V}_i = \mathbf{V}_e = \mathbf{V}_a = \mathbf{V}$. Experiments and estimations also show that it is possible to consider the case of single temperature mixture. As a result of transformation of the initial equations with regard to the above assumptions we obtain the following set of MHD equations:

$$\begin{aligned}
&\frac{\partial\,\rho}{\partial\,t} + div(\rho\,\mathbf{V}) = 0, \qquad \rho\frac{d\,\mathbf{V}}{d\,t} + \nabla P = \frac{1}{c}\mathbf{j}\times\mathbf{H}, \qquad \frac{d}{d\,t} = \frac{\partial}{\partial\,t} + (\mathbf{V},\nabla),\\
&\frac{\partial}{\partial\,t}(\rho\,\varepsilon) + div(\rho\,\varepsilon\,\mathbf{V}) + P\,div\,\mathbf{V} = \frac{\mathbf{j}^2}{\sigma} - div\,\mathbf{q} - div\,\mathbf{W}\ ,\\
&\frac{\partial\,\mathbf{H}}{\partial\,t} = rot\,(\mathbf{V}\times\mathbf{H}) - c\,rot\,\frac{\mathbf{j}}{\sigma}, \qquad \mathbf{j} = \frac{c}{4\pi}rot\,\mathbf{H}\,,\\
&P = P_a + P_i + P_e = (1+\alpha)(c_P - c_V)\,\rho\ T, \qquad \varepsilon = (1+\alpha)\ c_V\ T + \varepsilon_I\ ,\\
&k_B\ /\ m = R = c_p - c_v = c_v\ (\gamma - 1), \qquad \alpha = n_e\ /\ (n_a + n_i), \qquad \mathbf{q} = -\ \kappa_{e\to a}\ \nabla T\ .
\end{aligned} \tag{2.1}$$

Here $\rho = m\,(n_a + n_i)$ is the density of heavy particles, P is the total pressure, α is the degree of ionization, $\mathbf{q}$ is the heat flux, $\kappa_{e\,\to\,a}$ is the electron-atomic heat conductivity, and $\mathbf{W}$ is density of the radiation energy flux. The internal energy per unit of mass ε includes the additional term $\varepsilon_I = \varsigma\,\alpha\,I\ /\ m_i$ which is responsible for the energy loss due to ionization, where I is the atom ionization energy. The Joule heating $Q_{ei} = \mathbf{j}^2/\sigma$ in the equation for the internal energy of the set (2.1) considerably exceeds the heat generated by friction with other components.

The electrical conductivity of medium in equations is equal to $\sigma = e^2 n_e / m_e \nu_e$, where the average frequency of collisions of an electron with other particles is composed of the frequencies of collisions with atoms and ions: $\nu_e = \nu_{ea} + \nu_{ei}$, $\nu_{ea} = n_a\ \langle V_e\rangle\ S_{ea}$, $\nu_{ei} = n_i\ \langle V_e\rangle S_{ei}$. Here S_{ea} and S_{ei} are the effective collision cross sections. The main heat transfer mechanisms depend on the medium state. In the case of large degrees of ionization a significant role in the total heat transfer