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Sedimentation of a Fine Aerosol in the Acoustic Field and with the Electrostatic Charge of Particles

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Finding an efficient way to eliminate fine dust (particle diameter of 1–15 μm) from a room can be a challenging problem. Acoustic radiation emitters are widely used to accelerate particle coagulation and sedimentation. In this study, we propose one more method for depositing harmful particles – dispersion of electrostatically charged particles. These particles attract uncharged particles from the air and accelerate coagulation. The paper is devoted to a comparison of methods for the acoustic and electrostatic sedimentation of aerosols. The mathematical model for the coagulation of aerosols on the basis of Smoluchowski's equation is proposed in the options corresponding to acoustic and electrostatic coagulation. A number of conclusions about the most effective conditions of sedimentation were made on the basis of the analysis of a kernel type of Smoluchowski's integral equation. The results of the experiments on acoustic and electrostatic sedimentation of the model aerosol media (coal dust) are given. The results of the calculations according to the mathematical model of coagulation taking into account the proposed mechanisms for the sedimentation of aerosols in the acoustic field and electrostatic charging of particles are given.

Keywords: fine aerosol; size distribution; acoustic exposure; electrostatic charge; coagulation; sedimentation.

1. Introduction

Aerosol pollution in production rooms is deposited by means of various types of equipment, and most often by filters and ventilation systems. At the same time, particularly dangerous fine particles (diameter of 1–15 microns) are difficult to remove from the air. More complex methods are used to remove them: acoustic and ultrasonic processing (Korovina *et al.*, 2013; Kudryashova *et al.*, 2015a), dispersion of electrostatically charged particles (Kudryashova *et al.*, 2015b; 2016). However, comparisons of these exposure methods on fine aerosols have not been performed. The objective of this study is to obtain the optimal methods of sedimentation of fine aerosols by comparing acoustic and electrostatic methods.

Acoustic fields are known to increase the rate of aerosol sedimentation. This is generally linked to an increase in the particle coagulation rate under exposure to acoustic fields, fast particle integration, and sedimentation. A number of studies by Roman Wyrzykowski and other scientists are devoted to the effect of the acoustic coagulation of aerosols, in particular (Wyrzykowski, 1956; 1969; Czyz, 1997; Mednikov, 1966). The impact of the frequency and amplitude of sound on the aerosol particle coagulation process is studied in detail. In other studies (Khmelev *et al.*, 2008; 2016), ultrasound is used to increase the effectiveness of devices that purify gases from particles, using the aerosol coagulation mechanism.

The authors of (Kudryashova *et al.*, 2015a) proposed a mathematical model for the kinetics of coagulation based on Smoluchowski's equation (Smoluchowski, 1916). The equation for the probability of particle collisions includes acoustic radiation parameters (frequency and intensity).

As a new method the authors propose applying electrostatic particle charging of specially sprayed powder for the acceleration of coagulation and deposition of aerosols (Kudryashova *et al.*, 2016). The charged particles attract polluting particles because of electrostatic interaction forces. The observed effect of electrostatic coagulation shows that the electrostatically charged particles of the sprayed powder and harmful aerosol particles in the air coalesced.

2. Mathematical model

The mass function of the particle size distribution is determined by the sizes following from the solution of the Smoluchowski's balance equation (Smoluchowski, 1916):

$$\frac{\partial g(D,t)}{\partial t} = I_1 + I_2, \tag{1}$$

where I_1 describes the size reduction of particles with diameter D [μm] for a unit of time in a unit of volume due to the collision between D-diameter particles and any D_1-diameter particle:

$$I_1 = -g(D,t)\int_0^\infty K(D,D_1)g(D_1,t)\,\mathrm{d}D_1, \tag{2}$$

I_2 describes the emergence of particles with diameter D due to the collision of particles with diameters D_1 and $D - D_1$:

$$I_2 = \frac{1}{2}\int_0^D K(D-D_1,D_1)g(D_1,t)g(D-D_1,t)\,\mathrm{d}D_1. \tag{3}$$

Initial conditions for a set of equations (1)–(3):

$$g(D,t_0) = g_0(D) \tag{4}$$

is the initial particle size distribution. To describe the particle distribution function by size, the gamma distribution is usually used:

$$g_0(D) = aD^\alpha \exp(-bD), \tag{5}$$

where b, α are the distribution parameters, a is the normalizing coefficient. One of the statistical characteristics of the particle distribution function by size is the average surface-volume diameter (Sauter mean diameter, SMD) of particles of $D_{32} = (\alpha+3)/b$.

The higher the probability is of the collision of particles, the quicker coagulation will occur. Without any exposure, this value is caused by Brownian motion. In model (1)–(4) the probability of the collision of particles of an aerosol without any external exposure was considered to be proportional to the sum of the squares of diameters of particles:

$$K(D,D_1) = \frac{k_b n_0}{\nu}(D^2 + D_1^2), \tag{6}$$

where k_b is the constant of proportionality; ν is the kinematic media viscosity coefficient [m^2/s], and n_0 is the quantity of particles.

For driving particles in the field of external forces in (Mednikov, 1966) it was found that the number of meetings of particles N is proportional to the sum of the squares of diameters of particles, the square of the speed of their movement V [m/s], the number of particles n_0, and in inverse proportion to the media viscosity ν:

$$N \approx \frac{V^2 n_0 (D^2 + D_1^2)}{\nu}. \tag{7}$$

Following (Korovina *et al.*, 2013; Kudryashova *et al.*, 2015a), we give an equation for the probability of particle collisions of diameter D and D_1 in the acoustic field:

$$K(D,D_1) = \frac{k_b n_0}{\nu}(D^2 + D_1^2) \cdot \left(1 + k_a V^2 \left(1 - \frac{1}{\sqrt{1+\omega^2\tau^2}}\right)^2\right), \tag{8}$$

where ω is the frequency of the acoustic exposure [Hz]; $\tau = D^2/18\nu$ is the time of the Stokes relaxation of the particle [s]; ν is the kinematic coefficient of the viscosity, and k_a and k_b are the proportionality factors.

Now we get an equation for the probability of collisions of electrostatically charged powder particles and neutral particles of a harmful aerosol.

Let the powder particles have a charge of q [C] and diameter D, and the harmful aerosol particles have a charge q_1 (electroneutral particles will gain a counter charge because of the phenomenon of the electric flux density) and diameter D_1. The charges are opposite according to the sign. Then the Coulomb force works between particles:

$$F_c = k\frac{q_1 q}{r_{12}^2}, \tag{9}$$

where r_{12} is the distance between particles [m], $r_{12} \sim 1/\sqrt[3]{n_0}$; $k = 1/(4\pi\varepsilon\varepsilon_0)$; ε_0 is the vacuum permittivity [F/m]; ε is the media permittivity [F/m].

The resistive force is determined by the equation (Stokes law):

$$F_{st} = -3\pi D_1 \eta V. \tag{10}$$

where η [Pa·s] is the dynamic viscosity of air.

The constant speed of a particle V taking into account the frictional force Eq. (10) and Coulomb force Eq. (9) will be:

$$V = \frac{k}{3\eta}\frac{q_1 q}{r_{12}^2 D_1}. \tag{11}$$

The probability of the collision of particles in Smoluchowski's model is proportional to the number of meetings, and Eq. (6) taking into account Eqs. (7) and (11) will be written as:

$$K(D,D_1) = k_b N = k_b \frac{n_0^{5/3} k^2 (q_1 q)^2}{9\nu\eta_0^2}\left(1 + \left(\frac{D}{D_1}\right)^2\right). \tag{12}$$

Comparing equations for a kernel of the Smoluchowski equation in form Eq. (8) (for the acoustic exposure) and in form Eq. (12) (electrostatic coagulation) we draw your attention to the following.

1) In electrostatic coagulation the probability of collisions is more dependent on the concentration of particles than in acoustic coagulation (degree 5/3 instead of 1). However, it is also more dependent than in acoustic coagulation on the media viscosity (degree 3 instead of 1). This means that electrostatic coagulation will occur quicker in medias with a lower viscosity and with a larger concentration of particles.
2) The bigger the diameter of particles (the sum of squares of diameters of particles, equation Eq. (8)) the faster the acoustic coagulation. The dependence of a kernel of Smoluchowski's equation on the diameter of particles for electrostatic coagulation is more complex, but $K(D,\ D_1)$ in this case does not grow as the diameter of particles increases. This means that acoustic coagulation will occur faster for larger particles.
3) Other equation terms Eqs. (8) and (12) are responsible for the intensity of the exposure. It is evident that the higher the intensity of the acoustic exposure (higher than the oscillating moving speed of particles in equation (8)), the higher the frequency, the higher the probability of collisions. The higher the electrostatic charge of a particle and the lower the media permittivity, the higher the probability of collisions is in case of electrostatic coagulation.

3. Experimental study

Mineral coal dust was used as a model aerosol powder. The parameters of the initial particle size distribution (4) were: $\alpha = 3$, $b = 0.5\ \mu\text{m}^{-1}$, the average surface-volume diameter of the particles was $D_{32} = 12\ \mu$m.

To create a cloud of electrostatically charged powder particles, a START-50 combi electrostatic sprayer was used enabling powder to be sprayed in a small volume, with nozzle adjustment; it enables spraying in both electrostatic and pneumatic modes.

To create the acoustic field that acts on the aerosol, a USC 320 Solovey ultrasonic disk emitter was used. The main specifications of the ultrasonic device: diameter of the emitter – 320 mm, noise level – not less than 140 dB, oscillation frequency – 28 kHz. The disperse characteristics and concentration of the aerosol were measured by a measurement system using the low-angle scattering method (Kudryashova *et al.*, 2012). The measurement system enables the parameters of the distribution function to be determined by the size and concentration of particles of the aerosol in time. The experimental studies were conducted in a 1 m^3 measuring camera (Fig. 1).

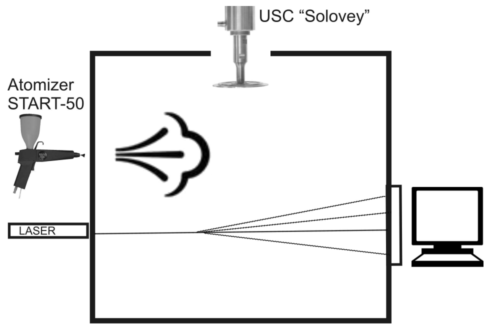

Fig. 1. Diagram of the experimental equipment.

In the experiment with the electrostatic charging of particles the mass of the sprayed powders was 10 g of electrostatically charged particles and 10 g of electroneutral particles. At the beginning an aerosol of coal dust was created in the camera by the pneumatic method (with the START-50 sprayer in the pneumatic mode), then the sprayer in the charging mode sprayed a portion of the charged particles of coal dust. For the experiments with ultrasonic sedimentation and for the control experiment, an aerosol was created by the sprayer in pneumatic mode; the mass of the sprayed powder was 20 g in these cases. The dispersion time was 20 s. Then in the experiment with ultrasonic sedimentation, the ultrasonic emitter was turned on. Measurements of the concentration and dispersion of the aerosol particles began right after the end of dispersion.

4. Results and discussion

In Fig. 2 the time change of the average surface-volume diameter of particles in three experiments is

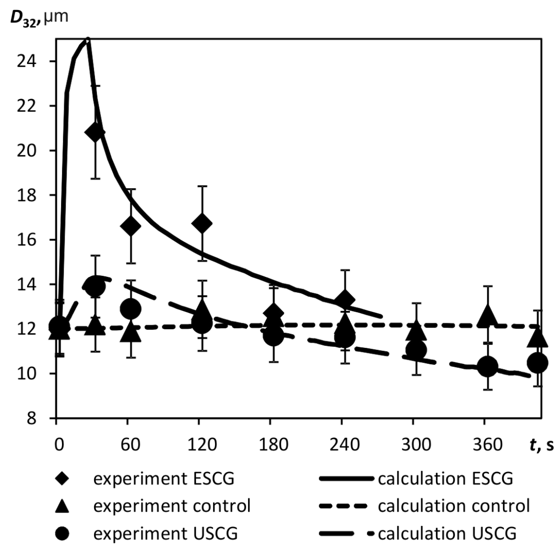

Fig. 2. Dependence of the average surface-volume diameter of particles on time.

shown (with electrostatic coagulation (ESCG), ultrasonic coagulation (USCG) and the control experiment without any external exposure (control). In the experiment with the electrostatic charging of particles the coagulation of particles is completed very quickly; in ten seconds, then they begin to sediment, and the size of the particles, still located in the air, gradually decreases. In the experiment with ultrasonic coagulation the particle coagulation process is slower, and they integrate less strongly than in the case with the electrostatic charge. In the control experiment the diameter of the particles does not change during the entire time of observation.

Calculations were carried out for the system of the Eqs. (1)–(3) with an initial condition (4) in the form of Eq. (4). A kernel of the Eqs. (2) and (3) has been chosen for ultrasonic coagulation in the form of Eq. (8) and for electrostatic one in the form of Eq. (12). Unknown coefficients of proportionality in the Eqs. (8) and (12) were calculated using experimental data for the first experimental point.

Figure 3 illustrates the change of the relative concentration of particles of m/m_0 where $m(t)$ is the mass of the particles of an aerosol, $m_0 = m(0)$ is the initial mass of the particles of an aerosol, in time for three specified experiments. Small particles of coal are deposited without any exposure for about 18 minutes. The ultrasonic exposure significantly accelerates this process, and sedimentation occurs in 10 minutes. In the dispersion of a portion of powder with an electrostatic charge, the sedimentation time drops to 5 minutes.

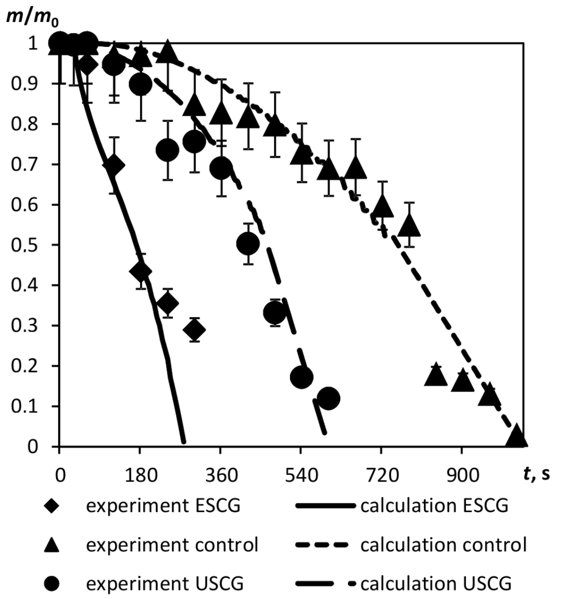

Fig. 3. Dependence of the relative concentration of particles on time.

It is evident from the diagrams that the theoretical calculations describe the experimental results adequately. The calculated values of Fischer criterion F_{calc} are less, than tabular one $F_{0.05}$: $F_{\text{calc}} < F_{0.05}$ (Table 1). Therefore the mathematical model is accepted adequate at significance value 0.05.

Table 1. Calculated values of Fisher criterion.

Experiment	F_{calc}	$F_{0.05}$
ESCG	2.3	4.28
Control	0.91	2.46
US	1.21	2.91

5. Conclusions

A mathematical model for aerosol particle coagulation under ultrasonic exposure and with the electrostatic charge of particles was proposed. A comparison of the probability of particle collisions in case of ultrasonic and electrostatic coagulation was performed. The analysis of the model equations shows that ultrasound in comparison with electrostatics is more effective in the sedimentation of larger particles and in the conditions of their lower concentration in air.

An experiment on the sedimentation of fine coal dust particles (reference size of $D_{32} \sim 12$ µm) by means of ultrasound and electrostatic charging of particles was conducted. It was shown that ultrasonic exposure and an electrostatic charge of particles greatly accelerates the sedimentation of coal dust particles in comparison with the control experiment (without exposure). In these conditions (high concentration of particles, small size) electrostatic coagulation was more efficient. The calculated curves describe the experimental points adequately.

Acknowledgments

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