ON A POSSIBILITY OF THE EXISTENCE OF DUSTY PLASMA OSCILLATIONS IN THE FRONT OF AN ALUMINUM PARTICLE FLAME[1]

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The occurrence of dusty plasma oscillations in the combustion zone of an aluminum laminar dust flame in a constant electric field is experimentally found. The characteristics of thermoemission plasma in the combustion zone such as the electron concentration $n_e \sim 10^{12}$ cm^3, charging numbers $Z_k = 100 - 150$ of Al_2O_3 particles with the diameter $d_{30} = 0.16$ μm, and the most probable oscillation frequency $\nu_k = 24.5$ kHz are determined. Due to the injection of easily ionizable additions to the initial fuel, we vary the dispersion of condensed-phase particles. The dependence of the dusty plasma oscillation frequency on the condensed-phase particle size is shown. The reason for oscillations is analyzed. The occurrence of oscillations is related to the current instability of charge carriers, electrons and Al_2O_3 particles, arising as a result of the large difference of their drift velocities in an electric field.

1. Introduction

One of the practical applications of dust metal particle flames is their use in the production of metal oxide nanoparticles which are of great interest for modern materials science. At the Institute of Combustion and Advanced Technologies of Mechnikov Odesa National University, the scientific foundations of a new method of gas-dispersed synthesis (GDS) for the production of disagglutivative nanopowders (the average size of spherical particles in the range 20–100 nm) of metal oxides Al_2O_3 ZrO_2, TiO_2, ZnO, Fe_2O_3, MgO, *etc.* [1, 2] are developed. The main idea of this method consists in the burning of metal particles (pure metals or mechanical mixtures or alloys of different metals) in specially organized dust flames. The end product is formed as a result of the physico-chemical condensation of gas-phase products of the combustion of metals in an oxidizer.

Within the GDS method, metal oxide nanopowders are produced in a self-sustaining laminar dusty flame, in which the metal powder is burned in a gaseous oxidizer. According to the procedure of mixing of a powdery fuel and a gaseous oxidizer, two primary types of dispersed flame exist: 1) laminar premixed flame (LPMF), when a carrying gas is the oxidizer [3] and 2) laminar two-phase diffusion flame (LTDF), when a dispersed fuel in the rarefied gas burns in the distrail of an oxidizer [4,5]. The main macroparameters of these types of flames are the mass concentration of fuel in a solid suspension, concentration of oxygen in a solid suspension (LPMF) or in the blowing distrail flow (LTDF), fuel dispersity, the kind of a carrying gas (nitrogen, argon, helium, oxygen), and the initial temperature of a fuel particle suspension. It is expected that, by varying these parameters, it is possible to influence the conditions of the combustion of metal particles in a flame, environment temperature, and concentration of the condensed phase in the dusty environment, and, consequently, combustion product dispersity. However, the earlier research [1,2] had found a rather weak influence of the listed macroparameters on dispersed properties of combustion products. Therefore, a problem of purposeful control over the dispersity of end products synthesized in flames is actual up to now.

A more promising way to change a dispersity of dispersed combustion products is to influence a dust flame from the outside (by magnetic and electric fields, irradiation by ultra-violet radiation, ionization of the system by additions or electric discharges, *etc.*) with the purpose to affect the processes of nucleation and condensation in the gas phase. On the combustion of metal particles or their solid suspension, the high temperatures up to and over 3000 K are developed. This results in the intensive processes of ionization of atoms and molecules which have a low potential of ionization and in the thermionic emission from the surface of condensed particles [6, 7]. The presence of the dust component in a flame significantly affects the collective processes in plasma [8,9]. The dust not only modifies,

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[1] The results of the work were reported at the 2nd International Conference "Dusty Plasmas in Applications" (August 26–30, 2007, Odesa, Ukraine).

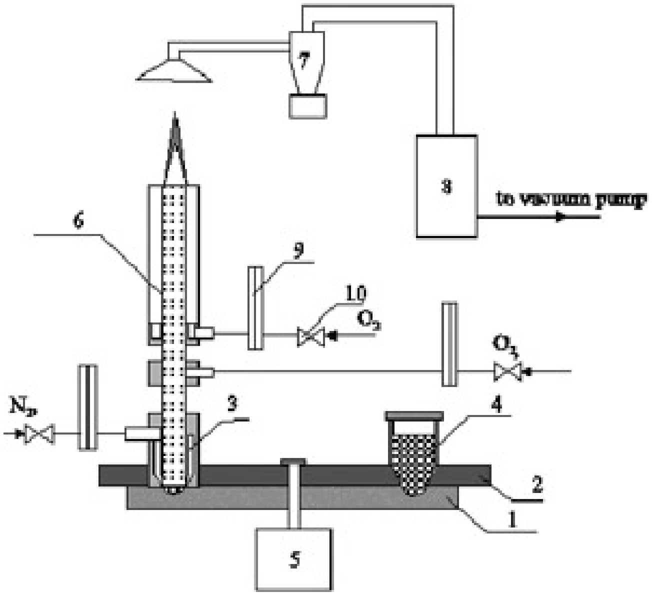

Fig. 1. Experimental setup: *1, 2* – feed system; *3* – dispersion unit (stage); *4* – bin with a metal powder; *5* – electric motor; *6* – dusty burner; *7* – cyclone; *8* – fabric filter (baghouse); *9* – flow rate meter; *10* – gas-main

but frequently defines a spectrum of oscillations and influences the effects of attenuation and instability. Moreover, the charged particles are good centers of condensation.

In the present work, we investigate the behavior of a laminar dust flame of aluminum particles in an external constant electric field. Aluminum was chosen as fuel, because the burning features of this metal and the characteristics of combustion products are investigated more than those for other metals [2, 10]. The basic purpose of these researches is to clarify an opportunity to influence the dispersity of metal dust combustion products by changing the concentration of charged particles, ions and electrons, and by affecting them by external electric and magnetic fields.

2. Experiment Technique

A dust flame of Al particles was obtained with the help of a “dust burner” [2, 10] consisting of two vertical coaxial cylinders (Fig. 1). Aluminum particles are fed by a carrying gas (inert gas, oxygen, a mixture of oxygen with nitrogen) through an internal burner pipe with a diameter of 2.4 cm. For LTDF, the oxidizing gas was fed through the annular gap between the external (the pipe diameter was equal to 5 cm) and internal pipes. The volumetric charges of gases in the feed-blow system were controlled by standard rotameters.

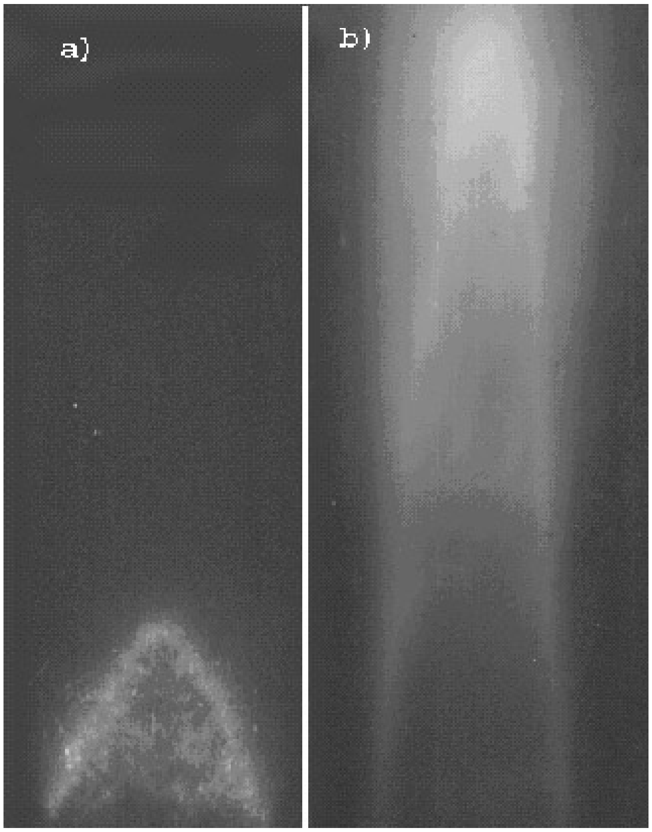

Fig. 2. Photos of flames a) Al LTDF; b) Al LPMF

The Al laminar diffusion and premixed flames for the same mass concentration of the metal and equal solid suspension flow velocities are shown in Fig. 2. The length of LPMF by some times exceeds that of LTDF. This can be explained by the fact that the burning-out intensity of a fuel in LPMF is defined by the rate of the chemical reaction of a metal dust with oxygen; whereas, in LTDF, the intensity is determined by the rate of the diffusion mixing of oxygen with a dispersed fuel which is fed by an inert gas (nitrogen, argon, helium). A chemical reaction rate is, as a rule, much more than the rate of diffusion. This is the reason for such a difference in the characteristics of LTDF and LPMF.

To reach the 100-% combustion efficiency in LPMF, an oxidizer surplus is created in the solid suspension. The combustion front in diffusion flames is established on the boundary, where the consumption of an oxidizer and a fuel takes place in the stoichiometric ratio.

The burning of metal particles occurs in the narrow (thickness of 1–2 mm) conic front of a flame. The

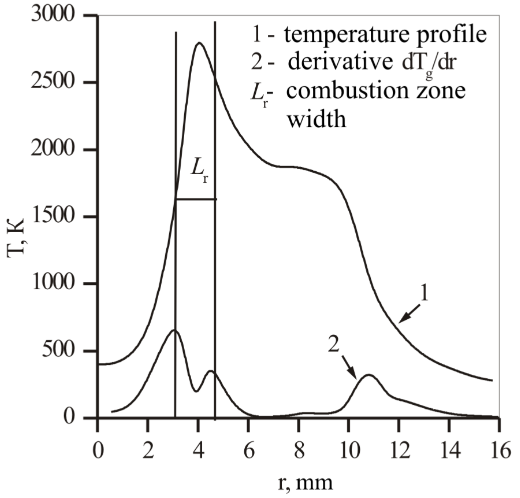

Fig. 3. Radial distribution of the Al LTDF temperature

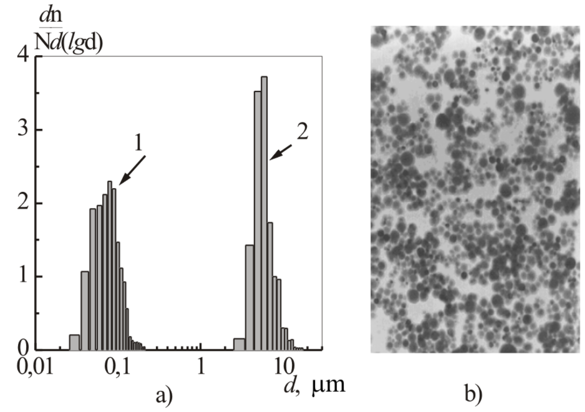

Fig. 4. Size distribution and appearance of Al_2O_3 nanoparticles: *a*) size distribution of Al_2O_3 particles (1) and initial Al fuel(2) *b*) photo of Al_2O_3 nanoparticles (magnification x20000)

temperature profile, which is typical of a laminar flame, in one of the flame sections is shown in Fig. 3 [5]. As will be shown below, the combustion zone of a burning Al flame can be considered as the thermal plasma with a condensed dispersed phase.

To produce nanoparticles, it is necessary that metal particles be burned with the formation of products in the gas phase, i.e. in the vapor-phase or gas-phase mode. The vapor-phase combustion of particles is realized, when the temperature of particles reaches the boiling temperature of metal particles. This condition is easily satisfied for such metals as Mg, Al, and Zn. Otherwise, particles are burned either in the gas-phase regime with the formation of nanoscale combustion product particles (metal oxides) (Zr, Al, Ti, Fe) or heterogeneously (Zr, Ti, Fe). On the heterogeneous burning, the consumption of an oxidizer occurs on the surface of a solid or a fused particle with the formation of the condensed phase of combustion products on it. In this case, oxide particles have the spherical form with a size close to that of the initial fuel.

The dispersion characteristics of nanoscale aluminum combustion products in a dust laminar flame depend slightly on a means of the organization of the solid suspension burning process (LTDF or LPMF) [2]. But, as the source of end products of aluminum oxide nanoparticles, LTDF is essentially more "technological" than LPMF, because the inert solid suspension of Al particles and the oxidizing gas (O_2) are fed separately, which excludes the flame breakthrough into the preparation system of a solid suspension. Therefore, we will consider a diffusion dust flame with Al particles.

In experiments, a commercial powder of aluminum (the average diameter of particles $d_{10} = 4.8$ μm) was used. The powder was fed by nitrogen with a purity of (97–99)%. Technical oxygen was used as an oxidizer. The volumetric charges of carrying and oxidizing gases were equal to $W_1 = 200$ cm^3/s (carrying gas) and $W_2 = (500 - 800)$ cm^3/s, respectively. The concentration of a fuel on the output of a flame C_{Al} was 3.5×10^{-4} g/cm^3 (the concentration of particles $n_p = 6C_{\mathrm{Al}}/\pi\rho_{\mathrm{Al}}d_{30}^3 = 2 \times 10^6$ cm^3, ρ_{Al} is the metal density; and d_{30} is the root-mean-cube diameter of Al particles). The solid suspension velocity averaged over a cross-section was $v = 50$ cm/s.

The dispersion analysis of combustion products was done by a technique which was developed at the Institute of Chemical Physics of Russian Academy of Science. This technique is based on the direct measurement of sizes of particles and the determination of their form with the help of an electron microscope. For aluminum oxide which was produced in LTDF, the basic parameters of the distribution are as follows: the average size $d_{10} = 0.1$ μm, root-mean-square size $d_{20} = 0.13$ μm, and root-mean-cube size $d_{30} = 0.16$ μm. A photo of Al_2O_3 particles and their size distribution are shown in Fig. 4.

The phase composition of combustion products was determined with the help of an x-ray diffractometer. It was found that (90–95)% of aluminum oxide is the γ-modification ($\rho_{\mathrm{Al_2O_3}} = 3.5$ g/cm^3). The remainder consists of a mixture of crystal phases of the α- and β-modifications. The γ-modification is in prevalence because of the "freezing" of the crystal structure of

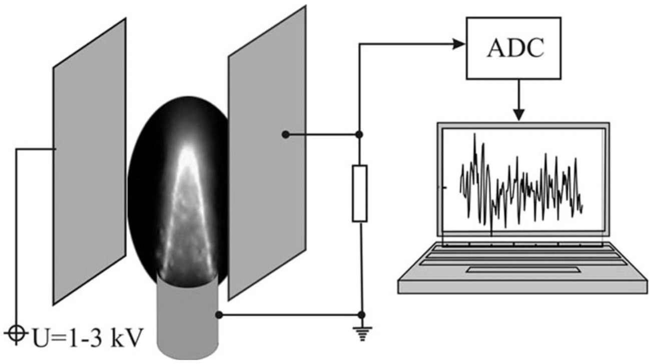

Fig. 5. Experimental setup for the observation and the determination of the frequency of dusty plasma oscillations

aluminum oxide fine particles as a result of their fast cooling outside of the combustion zone.

The temperature of the condensed phase of a flame with the above-mentioned macroparameters was defined by the spectral luminosity (r_λ) of the combustion zone in a wide enough spectral interval. From the dependence of ln ($r_\lambda \lambda^5$) on $1/\lambda$, we determined the wavelength interval, in which the plot represents a straight line. In this interval, the radiation can be considered grey, and this allows us to obtain the true temperature by the slope angle tangent of the line to the x-axis $T_k = (3150 \pm 100)$ K [10]. The temperature of the gas phase was determined by the intensities of the edging of the AlO lines [12]. The gas phase temperature $T_g = (3200 \pm 100)$ K. At a fixed difference between the gas phase temperature and the condensed phase temperature, the problem of heat transfer between the flame and the environment was solved in work [10]. For the problem which is investigated in the present work, this temperature difference is inessential, and we will consider that the combustion zone of a flame is quasiisothermal in the first approximation.

The observed width of the flame front (L_f), which was determined from the radial distribution of a light flux ($\lambda = 800$ nm) by performing the Abelian transformation, is $L_\mathrm{f} = (0.12 \pm 0.02)$ cm.

To study the influence of an external electric field on characteristics of a laminar dust flame with metal particles (the form and the height of a flame, dispersity of combustion product particles, sign of their charge at the combustion, *etc.*), an Al LTDF after the stabilization was placed in a constant electric field. The scheme of the experimental setup is shown in Fig. 5.

The field was created between the plates of a plane condenser, the distance between which d was equal to 7 cm and obviously exceeded the maximal diameter of a flame (2.8 cm). To the plates, we applied a direct voltage from 1 to 3 kV. The metal tube of a "dust burner" was grounded. The electric signal was taken from a resistance ($R = 70$ kΩ, and the time constant of the system $\tau = RC = 10^{-8}$ s, where $C = \varepsilon\varepsilon_0 d/S$ is the capacity of the condenser) and was digitized with the help of an analog-digital converter (ADC) with a frequency of 100–200 kHz. The signal was registered and processed with the help of a personal computer.

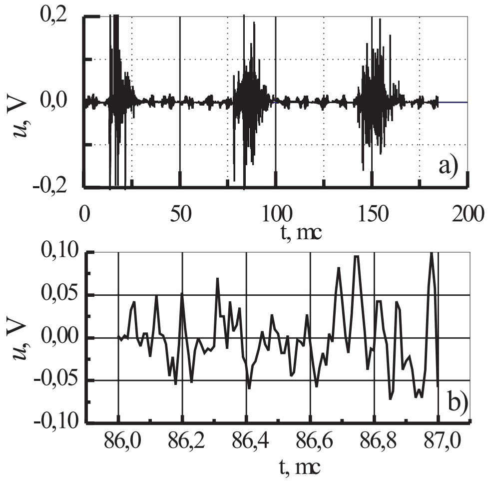

Fig. 6. Fragment of a signal digitized by ADC *a*) packages of impulses; *b*) structure of a package

3. Results and Discussion

On the application of a direct voltage to the plates of a condenser, the external field insignificantly deforms (stretches) the surface of a flame. The condensed combustion products are deviated by the field to the negatively charged plate (to the left in Fig. 5), but they are carried away by a gas stream, by having no time to reach the plate. The conduction current through the condenser is absent.

It was revealed that, at some voltage $U = U_\mathrm{cr}$ (in our experiments, $U_\mathrm{cr} = 2$ kV) in the circuit, there appear electric oscillations. These oscillations have form of wave packages (Fig. 6,*a*) which follow one by one with a frequency of about 15 Hz. Each package contains high-frequency (tens of kHz) oscillations in a wide enough range (Fig. 6,*b*). The amplitude of oscillations very quickly grows, but then there occurs a decay of oscillations (the amplitude of oscillations quickly enough falls up to zero). Oscillations are absent some time, then the process again repeats, by resulting in the generation

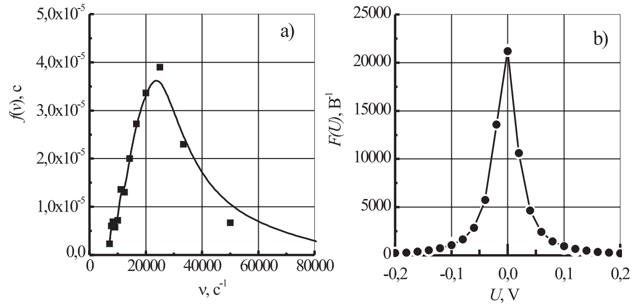

Fig. 7. Spectrum of electric oscillations (a) and the amplitude distribution function (b) ● – experiment; a continuous line – approximation

of the following wave package. We note that the change of the polarity of a voltage on the condenser does not affect both the conditions for the appearance and the characteristics of observable oscillations.

The statistical processing of the obtained oscillations has allowed us to construct the frequency spectrum $f(\nu)$ and to determine the frequency $\nu_0 = 24.5$ kHz corresponding to the maximum of a wave package distribution function (Fig. 7,a). We can see from Fig. 7,b that the oscillation amplitude varies in a random manner. However, signal-amplitude distribution function has the well-defined Lorentz shape (a continuous line in Fig. 7,b) with a factor of correlation equal to 0.997.

The observed oscillations can be a result of the recharge of the condenser. As the conduction current between plates is absent at all voltages, the condenser recharge can be explained by a change of the dielectric permittivity (ε) between the condenser plates. It is possible to show that, to ensure a peak value of registered signals ($U_{\max} \sim 0.1$ V), it is enough to change the condenser capacity ($\frac{\Delta C}{C} = \frac{U_{\max}}{U_{\rm cr}\tau\omega}$, where $\omega = 2\pi\nu$ is the oscillation frequency) by less than 2 %. However, this assumption does not allow us to explain the existence of the sufficiently high threshold voltage ($U_{\rm cr} \sim 2$ kV), at which the oscillations arise. The mechanism which results in the modulation of the dielectric permittivity in the combustion zone of a flame in a constant electric field is not clear as well.

The existence of a critical voltage is related, in our opinion, to the occurrence of the conduction channel between the grounded metallic tube of a burner and a plate of the condenser. In this case, there is the electric current of charged particles with essentially different drift velocities (particles of the condensed phase, thermoelectrons, ions), which is, most probably, a reason for the occurrence of the instability resulting in the occurrence of oscillations. The presence of the conduction channel between a flame and a plate of the condenser allows us to make conclusion on the nature of low-frequency electric signal packages. In our opinion, the fast growth of an instability in the thermal plasma, which is accompanied by a sharp increase in the signal amplitude, results in the disappearance of the conduction channel and, therefore, in the disappearance of oscillations. Its restoration occurs with a frequency of about 15 Hz.

The knowledge of the structure and characteristics of plasma components in the combustion zone of a dusty plasma flame is necessary in order to understand the nature of oscillations. The researched dispersed system contains molecules with a high ionization potential (N_2, O_2). The executed estimations show that, at temperatures about 3000 K, their ionization can be neglected. It is known that, at the combustion of Al particles, aluminum gaseous suboxides (AlO, Al_2O, Al_2O_2) are formed. The ionization of these suboxides can influence the general pattern of the process. But, as was shown in [13], these suboxides are localized in the narrow zones over the burning Al droplets. Therefore, their average concentration in the volume of the combustion zone is small, and we neglect their charge contribution. Hence, in the first approximation, we can neglect the ionic plasma component. We believe that, at atmospheric pressure, the temperature of the electron component is close to T_g, so that the plasma is isothermal. We have

$$n_e = Z_p n_p + Z_k N_k, \tag{1}$$

where Z_p and Z_k are the charging numbers for Al and Al_2O_3 particles, respectively. The concentration of Al_2O_3 particles can be obtained from the equation of mass balance

$$N_k = \frac{6C_{\rm Al}\xi}{\pi d_{30}^3\,\rho_{\rm Al_2O_3}} \approx 10^{11}\ {\rm cm}^{-3},$$

where $\xi = 1.89$ is the mass stoichiometric factor of the aluminum-oxygen reaction. In view of the tenfold ($T_g/300 \approx 10$) thermal expansion of the gas phase, $N_k \sim 10^{10}$ cm^{-3}. The concentration of submicron combustion product particles by 5–6 orders of magnitude exceeds the concentration of initial metal particles (with regard for the thermal expansion, $n_p \sim 10^5$ cm^{-3}). In our opinion, the ratio of charge numbers Z_p/Z_k of micron and submicron particles equals 2–3 orders. We note that the thermoelectric work function for aluminum oxide ($W_{\mathrm{Al_2O_3}} = 4.7$ eV) is more than that for aluminum ($W_{\mathrm{Al}} = 4.25$ eV) [14]. For this reason, the thermoemission property of aluminum is higher than that for aluminum oxide. But this difference is practically compensated by different temperatures of Al and $\mathrm{Al_2O_3}$ particles, so $\exp(-W_{\mathrm{Al_2O_3}}/k_bT_g) \approx \exp(-W_{\mathrm{Al}}/k_bT_{\mathrm{Al}})$. Therefore, the enough strong inequality $Z_kN_k/Z_pn_p \gg 1$ holds, which allows us to write down the equation of quasineutrality as

$$n_e \approx Z_kN_k. \tag{2}$$

The electron concentration was determined with the use of a double probe by a technique recommended in work [15] as $n_e = (1.5 \pm 0.5) \times 10^{12}$ cm^{-3}. The condition of quasineutrality (2) allows us to determine the average value of charging numbers: $Z_k = 100 \div 150$.

It is clear that, despite the very narrow combustion zone of a dust flame ($L_{\mathrm{f}} = 0.1 - 0.2$ cm), we have all bases to speak about the existence of a low-temperature thermal plasma in the combustion zone. Really, the Debye length has size

$$\lambda_k \approx \lambda_e = \sqrt{\frac{k_bT}{4\pi n_e e^2}} = 3.2 \times 10^{-4} \text{ cm}.$$

That is, the necessary condition for the existence of a plasma, $L_{\mathrm{f}} \gg \lambda_k$, is satisfied.

Electric oscillations observed by us cannot be caused by the electron component of a plasma, since the electron plasma frequency

$$\nu_e = \frac{1}{2\pi}\sqrt{\frac{4\pi n_e e^2}{m_e}} \approx 10^{10} \text{ Hz}.$$

This value is much more than the registered electric oscillation frequency $\nu_0 \sim 10^4$ Hz. At the same time, the frequency of these oscillations is close to the dusty plasma frequency

$$\nu_k = \frac{1}{2\pi}\sqrt{\frac{4\pi N_k Z_k^2 e^2}{m_k}} \approx 3.1 \times 10^4 \text{ Hz}. \tag{3}$$

The character of observable oscillations (a sharp increase of the amplitude, its fast reduction, and the periodicity of this process) allows us to assume that the reason for oscillations in an external electric field is the instability current which can arise due to the movement of electrons and ions relative to charged dust particles. The reason for this is the difference in the drift velocities of electrons, ions, and condensed phase particles in an electric field. This kind of instability was observed in a glow-discharge plasma [16] and in a collisional dusty plasma of negatively charged particles in a constant electric field [17].

To research the dependence of the spectrum of oscillations on the time, we present the oscillation frequency as $\omega = \omega_r + i\gamma$, where $\omega_r = \mathrm{Re}(\omega)$ and $\gamma = \mathrm{Im}(\omega)$ are the real and imaginary parts of the frequency [18, 19]. The conditions $\gamma > 0$ and $\gamma < 0$ correspond, respectively, to the increase of oscillations (increment of growth, occurrence of instability) and the attenuation of oscillations (logarithmic decrement). By analogy with work [16], the condition $\varepsilon(\omega, k) = 0$ and the inequality $\omega_r \gg \gamma$ yield the low-frequency spectrum of a dusty plasma:

$$\omega_r^2 = \omega_k^2 \frac{k^2\lambda_k^2}{1 + k^2\lambda_k^2}, \tag{4}$$

$$\gamma = -\sqrt{\frac{\pi}{8}} \frac{\omega_r^2}{\omega_k^2 k^3 \lambda_k^2} \frac{\omega_r - u_e k}{v_e}, \tag{5}$$

where u_e – electron-drift velocity, $k = 2\pi/L$ – wave number, $v_e = \sqrt{\frac{8T_gk_b}{\pi m_e}}$ – average thermal velocity of electron movement, and $\omega_k = 2\pi\nu_k$ – cyclic plasma frequency.

The model of work [16] cannot be used for the adequate description of the oscillation spectrum, because its substantiation is based on the model of collisionless plasma. Nevertheless, this model allows explaining the reason for the occurrence and the qualitative features of observed oscillations.

The instability arises, when $\gamma > 0$. It follows from (5) that this takes place if the phase velocity

$$v_{\mathrm{ph}} = \frac{\omega_r}{k} < u_e. \tag{6}$$

The electron-drift velocity $u_e = \mu_e E$, where μ_e – electron mobility, whose value can be estimated by the Einstein's formula $\mu_e = \frac{eD_e}{k_bT}$. According to work [20], the diffusion coefficient of electrons in nitrogen at atmospheric pressure and $T \sim 2000$ K is $D_e \sim 0.3$ m^2/s. At the environment temperatures about $T_g \sim 3000$ K, it is possible to expect a higher values of D_e. The electron-drift velocity at the such parameters of the environment and the electric field intensity is of the order of magnitude of $u_e \sim 10^3$ m/s.

In Fig. 8, we present the calculated dependences of the dispersion $\omega_r(k)$ (Fig. 8,*a*) and the growth increment $\gamma(k)$ (Fig. 8,*b*) constructed from Eqs. (4) and (5). The

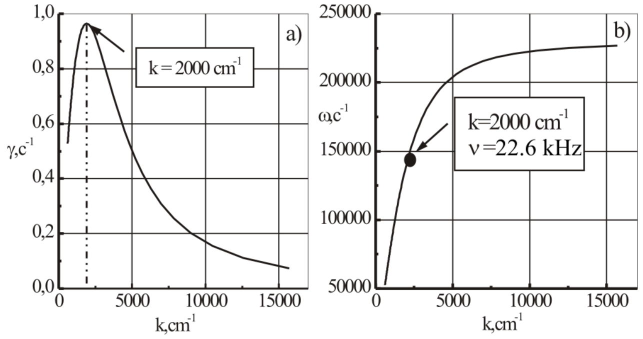

Fig. 8. Dispersion $\omega(k)$ (a) and the growth increment $\gamma(k)$ (b) of dusty plasma oscillations

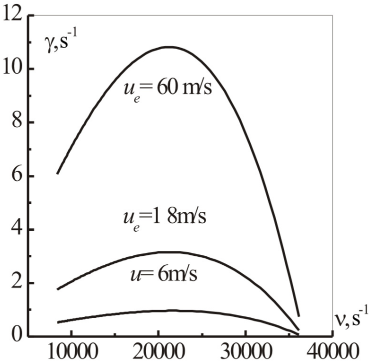

Fig. 9. Growth increment of oscillations versus the frequency ($\nu = \omega_r/2\pi$)

growth increment has a maximum at $k = k_m = 2000$ cm^{-1}. This value of the wavenumber corresponds to the cyclic oscillation frequency $\omega_r = 142000$ s^{-1} or $\omega_r = 22.4$ kHz. The dust-acoustic wavelength is $L = 2\pi/k = 3.1 \times 10^{-3}$ cm, and the phase velocity of wave propagation is $v_{\text{ph}} = \omega_r/k \approx 65$ cm/s. We note that the value of the dusty plasma frequency ν_r which was obtained from the model developed in [16] is in good correspondence with the oscillation frequency observed in our experiment, $\nu_0 = 25.4$ kHz.

The value of the phase velocity v_{ph} is significantly less than that of the electron-drift velocity (u_e). Thus, the condition for the occurrence of instability (6) will be practically satisfied at any voltage on the condenser. However, the oscillations appear probably only in the presence of the electric current of charge carriers with various drift velocities. As was mentioned above, such a current arises in the presence of the conduction channel between the combustion zone of a flame and plates of the condenser at some critical voltage (U_{cr}). The disappearance of the conduction channel results in the disappearance of oscillations.

The growth increment of oscillations rather strongly depends on the electron-drift velocity (Fig. 9, calculation by formula (6)). At the same time, a position of the maximum of the dependence $\gamma = f(\omega_r)$ does not depend on the electron-drift velocity.

It is shown in work [2] that the introduction of $(1 \div 5)$ mass. % of a metal powder into the solid suspension can increase essentially the dispersity of combustion products. This effect was explained by that the impurities (through the ionization of the environment) influence the processes of nucleation and condensation of combustion products. To find out how the impurities affect the characteristics of dusty plasma oscillations, we carried out the LTDF experiment with Al + 1 % KCl. KCl was chosen as an impurity in order that the thermionic emission conserve the leading part in the environment ionization (potassium easily gives electrons, and chlorine effectively captures them; thus, the electron concentration is defined by thermoemission properties of the environment and, as before, the equation of quasineutrality (2) is valid). The impurity was injected to the mixture by the following way. The initial mixture was prepared from 99 % of an Al powder by mass with the average size of near 4 μm and from 1% of a KCl powder by mass. KCl was dissolved in distilled water. The Al powder was put into that solution, and then the solution was mechanically homogenized. The resulting mixture was dried in a drying box at a temperature up to 800–900 C. Then the drew-through powder was mechanically dispersed and sifted.

The dispersion analysis of combustion products of Al LTDF was done earlier in [2], where we used an electron microscope (the main characteristics of the distribution of Al_2O_3 particles are $d_{10} = 0.1$ μm, $d_{20} = 0.13$ μm, and $d_{30} = 0.16$ μm) (see in Fig. 1). Such an analysis is a very laborious method which needs plenty of time and efforts. Therefore, in this case, we didn't go beyond the qualitative comparison of a pure Al combustion product with a pure Al + 1% KCl combustion product. In Fig. 10, the photographs of the water suspension of products of Al GDS, which were prepared simultaneously and photographed after 30 days, are shown. The different ranges of precipitation are the evidence of the increased dispersity of combustion product particles of Al LTDF with KCl as an impurity.

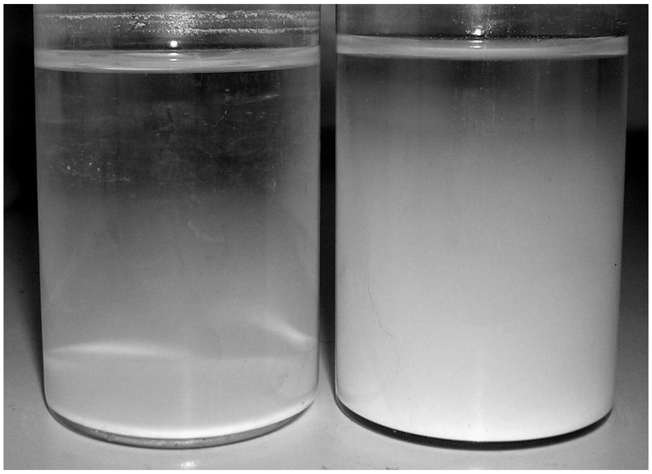

Fig. 10. Photos of Al_2O_3 water suspensions *a*) product of Al LTDF; *b*) product of Al+1% KCl LTDF

4. Conclusions

The experimental researches of aluminum particle dust flames in an external constant electric field have shown an opportunity of the occurrence of plasma oscillations of the condensed components of a thermal plasma in the combustion zone of a dust flame of metal particles at atmospheric pressure under certain conditions.

The reason for the occurrence of oscillations most probably is the current instability which is caused by a great difference in the drift velocities of electrons and positively charged condensed particles in the combustion zone of a flame in an electric field. The positive point of such a mechanism of the instability in a thermal plasma is the absence of oscillations at voltages on the plates of the condenser less than the critical value (under our conditions, $U_{\rm cr} < 2000$ V), when the conduction current between the combustion zone of a flame and a plate of the condenser is absent.

The addition of an impurity (1% KCl) into the suspension of metal particles results in an increase in the dusty plasma oscillation frequency, which is caused by a reduction of the condensed product particle size. This allows us to offer a means, practically in the regime of real time, to obtain the information about the influence of conditions of the dust combustion on the combustion product dispersity by the control over the dusty plasma oscillation frequency in the front of a dust flame.

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ПРО МОЖЛИВІСТЬ ІСНУВАННЯ ПИЛОВИХ ПЛАЗМОВИХ КОЛИВАНЬ В ФРОНТІ ПОЛУМ'Я ЧАСТИНОК АЛЮМІНІЮ

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Резюме

Експериментально виявлено виникнення пилових плазмових коливань в зоні горіння ламінарного пилового полум'я частинок алюмінію в постійному електричному полі. Визначено характеристики термоемісійної плазми в зоні горіння – концентрацію електронів $n_e \sim 10^{12}$ см$^{-3}$, зарядових чисел $Z_k = 100-150$ частинок Al_2O_3 діаметром $d_{30} = 0,16$ мкм і найбільш імовірну частоту коливань $\nu_k = 24,5$ кГц. Шляхом введення легкоіонізуючих добавок змінювали дисперсність конденсованої фази. Показано залежність частоти пилових плазмових коливань від розміру частинок конденсованої фази. Проаналізовано причину коливань – виникнення нестійкості носіїв заряду, електронів і частинок Al_2O_3, в результаті більшої різниці їх дрейфових швидкостей в електричному полі.