EXPANDING PLASMA JET IN A VACUUM VESSEL

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Introduction

Plasma jets are applied to many laboratory and technological devices, for example to MHD - generators and plasma dynamic lasers, to the plasma processing of various materials and the plasma etching, etc. A good control of the plasma parameters is very necessary for these applications. However in all these cases, plasma jet interactions with solid state surfaces take place so that essential changes of plasma jet parameters can take place, especially at ionization -recombination processes in plasma jets. Experimental difficulties cause the necessity of theoretical simulations of these parameter changes, especially closely to solid state surfaces.

The aim of this work is numerical calculations of parameters of the supersonic quasineutral argon plasma jet expanding into the cylindrical vacuum vessel and interacting with inner surfaces of this vessel.

Model

The quasineutral low ionized argon plasma jet enters with the axis supersonic velocity W_0 into the cylindrical vacuum vessel with radius R_c and length L_c through the round hole with radius R_n (Fig. 1) at some initial time. All plasma parameters are constant in this cross-section during a simulation time. The plasma consists of heavy particles (neutral atoms and single ionized ions) as well as electrons.

The plasma jet moves in this vessel with some expansion, interacts with its walls and departs trough the side hole with the length L_h. Some elementary processes take place in the plasma jet, namely: three particle electron-ion recombination, the ionization by the electron impact, the electron-ion energy exchange due to Coulomb collisions, the surface recombination as well as the electron heat conduction and the viscosity of electrons and heavy particles. It is assumed that the electron density n_e is equal the ion density n_i, ($n_e = n_i$) and the ion temperature T_i is equal the atom temperature T_n ($T_i = T_n = T_h$). Some difference between the electron temperature and the temperature of heavy particles is assumed in this plasma due to the large difference between the electron mass and the ion one.

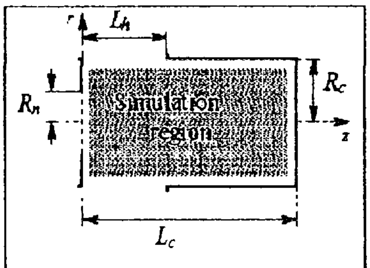

Fig 1

In some cases, an interaction is investigated of this plasma jet with a plane wall for comparing.

The following set of hydrodynamic equations are used for electrons as well as for heavy particles (ions and atoms) with taking into account elementary processes indicated above:

$$\rho\left(\frac{\partial w_\alpha}{\partial t} + (\vec{w}grad)w_\alpha\right) + \frac{\partial P}{\partial x_\alpha} + \frac{\partial \pi_{\alpha\beta}}{\partial x_\beta} = 0, \quad \{\alpha,\beta\} = \{z,r\} \qquad (1)$$

$$\frac{\partial n_e}{\partial t} + div(\vec{w}n_e) = n_e n_h \Gamma_i - n_e^2 n_i \Gamma_r \qquad (2)$$

$$\frac{\partial n_n}{\partial t} + div(\vec{w}n_n) = n_e^2 n_i \Gamma_r - n_e n_h \Gamma_i \qquad (3)$$

$$\frac{\partial (n_h E_h)}{\partial t} + div(n_h E_h \vec{w}) + div(P_h \vec{w}) = Q_{eh} + Q_{h visc} \qquad (4)$$

$$\frac{\partial (n_e J_e)}{\partial t} + div(n_e J_e \vec{w}) + \vec{w}grad(P_e) + div(\chi(J_e)gradJ_e) = -Q_{eh} + Q_{ion.-rec.} + Q_{e visc} \qquad (5)$$

where ρ is the total plasma density, $P = P_h + P_e$ is the total plasma pressure, $\vec{w}$ is the plasma velocity vector, $P_h = P_i + P_n$ and P_e is the partial pressure of heavy particles and electrons, n_e, n_n, n_h is the density of electrons, atoms and heavy particles, J_e, E_h is the density of the heat electron energy and the total energy of heavy particles, respectively.

The rate of the energy exchange between electrons and heavy particles due to elastic collisions is given by [1] $Q_{eh} = 3n_e(m_e/m_h)\nu_{eh}k(T_e - T_h)$, (6), where ν_{eh} is the mean rate of electron collisions with heavy particles, m_e and m_h is the electron mass and the heavy particle one, respectively.

The rate of both the three body recombination Γ_r and the ionization Γ_i is given according to [2]. One electron received at one act of three body recombination the energy given by $Q_{ion.-rec.} = -H_i\left(n_e n_h \Gamma_i - n_e^2 n_i \Gamma_r\right)$, (7). The flux of electrons and ions to vessel walls is given by $\vec{\Gamma} = n_e \vec{w}(1 + C_{s^i}/|\vec{w}|)/4$, (8), where $C_{s^i} = \sqrt{kT_e / m_h}$ is the ion sound velocity. It is assumed that all electrons and ions which reach vessel walls, recombine there and return back as neutral atoms.

The member $div(\chi(J_e) grad J_e)$ describes in (5) the electron heat conduction where $\chi(J_e) = -0.97 J_e^{5/2} / (m_e^{1/2} Z e^4 \Lambda)$ is the coefficient of this heat conduction.

The viscosity heat extraction is given by $Q_{visc} = -\pi_{\alpha\beta}\, \partial W_\alpha / \partial x_\beta$, where $\pi_{\alpha\beta} = -\eta_o\, W_{\alpha\beta} = -(\eta_{o_e} + \eta_{o_h})\, W_{\alpha\beta} = \pi_{e_{\alpha\beta}} + \pi_{h_{\alpha\beta}}$ is tensor of the viscosity strength without a magnetic field. Following viscosity coefficients are taken for electrons and heavy particles: $\eta_{o_e} = 0.73\, n_e\, T_e\, \tau_e$, $\eta_{o_h} = 0.96\, n_h\, T_h\, \tau_h$, where $\tau_e = \dfrac{3\sqrt{m_e}\, T_e^{3/2}}{4\sqrt{2\pi}\, \Lambda e^4 Z^2 n_e}$, $\tau_h = \dfrac{3\sqrt{m_h}\, T_h^{3/2}}{4\sqrt{2\pi}\, \Lambda e^4 Z^4 n_h}$ and Λ is Coulomb logarithm.

The modified method of big particles [3] is used for the computer modeling of this problem. In this method, the complex set of equations is separated on simpler components which describes separated physical processes. The general solution consists of additive members of time influences of each process on spatial parameter distributions. Each process is simulated with the corresponded minimum characteristic time what allows to obtain higher simulation precision. The dynamic separation boundaries are marked by some special symbols what allows to follow up a motion of these boundaries.

Results

Spatial distributions were simulated of main parameters of argon plasma jet for different times after the enter of this jet into the vacuum vessel, namely: the jet velocity field, the full plasma pressure, the electron temperature, the temperature of heavy particles as well as the ionization degree. Simulation parameters are shown in Table 1.

Variant	n_h m^{-3}	n_e m^{-3}	T_e eV	T_h K	$u = \lvert \vec{W}_0 \rvert$ m/sec	L_c m	R_c m	L_h/L_c	R_n m
1	10^{22}	10^{21}	1	300	3×10^{3}	5×10^{-2}	5×10^{-3}	1/4	10^{-3}
2	10^{22}	10^{21}	1	300	5×10^{2}	5×10^{-2}	5×10^{-3}	1/4	10^{-3}
3	10^{22}	10^{21}	1	300	3×10^{3}	5×10^{-2}	5×10^{-3}	1	10^{-3}
4	10^{22}	10^{21}	1	300	5×10^{2}	5×10^{-2}	5×10^{-3}	1	10^{-3}

Table 1

In these simulations, the pressure, the temperature, the velocity, the coordinate and the time are divided by the characteristic parameters, namely: the neutral atom pressure $P_0 = n_0 k T_0$, the characteristic temperature $T_0 = m_h W_0^2 / k$, the initial jet velocity W_0, the characteristic size R_n and the characteristic time $t_0 = R_n / W_0$, respectively. Values of these parameters are shown in Table 2.

Variant	P_0, Pa	T_0, K	R_n, m	W_0, m/sec	t_0, sec
1	6.01×10^{4}	4.36×10^{4}	10^{-3}	3×10^{3}	3.33×10^{-7}
2	1.67×10^{3}	1.21×10^{3}	10^{-3}	5×10^{2}	2.00×10^{-6}

Table 2

Simulation results show that jet velocity fields differ essentially from these fields for the case of a plasma jet reflection from a plane wall and depend from the relation of the plasma jet velocity and the characteristic molecule velocity. In case of relative large jet velocities (Variant 1 in Tab. 1), a opposite plasma flow is formed along walls in the direction to the exit hole of the vessel due to the interaction plasma jet with the vessel wall. In case of relative small jet velocities (Variant 2 in Tab. 1), the plasma flow is only in the region between the enter hole and exit one but the larger part of the vessel is filled by a non-moving plasma.

Spatial distributions of the total static pressure are shown in Fig. 2 and Fig. 3 for variants 1 and 2 in Tab. 1, respectively. These distributions show a complex phenomena in the vessel.

As can be seen from Fig. 2 in the case of relative small jet velocities (variant 2 in Tab. 1), the region is formed of high pressures with some waves which have nearly a plane front and propagate under some corner to the vessel axis. These waves propagate in the region of non-moving plasma where a flow velocities are very small. In the case of relative large jet velocities (variant 2 in Tab. 1), the region is formed of nearly uniform and relative low pressures which is separated by a steady shock wave from the region of a moving plasma.

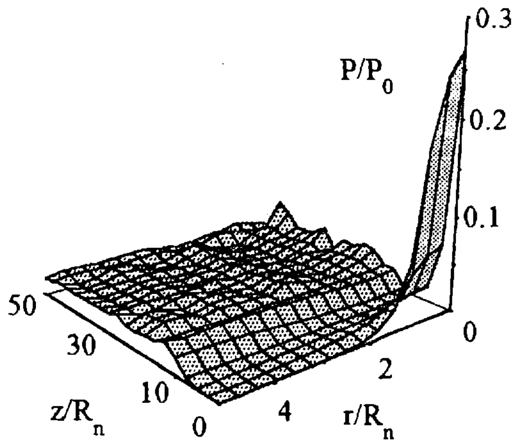

Fig. 2

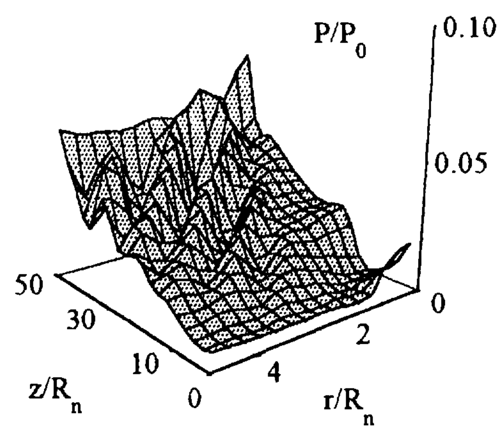

Fig. 3

Spatial distributions of main plasma jet parameters were obtained at different times, namely: the jet spread, the full plasma pressure, the electron temperature, the temperature of heavy particles as well as the ionization degree. These results show the essential influence of the plasma jet interaction on plasma parameters. First of all, shock waves can be appeared due to the plasma jet interaction with vessel walls. Besides, the rotate motion of plasma is appeared near the inner vessel angles.

References

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