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# Phenomenological Model of Propagation, Evolution and Destruction of Multiphase Aerosol in High-Frequency Acoustic Field

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*Abstract:* - The paper was presented a phenomenological model of propagation, evolution and destruction of multiphase aerosol under the action of external forces by high-frequency acoustic field. The model describes evolution of the dispersion composition of the aerosol cloud in time and space under the action of external forces. The model is based on the idea of aerosol as a continuous medium with the equivalent characteristic – in calculating particle concentration of each fixed chemical composition from the substances, which differ in density, of each fixed velocity. Developed model allowed revealing complex theoretical dependences of coagulation efficiency of two-phase aerosol in the model extensive channel on the different parameters both the particles (the initial sizes, the velocities of each phase, the ratio of phase densities, the ratio of the phase concentrations) and gas flow (the velocity, the density) carrying the aerosol cloud.

*Keywords:* - Ultrasonic, model, aerosol cloud, acoustic field, gas flow

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## 1. INTRODUCTION

The task of the study of the processes of dispersed particle interaction with alternating influences, for instance, acoustic, in the multiphase systems is one of current importance problems of gas and liquid mechanics, its practical significance is concerned with wide use of the technologies based on the mechanics of the heterogeneous systems, such as gas purification processes, separation of dispersed systems, etc.

Up to the present the processes and the phenomena in the dynamics of the heterogeneous media are not available for the experimental studies, that is why the research of the processes of the interaction of the acoustic vibrations with the multiphase aerosols by the methods of mathematical modelling is actual and relevant.

## 2. EXISTING EVOLUTION MODELS OF MULTIPHASE AEROSOLS AND PROBLEM STATEMENT OF THE STUDY

The existing models of the multiphase aerosols are based on Lagrange (the imitation models of the separate particle motion are considered) and Euler (it

is considered the aerosol cloud as a continuum having equivalent characteristics) approaches.

The models based on Lagrange approaches [1, 2] have computational complexity at the calculation of multiphase aerosol motion containing several types of the substances (it is necessary to calculate motion and evolution of each separate particle).

For the solution of practical tasks on the revealing of the aerosol behavior in open air, in the industrial areas, in the technological equipment there is no need to each separate particle, when the number of particles presenting in industrial premises can be several tens of billion and more.

The macroscopic characteristics of the aerosol (on concentration, specific area of free surface or flow of the particle mass) determining the pollution level of industrial waste gases, harm of the aerosol presence in the premises or efficiency of chemical-technological processes in the multiphase systems are the most interesting.

Thus, further special attention is paid to the models based on Euler approach.

Among the models of the class the effects generated by the ultrasonic action are taken into consideration by the probabilistic model of coagulation, which was first proposed by M. Smoluchowski in 1916 [1] and modified further by L.

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Song, C. Sheng and X. Shen [2] for the account of the secondary forces generated by ultrasonic vibrations.

The taking into account of ultrasonic action in this model is carried out by the calculation of the components of the probability of particle collision on the base of the analytical expressions for the forces of the second order leading to the particle approach due to the acoustic field.

The probabilistic model of coagulation proposed by M. Smoluchowski, L. Song, C. Sheng and X. Shen describes only the process of spatially homogeneous aerosol evolution and it does not take into account the possibility of content of several substances in the frames of dispersed phase.

Spatially-heterogeneous modification of the probabilistic model of coagulation proposed by D. Ramkrishna [3], F. Guias [4], M.A. Marchenko [5] does not consider possible dispersion of particle velocity with the same sizes and the possibility of the presence of several substances making the particle. The dispersion of the velocities of the particles with the same sizes is possible, if the particles are composed in different ways as a result of different consequences of the elementary coagulation acts (for instance, the particle with the mass of  $4m_0$  can be composed as a result of aggregation of two particles with the same mass  $2m_0$  or as a result of aggregation of two particles with the mass  $m_0$  and  $3m_0$ , respectively).

Moreover, proposed models of spatially-heterogeneous coagulation do not take into account the influence of velocity of stationary particle motion due to the drag by gas flow on the effect made by ultrasonic vibrations.

The attempt to consider the presence of more than two phases in the aerosol was made by M. Sommerfeld proposed multiphase model of the mixture [6, 7]. However this model can be applied only to the solutions and colloidal systems and it does not allow finding out the distribution of particle concentration according to their sizes.

Thus, developed generalized phenomenological model of multiphase aerosol evolution should simultaneously consider following factors:

1. The presence of several types of the substances composing the particle and the distribution of the particles not only to their size but to their chemical composition.

2. The dispersion of velocity of the particle with the same sizes and chemical compositions.

3. The influence of the velocity of the stationary particle motion on the effect of ultrasonic action.

Further it is given generalized phenomenological model developed by the authors of multiphase aerosol evolution under the action of external forces taking into account the factors mentioned above.

### 3. GENERALIZED PHENOMENOLOGICAL MODEL OF MULTIPHASE AEROSOL EVOLUTION UNDER THE ACTION OF EXTERNAL FORCES

Developed model describes evolution of the dispersion composition of the aerosol cloud in time and space under the action of external forces. The model is based on the idea of aerosol as a continuous medium with the equivalent characteristic – in calculating particle concentration of each fixed chemical composition from the substances, which differ in density, of each fixed velocity. At that this characteristic is determined by its spatial distribution and evolution in time.

The approach to the modelling is based on the consideration of aerosol cloud in the form of the continuum with the equivalent characteristics in the concentrations of the particles with different sizes, chemical compositions and velocities (Euler approach).

At the modelling of the aerosol evolution Euler approach is combined with Boltzmann approach [8], which allows describing the state of aerosol cloud in the form of common scalar function, which is called **the function of the aerosol state** depending on the masses of each substance in the dispersion phase, the velocity of the dispersion phase and the coordinates of the observed point and determining the concentration of each fraction of the aerosol cloud.

The dependence of the state function on stated set of the parameters takes into account the presence of several types of the substances composing the particle and the distribution of the particles not only according to their sizes, but to chemical composition; dispersion of the particle velocities with the same sizes and the chemical compositions.

At that the evolution of the aerosol cloud is described by the common partial differential equation and the integral of given scalar function.

The evolution of dispersion composition of the aerosol cloud according to proposed model occurs due to the appearance and the course of the following phenomena:

- the spatial shift of the aerosol cloud under the action of the steady forces [9, 10, 11];

- the concentration increase of the coarse fraction of the aerosol cloud due to the integration of fine fraction (coagulation) under the action of alternating forces and the secondary forces initiated by them [12, 13];

At that the steady forces initiated spatial particle shift can be flow force from the side of stationary air flow, gravitation force, etc. The steady forces can lead to the coagulation due to the fact that the forces

depend on the characteristics of determined fraction of the aerosol cloud (the diameter, the mass, the velocity) and can speed up or slow down the fractions of the aerosol cloud up to different velocities. For instance, in the steady air flow the fractions of the aerosol cloud with the size of 5 micron will coagulate with the fraction with the size of 100 micron, as fine fractions are involved totally into airflow and coarse fractions are not involved, i.e. it occurs the dispersion of the aerosol cloud velocities leading to their collision and the increase of the coarse fraction concentration.

As alternating forces, which initiate coagulation, orthokinetic forces generated by vibrating air motion (due to acoustic action) can appear. Said alternating forces can initiate the secondary forces under certain conditions, which additionally promote coagulation, such the forces of hydrodynamic interaction and Oseen forces due to convective transfer at vibrating motion of the gas flow [2, 12].

Taking into account the passing of mentioned above phenomena the evolution of the aerosol cloud is described by **the function of the aerosol state** depending on the mass  $m_i$  (kg) of the substances of each  $i$ - type (totally  $l$  types of the substances) being a part of the certain fraction, the vector of observed point coordinate  $\mathbf{r}$  (m), in which neighborhood the aerosol state is considered, the vector of fraction velocity of the aerosol cloud  $\mathbf{v}$  (m/s) and the time  $t$ . The function of state determines the fraction mass of the aerosol cloud being in the volume of the phase

space  $d\mathbf{r}d\mathbf{v}\prod_{i=1}^l dm_i$  (separated fraction of the aerosol cloud is in the volume  $d\mathbf{r}$ , the velocity of separated fraction is in the range of the values from the volume  $d\mathbf{v}$  of the velocity space and the mass of each  $i$ -substance is within the range of the width  $dm_i$ ) in the moment of time  $t$ , which equals

$$f(m_1, \dots, m_l, \mathbf{r}, \mathbf{v}, t) d\mathbf{r}d\mathbf{v}\prod_{i=1}^l dm_i.$$

With the purpose of reducing of the modelling task of distribution, evolution and destruction of the aerosol to the solution of differential integral equation in multidimensional space with the identical coordinate dimension in order to use further standard numerical methods based on multidimensional finite element method it was entered “mass-pulse” vector, determining the parameters of the fraction of the aerosol cloud:

$$\mathbf{p} = (m_1c \quad \dots \quad m_l c \quad Mv_1 \quad \dots \quad Mv_n)^T;$$

where  $c$  is the sound velocity in gas, m/s;  $m_i$  is the mass of  $i$ - substance being a part of the virtual particle of the fraction, kg;  $M = \sum_{i=1}^l m_i$  is the mass of the

virtual particle of the fraction, kg;  $v_i$  is  $i$ - component of the velocity of the aerosol cloud fraction, m/s. This vector characterizes totally the state of the aerosol cloud fraction, which is in the neighborhood of the point with fixed coordinate  $\mathbf{r}$ , and all components of the vector have identical dimensions, kg·m/s.

At the collision and coagulation of the fractions of the aerosol cloud “mass-pulse” vector has additive property:

$$\mathbf{p} = \mathbf{p}_1 + \mathbf{p}_2, \quad (1)$$

as the law of mass conservation of the substances composing the virtual particle of the aerosol cloud fraction is true:

$$\begin{aligned} m_j &= m_{1j} + m_{2j} \Rightarrow m_j c = m_{1j} c + m_{2j} c \Rightarrow \\ &\Rightarrow p_j = p_{1j} + p_{2j} \end{aligned}$$

for  $j=1 \dots l$  and momentum conservation law, as the coagulation process in the most cases is instantaneous in comparison to characteristic time of approach and, respectively, the duration of viscous force of gas changing the pulse is very short:

$$M\mathbf{v} = M_1\mathbf{v}_1 + M_2\mathbf{v}_2 \Rightarrow p_{l+j} = p_{1(l+j)} + p_{2(l+j)}$$

for  $j=1 \dots n$ .

According to proposed generalized model the change of the aerosol state function describes by differential equation:

$$\frac{\partial f}{\partial t}(\mathbf{p}, \mathbf{r}, t) = (I - P - F)[f]; \quad (2)$$

The summands of the right part of the equation (2) are linear ( $P$ ) and non-linear ( $I, F$ ) functionals at the space of the aerosol state function. Along with the state function they depend on the field of external steady, alternating and secondary forces.

The functionals look like this:

$$P = (\mathbf{v}, \nabla_{\mathbf{r}})f; \quad (3)$$

$$F = (\mathbf{F}[f], \nabla_{\mathbf{p}})f; \quad (4)$$

$$\begin{aligned} I &= \int \int_{(0, \dots, 0) \times (M_1, \dots, M_l) \times (m_1, \dots, m_l)} \beta(\mathbf{p}_1, \mathbf{p} - \mathbf{p}_1) \times \\ &\times f(\mathbf{p}_1, \mathbf{r}, t) f(\mathbf{p} - \mathbf{p}_1, \mathbf{r}, t) d\mathbf{p}_1 - \\ &- f(\mathbf{p}, \mathbf{r}, t) \int \beta(\mathbf{p}, \mathbf{p}_1) f(\mathbf{p}_1, \mathbf{r}, t) d\mathbf{p}_1 \end{aligned}; \quad (5)$$

where  $\beta(\mathbf{p}, \mathbf{p}_1)$  is the probability of the fraction collision with “mass-pulse” vectors  $\mathbf{p}$  and  $\mathbf{p}_1$  at single mass concentrations per time unit,  $m^3/(\text{kg}\cdot\text{s})$ .

The dependence of the collision probability on the velocities or the particle pulses composing “mass-pulse” vector takes into consideration the influence of gas flow velocity on the effect of the ultrasonic coagulation.

The collision probability is determined by action and it is a sum of two components [2] – orthokinetic  $\beta_{Oi,j}$  caused by the difference of vibration

amplitudes of the fractions and hydrodynamic  $\beta_{Hi,j}$  caused by the forces of radiation pressure:

$$\beta_{i,j} = \beta_{Oi,j} + \beta_{Hi,j}.$$

The components of the collision probability are defined in a following way:

$$\beta_{Oi,j} = \frac{1}{2} \frac{M_i + M_j}{M_i M_j} (d_i + d_j)^2 U_0 H_{i,j};$$

$$\beta_{Hi,j} = \frac{(d_i + d_j)^2}{6\mu} \frac{M_i + M_j}{M_i M_j} \left( \frac{1}{d_i} + \frac{1}{d_j} \right) \int_0^\pi h(f_{21}) f_{21} \sin \theta d\theta;$$

where  $d_i, d_j$  are the sizes of the virtual particles in a fraction,  $m$ ;  $H_{i,j}$  is the difference module of the complex coefficients of the fraction increase in the ultrasonic field and the steady flow of the gas phase;  $f_{21}$  is the force of hydrodynamic interaction of the fractions;  $U_0$  is the amplitude of vibration velocity of the fractions, m/s;  $\mu$  is the viscosity of the carrying gas phase, Pa·s.

In view of additivity law (1) for “mass-pulse” vector the integral summand (5), which characterizes coagulation of the fractions of the aerosol cloud, is similar to Smoluchowski integral equation [2].

However, presented form of the equation rewriting of the evolution of the function of the aerosol state does not allow applying standard numerical methods of the solution of differential-integral equations because of the presence of the coordinate vector, from which does not depend the coefficients in the bilinear operators.

In order to make possible the calculation of the evolution of the function of the aerosol state with the help of multidimensional finite element method and iterative methods of solution of the set of the linear equations with large dispersed matrices, the arguments of state function are in the form of the single vector of state  $\mathbf{s}$  of the aerosol cloud fraction and time and time scalar  $t$ . Vector  $\mathbf{s}$  describes totally the state of the aerosol cloud fraction, i.e. determines the mass of each substance composing the fraction, pulse and the coordinate of the mass center of separated fraction:

$$\mathbf{s} = \begin{pmatrix} \mathbf{p} \\ \omega M \mathbf{r} \end{pmatrix},$$

where  $\mathbf{p}$  is “mass-pulse” vector of the fraction, kg·m/s;  $\omega$  is the angular frequency,  $s^{-1}$ .

Using vector  $\mathbf{s}$ , the equation (2) is converted in a following way:

$$\frac{\partial f}{\partial t}(\mathbf{s}, t) + (\mathbf{U}, \nabla) f =$$

$$= \int \int \beta(\mathbf{p}_1, \sigma_p(\mathbf{s}) - \mathbf{p}_1) \times$$

$$(0, \dots, 0) \times (M_1, \dots, M_l) \times (m_1, \dots, m_l) ; \mathbf{U} = \begin{pmatrix} \mathbf{N}_m \\ \mathbf{F}[f] \\ \omega M \mathbf{r} \end{pmatrix}; (6)$$

$$\times f \left( \mathbf{s} + \begin{pmatrix} \mathbf{p}_1 - \sigma_p(\mathbf{s}) \\ \mathbf{N}_r \end{pmatrix}, t \right) f \left( \mathbf{s} - \begin{pmatrix} \mathbf{p}_1 \\ \mathbf{N}_r \end{pmatrix} \right) d\mathbf{p}_1 -$$

$$- f(\mathbf{s}, t) \int \beta(\sigma_p(\mathbf{s}), \mathbf{p}_1) f \left( \mathbf{s} + \begin{pmatrix} \mathbf{p}_1 - \sigma_p(\mathbf{s}) \\ \mathbf{N}_r \end{pmatrix}, t \right) d\mathbf{p}_1$$

where  $\mathbf{N}_r$  is  $n$ -dimensional vector consisting only from zeros;  $\mathbf{N}_m$  is  $l$ -dimensional vector consisting only from zeros;  $\sigma_p(\mathbf{s})$  is the vector projection  $\mathbf{s}$  on the components with the numbers  $l+1, \dots, l+n$ .

Obtained equation (6) is the equation of flow in a  $(l+2n)$ -dimensional space, where  $n$  is the space dimension of the particle position,  $l$  is the number of the substances type composing the particle.

For instance, the task of calculation of the aerosol evolution consisting of two types of the substances in 3-d space of the positions is the task of the solution of the flow equation (or the convective transport equation) in 8-dimensional space.

The equation of such type can be solved by finite element method.

The equation of the aerosol evolution (6) is completed by the boundary conditions of the following types:

– the condition of aerosol supply characterizing the aerosol generation from a surface  $S$  (for instance, the surface of liquid film or the cross-section of the pipe-line, through which gas flow with the particles come):

$$f(\mathbf{s}, t) \Big|_{\sigma_r(\mathbf{s}) \in S} = n(\mathbf{s}, t); (7)$$

– the condition of concentration decreases of the aerosol cloud, which characterizes the absence of the fractions near specified surface, which move inside to considered area of propagation and evolution of the aerosol cloud:

$$f(\mathbf{s}, t) \Big|_{\sigma_r(\mathbf{s}) \in S, (\sigma_p(\mathbf{s}), \mathbf{n}) \geq 0} = 0; (8)$$

– the condition of impermeability of the wall of propagation area and evolution of the aerosol cloud:

$$f(\mathbf{s}, t) \Big|_{\sigma_r(\mathbf{s}) \in S} = f \left( \mathbf{s} - (1 + \lambda) \mathbf{n} \begin{pmatrix} \mathbf{N}_m \\ \sigma_p(\mathbf{s}), \mathbf{n} \\ \mathbf{N}_r \end{pmatrix}, t \right) \Big|_{\sigma_r(\mathbf{s}) \in S}; (9)$$

where  $\sigma_r(\mathbf{s})$  is the projection  $\mathbf{s}$  vector on the components with the numbers  $l+n+1, \dots, l+2n$ ;  $\lambda$  is the proportionality coefficient determining the reflection character of the aerosol cloud fraction from the wall. This coefficient depends on adhesive properties of the wall material and the substance of the dispersion phase of the aerosol cloud. At  $\lambda=0$  the reflection is absolutely inelastic (selected element of the aerosol cloud after the collision with the wall moves at a tangent to the last one). At  $\lambda=1$  the reflection is absolutely elastic (the angle of incidence of specified element of the aerosol cloud equals to the reflection angle). The solution of given equation (2) with boundary conditions (7-9) allows revealing main principals of ultrasonic coagulation of the two-phase aerosol at the motion in the model channel.

Revealed  $\sigma_p$  regularities are described in the next part.

#### 4. THE PRINCIPALS OF ULTRASONIC COAGULATION OF THE TWO-PHASE AEROSOL AT THE MOTION IN THE MODEL EXTENSIVE CHANNEL

The analysis of the model of the propagation and the evolution of the multi-phase aerosol was carried out at the example of the two-phase aerosol, which is the most widely used in practice in the processes of chemical technology.

For instance, during spray drying the particles of the sprayed aerosol consist of both from solid dried material and from liquid phase (removed moisture); during wet gas purification dust-gas flow consists of initial aerosol (solid particles of smoke and ash), which is to be separated from the flow, and the auxiliary absorbing aerosol (water drops) absorbing the initial aerosol and promoting additional efficiency increase of gas purification.

During the model analysis it was revealed the principals of ultrasonic coagulation at injection (generation), propagation and coagulation of two-phase aerosol moving in flow in the model channel of 2 m long. The two-phase aerosol near its place of injection into the channel (input  $S_{in}$ ) consists of two monophasic subaerosols – the initial aerosol (initial dispersion phase, as a rule solid substance) and the auxiliary aerosol (auxiliary dispersion phase, as a rule liquid), composed of the substance, which can vary in physical properties from the substance of the initial aerosol. At that the velocity of the initial aerosol equals to the velocity of gas flow, as in practice the size of the particles of the initial aerosol does not exceed 10 micron and they are all carried by the gas flow.

At the surface of the input to the channel  $S_{in}$  it is set following boundary condition of the aerosol supply:

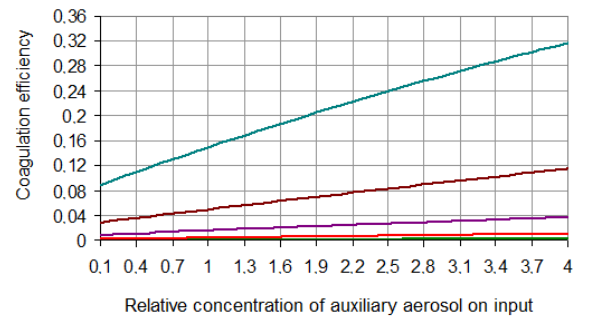
$$f(s, t)_{\sigma_r(s) \in S_{in}} \cdot 1 \frac{m^3 \cdot kg}{c^3} = n_{prim.in} \delta \left( m_1 - \frac{\rho_{10} \pi d_{10}^3}{6} \right) \delta(\mathbf{v} - \mathbf{n} V_{flow}) \cdot \delta(m_2) \frac{\rho_{10} \pi d_{10}^3}{6} + \delta(m_1) \delta \left( m_2 - \frac{\rho_{20} \pi d_{20}^3}{6} \right) \delta(\mathbf{v} - \mathbf{n} V_{20}) \frac{\rho_{20} \pi d_{20}^3}{6} n_{sec.in}$$

$\rho_{10}$  is the density of the substance of the initial subaerosol,  $kg/m^3$ ;  $d_{10}$  is the diameter of the particles of the initial subaerosol,  $m$ ;  $V_{flow}$  is the velocity of the gas flow in the channel,  $m/s$ ;  $n_{prim.in}$  is the number concentration of the particles of the initial subaerosol,  $m^{-3}$ ;  $\rho_{20}$  is the density of the substance of the auxiliary subaerosol,  $kg/m^3$ ;  $d_{20}$  is the diameter of the particles of the auxiliary subaerosol,  $m$ ;  $V_{20}$  is the velocity of the particles of the auxiliary subaerosol,  $m/s$ ;  $n_{sec.in}$  is the number concentration of the particles of the auxiliary subaerosol,  $m^{-3}$ .

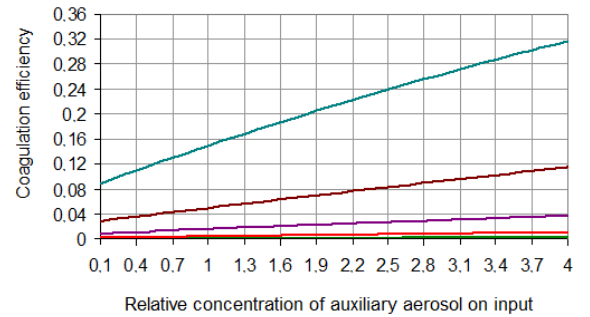
The boundary conditions of the reflection of the particles from the walls and the aerosol decrease remain in a general view (8, 9) without changes.

The coagulation efficiency (the portion of the particles of the initial aerosol coagulated with each other or with the particles of the auxiliary aerosol) is estimated by the following expression:

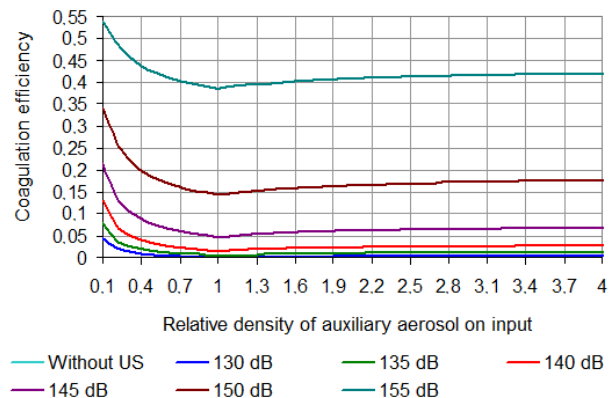
$$\mathcal{E} = \frac{n_{prim.out} - n_{prim.in}}{n_{prim.in}} = \frac{\lim_{\Delta m_2 \rightarrow 0} \int_{S_{out}} \int_{R^3} \int_{m_2 - \Delta m_2}^{\infty m_2 + \Delta m_2} f(m_1, 0, \mathbf{r}, \mathbf{v}, t) dm_2 dm_1 d\mathbf{v} dS(\mathbf{r})}{S_{out} n_{prim.in}} - 1$$



a) on relative concentration  $\frac{n_{sec.in}}{n_{sec.in0}}$



b) on relative diameter of the particles  $\frac{d_{20}}{d_{10}}$



c) on relative density of the particles  $\frac{\rho_{20}}{\rho_{10}}$

Figure 1. Dependences of the coagulation efficiency on the parameters of the auxiliary aerosol

On the base of numerical solution of the equation (1) with the boundary conditions (6-8) it was revealed the dependences of the efficiency of ultrasonic coagulation on the parameters of the auxiliary aerosol (Figure 1) at different levels of sound pressure (the frequency of action is 22 kHz, the velocity of gas flow of the initial and the auxiliary aerosol are equal and they are 60 m/s).

According to the dependences of the efficiency of ultrasonic coagulation on the parameters of the auxiliary aerosol it is determined, that at the absence of the auxiliary aerosol (the concentration is closed to zero) effect of the destruction of the initial aerosol can be observed only at the application of the ultrasonic vibrations with the level of acoustic pressure of no less than 130 dB (Figure 1a). It is concerned with the fact that in this case the coagulation of the particles of the initial aerosol can occur only between themselves.

However, the coagulation efficiency at absence of the auxiliary aerosol does not exceed 10% even at the level of the acoustic pressure of 155 dB. The introduction of the auxiliary aerosol increases coagulation efficiency in up to 3 times (Figure 1a). This arises from the fact that to elementary acts of the particle coagulation of the initial aerosol between themselves elementary acts of the coagulation of the initial aerosol with the auxiliary one are added. At that the efficiency is in proportion to the concentration of the auxiliary aerosol. It is established, that additional presence of the auxiliary aerosol with simultaneous application of ultrasonic vibrations allows achieving the destruction efficiency of the initial aerosol (concentration decrease) up to 50%, if the time of the initial aerosol being in the channel is no more than 0.1 s.

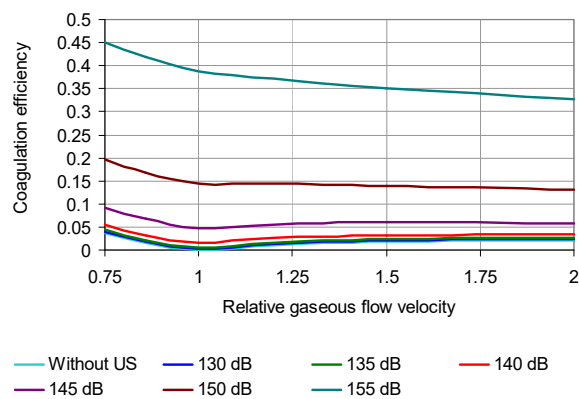
It is obtained dependence of influence the particle diameter of the auxiliary aerosol (Figure 1b) on the efficiency of destruction of the initial aerosol (the coagulation of the initial aerosol). It is determined, that for the most efficient destruction of the initial aerosol the diameter of the particles of the auxiliary aerosol should exceed the diameter of the particles of initial aerosol more than in 2 times.

It is established the existence of the least efficient diameter of the auxiliary aerosol, at which the number of coagulated particles achieves minimum value because of attainment of minimum of the relative vibration velocity of the particles of the initial and auxiliary aerosols. It is determined, that the least efficient diameter is 0.7...1 from the diameter of the particles of the initial aerosol.

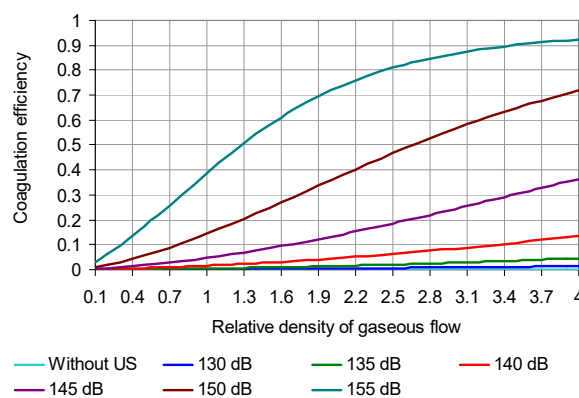
The dependences of influence of the density of the particles of the auxiliary aerosol (Figure 1c) on the coagulation efficiency are revealed. It is determined the existence the particle density of the auxiliary aerosol, at which the coagulation efficiency achieves

minimum value because of low relative vibration velocity of the particles of the initial and auxiliary aerosols. According to obtained dependences the least efficient density of the substance of the auxiliary aerosol is 1...1.05 from the density of the particles of the initial aerosol.

Further obtained dependences of the coagulation efficiency on the parameters of gas flow (Figure 2) are given.



a) on relative velocity of gas flow  $\frac{V_{flow}}{V_{20}}$  (relative to the velocity of the auxiliary aerosol)



b) on relative density of gas flow or  $\frac{\rho}{\rho_0}$  ( $\rho_0$  is the density of air at normal conditions)

**Figure 2.** Dependences of coagulation efficiency on the parameters of gas flow

According to obtained dependences it is established regularities of influence of the velocity of gas flow on the coagulation efficiency (Figure 2a).

It is determined, that at low levels of the acoustic pressure (up to 145 dB), there is the least efficient velocity of gas flow close to the velocity of the auxiliary aerosol, at which the coagulation efficiency is minimal. It is connected with the fact that the difference of the velocities of gas flow practically totally carrying small particles of the initial aerosol and the auxiliary aerosol contributes additionally to frequency of the particle collision. Specified effect is

observed as at the velocities of gas flow exceeding the velocity of the auxiliary aerosol and at the velocities having lower values than the velocity of the auxiliary aerosol.

However, at higher levels of acoustic pressure (more than 145 dB) it can be smoothing of the velocity extremum of gas flow. At that the higher velocity speed the lower coagulation efficiency, as the time of the presence in the channel decreases and consequently the time, during which two-phase aerosol is under the action of ultrasound, reduces.

It is established the regularities of influence of the density (Figure 2b) of gas flow on the coagulation efficiency. It is revealed, that at higher densities of gas flow the coagulation efficiency improves due to increased forces of the particle interaction, as the forces are carried through the molecules of gas. For instance, if the density is in 4 times more than air density at normal conditions and the level of acoustic pressure is 155 dB, the coagulation efficiency is more than 90% at the time of action of no more than 0.1 s.

## 5. CONCLUSIONS

As a result of carried out studies it was proposed phenomenological generalized model and it was developed mathematical description of the process of the propagation and the evolution of the aerosol cloud in time and space. In the model for the first time Euler approach is combined with Boltzmann approach [8], which allows describing the state of the aerosol cloud as a single function of the aerosol state depending on the masses of each substance in the dispersion phase, the velocity of dispersion phase and the coordinate of observed point.

For the first time the model simultaneously takes into account 3 influencing factors:

1. The presence of several types of the substances composing the particle and the distribution of the particles not only to their sizes but to chemical composition.

2. The dispersion of the particle velocity with the similar sizes and chemical compositions.

3. The influence of the velocity of the steady motion of the particles on the effect from ultrasonic action.

Developed model allowed revealing complex theoretical dependences of coagulation efficiency of two-phase aerosol in the model extensive channel on the different parameters both the particles (the initial sizes, the velocities of each phase, the ratio of phase densities, the ratio of the phase concentrations) and gas flow (the velocity, the density) carrying the aerosol cloud.

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