# SIMULATION OF THE PLASMA JET WITH A DISPERSED PHASE IN AN AXISYMMETRIC CHAMBER

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The injection of plasma flow with dust particles into axially symmetric chamber filled with neutral gas is investigated using computer simulation. Calculations were carried out at different plasma flow velocities and dust particles sizes. As a result, the spatial distributions of the plasma and dust component parameters were obtained in the chamber at different times from the start of injection. All held calculations based on hydrodynamic approximation of plasma (without taking into account the effects of turbulence and absorption of particles on the walls of vessel) and processed by method of large particles. It is shown that large dust particles are distributed in chamber along its axis. In this case a narrow plasma jet is formed in the chamber. Dust particles of small size also extend in a radial direction, forming a wave structure. In this case, it is observed a significant expansion of the plasma jet.

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## INTRODUCTION

Two-phase flows of plasma with solid or liquid particles are widespread in the various processes of energy, plasma-chemical technologies, aviation, etc. With increasing concentration of the dispersed phase its impact on the transport processes in the carrier medium increases. In this case, plasma has a significant effect on the propagation of dispersed particles in two-phase flow. Therefore there is a need to consider the mutual influence of the two phases at each other.

Earlier in the measurements observed the phenomenon of the concentration of particles in the axial zone of the jet and the intense scattering dispersed particles in the cross section of the jet [1]. The transition from one regime to the other occurs with increasing particle diameter. In [2] shows the importance of the flow prehistory on the propagation of dispersed particles.

Despite the large number of studies in this field, a number of questions of the dynamics of the plasma jets with the dispersed phase remain unexplored. In particular, the mechanism for the transition from the regime of pinching to dispersal of dust particles is not sufficiently researched. Particularly, it is important to study the effect of dust particles on the spatial distribution of ions and electrons, their size and concentration on dynamics of two-phase jets for solving of plasma chemistry problems.

## 1. MODEL

This paper considers the problem of propagation of dispersed particles in a two-phase axisymmetric submerged jet. The plasma jet with disperse phase (spherical dust particles) enters into the cylindrical chamber with radius $R$ and length $L$ through the round hole (with radius $R_0$) at some initial time. All plasma parameters are constant in this cross-section during a simulation time. The chamber is filled with neutral gas at a pressure $p_0$. At the side of the camera there are holes through which the gas can come out from the chamber.

We adopt the basic assumptions of mechanics of multiphase media [3]. In addition, we assume that there are no phases transformations, spherical dust particles do not collide with each other, do not break up and have a constant heat. The study was conducted in the framework of in viscid perfect gas.

Plasma jet with dust particles can be described by set of hydrodynamic equations for carrier and dispersed phases:

$$\frac{\partial \rho_1}{\partial t} + div\left(\rho_1 \vec{w}_1\right) = 0,$$

$$\frac{\partial \rho_2}{\partial t} + div\left(\rho_2 \vec{w}_2\right) = 0,$$

$$\frac{\partial n_i}{\partial t} + div\left(n_i \vec{w}_1\right) = -\beta_r n_e^2 n_i,$$

$$\frac{\partial\left(\rho_1 u_1\right)}{\partial t} + div\left(\rho_1 u_1 \vec{w}_1\right) = -\frac{\partial P}{\partial r} - n_d f_r,$$

$$\frac{\partial\left(\rho_2 u_2\right)}{\partial t} + div\left(\rho_2 u_2 \vec{w}_2\right) = -\alpha_2 \frac{\partial P}{\partial r} + n_d f_r,$$

$$\frac{\partial}{\partial t}\left(\rho_1 E_1 + \rho_2 E_2\right) + div\left(\rho_1 E_1 \vec{w}_1 + \rho_2 E_2 \vec{w}_2\right) + \ldots$$

$$div\left(\alpha_1 P \vec{w}_1 + \alpha_2 P \vec{w}_2\right) = 0,$$

$$\frac{\partial\left(\rho_2 I_2\right)}{\partial t} + div\left(\rho_2 I_2 \vec{w}_2\right) = n_d Q,$$

$$E_1 = \frac{u_1^2}{2} + \frac{v_1^2}{2} + I_1,$$

$$E_2 = \frac{u_2^2}{2} + \frac{v_2^2}{2} + I_2,$$

$$\vec{f} = \left(\pi r_d^2 / 2\right) \rho_1 C_d \left|\vec{w}_1 - \vec{w}_2\right| \left(\vec{w}_1 - \vec{w}_2\right),$$

$$Q = 2\pi r_d Nu_1 \left(T_1 - T_2\right),$$

$$I_1 = \frac{3}{2} T_1, \quad I_2 = \frac{3}{2} T_2, \quad P = \frac{2}{3} I_1 R \rho_1.$$

Here the subscripts 1 and 2 refer to the parameters of the carrier and the dispersed phase; $\rho, \vec{w}, I, E$ are normalized density, velocity vector ($u_i, v_i$ - its components along $r$ and $z$ axis), internal and full energies; $\vec{f}, Q$ are a force of an aerodynamic interaction between a plasma and a dust particle ( $f_r$ and $f_z$ - its components along the r and z) and an intensity of their heat; $P, n_d, n_i, n_e, \alpha_2$ are a plasma pressure, dust, ion and electron concentrations, volume fraction of the dust; $C_d$ is drag coefficient of dust, $Nu_1$ is Nusselt number, $\lambda_1$ is the thermal conductivity of the plasma, $\beta_r$ is three-body recombination rate, $R$ is gas constant.

The system of equations is solved numerically by the method of large particles [4]. The calculations were carried out at different parameters of plasma flow entering in the vessel and continued until a steady flow of plasma.

## 2. SIMULATION RESULTS

The calculations were performed for various sizes of dust particles, different values of the dust density and velocities of the plasma jet at the nozzle exit. Simulations continued until a steady flow of plasma. As results, spatial distributions of the plasma parameters and disperse phase parameters (densities, drift velocities, temperatures and the plasma pressure) were obtained in various times after entering of the plasma jet into the chamber.

Fig.1 shows spatial distribution of dust density at time $t = 150$ for two cases, corresponding to the radius of the dust $R_d = 1 \mu m$ (see Fig. 1,a) and $R_d = 20\ \mu m$ (fig.1b). Densities are normalized to plasma density at the nozzle exit $\rho_0$, spatial coordinates are normalized to $R_0$, and time is normalized to $t_0 = R_0 / v_0$. In both cases the velocity of the plasma flow was $v_0 = 200\, m/s$ and the dust density was $\rho_d^0 = 0.1\, kg/m^{-3}$ at the nozzle exit. The gas pressure was $p = 1\, atm$ in the chamber prior to injection of the plasma jet.

One can see from this figure, that small dust particles ( $R_d = 1 \mu m$ ) are distributed effectively in the radial direction, forming a wave structure. As a result there is a significant density of dust particles along the axis of the chamber and close the chamber walls. Between the axis and the chamber walls can be seen forming a region with a very low concentration of dust. Large dust particles practically do not expand in the radial direction, so their concentration is significant only along the axis of the camera.

The results showed that the dust particles have a significant effect on the parameters of the plasma flow, which can be seen in Figs. 2 and 3. Figure 2 shows the distribution of the plasma density for the variants presented in Fig. 1. It is evident that in areas of high concentration of dust particle the plasma density is also increased. In this regard, the characteristic feature is the forming of the region with low plasma density in Fig. 2, which corresponds to the low density of the dust particles (Fig. 1,a). The cause of the observed relationship between the dispersed and the carrier phase flows is the force of the hydrodynamic friction.

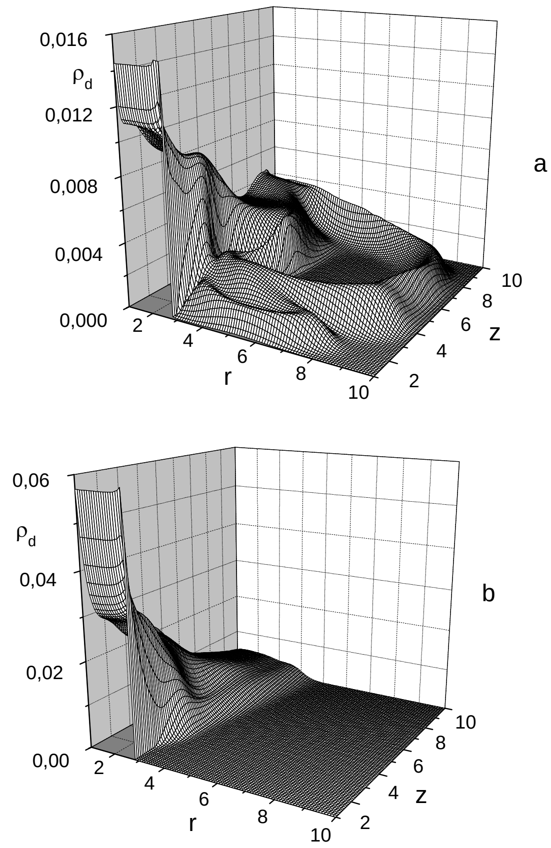



*Fig. 1. Spatial distributions of dust density in the chamber at $R_d = 1\ \mu m$ (a) and at $R_d = 20\ \mu m$ (b)*

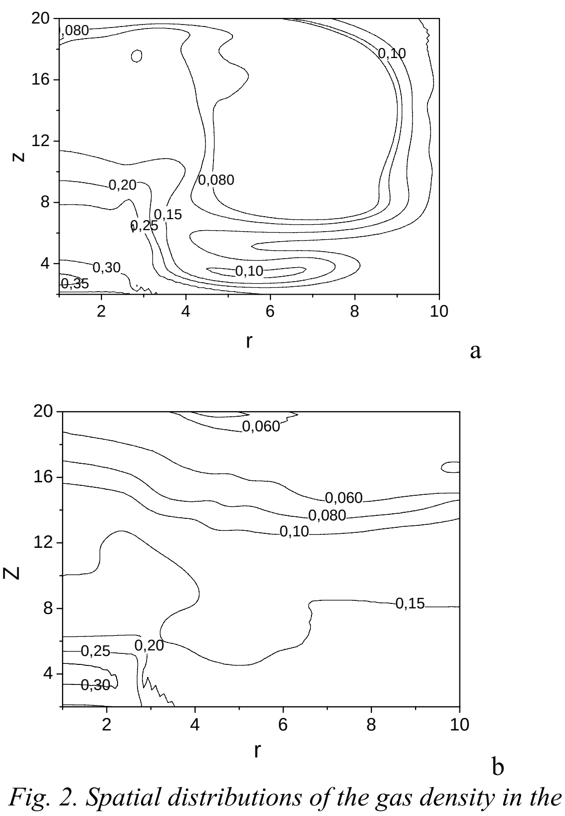
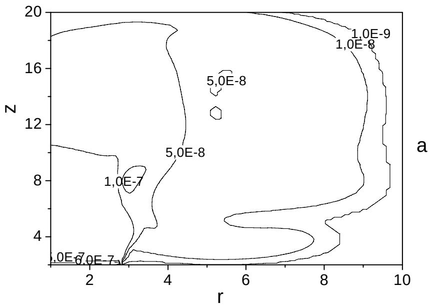



*Fig. 2. Spatial distributions of the gas density in the chamber at $R_d = 1\ \mu m$ (a) and at $R_d = 20\ \mu m$ (b)*

In Fig.3 are presented spatial distributions of the ion concentration normalized to the neutral atom concentration in the nozzle exit. Figure 3,a and figure 3,b correspond to the cases of small ( $R_d = 1\ \mu m$ ) and large ( $R_d = 20\ \mu m$ ) dust particles. As the figure shows, the concentration of ions in the case of small dust particles is much larger than in the case of large dust particles. In the case of injection of large dust particles visible ion concentration is realized only near the nozzle.



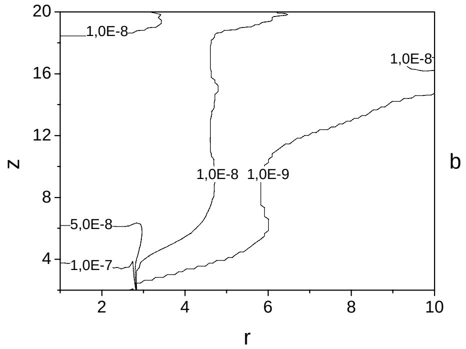




*Fig. 3. Spatial ddistributions of the ion density in the chamber at $R_d = 1\ \mu m$ (a) and at $R_d = 20\ \mu m$ (b)*

The degree of the gas ionization in the rest of the chamber is insignificant. In the case of injection of small dust particles the degree of the gas ionization in the chamber is substantially higher. This result is due to the friction of plasma jet with the dust component, which is greater in the case of large dust particles. The size increasing of dust particles at a constant relative density of the dispersed phase decreases the mixing of plasma jet and the neutral gas in the chamber.

## CONCLUSIONS

Results of simulations show that the injection of the plasma jet with a dispersed phase in a chamber filled with neutral gas is more effective in the case of small dust particles due to the decrease of the friction force with the dispersed phase with decreasing particle size.

It is shown that dust particles of a large radius move along the axis of the chamber, but the small particles also propagate in the radial direction, forming a wave structure.

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## МОДЕЛИРОВАНИЕ ПЛАЗМЕННОЙ СТРУИ С ДИСПЕРСНОЙ ФАЗОЙ В ОСЕСИММЕТРИЧНОЙ КАМЕРЕ

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С помощью компьютерного моделирования исследуется инжекция плазменного потока с пылевыми частицами в аксиально-симметричную камеру, заполненную нейтральным газом. Расчеты выполнены при различных скоростях инжекции струи и различных размерах пылевых частиц. Вычисления основаны на гидродинамическом приближении для плазмы и дисперсной фазы и проведены методом крупных частиц. Получены пространственные распределения параметров плазмы и пылевой компоненты в камере в разные моменты времени от начала инжекции. Показано, что пылевые частицы большого размера распространяются в камере вдоль ее оси. При этом в камере формируется узкая плазменная струя. Пылевые частицы малого размера распространяются также в радиальном направлении, образуя волновую структуру. В этом режиме наблюдается значительное расширение плазменной струи.

## МОДЕЛЮВАННЯ ПЛАЗМОВОГО СТРУМЕНЮ З ДИСПЕРСНОЮ ФАЗОЮ В ОСЕСИМЕТРИЧНІЙ КАМЕРІ

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За допомогою комп'ютерного моделювання досліджується інжекція плазмового потоку з пиловими частинками в аксіально-симетричну камеру, заповнену нейтральним газом. Розрахунки проведені при різних швидкостях інжекції струменю та при різних розмірах пилових частинок. Обчислення ґрунтуються на гідродинамічномунаближаннідля плазми та дисперсійної фази і проведеніметодом крупних частинок. Одержані просторові розподіли параметрів плазми та пилової компоненти в камері в різні моменти часу від початку інжекції. Показано, що пилові частинки великого розміру розповсюджуються в камері вздовж її осі. При цьому в камері формується вузький плазмовий струмінь. Пилові частинки малого розміру розповсюджуються також в радіальному напрямі, утворюючи хвильову структуру. В цьому випадку спостерігається значне розширення плазмового струменю.