

THE COMPARATIVE ANALYSIS OF THE COMPRESSIBLE PLASMA STREAMS GENERATED IN QSPA FROM THE VARIOUS GASES

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The numerical research of streams dynamics in the channel and the compressible flows at the QSPA output is carried out for the plasma generated from hydrogen, helium, argon and xenon. The MHD equations in the one-fluid approach taking into account the final conductivity of medium, the heat conductivity and the effective losses of radiation energy underlie the numerical model of the two-dimensional axisymmetric plasma flows. Features of the compressible plasma streams generated from various gases are revealed.

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INTRODUCTION

Studying of the multicomponent plasma dynamics is one of the actual directions of researches in the modern plasma physics and the computing plasmadynamics. Presence of impurity renders the essential influence on the dynamic characteristics of the plasma streams. The first stage of these complex researches is directed on revealing of properties and the comparative analysis of plasma streams of various structures. The modern level of researches of the quasi-steady plasma accelerators (QSPA) (see, for example, [1-4]) including their modifications at the presence of an additional longitudinal magnetic field [5-6], and the magneto plasma compressors (MPC) (see, for example, [7-8]) allows using the various gases for plasma generation.

The plasma accelerator with an azimuthal magnetic field schematically consists of two coaxial electrodes connected to the electric circuit. The plasma current \mathbf{j} has mainly radial direction proceeds between electrodes of the plasma accelerator. At presence of the azimuthal magnetic field H_φ which is generated by an electric current passing into the internal electrode the plasma is accelerated in the channel along the axis of system due to the Ampere force $\frac{1}{c}[\mathbf{j}, \mathbf{H}]$.

The QSPA are multipurpose systems taking into account the opportunity of operation in the accelerating and compressible modes. Use of the plasma accelerators as the electro jet engines assumes the optimum organization of the accelerating modes. The compression of plasma is carried out on axis of system. It is of interest for the various plasma technologies.

Basis of the axisymmetric plasma flows theory are presented in the monography [1], for example. The essential role in the development of QSPA and the understanding of the occurring processes is allocated to the mathematical models and numerical researches of plasma dynamics and the ionizing gas in the accelerator channels. A lot of the publications (see, for example, [1, 9-10]) are devoted to these researches. Theoretical and numerical researches of the enough dense plasma are spent within the framework of MHD-models.

1. FORMULATION OF PROBLEM

The two-dimensional axisymmetric plasma flows is considered in the channel between the two coaxial profile electrodes (Fig. 1) and also outlet from the accelerator provided that the internal electrode is shorter external. At presence only the azimuthal components of a magnetic field H_φ the two components of velocity $\mathbf{V} = (V_z, V_r, 0)$ participate in the problem.

Taking into account of the parameters it is possible to consider the quasi-neutral plasma $n_i = n_e = n$. Also we neglect the inertia of electrons ($m_e \ll m_i$). Within the framework of the one-fluid model ($\mathbf{V}_e = \mathbf{V}_i = \mathbf{V}$) the statement of a problem includes the traditional equations magnetic gas dynamics in case of the final conductivity of medium

$$\frac{\partial \rho}{\partial t} + \text{div} \rho \mathbf{V} = 0; \quad \rho \frac{d\mathbf{V}}{dt} + \nabla P = \frac{1}{c}[\mathbf{j}, \mathbf{H}] \quad (1)$$

$$\rho \frac{d\varepsilon}{dt} + P \text{div} \mathbf{V} = \frac{\mathbf{j}^2}{\sigma} + \text{div}(\kappa \nabla T) - Q_{rad}; \quad \varepsilon = 2 c_v T$$

$$\frac{\partial \mathbf{H}}{\partial t} = \text{rot}[\mathbf{V}, \mathbf{H}] - c \text{rot} \frac{\mathbf{j}}{\sigma}; \quad \mathbf{j} = \frac{c}{4\pi} \text{rot} \mathbf{H}$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + (\mathbf{V}, \nabla); \quad \rho = m_i n; \quad P = P_i + P_e = 2 k_B n T$$

Here all variables have usual sense, and the conductivity of medium is equal $\sigma = e^2 n_e \tau_e / m_e$.

We neglect the molecular viscosity of the plasma component. The standard estimations of the heat transfer and the characteristic time of the energy exchange between components show that $T_i \approx T_e = T$. The heat conductivity of medium is defined by means of relation $\kappa = \kappa_{\perp e} = k_B^2 n_e T_e \tau_{ei} \gamma_0(\chi) / m_e$ where the function $\gamma_0(\chi)$ considers the influence of the magnetized electronic components of plasma $\chi = \omega_e \tau_{ei}$. The effective losses of the radiation energy are caused by radiation of the spectral lines, recombination and braking radiation

$$Q_{rad} = Q_{lin} + Q_{rec} + Q_{free}; \quad \frac{Q_{lin}}{n_e n_i} = 8 \cdot 10^{-23} \frac{Z_i^6}{T_e^{3/2}};$$

$$\frac{Q_{rec}}{n_e n} = 4.4 \cdot 10^{-24} \frac{Z_i^4}{\sqrt{T_e}}; \quad \frac{Q_{free}}{n_e n_i} = 1.54 \cdot 10^{-25} Z_i^2 \sqrt{T_e}$$

Here Z_i is the atomic charge, and temperature T_e is expressed in eV.

In the numerical model the dimensionless variables were used. Units of measure are the length of the channel L , the characteristic values of concentration n_o ($\rho_o = m_i n_o$), temperature T_o and the azimuthal component of the magnetic field in the channel inlet cross section $H_o = H_\phi^o = 2 J_p / c R_o$ where R_o is the radius of the external electrode, J_p is the discharge current. By means of these values we form the units of velocity $V_o = H_o / \sqrt{4 \pi m_i n_o}$ and time $t_o = L / V_o$. Thus the following dimensionless parameters participate in a problem: $\beta = 8 \pi P_o / H_o^2$ - the ration of gas and magnetic pressure in the inlet where $P_o = 2 k n_o T_o$; $\nu = 1 / \text{Re}_m = c^2 / 4 \pi L V_o \sigma$ - the magnetic viscosity which is inversely proportional to magnetic Reynolds number; the dimensionless values $\tilde{\kappa}$ and \tilde{Q}_{rad} .

Statement of a problem includes the traditional boundary conditions. In the inlet cross section we believe that plasma inflows with the known values of density $\rho(r) = f_1(r)$ and temperature $T(r) = f_2(r)$. We consider that the current is a constants and it passes in system only through electrodes, i.e. $j_z = 0$ at $z = 0$ or $r H_\phi = r_o = \text{const}$ ($r_o = R_o / L$). The plasma inflowing is carried out along the certain direction, for example, along coordinate lines. On the outlet for the investigated transonic streams we believe that plasma follows freely.

Except for that the electrodes forming the channel walls represent the equipotential ($E_r = 0$) and impenetrable surfaces for plasma ($V_n = 0$). On the axis ($r = 0$) we have the obvious boundary conditions:

$$V_r = 0; \quad H_\phi = 0$$

The technique of numerical integration is presented in [5]. The numerical solution of the non-stationary problem is carried out by the establishing method.

2. CALCULATIONS OF PLASMA FLOWS

On the basis of the given model a series of the numerical experiments for the various values m_i and identical magnitudes n_o, T_o, J_p and L corresponding the experiments under the QSPA program [1-4] is lead. For example, for values $n_o = 10^{15} \text{ cm}^{-3}$, $T_o = 2 \text{ eV}$, $J_p = 300 \text{ kA}$, $L = 60 \text{ cm}$, $R_o = 20 \text{ cm}$ we have $\beta = 0.009$. Numerical experiments answer small values $\beta \ll 1$ which are characteristic for plasma accelerators.

The geometry of the channel corresponds to the analytical researches of two-dimensional plasma flow

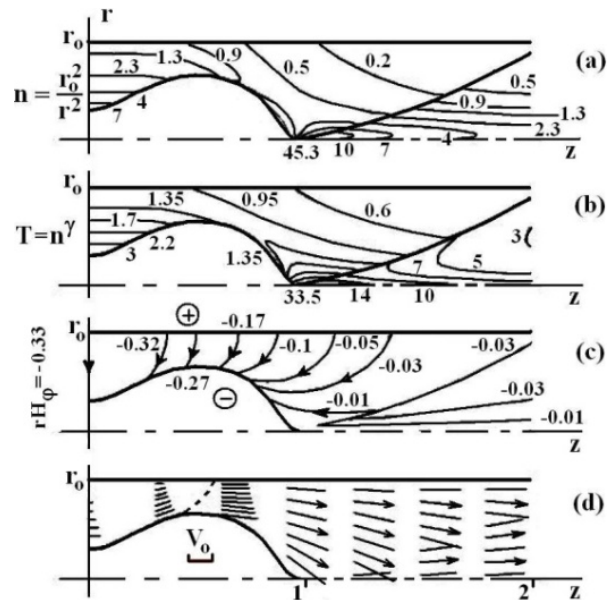


Fig. 1. The compressible flow of the hydrogen plasma

[5] according to which for the cold plasma ($\beta = 0$) the density on the channel inlet varies under the law $\rho(r) = r_o^2 / r^2$. Assuming that the inflowing plasma is isentropic we have $T = \rho^{\gamma-1}$ at $z = 0$.

For parameters specified above the quasi-stationary compressible flow of the hydrogen plasma is presented in Fig. 1 under condition of the non-uniform inflowing on the inlet. The level lines of functions $\rho(r, z)$ and $T(r, z)$ are represented in Fig. 1, a and 1b accordingly. The conic shock wave is distinctly observed. The level lines of function $r H_\phi = \text{const}$ in Fig. 1, c define the direction of the plasma current depending on polarity of electrodes. For determinacy we shall consider that the external electrode is the anode. The projections of the vector (V_r, V_z) onto the (r, z) plane is given in Fig. 1, d. The length of vectors is equal to the dimensionless value of velocity. The scale of vectors is defined by the characteristic velocity V_o specified in figure. The dotted line in Fig. 1, d answers to the transition of the stream velocity through the signal velocity [1].

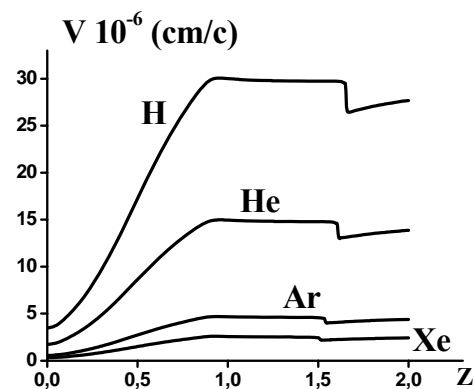


Fig. 2. The change of the velocity module along the average coordinate line of the channel for the plasma generated from hydrogen, helium, argon and xenon

Table of the maximal values of concentration and temperature in the compressible flow of plasma generated from hydrogen, helium, argon and xenon

	hydrogen	helium	argon	xenon
$n_{\max} \cdot 10^{-15}$	45.3	32.5	19.4	16.4
T_{\max}, eV	67.0	75.6	107.9	130.4

The characteristic break of stream lines is observed on the conic shock wave. There is the discontinuous change and the sharp increase in density, temperature and pressure. Behind the shock wave there is a further growth of density and temperature in the adiabatic compression mode.

The following results concern the evolution of the compressible flow at change of values m_i , i.e. at the transition from one gas to another. Dependencies of velocity module on z along average coordinate line for different gases are presented in fig. 2. We can see that the stream velocity decreased in the QSPA channel with increasing ion mass. The behavior of variables on the conic shock wave where jump of all values is observed is kept at use of the various gases. However the value of the velocity jump on a shock wave decreases at transition to heavier gases. With the increasing ion mass we observe increasing the corner between conic surface of the shock wave and system axis.

The decreasing of the stream velocity at the transition to heavier gas leads to decrease of the plasma compression parameters. In table the maximal values of concentration and temperature in the compressible plasma stream generated from various gases are presented. The value n_{\max} for hydrogen is essentially more than for helium, argon and xenon.

CONCLUSIONS

On the basis of the numerical MHD-model the comparative analysis of the compressible plasma streams generated by QSPA from the various gases was performed. For all gases the zone of compression contains the conic shock wave on which there is the discontinuous change of density, temperature and pressure. As a whole the compression zone represents an area of the compressed and heated plasmas. At transition to heavier gases the stream velocity in the

channel accordingly compression of plasma and value of the velocity jump on the conic shock wave decreases.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ КОМПРЕССИОННЫХ ПОТОКОВ ПЛАЗМЫ, ГЕНЕРИРУЕМОЙ В КСПУ ИЗ РАЗЛИЧНЫХ ГАЗОВ

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Проведено численное исследование динамики потоков в канале и компрессионных течений на выходе из КСПУ для плазмы, генерируемой из водорода, гелия, аргона и ксенона. В основе численной модели двумерных осесимметричных течений плазмы лежат МГД-уравнения в одножидкостном приближении с учетом конечной проводимости среды, теплопроводности и эффективных потерь энергии на излучение. Выявлены особенности компрессионных потоков плазмы генерируемой из различных газов.

ПОРІВНЯЛЬНИЙ АНАЛІЗ КОМПРЕСІЙНИХ ПОТОКІВ ПЛАЗМИ, ЯКІ ГЕНЕРУЮТЬСЯ В КСПУ ІЗ РІЗНИХ ГАЗІВ

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Проведено чисельне дослідження динаміки потоків в каналі і компресійних течій на виході з КСПУ для плазми, яка генерується з водню, гелію, аргону і ксенону. В основі чисельної моделі двовимірних осесимметричних течій плазми лежать МГД-рівняння в однорідному наближенні з урахуванням кінцевої провідності середовища, теплопровідності і ефективних витрат енергії на випромінювання. Виявлено особливості компресійних потоків плазми, які генерується з різних газів.