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Studies of the Formation of Submicron Particles Aggregates under Influence of Ultrasonic Vibrations

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Abstract:- *The article presents the results of the studies of the formation of aggregates at ultrasonic coagulation of submicron particles. Proposed mathematical model of the behaviour of two separated particles allows to reveal the modes of ultrasonic influence providing the least time of dispersed particles convergence, and it helps to state the most possible form of generated aggregates. The new model takes into consideration the specific features of the flow of small-size particles (less than 1 μm) at their devergence from spherical form and presence of rotational motion under the influence of ultrasonic field. The analysis of the model lets determine, that optimum frequency range of influence is considered to be 20...50 kHz, if the level of acoustic pressure is more than 150 dB. It is ascertained, that at the initial stage of the coagulation the aggregates are ellipsoids of revolution with the most possible ratio of semi-axis of 2.8 oriented along the field. The basic mechanism of such aggregate formation is the approach of submicron particles under the influence of Oseen forces generated by the perturbations of second-order flow field. At further increase of the aggregates during the coagulation their rotational motion occurs, which makes great contribution into the mechanism of the particles coagulation. At the final stage of the coagulation, when the aggregates rise up to 200 μm and more in transverse size, their final orientation across the field takes place. Obtained results can be the base for understanding of aerosol development. Theoretical results allow to work out requierments to the radiators of ultrasonic vibrations for the realization of the process with maximum efficiency.*

Keywords: - *Aerosol, coagulation, hazardous emissions, submicron particles, ultrasound*

I. INTRODUCTION

One of the consequences of rapid growth of industry is noticeable worsening of the state of atmospheric air. The main sources of air pollutions are industrial enterprises, thermal power stations, transport, etc. Technological processes of different industrial branches are accompanied by the emission of dust-laden gases, which pollute production and ecological environment, impede the progress of technological processes and worsen the quality of final product. According to the specialists' estimation at present the industry daily emits into the atmosphere up to 1 milliard tons of aerosols. The most of aerosols formed in industry are fine-dispersed ones – the size of the particles is less than 1 μm. Such aerosol is especially dangerous for people's health, as it can easily penetrate into human lung alveoli and blood vascular system. In view of all mentioned above the protection of atmospheric air from the pollutions of industrial emissions remains of the main modern problems.

Along with harmful emissions many technological processes at the enterprises of various branches of industry are accompanied by the inflow of aerosols containing final product in the form of particles of submicron and nanometric size. There is a need to capture final product during the production process in the field of nanotechnologies, in food, chemical and mining industries. Thus, it is also necessary to develop the technology of particle capture of final product from gas-dispersed systems.

The necessity of solving problems listed above determines the urgency of issues aimed at the design of the equipment for high-efficiency capture of submicron particles from gas-dispersed systems.

To collect dispersed particles wide range of the apparatuses of dry and wet dust cleaning used different mechanisms of separation (settling chambers, various cyclones, electric or textile filters) is applied.

However the sphere of application of all known apparatuses is limited. It is caused by low efficiency, necessity of replacement or cleaning of filtering element, and sometimes it is principally impossible to capture submicron particles.

The most efficient of all existing dust collectors are inertial and centrifugal apparatuses, which successfully prove themselves at the capture of micron particles. However the collection of submicron particles by the use inertial apparatuses is inefficient. Superposition of external actions (such as steam-coagulation coalescence of the particles, change of surface tension) can influence the efficiency of aerosol settling. But original properties of finished product can be changed, that it is inadmissible for its further application.

The most promising way of efficiency increase of submicron particle capture is its preliminary coagulation in high-intensity acoustic fields.

Acoustic influence (acoustic coagulation) provides the increase of particle size in 10-35 times relative to its initial size. Preliminary coagulated particles of industrial aerosols can be collected by existing or specially developed settling methods without any difficulties. In spite of the fact that it have been done much in studies of physics of the process and industrial application of acoustic coagulation of the aerosols [1-13] (first investigations were carried out by S.V. Gorbachyev and A.B. Severnyi, O. Brandt, H. Freund, E. Hiedemann, H.W. St. Clair and others in the beginning of 30^{th} years of 20^{th} century [1-8]), up to the present moment there is no systematic theoretical and experimental research explaining the mechanism of the coagulation of dispersed particles in the acoustic field.

Misunderstanding of the mechanism of submicron particle coagulation makes it impossible to determine optimum modes of influence (the level of acoustic pressure and frequency) on gas-dispersed systems depending on their characteristics (concentration, dispersed composition, rate of powder-gas flow) providing maximum efficiency of the process.

Besides that existing theories [1-13] do not take into account the features of the flow of submicron particles by gas medium in the acoustic field. Among the features the most important are the following:

– the dominance of the forces of viscous stress due to small size of the particles, as Reynolds number does not exceed 0.1 even at very high levels of the acoustic pressure (up to 165 dB);

– the deviation of the form of solid particles and their aggregates from the spheric one leading to their rotation, while liquid drops always have spheric form, as they are in the state of minimum potential energy of surface tension.

The absence of studies aimed at the influence of these features on the coagulation process in the ultrasonic field does not allow obtaining valid data on optimum parameters of influence.

To determine the optimum parameters of influence it is necessary to investigate the mechanism of formation of fine-dispersed particle aggregates in the ultrasonic field. The definition of the dependences of coagulation efficiency on the parameters of acoustic influence and gas-dispersed system is required for the determination of optimum modes of process realization.

The theoretical study of the formation of fine-dispersed particle aggregates presented in the paper consists of four stages:

1) the development of the behavior model of separate particle in the acoustic field;

2) the development of the interaction model of two separate particles on the base of the behavior model of separate particle;

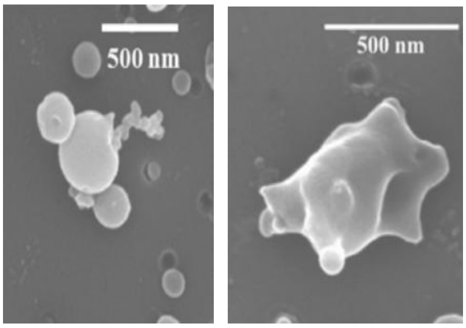
3) the analysis of the interaction model of two particles for determination of the main influencing factors resulting in the convergence and the modes of influence, at which convergence occurs at maximum rate;

4) the determination of the regularities of aggregates formation on the base of the results of the analysis of the interaction model of two particles.

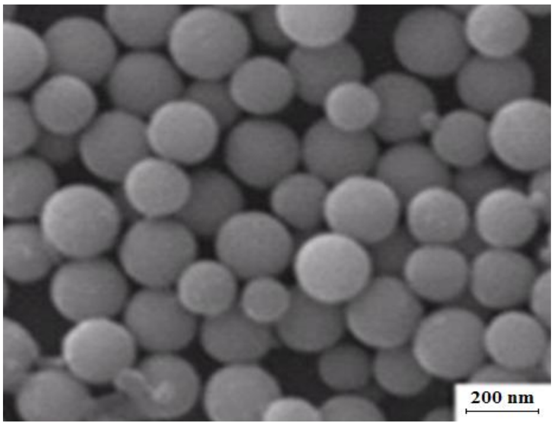
II. Mathematical model of the behavior of separate suspended particle in the acoustic field of ultrasonic frequency and space single interaction of two submicron particles in the acoustic field of ultrasonic frequency

The behavior model of separate particle is based on the dynamic equations of its translational and rotary motion. As it was mentioned above, the behavior of single particle should be considered for the case of small Reynolds numbers, the size of considered particles is within the submicron range.

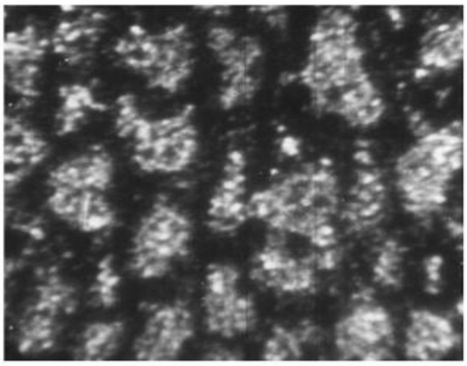
Moreover at the theoretical study of the coagulation of submicron particles the deviation of their form from spheric should be taken into consideration. In the context of proposed model it is assumed, that each particle is an ellipsoid of revolution, which is a sphere in the special case. The possibility to assume this fact is based on the results of experimental studies representing by the photomicrographs of dispersed particles (Fig. 1) of submicron size, which can be harmful emissions or materials in a suspended state used in technological processes [14-17].



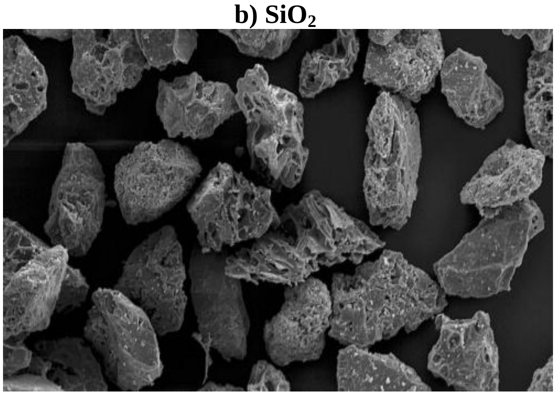
a) carbon black



b) SiO_2



c) smoke



d) volcanic ash

Figure 1: Photomicrographs of submicron particles

As the particles, which form is not spheric in the common case, are oriented at arbitrary angles to the direction of ultrasonic wave propagation, the rotation of particles is taken into consideration. In the context of presented model it is assumed, that the rotation of particles occurs only in one plane (yz), which is in parallel to the direction of ultrasonic wave propagation (axis z) (Fig. 2).

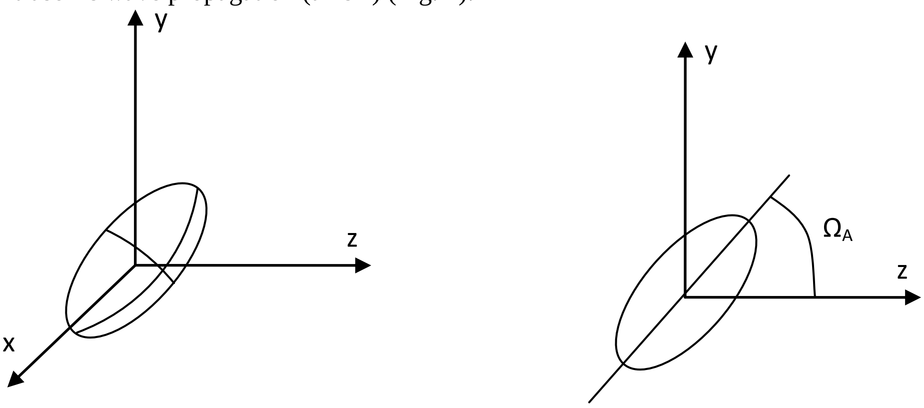


Figure 2: Scheme of the revolution of the ellipsoid

According to the scheme of the revolution of the ellipsoid desired motion equations of single particle can be presented in a following way:

$$m_A \frac{\partial^2 \mathbf{x}_A}{\partial t^2} = \mathbf{F}_A\left(\mathbf{x}_A, \frac{\partial \mathbf{x}_A}{\partial t}, \Omega_A, \frac{\partial \Omega_A}{\partial t}, U_0, k, \omega, t\right) \quad (1)$$

$$J_A \frac{\partial^2 \Omega_A}{\partial t^2} = M_A\left(\mathbf{x}_A, \frac{\partial \mathbf{x}_A}{\partial t}, \Omega_A, \frac{\partial \Omega_A}{\partial t}, U_0, k, \omega, t\right) \quad (2)$$

where m_A is the mass of the particle, kg; J_A is the moment of inertia of the particle, kg·m^2; F_{A_i} is the force acting on the particle, N; M_A is the force moment acting on the particle, N; Ω_A is the turning angle of the particle, rad; U_0 is the amplitude of vibration rate of gas medium, m/sec; k is the wave number of the ultrasonic field m^{-1}; ω is the circular frequency of the ultrasonic field, s^{-1}; a is the cross-section radius of the ellipsoid, m; s is the ratio of the dimension of rotational axis of the ellipsoid to cross-section dimension – diameter (dimensionless value); ρ is the density of particle substance, kg/m^3; n is the normal vector to the surface, η is the dynamic viscosity of gas medium, Pa·s.

The mass and the moment of inertia of the particle being the ellipsoid of the revolution are defined by the following expressions:

$$m_A = \frac{4}{3}\pi\rho s a^3 \tag{3}$$

$$J_A = \frac{\pi^2}{8}\rho a^5 s\left(1+s^2\right) \tag{4}$$

where a is the radius of ellipsoid cross-section, m, s is the ratio of the length of rotational axis of the ellipsoid to cross-section diameter (dimensionless value), ρ is the density of particle substance, kg/m^3.

The force and the force moment is defined based on perturbation of flow field according to the following expressions [11]:

$$F_{A_i} = \oiint_{S_A}\left(-pn_i + \sum_{j=1}^{3}\eta\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)n_j\right)dS, \tag{5}$$

$$M_A = \oiint_{S_A}\left(-pn_2 + \sum_{j=1}^{3}\eta\left(\frac{\partial u_2}{\partial x_j} + \frac{\partial u_j}{\partial x_2}\right)n_j\right)x_3 dS -$$

$$-\oiint_{S_A}\left(-pn_3 + \sum_{j=1}^{3}\eta\left(\frac{\partial u_3}{\partial x_j} + \frac{\partial u_j}{\partial x_3}\right)n_j\right)x_2 dS \tag{6}$$

where n the normal vector to the surface, η is the dynamic viscosity of gas medium, Pa·s, p is the pressure disturbance of the gas medium, Pa, u is the vector of velocity disturbance of the gas medium, m/s.

The velocity and pressure disturbances of the medium are defined on the base of the analysis of Navier-Stokes equations for viscous mode of flow, which is true at small Reynolds numbers [18]:

$$div\,\mathbf{u} = 0, \tag{7}$$

$$0 = -\nabla p + \eta\Delta\mathbf{u}. \tag{8}$$

At infinity of velocity and pressure disturbances of the medium p and u equal zero.

On the boundary of the particle the conditions of adherence are true, which are caused by adhesive forces of molecules between viscous medium and the surface. The conditions of adherence are experimentally proved. Thus, boundary condition on the surface of the particle is following:

$$\mathbf{u} = \begin{pmatrix} 0 \\ V_{A2} + U\sin(kz_0)\sin\Omega_A \\ V_{A3} - U\sin(kz_0)\cos\Omega_A \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{\partial\Omega_A}{\partial t} + kU\cos(kz_0)\sin\Omega_A \\ 0 & -\frac{\partial\Omega_A}{\partial t} & kU\cos(kz_0)\cos\Omega_A \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \tag{9}$$

where kz_0 is the initial phase of the ultrasonic wave, rad, k is the wave number of ultrasonic wave, m^{-1}.

For arbitrary shapes of the particles following multipole expansions of pressure and velocity of the medium are valid [19]:

$$p(\mathbf{r}) = \sum_{i=1}^{3} H_i^A \frac{\partial}{\partial x_i}\left(\frac{1}{X_A}\right) + \sum_{i=1}^{3}\sum_{j=1}^{3} H_{ij}^A \frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{1}{X_A}\right) + \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3} H_{ijk}^A \frac{\partial^3}{\partial x_i \partial x_j \partial x_k}\left(\frac{1}{X_A}\right) +$$

$$+ \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3} H_{ijkh}^A \frac{\partial^4}{\partial x_i \partial x_j \partial x_k \partial x_h}\left(\frac{1}{X_A}\right) + \ldots$$

$$\eta u_i(\mathbf{r}) = -\frac{2}{3}H_i^A\frac{1}{X_A} - \frac{3}{5}\sum_{j=1}^{3} H_{ij}^A \frac{\partial}{\partial x_j}\left(\frac{1}{X_A}\right) - \frac{4}{7}\sum_{j=1}^{3}\sum_{k=1}^{3} H_{ijk}^A \frac{\partial^2}{\partial x_j \partial x_k}\left(\frac{1}{X_A}\right) - \frac{1}{6}\sum_{j=1}^{3} H_j^A \frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{1}{X_A}\right)\cdot X_A^{\;2} -$$

$$-\frac{1}{10}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{jk}^{A}\frac{\partial^{3}}{\partial x_i \partial x_j \partial x_k}\left(\frac{1}{X_A}\right)\cdot X_A{}^{2}-\frac{1}{14}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}H_{jkh}^{A}\frac{\partial^{4}}{\partial x_i \partial x_j \partial x_k \partial x_h}\left(\frac{1}{X_A}\right)\cdot X_A{}^{2}-$$

$$-\frac{1}{18}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}\sum_{m=1}^{3}H_{jkhm}^{A}\frac{\partial^{5}}{\partial x_i \partial x_j \partial x_k \partial x_h \partial x_m}\left(\frac{1}{X_A}\right)\cdot X_A{}^{2}-\ldots$$

where $X_A=\sqrt{\sum_{i=1}^{3}(x_i-x_{Ai})^2}$.

Constant values H_i^A, H_{ij}^A, … are defined from the boundary conditions (5).

At final stage at the boundary conditions the coefficients are equated, if the monomials equal 1, (x_j-x_{Aj}), $(x_j-x_{Aj})(x_k-x_{Ak})$ etc.

Obtained formulae allow determining the position and the turning angle of the single particle depending on time.

In the case of the interaction of two particles the equations of translational (2d Newton's law) and rotational movement are true.

At that multipole expansions of the velocity and pressure will be the sum of expansions of the velocity and pressure of each particle (10,11):

$$p(\mathbf{r})=\sum_{i=1}^{3}H_i^A\frac{\partial}{\partial x_i}\left(\frac{1}{X_A}\right)+\sum_{i=1}^{3}\sum_{j=1}^{3}H_{ij}^A\frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{1}{X_A}\right)+\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{ijk}^A\frac{\partial^3}{\partial x_i \partial x_j \partial x_k}\left(\frac{1}{X_A}\right)+ \tag{10}$$

$$+\ldots+\sum_{i=1}^{3}H_i^B\frac{\partial}{\partial x_i}\left(\frac{1}{X_B}\right)+\sum_{i=1}^{3}\sum_{j=1}^{3}H_{ij}^B\frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{1}{X_B}\right)+\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{ijk}^B\frac{\partial^3}{\partial x_i \partial x_j \partial x_k}\left(\frac{1}{X_B}\right)+\ldots$$

$$\eta u_i(\mathbf{r})=-\frac{2}{3}H_i^A\frac{1}{X_A}-\frac{3}{5}\sum_{j=1}^{3}H_{ij}^A\frac{\partial}{\partial x_j}\left(\frac{1}{X_A}\right)-\frac{4}{7}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{ijk}^A\frac{\partial^2}{\partial x_j \partial x_k}\left(\frac{1}{X_A}\right)-\ldots-\frac{1}{6}\sum_{j=1}^{3}H_j^A\frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{1}{X_A}\right)\cdot X_A{}^{2}-$$

$$-\frac{1}{10}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{jk}^{A}\frac{\partial^{3}}{\partial x_i \partial x_j \partial x_k}\left(\frac{1}{X_A}\right)\cdot X_A{}^{2}-\frac{1}{14}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}H_{jkh}^{A}\frac{\partial^{4}}{\partial x_i \partial x_j \partial x_k \partial x_h}\left(\frac{1}{X_A}\right)\cdot X_A{}^{2}-$$

$$-\ldots-\frac{2}{3}H_i^B\frac{1}{X_B}-\frac{3}{5}\sum_{j=1}^{3}H_{ij}^B\frac{\partial}{\partial x_j}\left(\frac{1}{X_B}\right)-\frac{4}{7}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{ijk}^B\frac{\partial^2}{\partial x_j \partial x_k}\left(\frac{1}{X_B}\right)-\ldots-\frac{1}{6}\sum_{j=1}^{3}H_j^A\frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{1}{X_B}\right)\cdot X_B{}^{2}-$$

$$-\frac{1}{10}\sum_{j=1}^{3}\sum_{k=1}^{3}H_{jk}^{B}\frac{\partial^{3}}{\partial x_i \partial x_j \partial x_k}\left(\frac{1}{X_B}\right)\cdot X_B{}^{2}-\frac{1}{14}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}H_{jkh}^{B}\frac{\partial^{4}}{\partial x_i \partial x_j \partial x_k \partial x_h}\left(\frac{1}{X_B}\right)\cdot X_B{}^{2}-\ldots. \tag{11}$$

The second-order velocities and pressures u_2 and p_2, respectively, are defined on the base of the analysis of Oseen equations, which are true at small Reynolds numbers:

$$div\,\mathbf{u}_2=0 \tag{12}$$

$$\rho(\mathbf{u},\nabla)\mathbf{u}_2=-\nabla p_2+\eta\Delta\mathbf{u}_2\,, \tag{13}$$

where u is the component of velocity of first-order infinitesimal defined at the previous stage.

The second-order pressure and velocity disturbances are significant at small distances between particles of for the spheres of submicron size, for which there is practically no rotational movement.

Proposed model of the interaction of two particles lets determine the dependence of the distance between the particles on time at specified initial conditions (transverse dimensions of given particles and the ratio of longitudinal dimension to the transverse one, initial distance between the particles, frequency and level of acoustic pressure, density of the particle matter, angle between the particle center line and ultrasound direction) and state:

– main regularities of aggregates formation depending on dimensions, form and features of the ultrasonic field;

– optimum modes of the ultrasonic field depending on the size of particles;

– main parameters of the form of obtained aggregates.

III. THEORETICAL ANALYSIS OF THE AGGREGATES FORMATION PROCESS AT DIFFERENT PARAMETERS OF ULTRASONIC INFLUENCE

At the first stage we obtained the dependences of the distance between the particles on time at different level of acoustic pressure, the frequency of the exposure was 22 kHz, the diameter of the particles was 0.6 μm, the density of particle matter was 2200 kg/m^3 (SiO_2) and starting distance between the particles was 10.75 μm. Fig. 3 shows the dependences of the distance between the particles on time at different levels of sound pressure.

As it follows from presented dependences, the effects connected with the action of Oseen forces mostly influence on the coagulation of spheric particles of submicron size. Convergence of the particles occurs in a time, which equals to several periods of vibrations and the time of particle convergence before the direct contact decreases in inverse proportion to generated level of sound pressure.

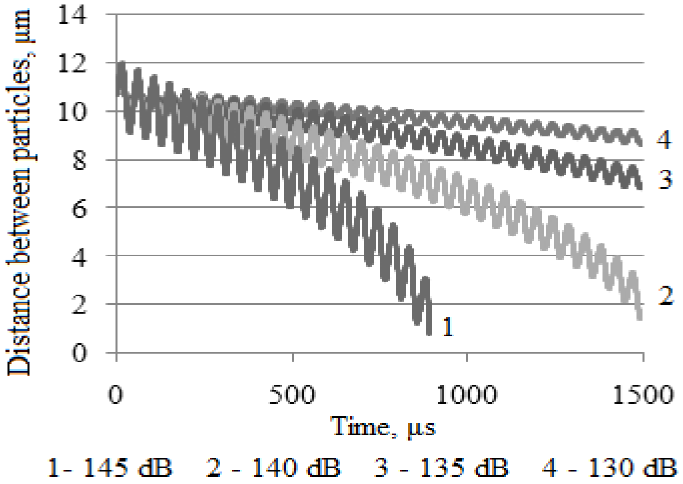


Figure 3: The dependences of the distance between the particles on time at different levels of sound pressure (130-145 dB)

Obtained data let determine the dependence of convergence time defining the coagulation efficiency on the level of sound pressure (Fig. 4).

The analysis of the dependence of process efficiency on the level of acoustic pressure allowed concluding the necessity of application of ultrasonic influences with the level of sound pressure of more than 150 dB.

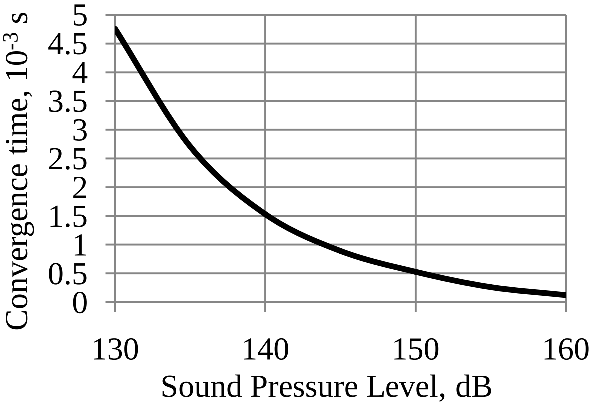


Figure 4: The dependence of convergence time on the level of sound pressure

Further we carried out the analysis of convergence time on the frequency of ultrasonic action. Obtained results are shown in Fig. 5.

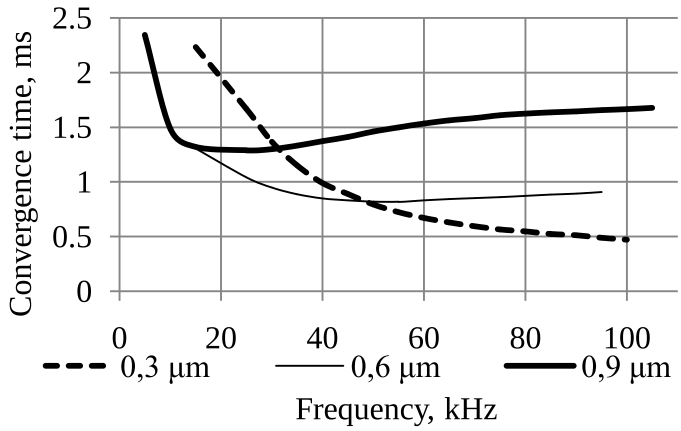


Figure 5: The dependence of convergence time of the particles of different size on the frequency

From obtained dependences it follows, that optimum frequency of coagulation for the particles with the size of 0.9 μm is 20 kHz. For smaller size of the particles it is necessary to increase the frequency of influence. However for the particles with the size of 0.3 μm and less it is observed small dependence coagulation time on the frequency beginning with 50 kHz. Experimental studies show, that ultrasonic vibrations in air at the frequencies of more than 100 kHz damp rather fast. That is why, it is considered to be optimum ultrasonic influence in the range of 20-50 kHz at the level of sound pressure of less than 150 dB.

To determine the main regularities of change of aggregate form at the coagulation of submicron particles the dependences of intensity of convergence on the orientation of their center line to the direction of acoustic wave propagation were studied. From the dependences shown in Fig. 6 it follows, that the highest speed of convergence is achieved at their longitudinal orientation.

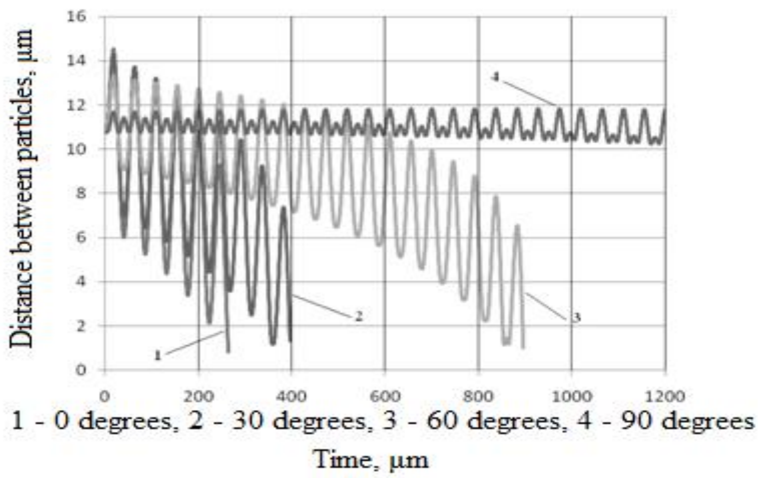


Figure 6: The dependence of the distance between the particles on time

The dependence of mean velocity of convergence with the distance of 10.75 μm (corresponding to the concentration of 200 gr/m^3) on the angle between particle center line and wave vector of the acoustic field is shown in Fig. 7.

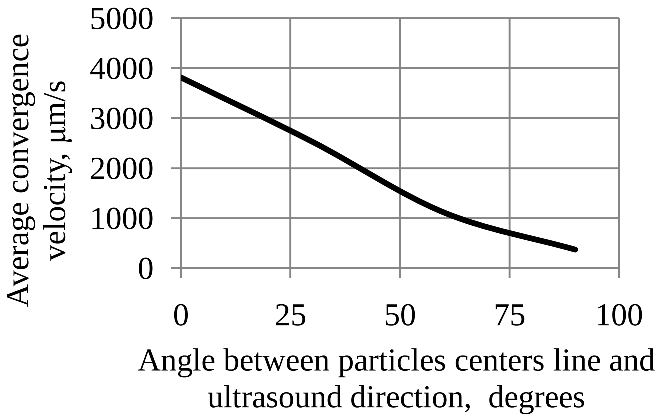


Figure 7: The dependence of average convergence velocity on the angle between particles Centers line and the wave vector of the acoustic field

As it follows from Fig. 7, the average convergence velocity depending on the angle to the direction of the acoustic field changes practically linearly, i.e. $v(r) \approx v_0(r)\left(\frac{\pi}{2} - \theta\right)$, where r is the distance between the particles, m.

Thus, at starting stages of the coagulation the particles are formed, which form at the first approach is the ellipsoid of revolution oriented along the field.

Assumed form of the aggregate generated at the first stage of the coagulation is shown in Fig. 8.

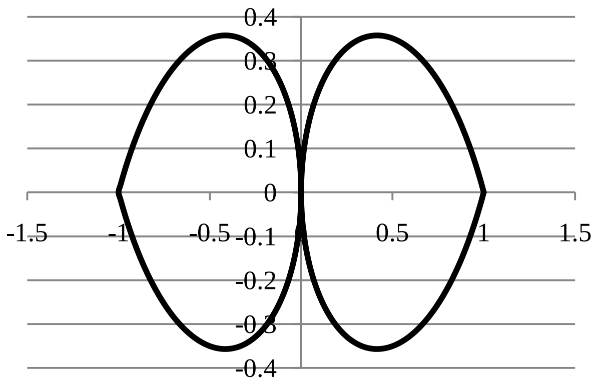


Figure 8: Assumed form of the aggregate generated at the first stage of the coagulation (the value of the coordinates on the axes is specified by relative units)

The estimations of number Re show, that if longitudinal dimensions of the ellipsoid equals 2 µm, it exceeds 0.05. At such values of Re the assumption of Oseen mode of the flow is still valid. However in the paper [10] it is pointed out, that under the action of velocity gradient in generated stationary acoustic flow the turning of ellipsoids in an angle relative to the initial orientation is observed. It leads to the rotation of the particles under the influence of the acoustic field, which is taken into account in presented model and depends on the ratio of the ellipsoid axes.

At further size increase of the ellipsoids up to 200 µm ad more they are finally oriented across the field that is observed experimentally.

Based on the dependence of approach velocity on the angle of location the ratio of longitudinal and transverse dimensions of generated aggregate was evaluated.

At the initial stage of the coagulation when particles have spheric form, the number of particles, with which the particle collides, is in the proportion to approach velocity of the particles multipled by space angle. To determine the number of the particles the summation is carried out for all possible distances from desired particle.

$$N(r)\Delta\Omega\Delta t \approx \int_0^\infty n v_0(r)\left(\frac{\pi}{2} - \theta\right) r^2 \partial r = n\left(\frac{\pi}{2} - \theta\right)\Delta\Omega \int_0^\infty v_0(r) r^2 \partial r,$$

where $\Delta\Omega$ is the small space angle, sr, n is the calculating concentration of the particles in the surroundings of desired particle, m^{-3}.

It follows, that local longitudinal dimension of the aggregate *D(x)* depending on longitudinal coordinate *x* is defined by the following dependence:

$$D(x) = L\left(\frac{\pi}{2} - \theta(x)\right)\sin\theta(x);\ x = \frac{L}{2}\left(\frac{\pi}{2} - \theta(x)\right)\cos\theta(x),$$

where L is the longitudinal dimension of the aggregate, m.

As it is assumed, that particles or aggregates have the form of the ellipsoid of revolution, transverse diameter of the ellipsoid is defined as maximum value of the function D(x), i.e. when

$$\frac{\partial D}{\partial x} = 0$$

or

$$\frac{\partial D}{\partial \theta} = 0,\ \text{i.e.}\ \frac{\partial D}{\partial \theta} = -\sin\theta + \left(\frac{\pi}{2} - \theta\right)\cos\theta = 0 \tag{14}$$

Numerical solution of the equation (14) shows, that $\theta \approx 40°$ that corresponds to maximum longitudinal diameter of 0.35L. It allows assuming, that at the initial stage of the coagulation the most possible ratio of the ellipsoid axes equals 2.8.

Further analysis of the model of two particles is carried out for the ellipsoids of revolution with the ratio of the axes S = 1…3.

Fig. 9 shows the dependences of the distances between the particles on time for the case of the ellipsoids of revolution with longitudinal diameter of 0.5 μm, which are oriented at the angle of 45° to the direction of ultrasonic wave propagation at different ratios of semi-axes lengths.

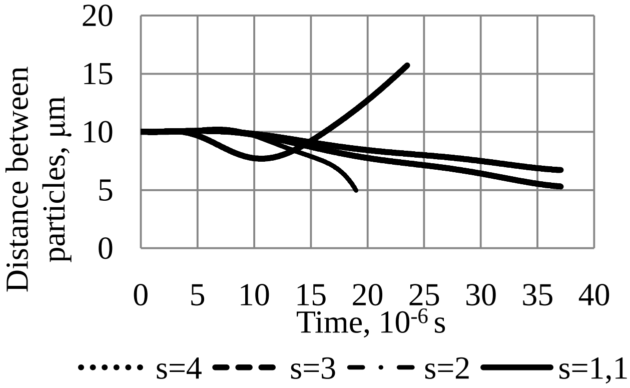


Figure 9: Dependences of the distance between the centers of the ellipsoids of revolution on time for different ratio of semi-axes

As it follows from presented dependences, at small differences of lengths of semi-axes the interaction of the particles is rather weak. The most interaction of the particles is achieved, when s=2. Further increase of the ratio of semi-axes length results in the fact, that the force of particle interaction decreases. It lets conclude, that the ratio of longitudinal dimensions of the ellipsoid to the transverse one is limited.

Total dependence, is shown in Fig. 10, of convergence time on the ratio of the semi-axes lying in the range of s=1,1…3, at which the approach occurs.

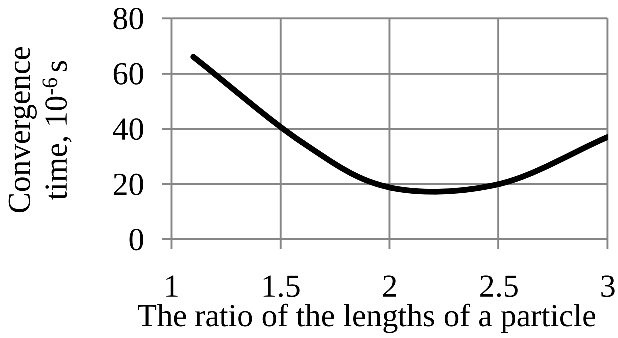


Figure 10: The dependence of convergence time on the ratio semi-axes lengths

At the next stage of the studies the convergence process at different transverse diameter with constant ratio of semi-axes s=2 is considered. The dependences of the distance between the particles on time at the diameters of 0.8 and 0.2 μm are shown in Fig. 11.

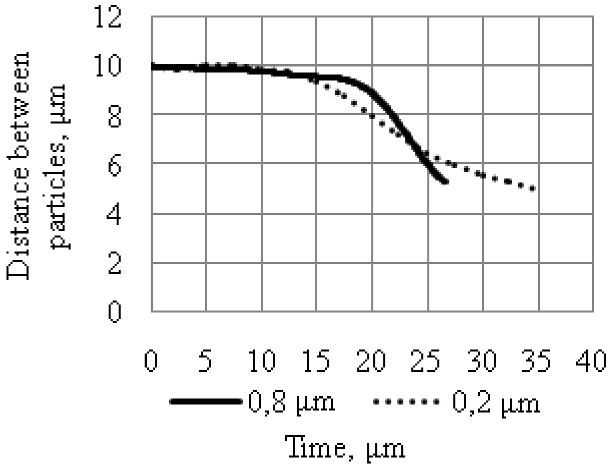


Figure 11: The dependence of the distance between the particles on time at their different transverse diameter

As it follows from presented dependences the transverse size of the particles essentially influences on their approach velocity and, consequently, on the efficiency of the coagulation.

Fig. 12 shows the dependence of convergence time on their transverse diameter, if s = 2 and the initial distance between the particles is 10 μm.

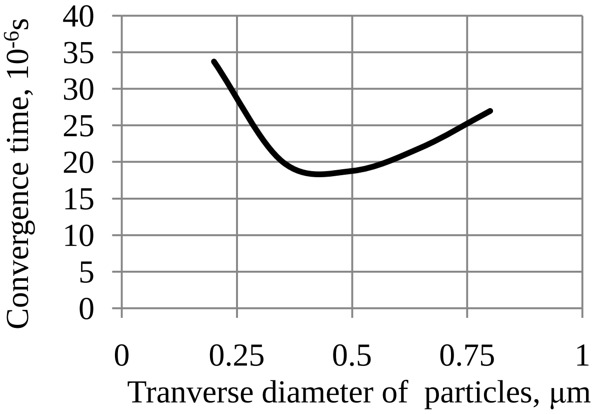


Figure 12: The dependence of convergence time of ellipsoid particles on transverse diameter

Thus for the case to be considered at the constant distance between the particles there is optimum size of the particles (0.4 μm), at which coagulation is the most efficient.

The increase of converegnce time at the diameters, which are more than optimum, can be explained by the reducing of the velocity of revolution, and the increase of converegnce time at the diameters, which are less than optimum, can be explained by reducing of the ratio of particle size to the distance between them.

IV. CONCLUSION

Thus during carried out researches the process of the coagulation of submicron particles at micro level due to the influence of high-intensity acoustic vibrations of ultrasonic frequency was studied. Proposed mathematical models of the behavior of single suspended particle and three-dimensional interaction of two submicron particles in the acoustic field take into account rotational motion of the particles and the influence of the viscosity of gas medium.

The analysis of the model allows revealing optimum modes of the ultrasonic influence providing minimal convergence time:

– the coagulation process of submicron particles occurs more efficiently in the range of the frequencies of ultrasonic influence of 20…50 kHz;

– the level of acoustic pressure should be no less than 150 dB.

Further analysis of the form of generated aggregates lets determine the following:

– at the initial stages of the coagulation generated aggregates have the form, which is close to the ellipsoid of revolution oriented along the field and the most possible ratio of the axes equals 2.8;

– ellipsoid aggregates under the action of the ultrasonic field are set in rotational motion, which determines main mechanism of the particle coagulation with the form, which is differed from spheric ones;

– at further increase of the particle size of the aggregates (up to 2…10 μm) rotational motion under the influence of the ultrasonic field occurs, as it determines the mechanism of the coagulation;

– at the final stage of the coagulation large aggregates (more than 200 μm) are finally oriented across the field.

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