

Energy and Technological Aspects of the Combustion of Ionized Gas-Dispersed Systems

N.I. Poletaev*, V.G. Shevchuk, M.E. Khlebnikova

Institute of Combustion and Advanced Technologies, I.I. Mechnikov National University,
Dvoryanskaya str., 2, Odessa, 65082, Ukraine

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Abstract

This paper discusses the flame ionization effect on the combustion processes in gaseous suspensions of the dispersed fuels. It is shown that the two-phase flame ionization affects almost all the processes of the fuel conversion – kinetics of the dispersed fuel combustion, processes of the interphase heat and mass transfer, processes of the nucleation and coagulation in the flame, formation of nanoscale products of the metal particles combustion. It is shown that the electrostatic interaction between the charged nanoparticles and ions or polar molecules in the gaseous phase leads to the appearance of molecular “pumps” that can significantly change the kinetics of the heterogeneous chemical reactions and the heat exchange between particles and gas. The influence of the thermal ionization of the flame on the nucleation mechanism and rate in gas-dispersed systems is discussed. The possibility of a barrier-free homogenous and heterogeneous nucleation in the dusty flame of metallic particles is shown. The effect of electrostatic and polarizing interactions of ions and molecules on the kinetics of the ternary gas-phase reactions is considered. The influence of the monodisperse aerosol ionization degree on the kinetics of its coagulation is analyzed. It is concluded that electrostatic interaction between the particles strongly affects the inhibition of the coagulation process in gas-phase combustion products and the possibility of very fast (explosive) charged particle coagulation of monodisperse aerosols. The possibility of the targeted size of metal oxides nanoparticles control, controlled ionizing of dusty flames and the role of ion particle entrainment, the dependency of their size of the flame ionization degree are discussed. Some effects arising in complex plasma of condensed combustion products under its own electric fields in flames, also when the burning dust is entrained into a constant electric field and their practical applications for diagnosis are considered.

1. Introduction

The idea of using plasmas to improve fuel burning has a long history and the last two decades is actively developing. Moreover, this became a relevant scientific and technical direction named Plasma Assisted Ignition and Combustion. For today, the majority of data of plasma impact on fuel conversion processes are obtained for a gas flame. Recent researches in this area are reviewed in [1].

The plasma impact on a dispersed fuel ignition and combustion processes in the oxidizing gas is less studied. At the same time, the available results of the gas-dispersed systems combustion show the effectiveness of this approach in the dispersed fuel conversion in energetics. For example, to intensify the burning of coals and the flame stabilization

in the industrial furnaces using the plasmatron [2] or to produce hydrogen from the combustion of the particles in the aluminum steam [3]. In [3] it is shown that the rate of the reaction of aluminum with water vapor in a nonequilibrium plasma is by 2–3 orders of magnitude greater than the rate of reaction without the plasma, i.e. the creation of plasma in a two-phase system leads to a significant acceleration of heterogeneous chemical reactions. The Institute of Combustion ONU conducted pilot experiments in order to stabilize the flame and to increase the intensity of combustion of organic dusts (guano, peat) using streamer discharges obtained by the Tesla generator. A significant achievement in stabilizing and enhancement of the burning rate of the investigated dust flames is reached.

* Corresponding author. E-mail: Poletaev@ukr.net

The presence of the dispersed phase in the flame causes the new effects as compared with the pure gases because of the particles charge. The great interest are unusual mechanisms of mass and heat transfer induced by the electric interaction between electrically charged particles of fuel and gas ions [4]. The complex plasma of the fuel combustion products makes the strong influence on the processes of condensation in flame [5–7].

Obviously, for the use of dusty plasmas in energetics and for the improvement of the technologies of the nanostructured materials synthesis by combustion methods it is necessary to understand the nature of the plasma effect on all the processes involved in the transformation of the dispersed fuel. Specifically – the initiation of the flame and its stabilization, the combustion intensity and kinetic processes of the formation of condensed combustion products – nucleation, coalescence and coagulation of the combustion products.

The understanding of the processes that occur in the ionized gas-dispersed systems will allow us to reach a qualitatively new level in increasing the efficiency of dispersed fuel combustion and technological applications of gas-dispersed systems combustion for better control of the condensed combustion products as target chemicals.

The purpose of this paper is to analyze the key effects, according to the authors, in a dust flame with a thermal ionization. These effects affect all major processes of dispersed fuel conversion which can be used in the development of variety techniques of nanoscale materials synthesis by combustion methods.

2. Discussion

2.1. Mechanisms of the ionization of gas and dispersed phases in a dusty flame

In the combustion process of dispersed metallic fuels and their gas-mixtures in the oxygen-containing environment the temperature increases to 2000–3000 K. This causes the thermal ionization of gas-phase atoms and molecules and charging of the condensed phase particles because of a thermal or photoelectron emission [8]. An important role in the ionization of two-phase high-temperature medium is played by atoms of electropositive and electronegative gases having a low electron work function or a high energy of electron affinity. In thermal ionization of flame the complex plasma consisting of electrons, positive and negative ions, charged particles of condensed phase and neutral gas is formed.

In the nonequilibrium plasma the condensed phase particles acquire a charge as a result of inter-

actions with ionized gas. An effective way of gas ionization is an electrical discharge in gas. Several types of discharges at atmospheric pressure, which form plasmas with different properties, are used for the intensification of a gas combustion [9]. Cold plasma is formed at the impact ionization by fast electrons in the corona discharge streamers, spark discharges, discharges through the dielectric barrier and is strongly nonequilibrium. The hot plasma is generated in electric arc AC or DC and leads to a strong heating of the ambient in the discharge channel, which significantly reduces the energy of electrons required for the flame ionization (in comparison with the cold plasma). In such plasmas, the electrons temperature is close to the gas temperature and the gas phase of plasma is close to equilibrium. There are also an intermediate plasma type, between cold and hot – “warm” plasma. “Warm” is a non-equilibrium plasma (electron temperature $T_e = 1\text{--}3\text{ eV} \gg T_g \sim 2000\text{ K}$) and can be obtained practically with any of the gas discharge.

The presence of particles in the condensed gas phase greatly complicates the description of such systems. If plasma is in equilibrium state (all plasma components have the same temperature) and a condensed component can be regarded as a plasma component (number of particles $N_{\lambda_D} = 4/3\pi\lambda_D^3 n_k$ in the Debye sphere is much greater than 1, where λ_D – the Debye screening radius for the electron and ion components, n_k – particle concentration), the ionization equilibrium in the system can be calculated by solving the system of Saha equations. This approach was used in [7.10] for the analysis of the ionizing equilibrium in the combustion zone of the metal particles dust flame.

In the non-equilibrium plasma of gas discharges the ionizing equilibrium of the nanoparticle with a radius r_k with the gas phase, in the condensed and gas phases with the parameters $r_k \ll \lambda_D \ll l_g$ can be determined in a limited approximation of the orbital motion (OML) [8]. For determination of charges of the microdispersed particles the diffusion approximation is used [8.11].

2.2. The ionization impact in kinetics of chemical reactions and transport processes

In the ionized gas-dispersed systems, the rate of heterogeneous chemical reactions may depend on electric charge of a particle. This effect is explained by increase in the kinetic energy of charged or electrically neutral polar gas molecules in the electric field of the charge on the mean free path of gas molecules l_g distance. The increase in the kinetic energy of the polar molecule (ε_T) is equal

to the variance of the electrostatic dipole energy $u(r) = -\frac{1}{4\pi\epsilon_0} \frac{pQ}{r^2}$ in the electric field of the particle in the length l_g (p – dipole moment of the molecule, Q – charge of the particles of a condensed phase, r – distance from the center of the particle to the dipole, ϵ_0 – electric constant). For the particle radius $r_k \ll l_g$ we obtain:

$$\epsilon_T = \frac{1}{4\pi\epsilon_0} \frac{pQ}{r_k^2} - \frac{1}{4\pi\epsilon_0} \frac{pQ}{(l_g + r_k)^2} \approx \frac{1}{4\pi\epsilon_0} \frac{pQ}{r_k^2} \quad (1)$$

When a charged particle interacts with an opposite sign charged ion q the ion kinetic energy will change as $\epsilon_T \sim qQ/r_k$. If $\epsilon_a = E_a/N_A$ is the activation energy of a chemical reaction per molecule (N_A – Avogadro's number, E_a – the activation energy of chemical reaction), only molecules with kinetic energy $\epsilon \geq \epsilon_a$ initiate the chemical reaction on the surface of the particle. The amount of those active molecules (ΔN) from the total number N can be estimated from the Maxwell distribution:

$$\Delta N = \frac{2N}{\sqrt{\pi}} \int_z^\infty \sqrt{z} e^{-z} dz \quad (2)$$

where $z = \epsilon_a/k_B T_B$ (k_B – Boltzmann constant, T_g – gas temperature). To consider the kinetic energy which the molecule acquires in the electric field of the condensed phase particle it is needed to replace the lower limit of integration in (2) to $z = \epsilon_a/(k_B T_g + \epsilon_T)$. For example, upon oxidation in steam of aluminum particles with radii $r_k = 1$ nm and minimal charge of $Q = 1.6 \cdot 10^{19}$ K at a temperature $T_g \sim 900$ K electrostatic interaction between the metal particles and water molecules lead to a 4-times increase in the number of molecules overcoming the barrier E_a , comparing to the case where this interaction is not considered (in the estimation $E_a = 200$ kJ/mol) [4]. This effect is equivalent to the “lowering” of the activation energy in the reaction by 1.7 times.

Thus, electrostatic and polarizing interactions in the plasma cause the powerful molecular pumps appearance. They affect the transport processes of the active reagents and thereby indirectly affect the kinetics of chemical reaction. In [4] it is shown for iron and aluminum particles oxidized in moist air that molecular pumps can lead to unexpected effects, when the main metal oxidant is not oxygen of the air but water vapor, the mole fraction of which is an order less than the oxygen concentration.

Another “kinetic” aspect of the condensed phase charged particles interaction with neutral

polar molecules or ions is the dependency of the effective cross section of the molecules collisions with a particle on the value of the electrostatic potential of the dipole (or ion) in the particle field. For polar molecules the effective radius of the collision cross section b can be estimated by equating the thermal energy potential of the dipole molecule

$$3k_B T_g / 2 = pQ / 4\pi\epsilon_0 b^2, \text{ hence } b = \sqrt{pQ / 6\pi\epsilon_0 k_B T_g}.$$

For particles smaller than 1–2 nm the effective cross section of collision may be several times greater than the geometric cross section of the particle. Therefore, the frequency of collisions of gas molecules with the particle's surface, which determines the pre-exponential factor in the Arrhenius law, may be significantly greater than in the absence of electrostatic interactions.

The intensity of heat exchange between particles in the free molecular regime is also determined by the collision frequency and thermal energy accommodation coefficient. As a result, the interaction of charged particles (clusters) with a polar molecule should lead to an improvement of heat exchange of small particles with the ambient. This mechanism is important for resetting the heat of combustion or condensation of small particles of the condensed phase.

If the particle size $r_k \gg l_g$, then from equation (1) it follows that $\epsilon \rightarrow 0$ and the molecular electrostatic pumps stop working. As in the neutral gas suspensions, thermal mass transfer of particles from gas is determined by the diffusion-kinetic factor $k\beta/(k + \beta)$. Moreover, the chemical reaction rate (k), and the rate of mass transfer (β), to a greater or lesser extent will influence flame ionization (rapid reaction with the radicals and ions, the Coulomb interaction reagents ambipolar diffusion of reactants, etc.).

2.3. Nucleation in the ionized dusty flames

Specificities of condensation of the ionized products in the metal dust flame in relation to the controlled synthesis of metal oxide nanoparticles was investigated in [5–7]. In [6] it is shown that in the conditions of metal dust flames, which are the source of metal oxide nanoparticles, nucleation is “fast”^[1]. This fact allows us not to take into account the evaporation of molecules from the surface of nuclei and therefore does not require a detailed analysis of the potential barrier of nucleation.

The effect of nuclei electrical charges on their free energy for Al_2O_3 is illustrated for homogeneous nucleation (Fig. 1a) and a heterogeneous ion-induced nucleation (Fig. 1b) for potassium ions. These curves were obtained in [6] for $T_g = 3150$ K, the degree of satiety condensable

vapors $S = 1.5$, the concentration of potassium ions $n_i \sim 10^{21} \text{ m}^{-3}$ and the concentration of particles of condensed phase $n_k = 10^{16} \text{ m}^{-3}$. Thermionic plasma is considered in the limiting cases $n_e \approx Z_k n_k$, where n_e – concentration of electrons, Z_k – charge number of nuclei (curves 1) and thermal ionization of impurities (potassium atoms), the concentration of which obeys the condition (curves 3). The “fast” nucleation ends with the exhaustion of the monomer atoms and the transition to the stage of the coalescence and coagulation.

Calculations made in [6] revealed an important distinction for the homogeneous nucleation of charged nuclei against classical homogeneous nucleation, which is the possibility of a barrier-free flow of nucleation (curve 1 in Fig. 1a). The absence of the activation barrier of the nucleation means that each molecule of the monomer is capable of growing as nucleus of the condensed phase. In this case, of fundamental importance is the primary rate of the nucleus, which is usually formed in triple collisions (this is important to reset the heat of condensation). If we do not take into account the reverse process, the reaction rate of the triple $A+B+C \rightarrow AB+C$ can be written as:

$$\frac{d[AB]}{dt} = K[A][B][C] \quad (3)$$

where C – buffer gas molecule. The constant of the triple reaction C , included in (3), can be estimated by the relation [13]:

$$K = b^3 \sigma v_T \quad (4)$$

where σ – molecular collision cross section,

v_T – average velocity of the thermal motion of gas molecules, b – critical distance between the molecules, which can be estimated from the condition of equality of the kinetic energy of the thermal motion of molecules and interaction potential of molecules A and B.

For electrically neutral molecules $K \sim 10^{-45} \text{ m}^6/\text{s}$ [13]. The presence of gas phase molecular ions can significantly affect the value b , and, therefore, a constant of the triple collisions (4). If the molecule is polar, the critical distance b to the interaction of those molecules with a molecular ion can be measured by the ratio $b \approx \sqrt{pQ/6\pi\epsilon_0 k_B T_g}$ (see 2.2),

where p and q are charge and dipole moment of the molecule, respectively. The values of the constants of triple collisions are estimated in [6] and for metal oxides they are $K \sim 10^{-43} \text{ m}^6/\text{s}$.

In the case of interactions of the molecular ion with the non-polar molecule a critical distance b can be expressed in terms of the molecular polarizability α . For example, in the reaction of a singly ionized molecule with an oxygen molecule ($\alpha = 1.51 \cdot 10^{-30} \text{ m}^3$, $q = e$, $T_g = 3200 \text{ K}$) the critical distance is $b = 1.4 \cdot 10^{-10} \text{ m}$ [6]. The reaction rate constant $K = 2 \cdot 10^{-45} \text{ m}^6/\text{s}$ of the same order of magnitude as one for triple collisions of electrically neutral molecules [13].

The reaction rate constant has its maximal value in the case of the oppositely charged particles. In the case of the Coulomb interaction of singly charged

ions of opposite sign $b \approx \frac{e^2}{6\pi\epsilon_0 k_B T_g}$ and, respectively, $K \sim 10^{-41} \text{ m}^6/\text{s}$.

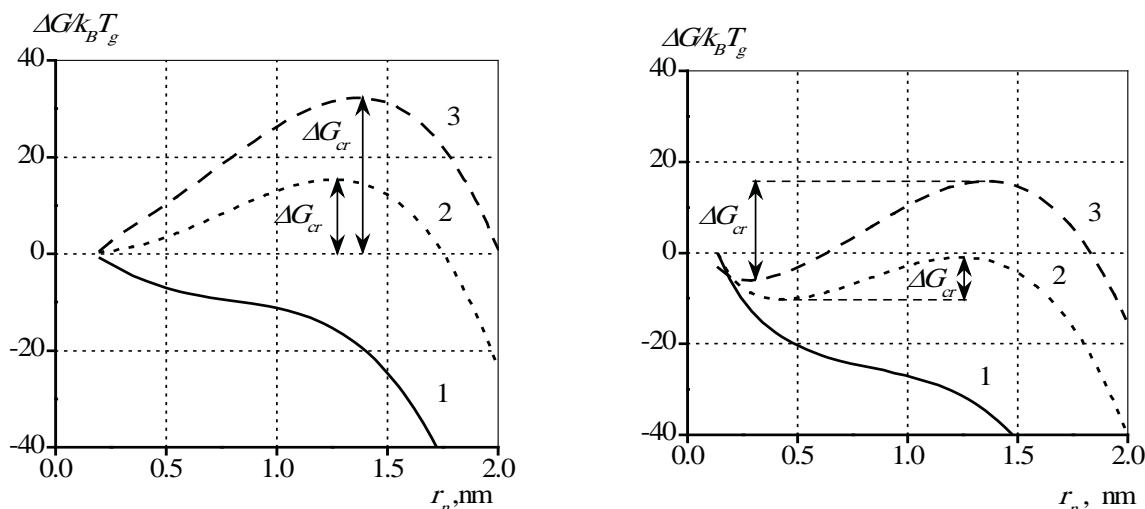


Fig. 1. Free energy of formation of Al_2O_3 nuclei versus their size) [6]: (a) homogeneous nucleation; (b) heterogeneous nucleation on potassium ions; 1 – thermionic plasma ($Z_n > 0$ and $n_k = 10^{16} \text{ m}^{-3}$); 2 – uncharged nuclei ($Z_n = 0$); 3 – capture of electrons from the gas phase ($Z_n < 0$, $n_i = 10^{21} \text{ m}^{-3}$).

^[1] According to [12] the nucleation is fast if the ratio of the time of formation of the nuclei to the time of the steam monomers collision is less than $10^3 \div 10^4$

The dependency of the rate constants of triple collisions of the electrostatic interaction of the reagents leads to a strong dependency of the rate of nucleation of nuclei sizes. It is estimated in [6] for aluminum products of combustion that values of $K = 10^{-41}$, 10^{-43} and 10^{-45} m⁶/s correspond to the characteristic times of nucleation $\tau = 3.8 \cdot 10^{-8}$, $2.7 \cdot 10^{-7}$ and 10^{-6} s with the number of molecules in the nuclei Al₂O₃, $n = 3, 50, 1490$.

2.4. Specificities of the ionized aerosol coagulation

According to the results of numerous studies focused on the development of methods for producing nanoparticles by combustion of organic and inorganic precursors in the flame, the coalescence and coagulation are the main processes that determine the final size of the synthesis products [11].

We show that the ionization of the coagulating aerosol leads to the appearance of some specificities that the neutral systems do not have. For example, let us consider the formation of monodisperse aluminum oxide nanoparticles in the combustion zone of aluminum particles dusty flame. The growing dynamics of the monodisperse aerosol in the ionized gas-dispersed system depends on the electrostatic interaction of coagulating particles and can be written as [7]:

$$\frac{dN}{dt} = -\frac{1}{2}k_{00}N^2 \left[\frac{k_{++}}{k_{00}}\alpha^2 + 2 \cdot \frac{k_{+0}}{k_{00}}\alpha \cdot (1-\alpha) + (1-\alpha)^2 \right] \quad (5)$$

where N – concentration of monodisperse particles, $\alpha = N_+/N$ – the degree of ionization of the condensed-phase particles, $k_{00} = 4 \cdot \sqrt{12k_B T_g r_n / \rho}$ – coagulation rate constant of neutral particles, which contain n molecules, ρ – particle density, $k_{++} = k_{00} \exp(-U_n/k_B T_g)$ – coagulation rate constant of like-charged particles, $k_{+0} = K_{00} [1 + (pE_n/9k_B T_g)^2]$ – coagulation rate constant of taking into account the polarization interaction of charged and neutral particles [7] in the non-uniform electric field E_n ,

generated by a charged particle, $U_n = \frac{1}{4\pi\epsilon_0} \frac{Z_n^2 e^2}{R_{min}}$ –

the energy of electrostatic interaction of particles with charge Z_n , $R_{min} = 2r_n$ – the minimum distance to which particles of radius r_n approach each other.

For strongly ionized systems ($\alpha \rightarrow 1$) it follows from (5) $\frac{dN}{dt} \approx -\frac{1}{2}k_{++}N^2$. Increase in the particle charge leads to an exponential decrease in the

coagulation rate of like-charged particles k_{++} and inhibition of coagulation (Fig. 2). The vertical line on the graph corresponds to the residence time of fuel particles in the combustion zone (the particle burning time $t_b = 4 \cdot 10^{-3}$ s). The unipolar charge of the particles leads to a decrease in the particle size with increasing temperature (curve 1 in Fig. 2). At temperatures 2900 K, 3000 K and 3150 K the calculated particle size decreases to 23 nm, 20 nm and 16 nm, respectively. Such a particle size dependency on temperature is confirmed by data of experiments [14], in which, for given temperatures, particle radii of 38 nm, 32 nm and 28 nm, respectively, were obtained.

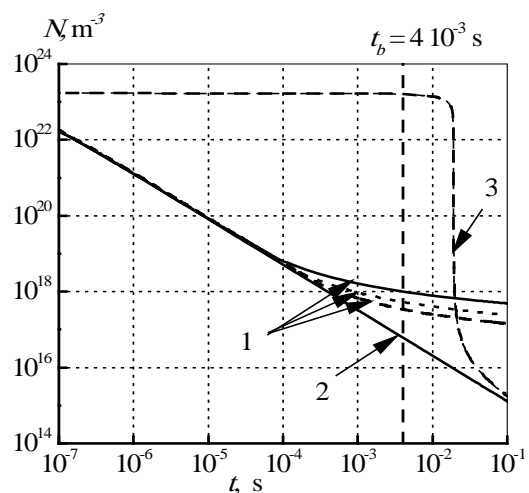


Fig. 2. Coagulation of Al₂O₃ particles with thermal ionization [7]: 1 – calculation by (6) for a single ($Z_n=1$) Saha ionization for $\alpha < 1$; 2 – calculation by (6) for $\alpha = 0$ ($Z_n = 0$, $T_g = 3000$ K); 3 – calculation of the particles charge $Z_n=1.3$ ($T_g = 3000$ K). Solid curve – $T_g = 3150$ K; curve points – $T_g = 3000$ K; dashed curve – $T_g = 2900$ K.

The curve 3 in Fig. 2 was obtained for constant charge of condensed-phase particles during coagulation and show that coagulation of the charged nuclei can be very fast. The charge $Z_n = 1.3$ was chosen to demonstrate that very rapid coagulation of the charged nuclei begins in a time t , exceeding the particle burning time $t > t_b$, i.e., the nuclei can leave the dust flame, bypassing coagulation stage.

In addition to emission processes, other factors that strongly influence the ionization equilibrium in the combustion zone of dust flames are natural or specially added impurity atoms of substances which can be easily thermally ionized. Thermal ionization of the additives leads to a redistribution of charges between the condensed and gas phases, a change in the charge of the particles and, hence, a change in the rate of their coagulation [7, 10, 15].

The results of numerical solution of Eq. (5) with the constant coagulation rate k_{++} at different concentrations of easily ionized additive in the micro-flame of aluminum particle are shown in Fig. 3 [7]. Increasing the concentration of potassium atoms (n_{A+}) in the range $n_{A+} = 3.3 \cdot 10^{19} - 3.3 \cdot 10^{22} \text{ m}^{-3}$ results in a marked inhibition of the coagulation process. As a result, it significantly decreases the size of Al_2O_3 nanoparticles. According to the calculations, the points of intersection of the straight line $t_b = 4 \cdot 10^{-3} \text{ s}$ with the curves of $N = f(t, n_A)$ correspond to particle sizes $r_n = 39, 16, 7,$ and 5 nm .

Reducing the size of Al_2O_3 nanoparticles with increasing concentration of impurities was confirmed experimentally [10, 15]. It has been found that the dependency of the average particle size Al_2O_3 on the concentration of easily ionized additive has an extremum (a minimum, Fig. 4). In these experiments, as fuel, the aluminum powder with a mean particle diameter 4.8 microns was used. The studies were carried for three kinds of thermally easily ionized additive: potassium carbonate (K_2CO_3), potassium chloride (KCl) and cesium iodide (CsI). Features of received dependencies were analyzed in the detail in [10, 15].

The drop-down dependencies which observed at low concentrations of impurity atoms were explained in [10] by slowing the coagulation rate of the like-charged particles. The growth of Al_2O_3 particles with increasing concentration of easily ionized impurities is due to the polarization interaction between the dusty and ion subsystems of the plasma. At high concentrations ($n_i > 10^{20} \text{ m}^{-3}$) of ions, this interaction leads to an increase in the coagulation rate and size of Al_2O_3 particles [10].

Due to the exponential dependency of k_{++} on the particle charges, the coagulation rate is significantly affected by the parameters of the system that affect the charges of the particles – the ambient temperature and the particle concentration, the value of the electron work function, and the ion concentration in the gas phase. This effect can be estimated by assuming that the coagulation of like-charged particles practically ceases when $k_{00}/k_{++} \leq e$. Then equation $k_{++} = k_{00} \exp(-U_n/k_B T_g)$ leads to the inequality

$$k_B T_g \leq \frac{Z_n^2 e^2}{8\pi\epsilon_0 r_n}, \text{ which can be used to estimate the}$$

size of the aerosol particles depending on the characteristics of the medium [12].

Accounting the polydispersity of the coagulating charged aerosol will lead with time to a decrease in the mean particle size and narrowing the particle size distribution function (the dispersion of distribution function) [16]. These features of the coagulation process are also poorly understood.

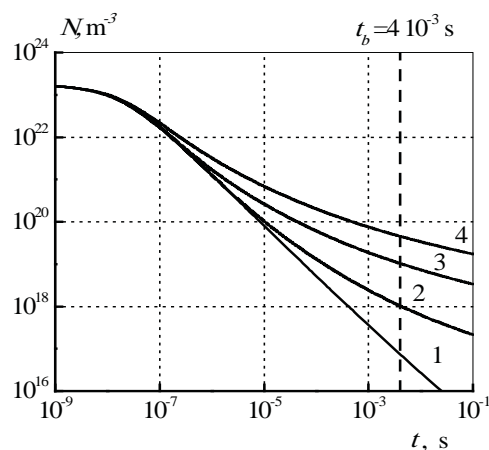


Fig. 3. Coagulation of Al_2O_3 particles in Al combustion with additives of K_2CO_3 [7]: 1 – $n_{A+} = 3.3 \cdot 10^{19} \text{ m}^{-3}$; 2 – $n_{A+} = 3.3 \cdot 10^{20} \text{ m}^{-3}$; 3 – $n_{A+} = 3.3 \cdot 10^{21} \text{ m}^{-3}$; 4 – $n_{A+} = 3.3 \cdot 10^{22} \text{ m}^{-3}$.

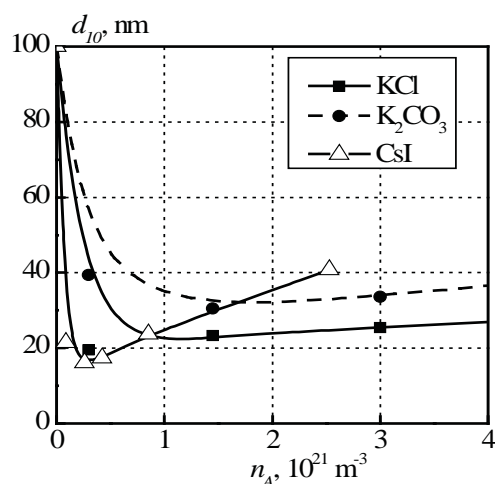


Fig. 4. Dependency of the average size of the Al_2O_3 particles on additive concentration [15]. (Points – experiment; line is an approximation).

2.5. The instability of the dusty plasma in the electric field

The presence in the flame of charged dust component has a substantial effect on the flame behavior in an electric field. For gas suspension of aluminum particles it has been shown [17] experimentally appearance of oscillations in the electric direct current circuit, which include a parallel-plate capacitor, between the plates, which are placed laminar dust flame. A possible cause of oscillations is the excitation stream instability [8], which is caused by the difference between the drift velocities of electrons, ions and charged particles in the plasma in an external electric field.

Theoretical analysis of the oscillations appearing in dusty plasmas of nanosized aluminum combustion products taking into account the interaction of charge carriers with neutral atoms is made in

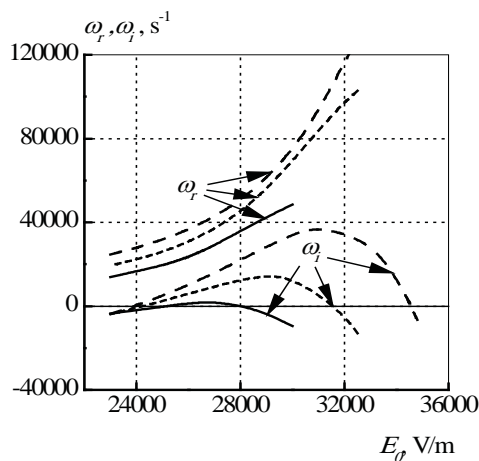


Fig. 5. Dependency of real (ω_r) and imaginary (ω_i) parts of electric field E_0 frequency at frequency wave number $K = 2.3 \cdot 10^5 \text{ m}^{-1}$ and $r_k = 80 \text{ nm}$ [18]. Particle charge number: Solid line – $Z_k = 60$; Shot-dash line – $Z_k = 80$; dash line – $Z_k = 100$.

[18]. The authors obtained the dispersion relation for the dielectric constant of the dusty plasma $\varepsilon(\omega, K) = 0$ (ω – oscillation frequency, K – wave number), which allowed them to show the existence of the critical electric field at which in the plasma the low-frequency oscillations of the condensed-phase particles have been raised (Fig. 5).

The oscillations arise only within a narrow range of the electric field parameter $E_0 = 24.0 \div 36.0 \text{ kV/m}$, when the growth increment of oscillations ω_i becomes greater than zero, and disappear with increasing E_0 , when $\omega_i < 0$. From calculations it follows sufficiently strong dependency of the electric field strength range E_0 on the particle charge Z_k (Fig. 5). The value of the critical electric field ($E_0 > 20.0 \text{ kV/m}$), which was observed in the experiments [17] is in a good agreement with calculated values [18].

Based on the effect observed in [17], it is proposed a new noncontact method of determination of the size and charge of the particles of combustion products [19]. The method is based on the excitation of plasma oscillations in the dust flame and the study of the frequency spectrum. The size and charge of the particles is determined by solving the equations for the charge of the particles, the plasma oscillation frequency and the dispersion relation $\varepsilon(\omega, K) = 0$.

3. Conclusions

The analysis of the ionization effect in dusty flames on the main flame processes – the heat and mass transfers, chemical kinetics, and the formation of the condensed combustion products – is made for the equilibrium thermal complex plasma.

There is good reason to believe that the considered specificities of the ionized gas-dispersed systems combustion will have an important application for energetics and technology. However, the degree of thermal ionization of the two-phase system is limited by the physical and chemical properties of the fuel, its combustion process and the environment temperature. From the standpoint of increasing the ionization degree of the gas-dispersed system it can be assumed that a non-equilibrium dusty plasma, which is produced by electrical gas discharges, has great perspectives in the affecting the combustion process.

For today, we have a little data on the effect of non-equilibrium gas discharge plasma on all stages of the dispersed fuel conversion. The high reactivity of ambient caused by radicals and atoms, excited molecules of oxygen and ozone can significantly affect the mode and rate of fuel particles combustion. The higher ionization degree of the gas and dispersed phase due to electric gas discharges, can lead to significant changes in the kinetics of chemical reactions and kinetics of the combustion products condensation. The rate of the condensed phase nuclei formation can be increased and their size decreased. In a strongly ionized system, the coalescence and coagulation rates of same-sign charged particles can significantly slow down. New opportunities for practical applications of dusty plasmas stimulate the development of scientific researches in this area.

It is important to note that the energy expenses for the ambient ionization via electrical gas discharge are not of a fundamental importance for the technological problems in the area of the synthesis of new materials by combustion methods in contrast to the energy production problems. This allows us to use all advantages of different types of gas discharges with great efficiency. This also requires better understanding of the processes occurring in complex plasmas in the dusty flame combustion zone. Finally, it will allow developing the effective methods to control the properties of the nanoscale materials synthesized by the combustion methods.

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