



Deposition of Toxic Dust with External Fields

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ABSTRACT

The harmful effects of fine dust on health in industrial facilities are a significant problem. The development of new deposition methods for dust particles with a diameter less than 10 microns is particularly difficult. The purpose of this study is to describe and compare new deposition methods for such aerosols by means of external fields: an acoustic wind, an electrostatic field, and specially atomized powder.

It has been shown that the method of spraying a powder affects its adsorption ability. An experimental study of the dispersity and specific surface of nanopowder particles atomized by different methods was carried out. As a result of atomization, the specific surface area of the particles decreases, and this decrease is smaller in the case of atomization by the shock-wave method.

The proposed mathematical model of aerosol coagulation is based on the integral version of the Smoluchowski equation with the type of kernel depending on the types of external influence. In the model, the effect of acoustic wind is considered, as the acoustic wind plays an important role in the deposition of finely divided particles. A calculation of the drift velocity of particles in an electric field and gravitational field is performed. The results of the pilot and theoretical study of the acoustic and electrostatic deposition of fine aerosols are presented in this article. Depending on the deposition method and particle size, calculations confirmed experimentally enable the reference time of the deposition of a dust cloud to be established. Recommendations are provided about the use of ultrasound sources, electrostatic precipitators, water aerosol sprays, and electrostatic spray guns for the optimum removal of dust from air in the workplace, taking into account dust particle sizes. The results of this study can be applied to air purification systems to filter harmful dust emissions.

Keywords: Fine aerosol; Electrostatic charge; Ultrasound; Coagulation; Deposition.

INTRODUCTION

Aerosol pollution in production areas is deposited by means of various types of equipment, and most often by filters and ventilation systems. At the same time, particularly dangerous P_{10} fine particles (diameter of 1–10 microns) are difficult to remove from the air. More complex methods are used to remove them: electrostatic precipitators (Rose and Wood, 1966; Oglesby and Nichols, 1978; Parker, 2012), acoustic and ultrasonic processing (Antonnikova *et al.*, 2013; Kudryashova *et al.*, 2015), and dispersion of electrostatically charged particles (Kudryashova *et al.*, 2015b; Kudryashova and Stepkina, 2016). The aim of this study is to obtain the optimal deposition methods of fine aerosols.

Acoustic fields are known to increase the rate of aerosol deposition. This is generally linked to an increase in the particle coagulation rate under exposure to acoustic fields, fast particle integration, and aerosol deposition. A number of studies are devoted to the effect of the acoustic coagulation of aerosols (Mednikov, 1965; Czyż, 1990; Magill *et al.*, 1991; Khmelev *et al.*, 2010; Amiri *et al.*, 2016; Khmelev *et al.*, 2016). The impact of the frequency and amplitude of sound on the aerosol particle coagulation process is studied in detail.

As shown in the study (Tepper and Kessick, 2008), the efficiency of the electric precipitator is significantly dependent on particle size, their density, and the dielectric permeability of the particle substance. When making a decision on the use of an electric precipitator or ultrasonic source, we need to consider the deposition speeds characteristic of the aerosol.

The mechanisms by which ultrasound and the electric field affect aerosol particles differ greatly. In an electric field, the particle acquires a charge and drifts towards the collection electrode. The drift speed competes with the

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Stokes deposition speed of a particle under the force of gravity (Kudryashova and Stepkina, 2016). In the acoustic field, particles fluctuate, which increases the probability of their collision. This increases particle coagulation, and as a result deposition under the force of gravity is quicker. Another particle deposition mechanism in the acoustic field is drift under the effect of acoustic flows (Kudryashova et al., 2015a). Evidently, in different conditions, different aerosol deposition mechanisms will be effective.

Specially atomized nanostructured sorbent powder enables toxic gases and fine aerosol particles to be removed from the air (Fomkin, 2009; Kudryashova et al., 2015b).

In this case, the higher the dispersity of such an aerosol, the better the effect achieved because the large specific mass surface of the atomized particles helps increase the rate of adsorption. It is possible in principle to remove any pollutant from the emissions by its adsorption in a wide range of concentrations. Then sorbent powder needs to be deposited.

As a new method, the authors propose to apply electrostatic particle charging of specially sprayed powder for the acceleration of coagulation and deposition of aerosols (Kudryashova and Stepkina, 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.

The aim of this work is to describe and compare new deposition methods of toxic aerosols by means of external fields: acoustic, electrostatic, and additional disperse phase—charged aerosol particles sprayed electrostatically.

METHODS

Atomization Method and Neutralization of Toxic Substances

One of the methods of neutralizing toxic gaseous or aerosol substances distributed in the air of rooms is the dispersion in the air of sorbent particles with a high specific surface area (Kudryashova, Stepkina et al., 2015). When adsorption is complete, the waste sorbent needs to be removed. Fine toxic aerosol particles of toxic substances need to be removed also without the use of a sorbent. Regardless, the problem of deposition of fine aerosols is important.

In recent years, sorbents consisting of nanoparticles with a highly developed specific surface area and good sorption properties have been obtained. For example, one such nanopowder is a sorbent based on aluminum hydroxide (pseudoboehmite), which consists of loosely bound porous aggregates possessing high dispersity. The nanopowder exhibits high sorption activity due to the presence of submicron and nanodimensional pores in it.

When nanopowders are atomized in the air, their properties important for the neutralization of harmful gases (dispersity, specific surface area) change depending on the atomization method.

The study (Kudryashova, Stepkina et al., 2015) showed

that the specific surface during the atomization of powder decreases by 10–30% depending on the method of atomization. The authors of the study (Stepkina et al., 2016) established that the electrostatic atomization method, on the contrary, increases dispersion and the specific surface area of particles.

Research Methods and Experimental Equipment

An NaCl aerosol with an initial average volume and superficial particle diameter D_{32} of about 6 microns was chosen as the model aerosol. For the creation of such an aerosol 10 g of a saturated salt solution were sprayed in the 1 m³ camera by means of a pneumatic atomizer. In two minutes, after water evaporation, the NaCl aerosol remained in the air with a uniform concentration.

First Series of Experiments

After that an acoustic source or (in other experiments) an electric field source was applied within 10 minutes. The equipment used for the experiment is shown in Fig. 1. The acoustic impact in the experiment had the following characteristics: sound pressure level of 140 dB and frequency of 28 kHz.

The design parameters of the electric filter used in the experiment are as follows: area of deposition = 1,000 mm²; length of the corona discharging element, length of the active zone = 0.085 m; distance between the corona discharging electrodes = 0.01 m; distance between the planes of the corona discharging and precipitation electrodes = 0.005 m; radius of the corona discharging electrode = 0.004 m; average voltage on electrodes = 8,000 V, electric filter power = 20 W.

Second Series Experiments

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.

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 NaCl aerosol was created in the camera by the pneumatic method (with the START-50 sprayer in pneumatic mode); then the sprayer in charging mode sprayed a portion of the charged salt particles. For the experiments with ultrasonic deposition and for the control experiment, an aerosol was created by the sprayer in pneumatic mode; in these cases, the mass of the sprayed powder was 20 g. The dispersion time was 20 seconds. Then in the experiment with ultrasonic deposition, the ultrasonic emitter was turned on. Measurements of the concentration and dispersion of aerosol particles began to be taken right after the end of dispersion.

After the atomization of the powders, in the process of deposition of their aerosols, the function of the size distribution of aerosol particles was determined by the small angles method on the LID-2M setup of the Institute for Problems of Chemical and Power Technologies of the Siberian Branch of the Russian Academy of Sciences

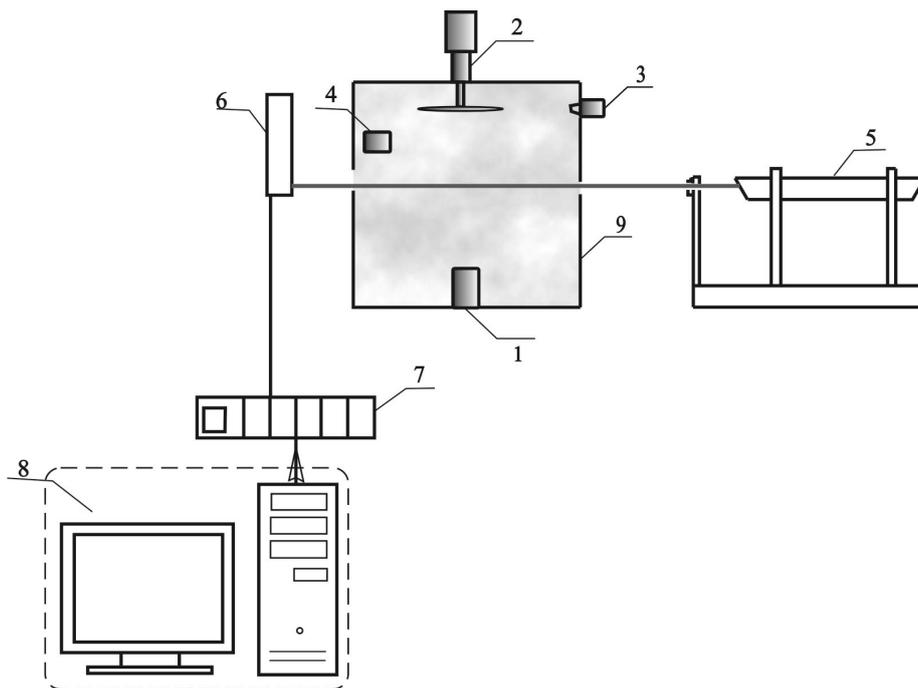


Fig. 1. Experiment equipment: 1 – Electric filter, 2 – Ultrasound source, 3 – Atomizer, 4 – Electrostatic sprayer, 5 – Laser, 6 – Photo detector, 7 – Multi channel amplifier, 8 – Computer, 9 – Aerosol chamber.

(Kudryashova *et al.*, 2012). Measurement error for this method is less than 15%. For representation of the change in the dispersion parameters of an aerosol with time, the mean surface-volume diameter of its particles was taken as a characteristic parameter.

In this study the modified small-angle scattering method was used. This method is based on the determination of the size distribution of particles in the process of solving a range of direct problems of aerosol optics (Kudryashova *et al.*, 2012). It, in essence, is this: The method consists in determining the size range of aerosol particles based on the measured small-angle scattering indicatrix as a result of the exhaustion of the corresponding parameters of their size distribution. As the base distribution, the following gamma-distribution was used:

$$f(D) = aD^\alpha \exp(-bD), \quad (1)$$

with the normalizing multiplier $a = b^{\alpha+1}/\Gamma(\alpha + 1)$, where Γ is the gamma function and α and b are parameters of the gamma distribution of particles by their sizes.

An important parameter characterizing the dispersity of a powder is the Sauter mean diameter of its particles (SMD): $D_{32} = (3 + \alpha)/b$.

The method allows the dispersity and concentration of aerosol particles with a diameter from 1 to 100 μm to be determined.

DEPOSITION RATES OF FINE AEROSOLS

The speed of Stokes deposition of a particle with a diameter of D and density of ρ_p in the environment with a dynamic viscosity of η is:

$$V_s = \frac{D^2 g}{18\eta} \rho_p, \quad (2)$$

where g is free fall acceleration.

The speed of a particle drift with a diameter of 2 to 50 microns is determined by the formula (Uzhov, 1987):

$$V_e = \frac{0,118 \cdot 10^{-10} E^2}{2\eta} D, \quad (3)$$

where E is the electric field strength depending on the arrangement of electrodes of an electric filter, the corona current density and dielectric constant of particles.

There are two mechanisms that can be considered for dust deposition under ultrasound. One of them is entrainment of particles by an acoustic flow (it operates not only on ultrasonic frequencies but also at lower frequencies). The particle drift speed under an acoustic flow is determined by a formula (Kudryashova *et al.*, 2015):

$$V_w = \frac{PD}{12\eta} \quad (4)$$

The sound radiation pressure P in the running wave is associated with the sound pressure p as follows: $P = 2p^2/\rho c^2$, where c is sound velocity and ρ is gas density.

Another particles deposition mechanism under ultrasound is the integration of particles due to coagulation and subsequent gravitational deposition. The coagulation of particles of a polydisperse aerosol is described by Smoluchowski's equation. The aerosol coagulation kinetics

is described in the book (Voloshchuk, 1984) in detail. In the studies (Kudryashova et al., 2015; Kudryashova and Stepkina, 2016) these equations are analyzed in relation to a fine aerosol. Following those works, we will write Smoluchowski's equation describing the change of particle size distribution over time for a solid-phase aerosol:

$$\frac{\partial f(D,t)}{\partial t} = I_1 + I_2, \quad (5)$$

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

$$I_1 = -f(D,t) \int_0^{D_{\max}(t)} K(D,D_1)f(D_1,t)dD_1, \quad (6)$$

where $K(D,D_1)$ is the probability of collision of the particles,

$$D_{\max} = \sqrt{\frac{9\eta H}{2g\rho_p t}}, \quad H \text{ is the upper limit of an aerosol cloud.}$$

All particles with a mass exceeding the maximum $D_{\max}(t)$ value will be deposited; the particle size distribution in each moment of t will be cut off on the right side due to the deposition of large particles, and gradually this limit will shift towards increasingly small particles (Voloshchuk, 1984).

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

$$I_2 = \frac{1}{2} \int_0^D K(D-D_1,D_1)f(D_1,t)f(D-D_1,t)dD_1, \quad (7)$$

Following the literature (Kudryashova et al., 2015), we shall write an equation for the probability of the collision of particles with diameters D and D_1 in the acoustic field:

$$K(D,D_1) = \frac{k_b n_0 \rho}{\eta} (D^2 + D_1^2) \left(1 + k_a U^2 \left(1 - \frac{1}{\sqrt{1 + \omega^2 \tau^2}} \right)^2 \right), \quad (8)$$

where U is the vibrational velocity of the particles in the field, proportional to the amplitude of the effect; ω is the acoustic field frequency; $\tau = D^2/18\nu$ is the time of the Stokes relaxation of the particle; ν is the kinematic coefficient of the environment viscosity; n_0 is the initial particle concentration; k_a and k_b are the proportionality factors.

From Eq. (8) it follows that the intensity of the effect rises (which increases the rate of the oscillation velocity of the particles), the collision probability increases. Therefore, the particle coagulation accelerates. On the other hand, there is some optimum frequency ω for each diameter of the particles at which the increase in the probability of collision will reach a maximum level. With a further increase in the frequency of $K(D, D_1)$, the probability of collision no longer increases (asymptotically). For each particle diameter,

there also exists a minimum frequency of the effect below which the probability of collision does not increase. Therefore, the acoustic field does not exert an effect on the aerosol deposition rate. For example, for particles of 1–2 micrometers in diameter, the minimum frequency of the effect will be approximately 10–15 kHz and the optimum will be greater than 100 kHz, which is outside the capabilities of ultrasonic sources for gaseous environments.

Solving numerically Eq. (5), we obtain the time of the complete deposition of an aerosol with a size distribution function of $f(D)$ (1). To compare the results of calculations of the deposition rates corresponding to the listed mechanisms for a polydisperse aerosol, we will take the Sauter mean diameter of particles of D_{32} as the reference size.

ACOUSTIC AND ELECTROSTATIC COAGULATION OF A FINE AEROSOL

The deposition of a fine aerosol under ultrasound happens as a result of the integration of particles due to acoustic coagulation. In the previous section, we compared deposition rates of a fine aerosol in the acoustic field, in an electric field, and under the force of gravity. How will the coagulation rate change if they have an electrostatic charge on their surface? In this section, we compare the processes of acoustic and electrostatic coagulation.

Eqs. (5)–(7) determine the coagulation of aerosol. The probability of particle collision in an acoustic field is determined by Eq. (8). 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 electric flux density phenomenon) and diameter D_1 . The charges have an opposite sign. Then the Coulomb force works between particles:

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

where r_{12} is the distance between particles, $r_{12} \approx 1/\sqrt[3]{n_0}$; $k = 1/(4\pi\epsilon\epsilon_0)$; ϵ_0 is the vacuum permittivity; ϵ is the media permittivity.

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

$$F_{st} = -3\pi D_1 \eta V. \quad (10)$$

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

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

The probability of the collision of particles in Smoluchowski's model is proportional to the number of

meetings. For particle motion in the field of external forces in Eq. (8) it was found that the number of meetings of particles N is proportional to the sum of the squares of the particle diameters, the square of the speed of their motion V , the number of particles n_0 , and in inverse proportion to the media viscosity ν :

$$N \approx \frac{V^2 n_0 (D^2 + D_1^2)}{\nu}. \quad (12)$$

The formula for the probability of collision taking into account Eqs. (11) and (12) will be written as:

$$K(D, D_1) = k_b N = k_b \frac{n_0^{5/3} k^2 (q_1 q)^2}{9\nu\eta_0^2} \left(1 + \left(\frac{D}{D_1} \right)^2 \right). \quad (13)$$

RESULTS AND DISCUSSION

The calculated values of particle deposition rates according to various mechanisms are given in Table 1. Velocity of gravitational deposition V_s is calculated by Formula (2), drift speed in an electric field V_e by Formula (3), speed of particles moving under action of the acoustic flow V_w by Formula (4).

If the velocity component caused by gravitation V_s is bigger than the component caused by radiation force V_w , then the leading mechanism is the Stokes deposition, and the coagulation processes are important for the deposition velocity of particles. On the contrary, if $V_w > V_s$ the leading deposition mechanism is the sound wind, which “blows off” particles to the bottom of the camera. The ratio of those velocities depends on the particle size.

Considering the “slowest” deposition mechanisms: natural gravitational force and under an acoustic flow, we observe that small particles (for NaCl in the air that are

particles with a diameter less than 6 microns) are more quickly “blown off by the sound wind,” than are deposited in the gravitational field.

The more intensively ultrasonic coagulation occurs, the higher the ultrasound frequency is (Eq. (8)). The effect of the acoustic flow is added to the effect of the integration of particles under ultrasound. Starting with a sufficiently large particle size (in our example NaCl has a diameter of about 18 microns), ultrasonic deposition cannot compete with the natural gravitational force and is useless.

For small particles (with a diameter less than 6 microns) the effect of ultrasound is slightly more pronounced than the effect of the electric field. But the drift speed for larger particles in the electric field is much higher than for other deposition mechanisms.

First Series of Experiments: Deposition Rates in the Acoustic and Electric Fields

In Fig. 2 the measured values of the Sauter mean diameter of particles are given in experiments with ultrasound, with an electric field and without any external field (gravitational deposition). The effect of an electric field does not lead to the integration of particles, and the mean particle diameter decreases more quickly over time than in the control experiment. This results from the fact that larger particles are deposited by an electric filter more quickly; only small particles remain in the air. This process goes quicker than with natural deposition. Fig. 2 shows an increase in particle size due to coagulation in case of ultrasonic impact.

The reduction curves of the relative mass concentration of particles of $C_m = m/m_0$, where m is the mass of particles in an instant of t , m_0 is the initial mass of particles, are given in Fig. 3.

As the calculations show (Table 2), the deposition rate of particles with a diameter of 6 microns in an electric and acoustic field is approximately identical, but higher than the gravitational deposition rate. In fact, in experiments with external fields, in 10 minutes practically no particles were observed in the air, and the mass concentration of particles 10 minutes after dispersion without an external field remained at the level of 20% of the initial concentration.

Second Series of Experiments: Acoustic and Electrostatic Coagulation

In Fig. 4 the change with time of the Sauter mean diameter of particles in three experiments is 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 deposit, 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 period of observation.

Calculations were carried out for the system of Eqs. (5)–(7) with an initial condition in the form of (1). A kernel of

Table 1. Calculated values of the deposition rate of particles according to various mechanisms (gravitational deposition, acoustic flow, drift in an electric field) depending on particle diameter.

D (μm)	V_e/V_s	V_w/V_s
1	46.1	6.14
2	23.0	3.07
3	15.4	2.05
4	11.5	1.54
5	9.21	1.23
6	7.68	1.02
7	6.58	0.877
8	5.76	0.767
9	5.12	0.682
10	4.61	0.614
11	4.19	0.558
12	3.84	0.512
13	3.54	0.472
14	3.29	0.439
15	3.07	0.409

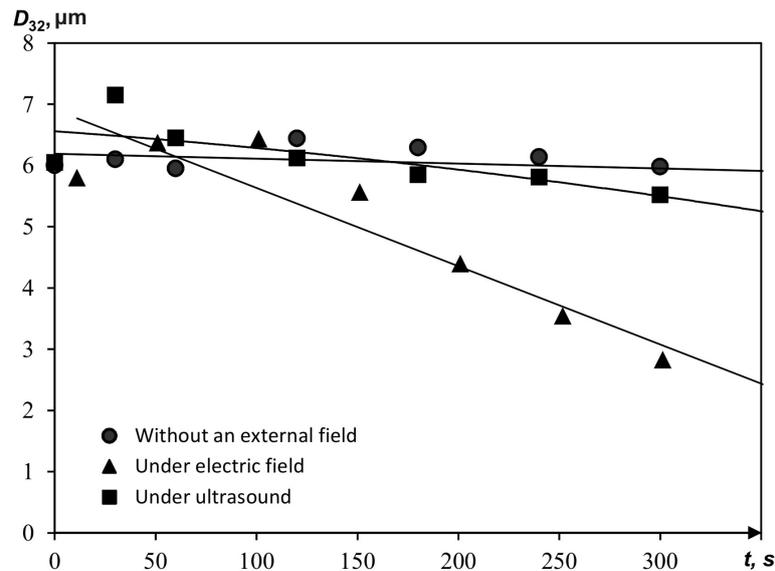


Fig. 2. Change of the Sauter mean diameter of NaCl particles with time in experiments with an electric field, ultrasound and in the control experiment without an external field.

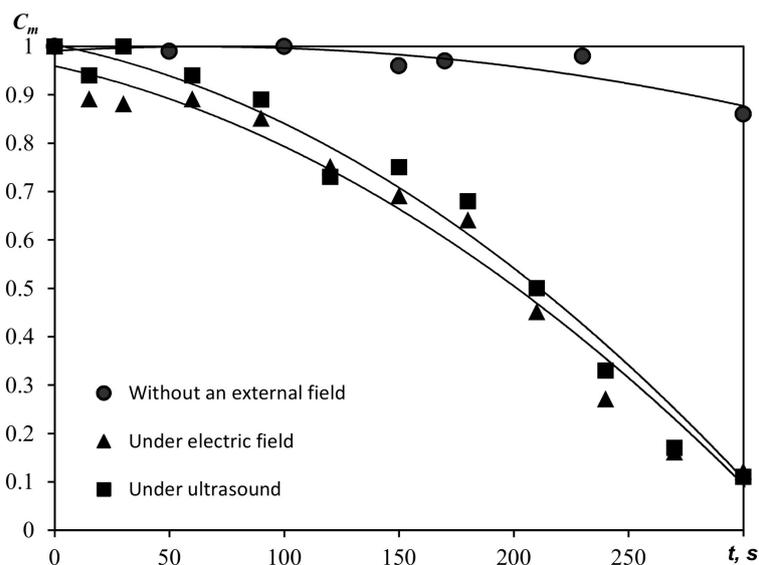


Fig. 3. Change of the relative mass concentration of an NaCl aerosol with time in experiments with an electric field, ultrasound and in the control experiment without an external field.

Eqs. (6) and (7) was chosen for ultrasonic coagulation in the form of (8) and for electrostatic coagulation in the form of (13). Unknown proportionality coefficients in Eqs. (8) and (13) were calculated using experimental data for the first experimental point.

Fig. 5 illustrates (for the three experiments) the change with time 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. Small NaCl particles are deposited without any exposure for about 18 minutes. Ultrasonic exposure significantly accelerates this process, and deposition occurs in 10 minutes. In the dispersion of a portion of powder with an electrostatic charge, the deposition time drops to 5 minutes.

It is evident from the diagrams that the theoretical calculations describe the experimental results adequately.

CONCLUSIONS

The collection of toxic fine aerosol particles represents a challenge. Different methods are used to solve this problem. We presented the results of calculations of the reference deposition rates of fine aerosols in an electric field, in an ultrasonic field, with acoustic flows, and under gravitational deposition (without external fields). The calculations showed that applying an electric filter to fine particles is effective for depositing relatively larger particles (with a diameter greater than 6 microns, in the example with

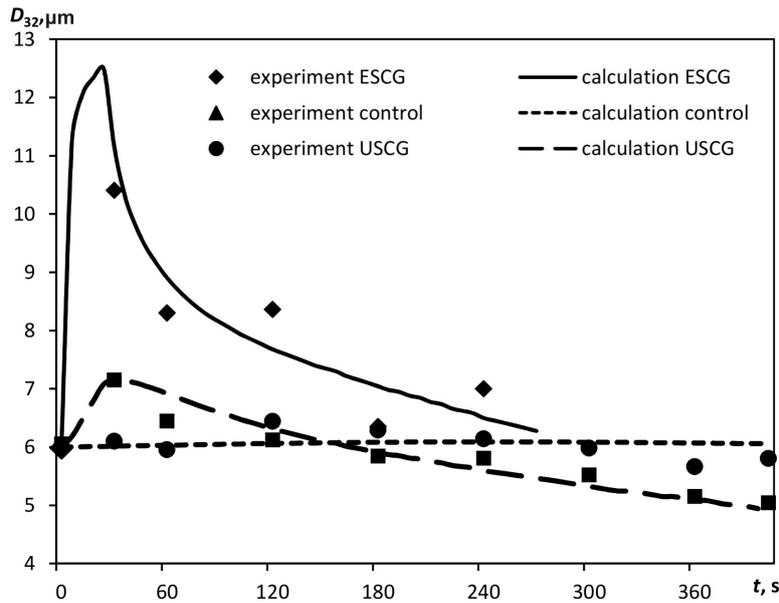


Fig. 4. Dependence of the Sauter mean diameter of particles on time.

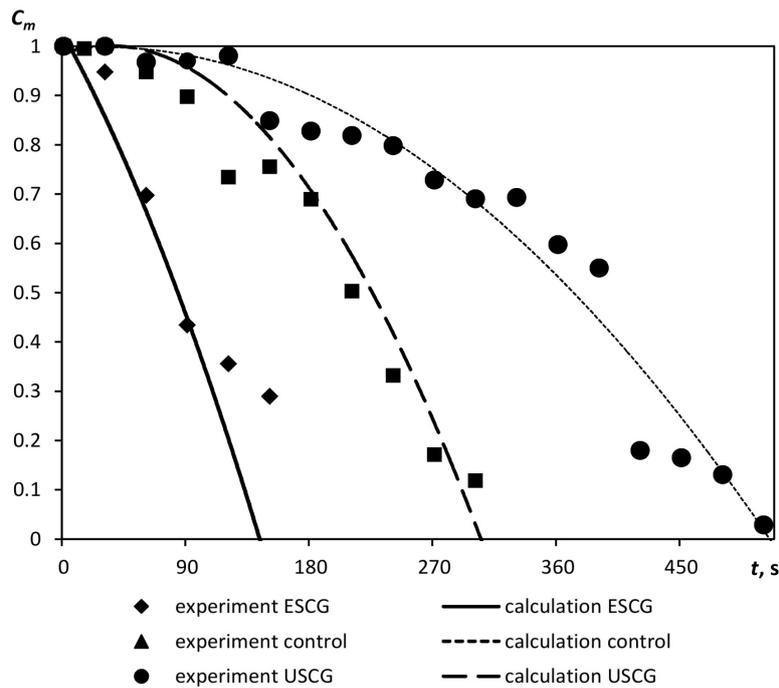


Fig. 5. Dependence of the relative concentration of particles on time.

NaCl). Ultrasonic deposition is effective in comparison with gravitational deposition for particles with a diameter less than 18 microns; larger particles quickly deposit just under gravity. Acoustic flow (sound wind) is the least effective deposition mechanism among those studied; it helps to deposit only the smallest particles (with a diameter less than 3 microns, for NaCl).

Both fields significantly accelerate the deposition process, and the deposition rate increases approximately equally in both cases, which confirms the calculations.

The deposition of aerosol particles with ultrasound is based

on the phenomenon of ultrasonic coagulation. However, there is the possibility of making particles coagulate quickly without external fields. For this purpose, it is necessary to spray electrostatically charged particles into the air, which will attract the particles of harmful substances.

The analysis of the model equations shows that in comparison with electrostatics, ultrasound is more effective in depositing larger particles and under conditions of lower concentrations in the air.

It was shown that ultrasonic exposure and an electrostatic charging of particles greatly accelerate the

deposition of particles in comparison with the control experiment (without exposure). In these conditions (a high concentration of small-sized particles), electrostatic coagulation was more effective. The calculated curves satisfactorily describe the experimental points.

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