DYNAMICS OF DUST PARTICLES IN A PLASMA JET

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In this paper carry out the computer simulation of the plasma jet with dust particles, which expands in rarefied neutral gas. The problem is considered in the framework of multi-fluid hydrodynamic model, which takes into account the difference in velocity and temperature of the plasma component. Calculations performed using method "big particles" for different ionization degree of plasma, its density and radii of dust particles. The spatial distributions of plasma parameters and dust components obtained at different time points after injection plasma jet. It is shown that at the large ionization degree of plasma (α> 0.001) velocity of the dust particles significantly decreased compared to the case of weakly ionized plasma stream. This result can be explained by deceleration of dust particles by an electric field, the effect of which increases with increasing concentrations of electrons and ions.

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INTRODUCTION

The application of nanoparticles is rapidly growing in nanoscale science and engineering. During the last years many techniques for nanoparticles synthesis have been developed, particularly several research groups worldwide apply plasma processes for the synthesis of particulate matter [1]. One of the most promising methods of coating is spraying using plasma jets [2, 3]. Coating quality depends on the physical parameters such as the velocity of sputtered particles, their charge and temperature. In this regard, the study of the dynamics of dust particles in the plasma jets that can be used for transportation of dust particles to the substrate is of considerable interest. Unlike gas jets with dispersed phase, where the drag force determines the movement of dust particles, dust particles are charged in plasma and the electric force acts on them too. The purpose of this work is to study the spatial distribution of dust particles in the plasma jet and influence of the electric field on their dynamics.

In this paper carry out the computer simulation of the plasma jet with dust particles, which expands in rarefied neutral gas.

1. MODEL AND SIMULATION METHOD

In this paper, we simulate the outflow of the plasma jet with dust particles through a round hole of radius R_0 in the rarefied neutral gas. It is assumed that the plasma velocity V_0 and its density ρ_0 are constant at the inlet during the plasma jet expansion. The plasma considered in this article consists of four species, namely electrons, neutral argon atoms, singly ionized argon ions and nanoparticles. They will be denoted by the subscript *e, a, i* and *d*, respectively. We use hydrodynamic model to describe the expansion of the plasma jet with dust particles. In the model ions, electrons and neutral atoms have the same drift velocity $\vec{w}=(u,v)$ due to effective momentum exchange, and dust particles have drift velocity $\vec{w}_d=(u_d,v_d)$. Here u, u_d are radial velocity components and v, v_d are axial velocity components.

The ions temperature equals to neutral atoms temperature T, but electrons temperature T_e can differ from them.

The continuity equation for heavy plasma component (ions and neutral atoms) is equal to

$$\frac{\partial n}{\partial t}+div(n\vec{w})=0. \quad (1)$$

Here n is sum of ion density n_i and neutral atom density n_a.

The continuity equation for ions is equal to

$$\frac{\partial n_i}{\partial t}+div(n_i\vec{w})=-\beta_r n_e^2 n_i - I_i n_d / e, \quad (2)$$

where n_e is electron density. The right hand side describes the ion destruction due to three particle recombination and recombination at the interaction with dust particles.

The rate coefficient for three particle recombination is given [4]

$$\beta_r = 1.1\cdot 10^{-20}\left(T_e\right)^{-9/2}\left(m^6 s^{-1}\right). \quad (3)$$

The ion current on dust particle I_i is described by OLM theory [5] and is equal to

$$I_i=\pi r_d^2 n_e e|w|\left(1-\frac{eq_d}{4\pi\varepsilon_0 r_d\left(m|w|^2/2+kT\right)}\right). \quad (4)$$

Here r_d is dust particle radius, T is ion temperature, q_d is dust particle charge, e is proton charge, m is the ion and neutral atom mass.

The continuity equation for dust particles is equal to

$$\frac{\partial n_d}{\partial t}+div(n_d\vec{w}_d)=0, \quad (5)$$

where n_d is dust particles density, $\vec{w}_d=(u_d,v_d)$ is drift velocity of dust particles.

The dust particle charge is calculated from the equation

$$\frac{\partial q_d}{\partial t}+(\vec{w}_d\cdot\nabla)q_d = I_e + I_i, \quad (6)$$

where electron current on dust particle is equal to

$$I_e=\pi r_d^2 n_e\left(\left(\frac{8kT_e}{\pi m_e}\right)^{1/2}\right)\exp\left(\frac{eq_d}{4\pi\varepsilon_0 r_d kT_e}\right). \quad (7)$$

The momentum equations for heavy plasma particles (ions and atoms) are given by

$$\frac{\partial(nu)}{\partial t}+div(nu\vec{w})=-\frac{1}{m_i}\frac{\partial P}{\partial r}-\frac{n_d f_r}{m_i}+\frac{e}{m_i}n_i E_r, \quad (8)$$

$$\frac{\partial(nv)}{\partial t}+div(nv\vec{w})=-\frac{1}{m_i}\frac{\partial P}{\partial z}-\frac{n_d f_z}{m_i}+\frac{e}{m_i}n_i E_z, \quad (9)$$

where $P=nkT$ is the plasma pressure, E_r and E_z are radial and axial electric field components, m_i is ion mass (in our case the neutral atom mass is equal to the ion mass), $\vec{f}$ is force of the aerodynamic interaction between plasma and dust particle (f_r and f_z – its components along axis r and z). It consists of a friction force between dust particles and neutral particles $\vec{f}_{dn}$, as well as between the ions and the dust particles $\vec{f}_{di}$.

According [5] neutral drag force can be approximate as

$$\vec{f}_{dn}=\frac{8}{3}\sqrt{2\pi}r_d^2 n_a m V_{Tn}\left(\vec{w}-\vec{w}_d\right), \quad (10)$$

where $V_{Tn}=\left(w^2+8kT/\pi m\right)^{1/2}$ is total atom speed (a combination of directed and thermal speeds). The ion drag force can be expressed as

$$\vec{f}_{di}=n_i m V_{Tn}\sigma^{col}\vec{w}+n_i m V_{Tn}\sigma^{coul}\vec{w}, \quad (11)$$

where σ^{col} (σ^{coul}) is the momentum collision cross section corresponding to the collection of ions by direct ion impacts (electrostatic Coulomb collisions).

The momentum equations for dust particles are given by

$$\frac{\partial(n_d u_d)}{\partial t}+div(n_d u_d\vec{w}_d)=-\frac{\alpha_d}{m_d}\frac{\partial P}{\partial r}+\frac{n_d f_r}{m_d}+ +\frac{q_d}{m_d}n_d E_r, \quad (12)$$

$$\frac{\partial(n_d v_d)}{\partial t}+div(n_d v_d\vec{w}_d)=-\frac{\alpha_d}{m_d}\frac{\partial P}{\partial z}+\frac{n_d f_z}{m_d}+ +\frac{q_d}{m_d}n_d E_z, \quad (13)$$

where α_d is volume fraction of dust particles.

Equations for internal energies ions and atoms ε, electrons ε_e and dust particles ε_d are given by

$$\frac{\partial(\rho\varepsilon)}{\partial t}+div(\rho\varepsilon\vec{w})+P\,div\,\vec{w}=Q_{ei}+Q_{en}-n_d Q, \quad (14)$$

$$\frac{\partial(\rho\varepsilon_e)}{\partial t}+div(\rho\varepsilon_e\vec{w})+P_e\,div\,\vec{w}+div\,q_e= -Q_{ei}-Q_{en}-n_d Q_{ed}, \quad (15)$$

$$\frac{\partial(\rho_d\varepsilon_d)}{\partial t}+div(\rho_d\varepsilon_d\vec{w}_d)=n_d Q+n_d Q_{ed}+Q_{id}. \quad (16)$$

Here the heat flux is given by $\vec{q}_e=-\chi(T_e)\nabla T_e$, where $\chi(T_e)$ is the coefficient of electron thermal conductivity, Q, Q_{ed}, Q_{id} are the energy exchanges between a dust particle and neutral atoms, electrons and ions [5], Q_{ei} is the energy exchange between electrons and ions, Q_{en} is the energy exchange between electrons and neutrals.

The equation of conservation of momentum for electrons if we neglect their inertia, as well as the force of friction of the electrons with atoms, ions and dust particles has the form

$$en_e\vec{E}=-\nabla P_e. \quad (17)$$

This relation expresses the electric field $\vec{E}$.

The system of equations (1-17) is solved numerically by the method of large particles [6].

2. RESULTS AND DISCUSSION

The calculations were performed for various densities of plasma ρ_0 and dust component ρ_{d0} at the inlet, various values of ionization degree of plasma α and radius of dust particles r_d. Simulations continued until a steady-state 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 the start of injection of the plasma jet into the space filled with gas.

An example of the spatial distribution of the plasma density is presented in Fig. 1 at $t=10$ ms after the jet injection. It is seen, that the shock wave is formed during the plasma jet expansion into a neutral gas.

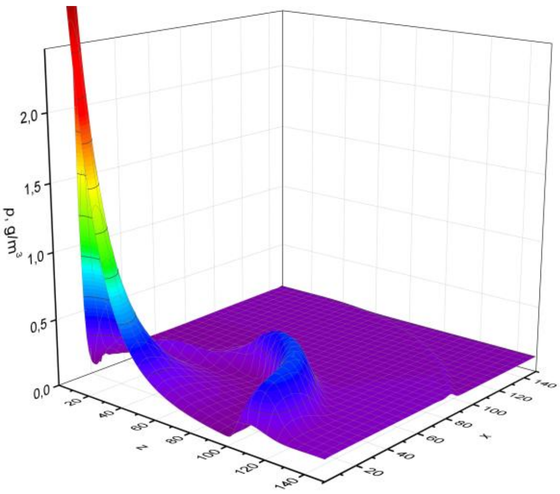

Fig. 1. Spatial distribution of plasma density at t=10 ms after the plasma jet injection

The spatial distributions of the dust particles velocity along the symmetry axis of the jet are shown in Fig. 2 for $r_d=100$ nm, $\rho_0=0.006$ kg/m^3, $V_0=40$ m/s. The solid curve corresponds to the plasma ionization degree $\alpha=0.001$, the dash curve correspond to $\alpha=0.05$ and the dot curve corresponds to $\alpha=0.1$. We can see that dust particles are accelerated in the stream in the region $z\le 3\cdot R_0$ to a velocity v_{dz}^m, which remains almost constant with further increase of coordinate z. The reason for this effect is the rapid reduction of the frictional force $\vec{F}_f$ between dust particles and the plasma with increasing z due to the reduction of plasma density at the jet expansion (Fig. 3). Our model also takes into account the effect of the electric force on dust particles. Its action is directed against the movement of dust particles, as they have a negative charge.

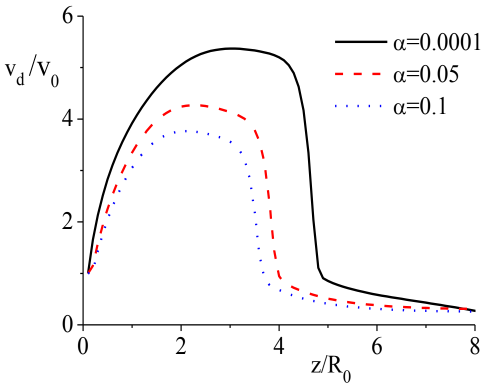

Fig. 2. Spatial distributions of dust particles velocity along z-axis for various plasma ionization degrees at $t=5\times10^{-3}$ s

Note, that the increase of ionization degree reduces the velocity of the dust particles, because the effect of the electrical force on their dynamics increases.

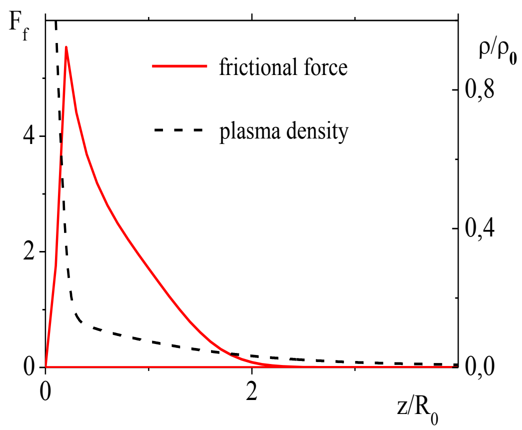

Fig. 3. Spatial distributions of the plasma density and the frictional force along z-axis

Fig. 4 shows distributions of dust component density in the expanding plasma jet along the axis of symmetry *z* at different radii of dust particles. It is seen that the density of dust particles with greater radius decreases with increasing of coordinate slower. The maximum velocity, to which the dust particles are accelerated, also depends on their radius and the plasma density in the flow. Appropriate dependences are shown in Fig. 5. Curve 1 represents the dependence of v_d^m on r_d in semi-logarithmic scale at $V_0=40$ *m/s*, $\rho_0=0.00122$ *kg/m*^{3}, $\alpha=0.001$. It is seen that with the increase of the dust particles radius their velocity decreases. Curve 2 represents the dependence of v_{dz}^m on the plasma density at the inlet in semi-logarithmic scale. The plasma flow velocity is much greater than velocities of dust particles and is about the same in all variants calculations. For example, the axial component of the plasma flow velocity is $v\approx14\cdot v_0$ (*m/s*) at $z=5\cdot R_0$. It indicates the need to use a two-speed hydrodynamic model describing the plasma jet with dust particles. An increasing of plasma density leads to an increase of the frictional force between the plasma and dust particles and to the increase of the dust particles velocity.

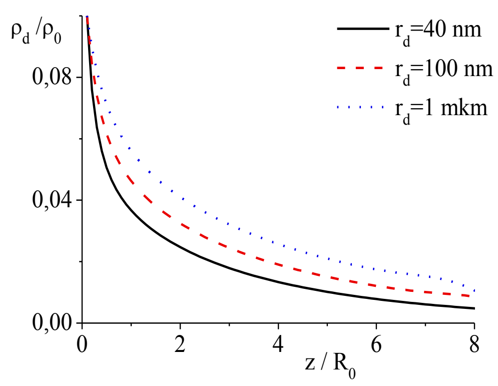

Fig. 4. Spatial distributions of the dust component density along z-axis for various radii of dust particles at $t=5\times10^{-3}$ s

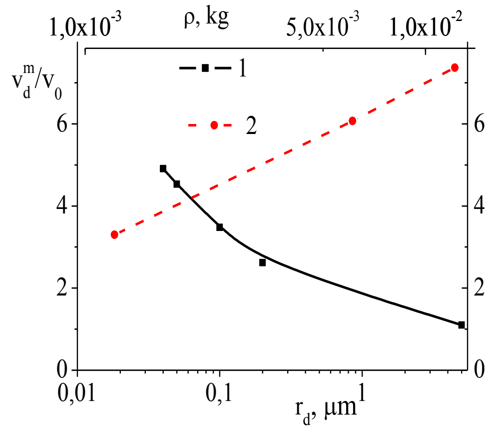

Fig. 5. Maximum velocity of dust particles in the plasma jet as a function of their radius (curve 1) and the plasma density at the inlet (curve 2)

Radial distributions of the axial flux of dust component are presented in Fig. 6 for the different radii of dust particles at the distance $z = 0.06$ *m* from the inlet. Our results demonstrate significant heterogeneity dust flow radially. First, the dust particles are distributed only within a certain channel, the radius of which is smaller for larger dust particles. The axial flow of the dust component has a maximum near the axis of symmetry of the plasma jet, and tends to zero with increasing radius.

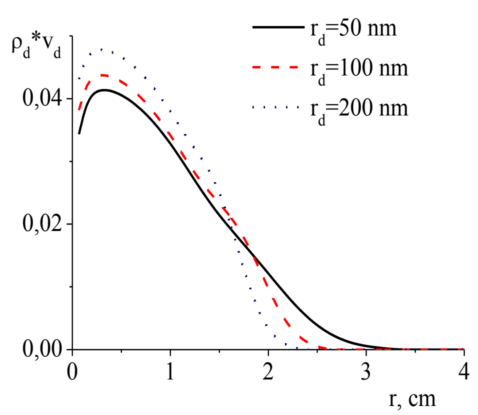

Fig. 6. Radial distributions of the axial flow of the dust component at $z = 0.06$ m and various dust particles radii

CONCLUSIONS

The plasma jet with dust particles has been investigated using a multi-hydrodynamic model, which takes into account the effect of the electric field on the dust particles dynamic. We studied spatial distributions of dust particles and their velocities in the plasma jet at different plasma ionization degrees, plasma densities at the inlet and radii of dust particles. It is shown that at the large ionization degree of plasma ($\alpha > 0.001$) velocity of the dust particles significantly decreased compared to the case of weakly ionized plasma stream due to their deceleration by electric field.

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ДИНАМИКА ПЫЛЕВЫХ ЧАСТИЦ В ПЛАЗМЕННОЙ СТРУЕ

А.Ю. Кравченко, И.С. Марущак

Проводится компьютерное моделирование расширения плазменной струи с пылевыми частицами в разрежённый нейтральный газ. Задача рассматривается в рамках многожидкостной гидродинамической модели, которая позволяет учитывать различия скоростей и температур компонент плазмы. Расчёты выполнены методом “крупных частиц” для различных значений степени ионизации плазмы, её плотности и радиусов пылевых частиц. Получены пространственные распределения параметров плазмы и пылевой компоненты в различные моменты времени после инжекции плазменной струи. Показано, что при большой степени ионизации плазмы ($\alpha > 0{,}001$) скорости пылевых частиц в струе значительно меньше, чем в случае слабоионизированного потока плазмы. Этот результат можно объяснить торможением пылинок электрическим полем, влияние которого увеличивается при увеличении концентраций электронов и ионов.

ДИНАМІКА ПИЛОВИХ ЧАСТИНОК У ПЛАЗМОВОМУ СТРУМЕНІ

О.Ю. Кравченко, І.С. Марущак

Проводиться комп’ютерне моделювання розширення плазмового струменю з пиловими частинками в розріджений нейтральний газ. Задача розглядається в рамках багаторідинної гідродинамічної моделі, яка дозволяє врахувати відмінності швидкостей і температур компонент плазми. Розрахунки виконані методом “крупних частинок” для різних значень ступеня іонізації плазми, її густини та радіусів пилових частинок. Одержані просторові розподіли параметрів плазми і пилової компоненти в різні моменти часу після інжекції плазмового струменю. Показано, що при великому ступені іонізації плазми ($\alpha > 0{,}001$) швидкості пилових частинок в струмені значно менші, ніж у випадку слабкоіонізованого потоку плазми. Цей результат можна пояснити гальмуванням пилинок електричним полем, вплив якого збільшується при збільшенні концентрацій електронів та іонів.