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Coagulation of charged particles in self-organizing thermal plasmas of welding fumes

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The dusty plasma behavior is studied in the process of coagulation of the primary particles, which are formed as a result of the nucleation and nuclei growth in the condensable high-temperature vapors. The study is concentrated to the example of the thermal plasma formed in the welding fume in the arc welding process where the electrodes covered with carbonate–fluorite are used. The tendency to self-organization of such a plasma and formation of the ordered spatial structures of primary particles is demonstrated. The number densities of the primary particles in these structures are much higher than at uniform spatial distribution that causes the rapid coagulation of the fine nano-sized primary particles. The coagulation of the particles with size more 10 nm into cluster-like agglomerates occurs during almost all cooling period of aerosol up to the ambient air temperature. The coagulation of the ultra-fine particles ($\sim$2 nm) occurs in two stages: at first the chain-like agglomerates are formed rapidly, and then they associate with the cluster-like agglomerates. As a result, the final agglomerates (inhalable particles) have the bimodal size distribution with different chemical compositions and fractal dimensions.

1. Introduction

The common name “dusty plasma” is referred to a wide range of heterogeneous physical systems, in which the ionized gas environment and suspended solid or liquid particles are present simultaneously. In some kinds of dusty plasmas the particles are formed as a result of the metal (metal compound) vapors' condensation, in others – as a result of the cluster coagulation or the gas and construction material interaction. In any case, formation of the dust component is accompanied by coagulation of the fine particles and modification of the dust size distribution.

The basic property of dusty plasmas is the charging of particles by the interphase interaction. Dependency of the particles' coagulation on their charge was studied by some authors, for example by Belov, Ivanov, Pal, Ryabinkin, and Serov (2002), Ivlev, Morfill, and Konopka (2002), Nguyen and Shklovskii (2002), Olevanov, Mankelevich, and Rakhimova (2004), Mankelevich et al. (2009). In particular, the collision frequency that corresponds to the thermal cross-section for the interaction between dust particles cannot account for such a high cluster growth rate observed experimentally (Bouchoule et al., 1996). The anomalously high coagulation rate is explained by assuming that collisions take place mostly between oppositely charged particles (Watanabe, 2006). Another approach is demonstrated by Olevanov et al. (2004), where the

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polarization model for the interaction between dust particles is considered. On the other hand, some authors note that a coagulation rate of the likely charged dust is less than for neutral dust; the calculations, which demonstrate the absence of aggregates' growth as a result of coagulation of the likely charged particles, are given by Smith, Lee, and Matsoukas (1999) and Belov et al. (2000). It is explained by the obvious Coulomb repulsion of the dust particles. Thus, the general theory of the charged dust particles coagulation in the plasma is absent, but it is possible to assume that all noted above effects can be present at the certain stages of the plasma dust coagulation.

A variety of mechanisms of the dust particle collisions cause the different morphological types of the agglomerates in the plasma. For example, the linear chain morphology has been observed in iron particles contained in the plasma of welding fumes (Zimmer & Biswas, 2001). Three morphological types of the agglomerates in welding fumes have been observed by Sowards, Ramirez, Dickinson, and Lippold (2010), Berlinger et al. (2011) and Oprya et al. (2012): the cluster-like agglomerates (densely or loosely packed spherical particles), the chain-like agglomerates with fractal geometry, and the coarse particles on which chain-like agglomerates are located. The mechanisms of the various morphology types' formation are not clear and need to be investigated.

It should be noted that attraction or repulsion of the dust particles in the plasma is determined by their interaction with the environment rather than by their charges. The situation when the likely charged particles are attracted is possible in the plasma. The source of attractive force is the ion drag force in the low-pressure collisionless plasma (Khrapak, Ivlev, Morfill, & Thomas, 2002), or the ion diffusion pressure force in the high-pressure collision plasma (Vishnyakov, 2005). The possibility of the long-range attraction between likely charged particles leads to the self-organization of dusty plasmas and to the formation of the spatial ordered structures such as the plasma crystals (Morfill, Thomas, Konopka, & Zuzic, 1999, 2004; Fortov, Khrapak, Khrapak, Molotkov, & Petrov, 2004).

In the paper by Olevanov, Mankelevich, and Rakhimova (2003) it has been noted that there exist two different types of the interaction between the particles in dusty plasmas: the first type is the formation of plasma crystals, and the second type is the particle coagulation. In the present paper the plasma self-organization and the coagulation are studied simultaneously, because the self-organization causes the accumulation of the fine particles in the small space area (Vishnyakov & Dragan, 2006), i.e. their local number density can be increased. It should lead to the increase of Brownian coagulation rate.

2. Conditions of the collision plasma self-organization

The self-organization of the thermal collision dusty plasma, to which the combustion plasma and the plasma of welding fumes belong, occurs due to the displacement of ionization balance near surfaces of the charged dust particles (Vishnyakov, 2005, 2006). The change of the electron number density in the space charge layer near a particle surface occurs as a result of the electrical interaction, and the balance between the thermal ionization of atoms and the electron–ion recombination are broken. It leads to occurrence of the nonequilibrium charge carriers whose spatial distribution is not determined by the Boltzmann factor. And, the plasma ionization is increased near a positive particle, but is decreased near negative particles.

The conservation of the nonequilibrium carrier number density δn is determined by the continuity equation, which in the stationary case reads

$$-D\nabla^2\delta n = \beta_I n_a(n_e+\delta n)-\gamma_R(n_e+\delta n)(n_i+\delta n),$$

where $D=2D_eD_i/(D_e+D_i)$ is the ambipolar diffusion coefficient; β_I is the ionization rate; γ_R is the recombination rate; n_a is the ionizable atom number density; n_e and n_i are the equilibrium electron and ion number densities respectively.

The flux of the nonequilibrium charge carriers to the particle surface can be obtained via solving this equation (Vishnyakov, 2005):

$$j_s = \frac{Dn_q}{r_D}\frac{\exp\frac{V_b}{k_BT}-1}{\sqrt{2\cosh\frac{V_b}{k_BT}-1}}, \tag{1}$$

where $r_D=\sqrt{k_BT/8\pi e^2 n_0}$ is the screening length; V_b is the potential barrier at the particle surface; k_B is the Boltzmann constant; T is the Kelvin temperature; n_0 and n_q are the unperturbed and quasiunperturbed number densities (discussed below).

The flux (1) determines the attractive force between likely charged particles in the thermal plasma. The repulsing occurs due to the electrical force. Existence of the competitive forces is the condition for the ordered structures formation (Vishnyakov & Dragan, 2006).

The attractive force between the likely charged particles, in reality, is the force which acts on the particles from the plasma and pushes these particles to each other contrary to the electrical forces. Such a pushing appears when the nonequilibrium carriers are distributed anisotropically around the particle. The total momentum, which is transferred from the flux of nonequilibrium positive ions to the particles by collisions, pulls particles together, when the ionization degree in the layer between negative particles is less than outside. The positive charge of the particles causes the increase of ionization degree and in the layer between particles it becomes larger than outside. But the field in this case suppresses the collisions of ions with particles and the excess momentum occurs due to the collisions with atoms whose number in the