

Sedimentation of toxic and hazardous aerosols by electrostatically charged sorbent

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Abstract

Terrorist attacks and possible industrial disasters may result in release of toxic aerosols. Such toxic and hazardous aerosols must be promptly neutralized or, at least, settled. Here we suggest that powdery nanosorbents should be atomized into a space contaminated with a harmful aerosol, in which case electric charge can enhance the sorption capacity of the nanopowders. For the sorption of harmful aerosol particles, we propose to electrostatically atomize a sorbent nanopowder whose particles will eventually acquire electrostatic charge. These charged particles attract and collect on their surface fine opposite-charged or electroneutral particulates (droplets) from the air or room surfaces. Here we consider a physico-mathematical model for the electrostatic coagulation of aerosol particles and compare calculated and experimental data.

Keywords: aerosol, electrostatic charge, coagulation, nanosized sorbent

1. Introduction

The problem of settling toxic dust clouds out of the aerial environment arises from industrial emissions, terrorist attacks, and demolition works (Kyoung Hee Lee et al.^{1,2}). Fine powders of high-energy materials (HEMs) escaping into the air threaten the human health when inhaled and provoke explosion risks.

The known method for neutralizing toxic airborne particulates is the sorption by precipitators (Lerner et al.³). There is also another option possible: to atomize a powdery nanosorbent into the air (Kudryashova et al.⁴). In doing so, it is suggested that the sorbent particles are electrostatically charged to improve their sorption capability (Kudryashova and Stepkina⁵). These charged particles draw pollutant particles by electrostatic forces. The observed effect of electrostatic coagulation shows that the sorbent and toxic particles adhere to each other. The sorbent particles enlarged in size due to adhered toxic fines become heavier and settle down by gravitational forces. The question is, how quickly and effectively do electrostatic coagulation and subsequent aerosol sedimentation occur?

Here we aimed to theoretically and experimentally

investigate the electrostatic coagulation of aerosols and their further gravitational sedimentation.

2. Theoretical

Let us consider the aerosol particles spherical, with each collision leading to their coagulation. Let the sorbent and pollutant particles obey the same particle size distribution function; the amounts of the sorbent and pollutant particles are also the same; these particles are evenly distributed in space. The sorbent particles are electrostatically charged.

Noting Kudryashova et al.⁶, we write down the balance equation (Smoluchowski integral equation⁷) describing the time-course of the change in the mass function of particle size distribution:

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

where I_1 describes the decrement of the particles with diameter D per unit time in unit volume due to the droplet with diameter D colliding with any droplet with diameter D_1 :

$$I_1 = -g(D, t) \int_0^{D_{cr}(t)} K(D, D_1) g(D_1, t) dD_1 \quad (2)$$

where $K(D, D_1)$ is the collision probability for the particles with diameters D and D_1 ; $D_{cr} = \sqrt{18\eta H / (G\rho_p t)}$, H is the upper boundary of the particle cloud by height; G is the free-fall acceleration; η is the dynamic viscosity of the environment; and ρ_p is the particle density.

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

$$I_2 = \frac{1}{2} \int_0^D K(D - D_1, D_1) g(D_1, t) g(D - D_1, t) dD_1, \quad (3)$$

The initial conditions for the equation system (1)–(3) are as follows:

$$g(D, t_0) = g_0(D) \quad (4)$$

which is the initial particle size distribution. To describe the particle size distribution function, a gamma distribution is usually applied:

$$g_0(D) = aD^a \exp(-bD), \quad (5)$$

where b , a are the distribution parameters and a is the normalizing coefficient. One of the statistical characteristics of the particle size distribution function is the Sauter mean diameter, $D_{32} = (a + 3)/b$.

The higher the particle collision probability, the faster the coagulation to occur. When no exposure exists, the collision probability is governed by the Brownian movement. In the model (1)–(4), the collision probability of the aerosol particles without external exposure was considered proportional to the squared sum of the particle diameters (Smoluchowski⁷):

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

where k_b is the proportionality factor; ν is the kinematic coefficient of the environment viscosity; and n_0 is the number of the particles.

Let the sorbent particles have charge q and diameter D , while the aerosol particles have charge q_1 (electroneutral particles will be oppositely charged due to the electrostatic induction) and diameter D_1 . The charges are of opposite signs. Then, the Coulomb force acts on the particles:

$$F_c = k \frac{q_1 q}{r_{12}^2}, \quad (7)$$

where r_{12} is the distance between the particles; $k = 1/(4\pi\epsilon\epsilon_0)$; ϵ_0 is the electric constant; ϵ is the dielectric permittivity of the environment. The drag force is defined by the expression (the Stokes law):

$$F_{st} = -3\pi D_1 \eta V, \quad (8)$$

where η is the dynamic viscosity of the air and V is the particle velocity.

The stabilized particle velocity, V with the friction force (8) and the Coulomb force (7) taken into account, is:

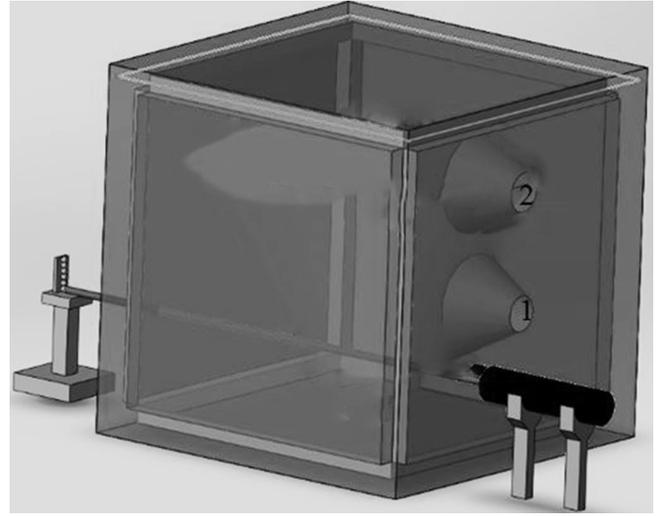


Figure 1 The layout of spraying devices and instruments of the test chamber with openings to atomize (1) pollutant powder and (2) sorbent powder.

$$V = \frac{k}{3\eta} \frac{q_1 q}{r_{12}^2 D_1}. \quad (9)$$

For the particle movement in the external-force field, it was found by Mednikov⁸ that the number of particle encounters, N is proportional to the squared particle diameter, squared particle movement velocity and particle concentration, and is inversely proportional to the dynamic viscosity of the environment:

$$N \approx \frac{V^2 n_0 (D^2 + D_1^2)}{\nu}. \quad (10)$$

The particle collision probability in the Smolukhowski model is proportional to the number of encounters, and Equation (6) taking into account Equations (9) and (10) is written as:

$$K(D, D_1) = k_b N = \frac{n_0 k_b k^2 (q_1 q)^2}{9\nu\eta_0^2 r_{12}^4} \left(1 + \left(\frac{D}{D_1}\right)^2\right). \quad (11)$$

The Equation system (1)–(3) with the initial conditions of Equation (4) in the form of Equation (5), taking into account the core of integral Equations (2) and (3) in the form of Equation (11), will describe the particle coagulation due to the electrostatically charged particle surface.

3. Experimental

The model sorbent used in the experiments was aluminum oxide whose particles are nanostructured porous agglomerates. The model pollutant was a methylene blue powder. The parameters of the initial particle size distribution (5) were as follows: $a = 0.3$, $b = 1 \mu\text{m}^{-1}$, and Sauter mean diameter $D_{32} = 13 \mu\text{m}$.

To generate the cloud of electrostatically charged sorbent particles, we used a START-50-combi adjustable-nozzle electrostatic spray gun that can atomize powders in a small volume. This spray gun can operate both in the electrostatic atomization mode and in the pneumatic.

The evolution of coagulation processes taking place in

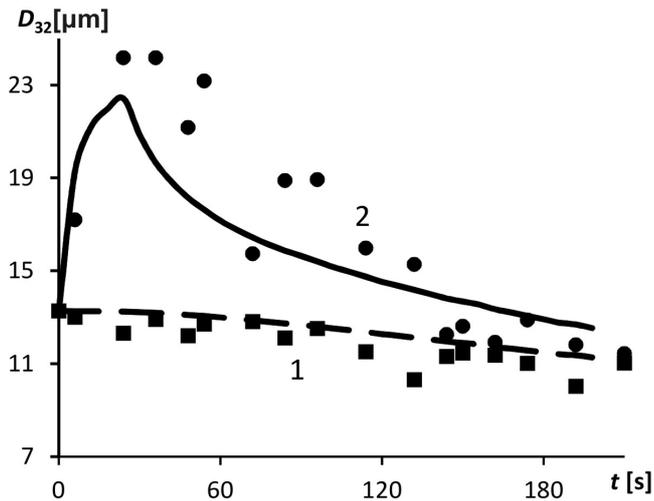


Figure 2 The Sauter mean diameter of the particles as a function of time: 1: electroneutral particles, 2: electrostatically charged sorbent particles; curves stand for calculations and points denote experiment.

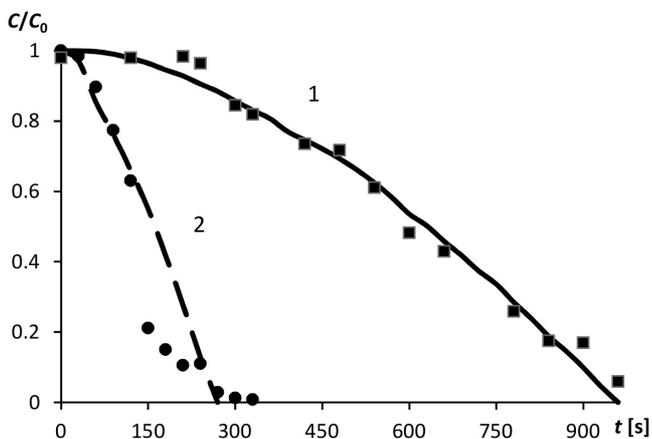


Figure 3 The time course of the relative particle concentration: 1: electroneutral particles; curves stand for calculations and points denote experiment. 2: electrostatically charged sorbent particles: curves stand for calculations and points denote experiment.

the aerosol was observed using a laser instrument system based on the small-angle scattering method (Kudryashova et al.⁹). This instrument system can measure the particle size distribution function parameters and aerosol particle concentration over time.

The experiments were done in a 1 m³ test chamber. Inside and outside the test chamber were placed spraying devices for the electrostatic atomization of the charged sorbent particles (1) and for the pneumatic atomization of pollutant particles (2) (Figure 1). The weight of the atomized powders was 50 g each. The atomization time was 20 seconds. In the first experiment, the sorbent was atomized by the electrostatic method, while the pollutant by the pneumatic method. In the control experiment, the Al₂O₃ powder was atomized in the same manner as was the model pollutant powder, pneumatically.

4. Results and discussion

The experimental measurement results for the Sauter mean diameter and concentration of the resultant aerosol

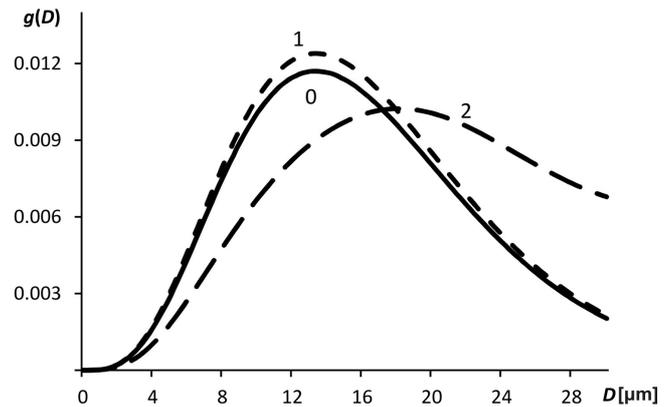


Figure 4 The particle size distribution function 100 sec after aerosol was generated: 0: initial particle size distribution, 1: electroneutral particles; 2: electrostatically charged sorbent particles.

particles are displayed in Figures 2 and 3.

In the first experiment (the charged sorbent), fast gravitational sedimentation (within 5 min) took place after the particle coagulation, and the particle concentration in the air dropped to zero. In the control experiment, the gravitational sedimentation, in the absence of particle coagulation and size enlargement, occurred much slower (within 15 min). Note that in case the coagulation was absent, no sorption occurred. The sorbent and pollutant particles settled down almost without interacting with each other.

As can be seen in the Figures, the particles coagulated for 20 sec after the powders were atomized, and the Sauter mean diameter sharply increased nearly 2 times. In the case of the electroneutral particles, no discernible coagulation occurred.

As is seen in the Figures, the theoretical calculated curves are in good agreement with the experimental points. As per the statistical calculations, the model is recognized as adequate, with a significance level of 0.05.

Figure 4 shows the calculated particle size distribution function at the time moment of 100 sec in cases the particles are charged (curve 2) and not charged (curve 1). Curve 0 is the particle size distribution at the initial instant (experimentally measured).

It can be seen in the Figure that the electrostatic coagulation considerably deforms the shape of the particle size distribution function.

5. Conclusions

We have introduced a mathematical model to describe the electrostatic coagulation of aerosols. Experiments have been done that corroborate the adequacy of the model suggested. An abrupt particle size enlargement due to coagulation was shown to occur in the aerosol cloud of electrostatically charged particles within a few seconds. In the control experiment and theoretical calculations, the sorbent particles were electroneutral and did not coagulate with the model pollutant particles, which means that no sorption took place. The sorbent and pollutant particles were settling down by gravity three times

slower than in the experiment with the charged particles. A method has been suggested for neutralizing fine harmful aerosols contained in the air by atomizing an electrostatically charged nanosorbent. This method can be used to fight the consequences of terrorist incidents, industrial emissions, explosions and fires.

Acknowledgements

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