Theoretical Studies of the Influence of Acoustic Action on the Probability of Pair Collision of the Submicron Particles

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Abstract: - The paper presents the model of influence of acoustic action on the probability of pair collision of the submicron particles and the new method of the action in the shock-wave mode. The model takes into account new non-linear effects of acoustic action in the shock-wave mode for submicron particles. The main effect is changing of uncertainty of the spatial position of the particle due to Brownian motion. The model allowed determining the possibility of the additional efficiency increase of the coagulation in up to 5 times and more at the application of the shock-wave action for the submicron particles in comparison with the sinusoidal action (s.a) at the similar power consumptions. Under the action of the shock waves superposition generated by the real sources of the shock-wave action (for instance, by multi-frequency radiators forming the alternation of the harmonics of the multiple frequencies, interrupters of the flow, membranes), it is preferable to provide increased duration of the rarefaction wave in comparison with the compression wave. The proposed model can be used as a theoretical base of experimentally observed fact of accelerated coagulation of the submicron particles at the shock-wave action.

Keywords: - Shock wave, Brownian motion, coagulation, probability, acoustic influence

1. INTRODUCTION

The aerosols formed in the atmosphere due to the man impact, man-made accidents, terrorist attacks and also natural processes are the global problem. The mankind has to fight continuously with fogs, smokes, dust, aerosols of poisonous, explosive and radioactive substances [1–4].

At small mass concentration (less than 1% of the total aerosol concentration being in air) the aerosols of fine-dispersed particles have high surface area (more than 55% of the total surface of the particles emitted into the atmosphere) and the mass concentration of more than 95%. Due to the small sizes and the mass such aerosols can be kept in the air for a long period of time and are able to easily penetrate the lung alveolus of the man and the animals and they are hard to be caught by the existing dust-collecting equipment [3–8] (the catching efficiency is the ratio of the mass of the separated particles to the mass of the initial particles and it does not exceed 10%).

The promising method of the submicron particles removal is their coagulation under the action of ultrasonic oscillations – ultrasonic coagulation. At present the ultrasonic coagulation is successfully applied for the aggregation of the submicron range particles in order to increase the efficiency of the gas purification [3, 4, 8–12].

In the papers [2–4, 11] it is theoretically found out and experimentally proved the optimum modes of the ultrasonic action and it is designed the apparatuses for the action with the special reflectors intended for the use both in open air and in the limited volumes.

However, for the coagulation of the submicron particles the application of the ultrasonic oscillation is limited by the following factors:

– insufficient area size of the efficient collision cross-section even taking into account the fluctuations induced by accidental Brownian motion of the particles [14, 15];

– total involvement of the submicron particles to the oscillating motion of the gas flow, which reduces their orthokinetic interaction [9–11] (as the difference of the oscillating components of the neighboring particles velocities is close to zero, even if the sizes of the particles are varied).

It is determined by the following specific features of such particles:

– small size of the particles, which square is in the proportion to the area of the efficient collision cross-section. In turn the less is the area of the collision cross-section, the less the contact probability between the particles surfaces at the relative motion of the last ones;

– short time of the particle relaxation due to the low inertia force in comparison with the viscous friction force, this reduces the known factor of the orthokinetic particle interaction, which additionally increases the probability of the coagulation;

– small mass of the particles leading to their Brownian motion as a result of the collision of the single molecules of the carrying gas phase with the particle, it essentially influences on the area of the efficient collision cross-section due to the uncertainty of the particle spatial location.

All these facts lead to the necessity to reveal new methods and modes of the acoustic action providing the appearance of the non-linear effects never studied before, promoting the increase of the probability of the approaching, the collision and the coagulation of the submicron particles.

As a new method of the action it is appropriate to consider the action in the shock-wave mode, at which according to the experimental studies [16, 17] the accelerated coagulation of the submicron particles occurs.

However, in the papers the shock-wave action on the submicron aerosols was carried out within the audio-frequency range (3 kHz – 4 kHz), which was dangerous for the people and moreover there were no attempts to determine optimum modes of the action providing accelerated particle coagulation.

Due to the complexity of the experimental studies and the process observations occurring under the ultrasonic action it is preferable to carry out theoretical studies of the coagulation process of the submicron particles taking into consideration the specific features of the last ones. It allows determining new non-linear effects influencing the coagulation velocity and revealing the optimum modes and the methods of the acoustic action providing maximum efficiency of the submicron particle coagulation.

2. PROBLEM STATEMENT

To develop generalized model of the coagulation of the submicron particle aerosol determining the optimum modes and the methods of acoustic action Smoluchowski probabilistic approach is the most-known and experimentally proved (X. Shen, C. Sheng). Within the frames of the approach it is studied the evolution of the concentration of the particles with different masses at the specified probability of the collision of the particle pair of the determined sizes. The evolution of the particle concentration is described by the equation (1):

$$\frac{\partial n_k}{\partial t}(t) = \frac{1}{2}\sum_{i=1}^{k-1} \beta_{i,k-i} n_i(t) n_{k-i}(t) - n_k \sum_{i=1}^{N} \beta_{i,k} n_i(t) \quad ; (1)$$

where n_k is the particle concentration with the conditional diameter $d_0\sqrt[3]{k}$, m^{-3}; $\beta_{i,k}$ is the probability of the particle collision with the conditional diameters $d_0\sqrt[3]{i}$ and $d_0\sqrt[3]{k}$, m^3/s.

The approach is experimentally proved even for the colloidal systems (the probability of the collision is determined indirectly on the base of the experimental data on the particle concentration [9, 10, 13]). However, there is no theoretical models, which allow to determine the probability of the pair collision of the submicron particles (the main characteristic defining the coagulation velocity) at the acoustic action and describe appearing non-linear effects induced by the special features of the submicron particles.

When developing a model that determines the effect of acoustic action in the gas phase on the probability of paired collision of submicron particles, it is assumed that:

– surrounding gas phase is isotropic [14, 15], i.e. the statistical characteristics of the velocities of the gas phase molecules in all directions are equal;

– the propagation of the acoustic pressure disturbances is adiabatic, as a gas phase has a low heat conductivity coefficient and consequently the characteristic time of the heat transfer is high in comparison with the characteristic time of the pressure disturbance change.

The studies are carried out within the range of the pulse durations from 2 μs and more, intensities of ultrasonic action averaged at the period of time up to 0.06 W/cm^2 (root-mean-squared value of the acoustic pressure does not exceed 500 Pa, the maximum instantaneous value of the disturbance at the shock-wave action can achieve 50000 Pa).

The range of the ultrasonic action intensities is caused by the limitations concerned with the wave resistance of the carrying gas phase and the design features of the sources of acoustic disturbances (the mean level of the acoustic pressure in a far field does not exceed 150 dB; in a focus having limited space volume (no more than 1 cm^3) it can achieve 160 dB) [3, 6, 8].

It is chosen the lowest range limit of the pulse durations, which can be generated at the shock-wave action. The force, which should be applied for the acceleration of the gas flow in order to form the shock wave, does not exceed in the range of the pulse durations (from 2 μs):

$$f_{V\max} \sim \frac{p_A}{\rho c \tau} \sim \frac{p_{RMS}}{\rho c \tau}\sqrt{\frac{T}{\tau}} = \frac{p_{RMS}}{\rho c \tau}\sqrt{\frac{1}{\tau f}} =$$

$$= \frac{500\ Pa}{1{,}22\ \frac{kg}{m^3}\cdot 343\ \frac{m}{s}}\sqrt{\frac{1}{\tau^3 \cdot 22000\ s^{-1}}} < .$$

$$< 3\ \frac{MN}{m^3} = 3\ \frac{kN}{dm^3}$$

Stated force is achievable with the help of the modern mechanisms of the generation of the pressure disturbances in a gas phase.

Studied range of the particle size is 0.1…0.5 micron – the submicron particles formed in practice at the technological processes. The density of the particle substance is 2000 kg/m^3, the characteristic density of silica dioxide or ashes.

Developed model for the determination of the probability of the pair collision of the submicron particles $\beta = \langle \beta[p](t) n \rangle$ (sign < > means time averaging) taking into account all mentioned above assumptions is described further.

3. THE MODEL OF INFLUENCE OF THE PRESSURE DISTURBANCES ON THE PROBABILITY OF THE PARTICLE COLLISION

Among the factors influencing on the probability of the submicron particle collision the hydrodynamic and orthokinetic interactions are the most studied at present.

The probability of the collision is defined by the following general expression [9, 10]:

$$\beta[p](t) = \beta_H[p](t) + \beta_O[p](t); \qquad (2)$$

where $\beta_H[p](t)$ is the component of the hydrodynamic interaction, m^3/s; $\beta_O[p](t)$ is the component of the orthokinetic interaction, m^3/s.

The components of the collision probability are defined by the following expressions:

$$\beta_H[p](t) = \frac{f_{21}[p](t)}{3\pi d \mu} S[p](t); \qquad (3)$$

$$f_{21}[p](t) = \frac{3\pi d^2 p'^2(t)}{64 \rho_0 c^2}\left(1 + \frac{p'^2(t)}{\rho_0{}^2 c^4}\right); \qquad (4)$$

$$S[p](t) = \pi\left(d + \sqrt{\sigma_r}[p](t)\right)^2; \qquad (5)$$

$$\beta_O[p](t) = \frac{1}{T}\int_0^T \left|\frac{p'(t+cl)}{\rho_0 c} - \frac{p'(t)}{\rho_0 c}\right| S[p](t)dt; \qquad (6)$$

where $f_{21}[p](t)$ is the force of the particles interaction, N; $S[p](t)$ is the area of the effective collision cross section, m^2; σ_r is the dispersion (squared uncertainty) of the spatial position of the particle, m; l is the characteristic distance between the particles, m; c is the velocity of the shock wave propagation in the carrying gas phase.

Carried out comparative evaluation of the 2 components of the collision probability shows, that at both sinusoidal and shock-wave action (at the specified range of the pulse duration of no less than 2 μs) $\beta_O[p](t) << \beta_H[p](t)$. Studies show that the main is the hydrodynamic effect. Further the influence of acoustic disturbances on the probability of the hydrodynamic action is studied.

As it follows from the expression (3), the probability of the hydrodynamic interaction is in proportion to the area of the effective collision cross section depending on the particle position uncertainty. According to the experimental data [18, 19] the area of the effective collision cross section essentially differs (even to several orders) for the submicron particles from the area of the particle projection on a plane. It is caused by the influence of Brownian motion.

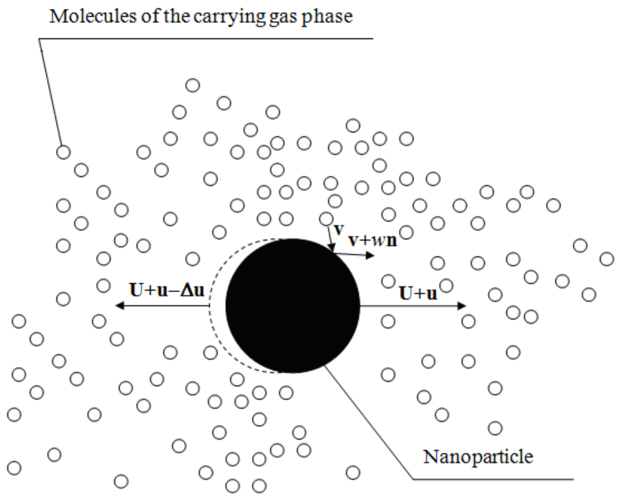
That is why to calculate the probability of the hydrodynamic interaction first of all it is necessary to study the influence of the acoustic disturbances on the area of the effective collision cross section.

In a general case the effective collision cross section of the particles at Brownian motion is defined by the initial size of the particles, on which depends the collision cross section without the influence of Brownian motion (for instance, the molecules of surrounding gas phase have high concentration or low velocity dispersion, i.e. gas phase has high density or low temperature) and also by the dispersion of the particle position:

$$S[p](t) = \pi\left(d + \sqrt{\sigma_r}[p](t)\right)^2; \qquad (7)$$

where σ_r is the dispersion of the particle spatial position.

It is evident, that random fluctuations of the particle spatial position defined by the dispersion σ_r are caused by the collision of the carrying gas phase molecules with the surface of the particle (Figure 1) and determined by the collision frequency and the molecules velocity at the collision moment [16–18].



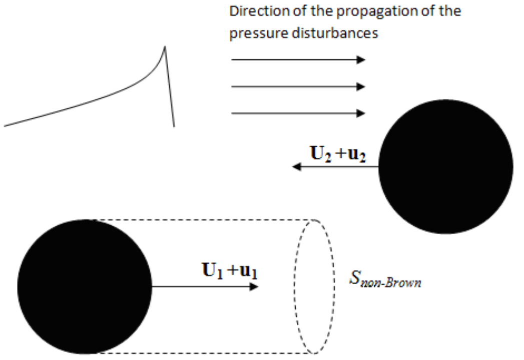
v – random velocity of motion of the carrying gas phase molecules;

u – random velocity component of the particle motion induced by the thermal collision of the carrying gas phase molecules with the particle;

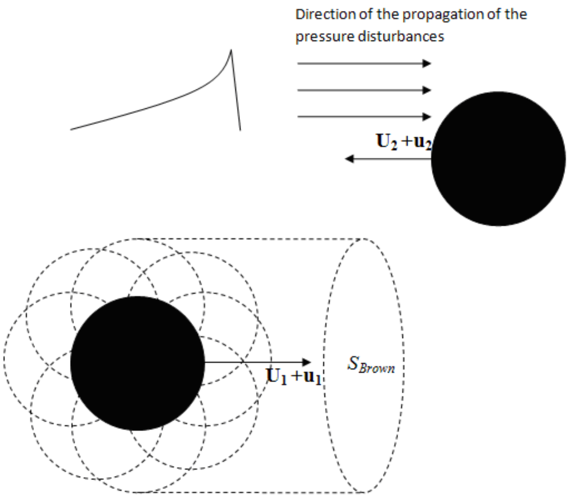
U – determined component of the motion velocity caused by the entrainment of the particle to oscillatory motion of gas flow

Figure 1. The scheme of the collision of the carrying gas phase molecules with the submicron particle and the change of the particle velocity as a result of the elementary collision act

The fluctuations of the particle spatial position lead to the change of the area of the effective collision cross section according to the expression (7) and the scheme shown in Figure 2.



a) the area of the collision cross section without Brownian motion



b) the area of the collision cross section with Brownian motion

Figure 2. Influence of Brownian motion of the submicron particle on the area of the collision cross section

The dispersion of the particle spatial position caused by the presence of the random component of the particle motion velocity defines the area of the effective collision cross section of the particle and consequently all the components of the collision probability.

To determine the dispersion of the particle spatial position it is proposed the numerical model based on Monte Carlo method and the following statements:

1. The velocity of the particle after the collision with the molecule is determined by the momentum conservation law.
2. The collision of the molecule with the particles is equally probable in all possible directions. This statement is followed from the isotropy of the carrying gas phase.
3. The collision of the molecule with the particle is perfectly elastic. The assumption is true due the potentiality of the interaction field of the molecule with the particle.

The spatial position of the particle as a result of the elementary collision acts “particle-molecule of the carrying gas phase” is defined by the following equation:

$$\mathbf{r}_{i+1} = \mathbf{r}_i + \mathbf{u}_i\left(t_{i+1} - t_i\right)$$

where t_i is the moment of time of the appearance of i-th elementary collision act of the molecule of the carrying gas phase with the particle, s; $\mathbf{u}_i$ is the particle velocity as a result of i-th elementary collision act of the molecule, m/s; $\mathbf{r}_i$ is the vector of the particle coordinates in the moment of the appearance of i-th elementary collision act, m.

The particle velocity as a result of i-th elementary collision act is determined by the momentum conservation law:

$\mathbf{v}-\mathbf{u} \to \mathbf{v}-\mathbf{u}+w\mathbf{n}$ is the change of the velocity of the molecule undergoing collision in the frame of references of the particle mass center;

$\mathbf{v} \to \mathbf{v}+w\mathbf{n}$ is the change of the velocity of the molecule undergoing collision in the laboratory frame of reference;

$m(\mathbf{v}+w\mathbf{n})+M\mathbf{u}_{new} = m\mathbf{v}+M\mathbf{u}$ is the momentum conservation law for the system "particle-molecule undergoing collision";

$\mathbf{u}_{new} = \mathbf{u}-\frac{m}{M}w\mathbf{n}$ is the common expression for the change of the particle velocity as a result of i-elementary collision act.

The unknown value W is defined from the energy conservation law

$$\frac{M\left(\mathbf{u}-\frac{m}{M}w\mathbf{n}\right)^2}{2}+\frac{m(\mathbf{v}+w\mathbf{n})^2}{2}=\frac{M\mathbf{u}^2}{2}+\frac{m\mathbf{v}^2}{2};$$

$$\mathbf{u}_{new} = \mathbf{u}+\frac{2\frac{m}{M}}{1+\frac{m}{M}}(\mathbf{v}-\mathbf{u},\mathbf{n})\mathbf{n};$$

$$\mathbf{u}_{i+1} = \mathbf{u}_i+\frac{2\frac{m}{M}}{1+\frac{m}{M}}(\mathbf{v}_i-\mathbf{u}_i,\mathbf{n}_i)\mathbf{n}_i;$$

where *M* is the mass of the particle, kg; *m* is the mass of the single molecule of the carrying gas phase, kg.

In the initial moment of time the particle velocity and its spatial position are zero.

The proposed numerical algorithm is based on the random generation of the moments of time of the molecule collision with the particle, the molecule velocities at the collision moment and the positions of the particle surface point, in which it collides with the molecule.

At the generation of the collision time of the molecule with the particle it is assumed, that the part of the particle surface in a small solid angle $\partial\Omega$ with the normal velocity components in the collision moment within the range from v_n to $v_n+\mathrm{d}v_n$ during the period of time *dt* it is possible the collision of the molecule with the probability:

$$\frac{\rho d^2}{4m}v_n f(\mathbf{u}_i,\mathbf{n},v_n)dv_n\partial\Omega dt;$$

where ρ is the density of the carrying gas phase, kg/m^3; *d* is the diameter of the particle, m; $f(\mathbf{u}_i,\mathbf{n},v_n)$ is the density of the distribution of the projections of the velocities of the carrying gas phase molecules to the normal vector $\mathbf{n}$ in the frame of reference moving forward with the velocity $\mathbf{u}_i$ relatively to the laboratory frame; $\mathbf{n}$ is the normal vector to the part of the surface $\partial\Omega$.

As the acoustic disturbances are propagated in a specified direction, it is proposed the submodel for the determination of the density of the distribution of the projections of the velocities of the carrying gas phase molecules to the normal vector $\mathbf{n}$ in the frame of reference moving forward with the velocity $\mathbf{u}_i$ relatively to the laboratory frame.

At the definition of the distribution density $f(\mathbf{u}_i,\mathbf{n},v_n)$ it is assumed, that the function of the velocity distribution at the arbitrary choice of the molecule adheres to Maxwell law.

$$f(\mathbf{u},\mathbf{v})=\sqrt{\frac{\rho}{2\pi p}}e^{-\frac{\rho|\mathbf{v}-\mathbf{u}|^2}{2p}};$$

$$f(\mathbf{u}_i,\mathbf{n},v_n)dv_n=\sqrt{\frac{\rho}{2\pi p}}e^{-\frac{\rho|\mathbf{v}-\mathbf{u}|^2}{2p}}.$$

The generation of the velocities, times and positions of the surface point, in which appears collision, takes place until the functions of the distribution of the positions of the single particle as a result of the next and previous elementary collision acts are equal.

$$F_{i+1}(\mathbf{r})=F_i(\mathbf{r})=F(\mathbf{r}). \qquad (8)$$

Carried out preliminary calculations show that the time, during which the condition (8) is achieved, is much less than the characteristic times of the pressure change. It allows considering the pressure to be constant at the calculation of the instantaneous effective collision cross section of the particles.

The proposed model helps to find out the dependences of the area of the equivalent collision cross section and the probability of the collision on the amplitude of the acoustic pressure for different methods of the acoustic actions (the types of the acoustic disturbances).

1. Continuous sinusoidal:

$$p'(t)=p_A\sin\left(2\pi\frac{t}{T}\right).$$

2. Shock-wave (pulse):

$$p'(t)=p_A e^{-\frac{t-\left\lfloor\frac{t}{T}\right\rfloor T}{\tau}}.$$

2.1. Compression shock wave:

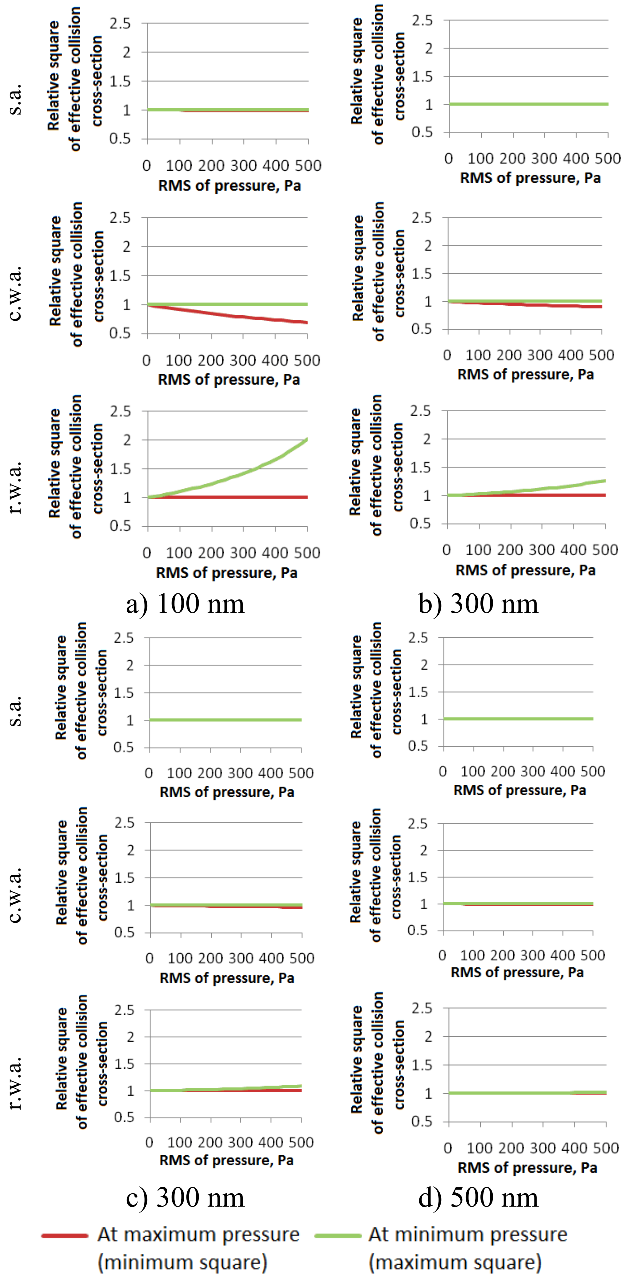
$p_A>0$.

2.2. Rarefaction shock wave:

$p_A<0$.

Figures 3a-c show the dependences of the range limits of the change of the area of the equivalent collision cross section on the root-mean-square value of the acoustic pressure $\sqrt{\langle p'^2(t)\rangle} = \sqrt{\frac{1}{T}\int_0^T p'^2(t)dt}$.

It is given the dependences of the instantaneous area of the effective collision cross section, when the value of the pressure disturbances achieves maximum (minimal area) $P' = \max_{t\in[0;T]} p'(t)$ at the specified root-mean-square pressure and method of the action and when the value of the pressure disturbances reaches minimum (maximum area) $P' = \min_{t\in[0;T]} p'(t)$.



a) 100 nm b) 300 nm

c) 300 nm d) 500 nm

Figure 3. The dependences of the change range limits of the relative area of the effective collision cross section of the particles on root-mean-square pressure value under the action of the various methods

Here and in the next figures s.a – sinusoidal action; c. w. a – compression waves action; r.w.a – rarefaction waves action.

The presented dependencies determine the range of the area of the collision cross section change under the action of the various methods.

As it follows from the graphs, at the sinusoidal action the change range of the area of the collision cross section is close to zero. It is caused by the fact, that the amplitude of acoustic pressure at the sinusoidal action is small in comparison with the static pressure in the environment.

The action by compression waves leads to the slight decrease of the area of the equivalent collision cross section relative to the initial value (at static pressure). It can be explained by the fact, that the submicron particles make Brownian motion even without the pressure disturbances. In turn, the rise of the pressure leads to decrease of the dispersion of particle spatial position because of the following reason.

As the propagation of the shock wave is adiabatic, the concentration of the molecules increases faster (according to the law $\sim p^{\frac{1}{\gamma}} = p^{0,71}$) than the standard velocity deviation (root of the temperature) of the surrounding gas phase molecules rises (according to the law $\sim p^{\frac{\gamma-1}{2\gamma}} = p^{0,15}$).

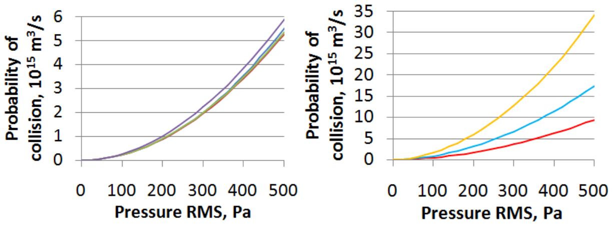
As a result the value of the characteristic change of the particle coordinates between consequent collision acts of two molecules moving with opposite velocities will be reduced $\Delta x \sim \frac{m}{M} v\Delta t \sim \sqrt[3]{\frac{1}{n}} \sim \sqrt[3]{p^{-\frac{1}{\gamma}}} = \frac{1}{p^{\frac{1}{3\gamma}}}$. As a consequence, the area of the effective collision cross section becomes smaller.

Similarly, the area of the effective collision cross section increases with the pressure reduction.

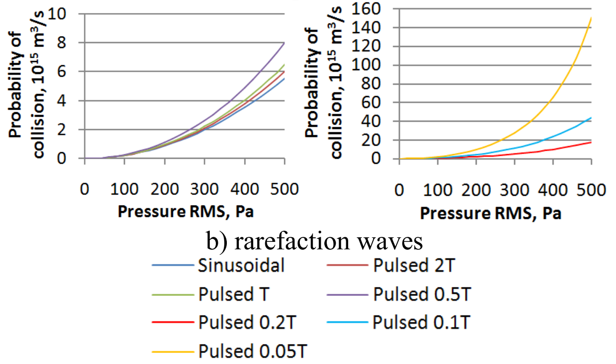
As it follows from given dependencies the area of the effective collision cross section can be enlarged for the submicron particles in up to 2 times, if oscillating energy is provided by the modern radiators [3, 4].

Further on the base of obtained collision cross section it is carried calculations of the probability of the collision depending on the method of the action and the value of entered energy at the various sizes of the particles to be coagulated (Figures 4–7). In Figures 4–7 variable T marks the period of ultrasonic oscillations at the continuous sinusoidal action, which equals 45 µs.

Studied range of the pulse duration is from 0.05T (2 µs) to 2T (90 µs).

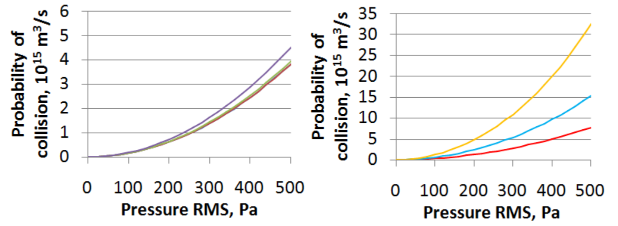


a) compression waves

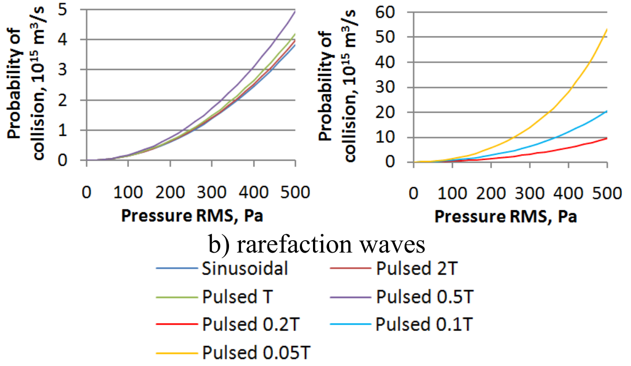


b) rarefaction waves

Figure 4. Dependences of the probability of the particles collision on root-mean-square value of the pressure at various methods of the action (sinusoidal and shock-wave) and the pulse duration at the shock-wave action (the particle diameter is 100 nm)



a) compression waves

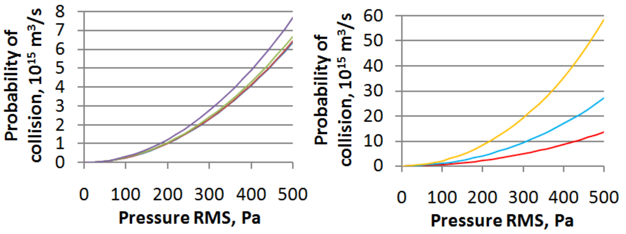


b) rarefaction waves

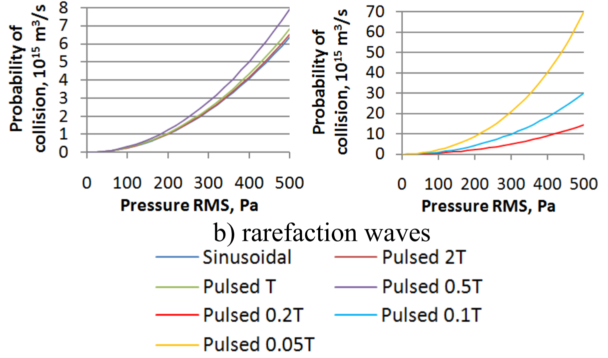
Figure 5. Dependences of the probability of the particles collision on root-mean-square value of the pressure at various methods of the action (sinusoidal and shock-wave) and the pulse duration at the shock-wave action (the particle diameter is 200 nm)

As it follows from presented dependences the action by the shock waves (both compression waves and rarefaction waves) increases the probability of the collision in comparison with the sinusoidal action.

The possibility of collision rises with the growth of the duration of compression or rarefaction pulse, even when root-mean-square value of the acoustic pressure retains (the total entered energy is retained).

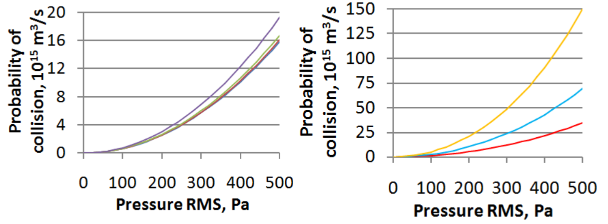


a) compression waves

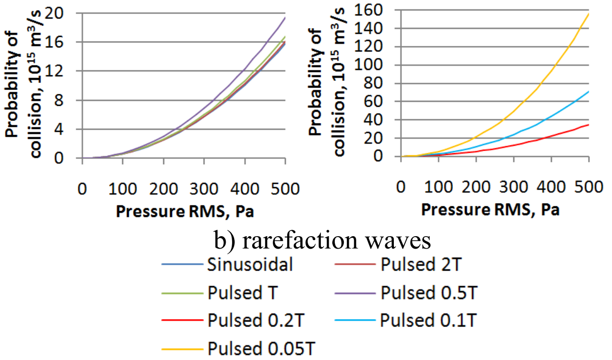


b) rarefaction waves

Figure 6. Dependences of the probability of the particles collision on root-mean-square value of the pressure at various methods of the action (sinusoidal and shock-wave) and the pulse duration at the shock-wave action (the particle diameter is 300 nm)



a) compression waves



b) rarefaction waves

Figure 7. Dependences of the probability of the particles collision on root-mean-square value of the pressure at various methods of the action (sinusoidal and shock-wave) and the pulse duration at the shock-wave action (the particle diameter is 500 nm)

It is explained by the non-linear effects appearing at sharp rise of the instantaneous value of the acoustic pressure. It proves the principal possibility of coagulation efficiency increase with the help of new method of shock-wave action without the rise of total energy entered to the carrying gas phase.

The action by rarefaction shock wave leads to the additional increase of the collision probability in up to 1.5 times in comparison with the action by compression shock wave. It is caused by the enlargement of the area of the equivalent collision cross section of the particles.

The effect of using the shock-wave action is increased for the particles of small sizes, as owing to small mass of such particles the shock-wave action provides larger dispersion of their spatial position and, consequently, the area of the collision cross section. It can be the explanation of experimental results presented in the papers [16, 17] fact of the acceleration of the coagulation of the submicron aerosols under the shock-wave action.

Further the dependences of the probability of the particles collisions on the pulse duration (Figures 8–11) are shown.

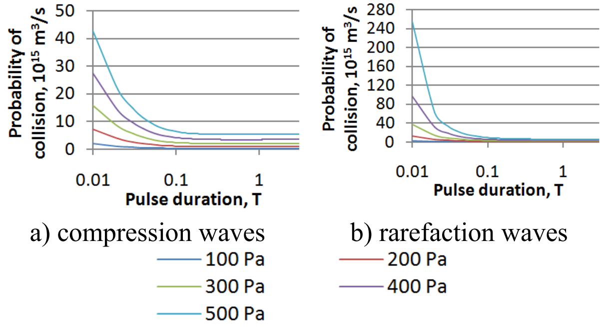

a) compression waves b) rarefaction waves

Figure 8. Dependences of the probability of the particles collision on the pulse duration under the shock-wave action (the particle diameter is 100 nm) at various root-mean-square values of the pressure disturbance

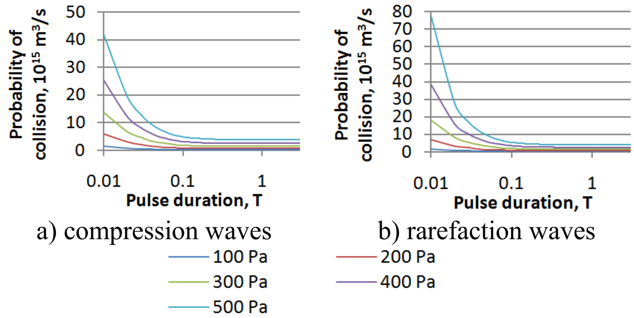

a) compression waves b) rarefaction waves

Figure 9. Dependences of the probability of the particles collision on the pulse duration under the shock-wave action (the particle diameter is 200 nm) at various root-mean-square values of the pressure disturbance

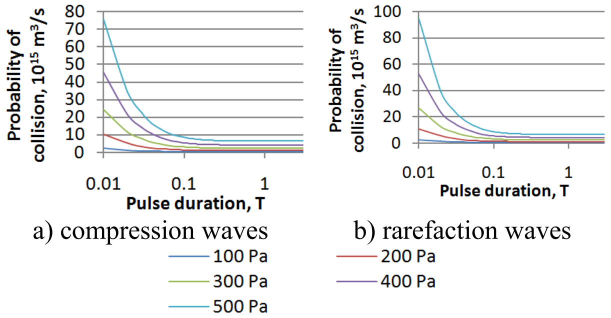

a) compression waves b) rarefaction waves

Figure 10. Dependences of the probability of the particles collision on the pulse duration under the shock-wave action (the particle diameter is 300 nm) at various root-mean-square values of the pressure disturbance

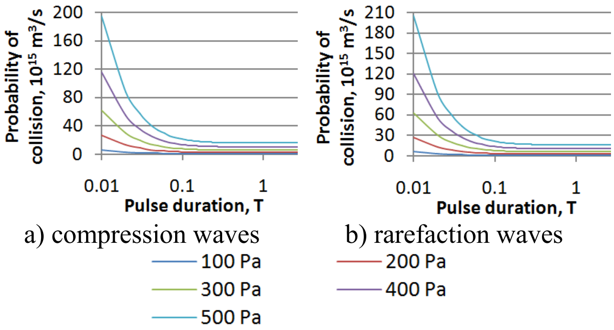

a) compression waves b) rarefaction waves

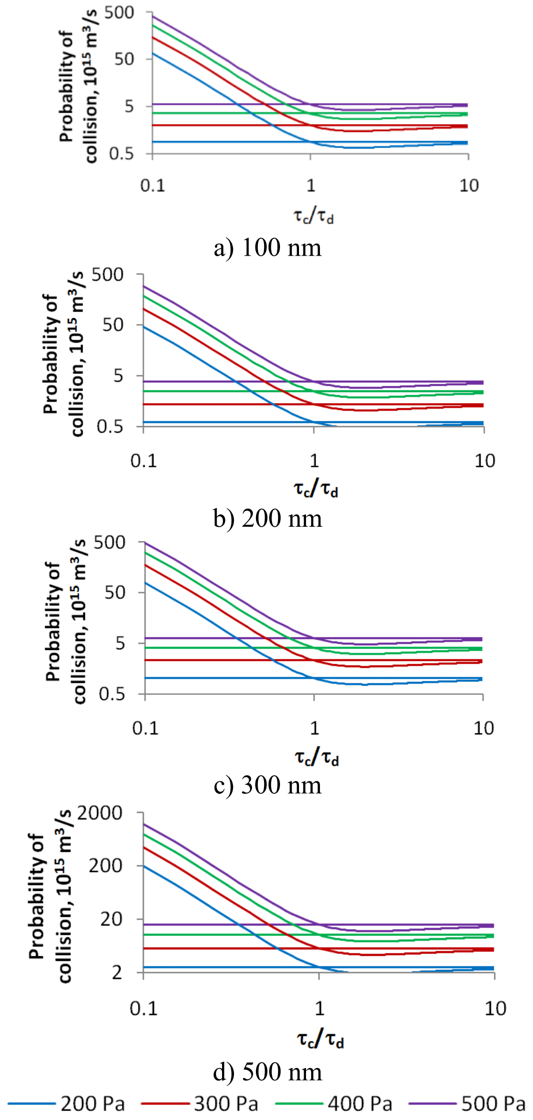
Figure 11. Dependences of the probability of the particles collision on the pulse duration under the shock-wave action (the particle diameter is 500 nm) at various root-mean-square values of the pressure disturbance

Given dependences proves the possibility to increase the probability of the collision in up to 10 times and more at the shock-wave action (under the action of compression and rarefaction waves) in comparison with the sinusoidal action at the same value of total entered energy (root-mean-square value of the pressure at all types of the action is similar).

As in practice it is impossible to generate compression shock waves without the periods of rarefaction or rarefaction shock waves without the periods of compression (because of the laws of conservation of mass and pulse of the carrying gas phase near the real radiator the compression wave obligatory follows the rarefaction wave or vice versa; the extreme case is sinusoidal oscillations – the alternation of the compression and rarefaction periods) on the base of proposed model it is carried out studies at different ratios between the durations of the compression wave and the rarefaction wave following it $\frac{\tau_c}{\tau_d}$.

Figure 12 shows the dependences the probability of the collision on the ratio between the durations of alternating compression and rarefaction shock waves at the different sizes of the particles and the root-mean-square values of the acoustic pressure.

Non-constant dependences mean the probability of the collision under the action of alternating compression and rarefaction waves. The horizontal dependences (the graphs of the functions, which are identically equal to the constant) denote the probability of the collision under sinusoidal action at the similar root-mean-square value of the acoustic pressure.



a) 100 nm

b) 200 nm

c) 300 nm

d) 500 nm

Figure 12. Dependences of the probability of the collision on the ratio of the pulse duration of the compression wave to the pulse duration of the rarefaction wave at different pressure RMS

As it follows from presented dependences the best effect (the acceleration of the coagulation in more than 10 times in comparison with the sinusoidal action) per unit of entered energy is provided by the action of the shock waves alternation, where the duration of the compression wave is less than the duration of the rarefaction wave ($\frac{\tau_c}{\tau_d} < 1$). It is explained by the fact, that rarefaction wave gives rise to the area of the collision cross section, which exceeds the modulus of the change of the area of the collision cross section downwards under the action of rarefaction wave.

4. CONCLUSIONS

In this paper was carried a theoretical study based on a model of the influence of the ultrasonic and shock-wave pressure disturbances in a gas phase on the probability of the submicron particles collision. For the first time the model took into consideration the influence of Brownian motion on the area of the effective particle collision cross section.

The model allowed determining the possibility of the additional efficiency increase of the coagulation in up to 10 times and more at the application of the shock-wave action for the submicron particles in comparison with the sinusoidal action at the similar power consumptions.

Under the action of the shock waves superposition generated by the real sources of the shock-wave action (for instance, by multi-frequency radiators forming the alternation of the harmonics of the multiple frequencies, interrupters of the flow, membranes), it is preferable to provide increased duration of the rarefaction wave in comparison with the compression wave.

Thus, proposed model can be used as a theoretical base of experimentally observed fact of accelerated coagulation of the submicron particles at the shock-wave action.

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