

Mechanisms of Aerosol Sedimentation by Acoustic Field

Olga KUDRYASHOVA, Alexandra ANTONNIKOVA,
Natalya KOROVINA, Igor AKHMADEEV

*Institute for Problems of Chemical and Energetic Technologies
of the Siberian Branch of the Russian Academy of Sciences
Socialisticheskaya 1, 659322 Biysk, Russia; e-mail: olgakudr@inbox.ru*

(received July 23, 2014; accepted September 6, 2015)

Acoustic radiation sources are successfully applied to cleaning rooms from dust of fairly large particle sizes (ten micrometers and larger). The sedimentation of fine aerosols (particle diameter of 1–10 microns) is a more complicated challenge. The paper is devoted to the substantiation of the acoustic sedimentation method for such aerosols. On the basis of the mathematical model analysis for aerosol sedimentation by the acoustic field the mechanisms of this process have been determined and include the particle coagulation acceleration and radiation pressure effect. The experimental results of the acoustic sedimentation of a model aerosol (NaCl) are shown. The calculation results according to the mathematical model for coagulation and sedimentation, on the basis of the Smolukhovsky's equation taking into account various mechanisms of aerosol sedimentation by sound depending on the particle sizes and sound intensity, are given. The necessity to use intensive sources of high-frequency sound has been confirmed, suggesting that these sources must be located above dust clouds.

Keywords: fine aerosol, size distribution, acoustic impact, coagulation, sedimentation, radiation pressure.

1. Introduction

Acoustic fields are known to increase the rate of aerosol sedimentation. This is generally connected with an increase in particle coagulation rate under the acoustic fields influence, fast particle integration, and sedimentation. A number of works of Roman Wyrzykowski and other scientists is devoted to the effect of acoustic coagulation of aerosols, in particular (WYRZYKOWSKI, 1956; 1969; CZYZ, 1997; MEDNIKOV, 1966). There, influence of frequency and amplitude of a sound on process of coagulation of particles of an aerosol is investigated in detail.

We suggest a mathematical model for the coagulation kinetics which relies on the Smolukhovsky's equation (SMOLUCHOWSKI, 1916). The expression for the probability of particle collisions includes acoustic radiation parameters (frequency and intensity) (ANTONNIKOVA *et al.*, 2012). The calculations made according to the model proposed describe well the experimental data for aerosols with characteristic particle sizes of 10 microns and larger (ANTONNIKOVA *et al.*, 2013). However, the sedimentation rate of aerosol

particles with characteristic sizes below 10 microns in the experiments is higher than that explained by the model of acoustic coagulation. Another mechanism of the acoustic sedimentation due to radiation pressure was recently suggested (KOROVINA *et al.*, 2013) to explain this effect. A question still remains as to which particle sizes lead to a variation of the principal mechanism of sedimentation and which radiation parameters it depends on.

The purpose of this work was to derive analytical expressions for the criterion responsible for the variation of the acoustic aerosol sedimentation mechanism and to compare the theoretical findings with the experiment.

2. Mathematical model

The mass function of the particle size distribution is determined by the sizes following from the solution of the Smolukhovsky's balance equation:

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

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

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

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

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

Following the literature (KOROVINA *et al.*, 2013), we shall write down an expression for the collision probability of the particles having diameters D and D_1 in the acoustic field:

$$K(D, D_1) = \frac{k_b n_0}{\nu} (D^2 + D_1^2) \left(1 + k_a U_0^2 \left(1 - \frac{1}{\sqrt{1 + \omega^2 \tau^2}} \right)^2 \right), \quad (4)$$

where U_0 is the rate of the particle movement; ω is the frequency of the acoustic influence; $\tau = D^2/18\nu$ is the time of the Stokes relaxation of the particle; ν is the kinematic coefficient of the environment viscosity, n_0 is the particle concentration; k_a and k_b are the proportionality factors.

From Eq. (6) it follows that the influence intensity rises (which increases the rate of the oscillating motion of the particles), the collision probability becomes higher. Therefore, the particle coagulation accelerates. On the other hand, there is some optimum frequency ω for each diameter of the particles, at which the increment in the collision probability will be maximal. With a further increase in the frequency of $K(D, D_1)$, the collision probability does not grow anymore (asymptotically). For each diameter of the particles, there also exists a minimal frequency of the influence, below which the probability of collisions does not increase. Therefore, the acoustic field does not exert anyhow an effect on the aerosol sedimentation rate. For example, for the particles of 1–2 micrometres in diameter, the minimal frequency of the influence will be approximately 10–15 kHz and the optimum will be greater than 100 kHz lying outside the capabilities of ultrasonic sources for gaseous environments.

It is important to note that Eq. (4) is derived from an “orthokinetic” hypothesis of the interaction between the particles exposed to sound. Except for the coagulation rate of the particles, their movement

in the acoustic field is influenced by the radiation pressure (“sound wind”). It is obvious that the smaller the particles, the more the influence exerted. Thus, the coagulation rate is not differ from the Brownian movements rate, can be slow, and it is not important for the sedimentation of particles. The sedimentation will be caused by the sound wind rather than the agglomeration of the particles and their movement in the gravitational field.

Consider the forces affecting the particle with diameter D . These forces are gravity, air resistance, and radiation pressure (Fig. 1). We shall consider the radiation pressure directed along the gravity (the source is located above the aerosol cloud). U is the particle drift rate, g is the gravity acceleration, and P is the sound radiation pressure. The force of radiation pressure is $F_r = \pi \frac{D^2}{4} P$, the gravity force is $F_g = \pi \frac{D^3}{6} g \rho_p$, and the Stokes strength is $F_s = 3\pi D \eta U$, where η is the dynamic coefficient of the environment viscosity, $\eta = \nu \rho_g$, ρ_p – density of particle, ρ_g – gas density.

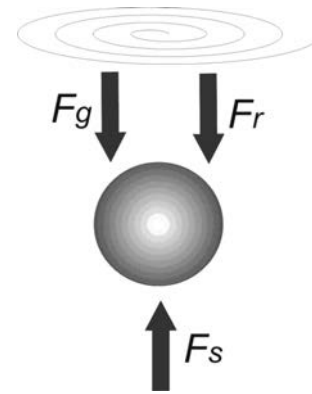


Fig. 1. Forces influencing the aerosol particle in the sound field.

By solving the equation of the particle movement under the influence of the listed forces, it is easy to derive an expression for the particle drift rate consisting of the Stokes sedimentation velocity V_s and the sound wind velocity V_w :

$$U = V_s + V_w = \frac{D^2 \rho_p g}{18\eta} + \frac{PD}{12\eta}. \quad (5)$$

In experimental studies a superposition of running waves and standing waves is observed. The standing waves lead to an intensive circulation of particles (MEDNIKOV, 1966) and to an acceleration of coagulation. The greater the speed of coagulation, the higher the speed of Stokes sedimentation. The acceleration of coagulation (increase in collision probability of the particles) under the influence of radiation is described by the Eq. (4). The running wave is the reason of the drift of a particle in the direction of the action of radiation. Small particles reach a camera bottom faster, being moved by the sound wind, and then they could

be coagulated, agglomerated and dropped out in the gravitation field. The sound radiation pressure P in the running wave is associated with the sound pressure p via the following relation: $P = \frac{2p^2}{\rho_g c^2}$, where c is the sound velocity.

If the velocity component caused by gravitation V_s is more than the component caused by the radiation force V_w , the leading mechanism is the Stokes sedimentation, and processes of coagulation are important for the speed of sedimentation of particles. On the contrary, if $V_w > V_s$, the leading mechanism of sedimentation is the sound wind, that “blows off” particles to a camera bottom. Ratio of those velocities depends on the size of particles. Table 1 gives values of the relation between the sound wind velocity and the Stokes sedimentation rate for various diameters of NaCl particles in the air at a sound level of 125 dB (corresponding to the sound radiation pressure $P = 35.6$ Pa). Table 1 gives also values of the time when the particle reaches a camera bottom (in initial moment it is in the height of 1 m) only because of the gravity t_g and with the additional impact of the sound wind t_u .

Table 1. Relations between the Stokes sedimentation rate and sound wind velocity, the time of the gravity sedimentation t_g and the time of the gravity plus the sound wind sedimentation t_u versus the diameter of NaCl aerosol particles in the air (125 dB sound level, 1 m height).

| D [μm] | V_w/V_s | t_g [s] | t_u [s] |
|-----------------------|-----------|-----------|-----------|
| 1 | 3.52 | 15136 | 3399 |
| 2 | 1.76 | 3784 | 1388 |
| 3 | 1.18 | 1682 | 782 |
| 4 | 0.88 | 946 | 508 |
| 5 | 0.71 | 605 | 358 |
| 6 | 0.59 | 420 | 267 |
| 7 | 0.50 | 309 | 207 |
| 8 | 0.44 | 237 | 165 |

The rates of the Stokes sedimentation and sedimentation by the sound wind for 3.5- μm particles are similar. With the increasing particles sizes, the Stokes sedimentation becomes predominant because the weight of the particles is critical. The coagulation leading to an increase in the weight of the salt particles with a diameter greater than 3.5 microns is accelerated by means of sound according to the mechanism described above, and they will fall down quicker as a result of more frequent collisions and coagulation. However, for the particles of less than 3.5 microns wide, the sound wind velocity becomes more important. Their agglomeration due to coagulation is therefore not so important. They will anyway be “blown off” quicker by the sound wind rather than they will coagulate and settle down under the gravity. Besides, for the coagulation acceleration

of the particles of less than 3.5 microns wide, as it was noted above, such high ultrasound frequencies not practically achievable in the existing sound sources for gaseous environments are required. Thus, the criterion of transition from one to another leading mechanism of acoustic sedimentation of fine aerosols should consider the relation between the Stokes sedimentation and radiation sedimentation rates:

$$\frac{V_s}{V_w} = \frac{2D_{cr}\rho_p g}{3P} = 1. \quad (6)$$

Equation (6) gives the critical diameter for the transition between the Stokes sedimentation and radiation sedimentation mechanisms as a function of the sound radiation pressure:

$$D_{cr} = \frac{3P}{2\rho_p g}. \quad (7)$$

The higher the pressure of the sound radiation, the more critical the diameter. So, the 140 dB sound ($P = 200$ Pa) faster carries away particles with a diameter of 40 microns and larger due to the radiation pressure, and the processes of coagulation and gravitational sedimentation may take place in the aerosol, while for the 100 dB sound level ($P = 2$ Pa) the diameter of such particles is only 0.4 microns.

A variation of the aerosol mass due to sedimentation can be written down as follows:

$$\frac{dm}{dt} = \int_0^\infty \frac{Um(t)}{H} g(D, t) dD, \quad (8)$$

where m is the aerosol mass in a given volume; H is the height of the cloud; $g(D, t)$ is the mass function of the particle size distribution. The particle drift velocity U is defined by Eq. (5).

Thus, Eqs. (1)–(4), (8) describe changes in the weight and the aerosol particle size distribution function in time. One of the statistical characteristics of the particle size distribution function is the surface-volumetric diameter of particles D_{32} equal to the relation between the volume of all the particles and their total surface. We will use it to compare calculations with the experiment. The second parameter measured in the experiment is the relative mass of the aerosol.

3. Results and discussion

A NaCl aerosol with an initial average volume and superficial particle diameter D_{32} of about 6 microns was chosen as the model aerosol. In accordance with the calculations given above, this characteristic size slightly exceeds the critical size determined by Eq. (7). So, it is expectable that the particle coagulation will somewhat be accelerated under the influence of sound; however, sedimentation in the acoustic

field will be quickened by the sound radiation mechanism.

The acoustic impact in the experiment had the following characteristics: 125 dB sound level and 32 kHz frequency. The disperse characteristics and the concentration of aerosol particles were measured using optical methods (small-angle scattering and spectral transparency) (KUDRYASHOVA *et al.*, 2012).

The results of the measurements (point) and calculations for the model given above (curve) with respect to the relative mass m/m_0 , where m_0 is the initial mass of the aerosol, are given in Fig. 2. The time change in the average surface-volumetric diameter of the particles without and with the exposure to the sound radiation is shown in Fig. 3.

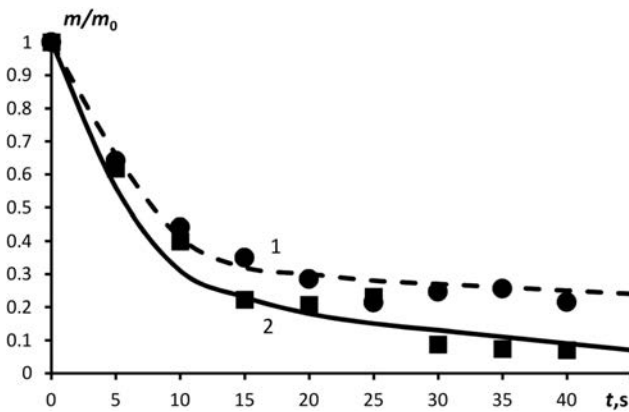


Fig. 2. The relative mass of NaCl aerosol as a function of time: curve 1 – calculation, no sound; curve 2 – calculation, with sound; circles – experiment, no sound; squares – experiment, with sound.

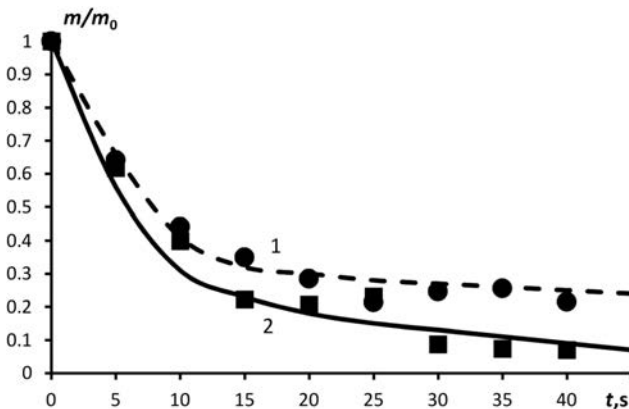


Fig. 3. The average surface-volumetric diameter of NaCl aerosol particles *versus* time: curve 1 – calculation, no sound; curve 2 – calculation, with sound; circles – experiment, no sound; squares – experiment, with sound.

The overall sedimentation time of the aerosol is reduced by a factor of about 2.7 when exposed to sound (from 165 minutes to 60 minutes), but the average surface-volumetric diameter of the particles slightly increases (by 10%).

The Stokes sedimentation time for 7- μm particles is only 1.4 times less than that for 6- μm particles. It means that if the coagulation was the leading mechanism, the sedimentation would be only 1.4 times faster but not 2.7 times faster as we observed in our experiment. This supports a theoretical conclusion that with such particle sizes the leading mechanism of the acoustic aerosol sedimentation is the sound wind.

Taking into account the measurement error (up to 15%), the calculations show that the suggested mathematical model describes experimental data quite well.

4. Conclusions

On the basis of the mathematical model for sedimentation of a micron-scale aerosol by sound, two aerosol sedimentation mechanisms have been described and are governed by coagulation and sound radiation pressure. The criterion defining the leading mechanism of sedimentation has been suggested: the relation between the sound wind velocity and the Stokes sedimentation rate. The leading mechanism of sedimentation was shown to vary within the particle size range under question; therefore, for the description of the acoustic sedimentation of fine aerosols, it is necessary to consider both the coagulation and the sound radiation pressure.

By using numerical calculations, the relative aerosol mass and the particle size mass distribution in time were plotted for the model aerosol. The comparison with the experiment showed adequacy of the proposed model. The impact of the sound accelerates the sedimentation of the aerosol with a characteristic particle diameter of about 6 microns by a factor 2.7, and the particle diameter slightly alters during the sedimentation. The effect of the acoustic field on such aerosols cannot therefore be explained by the coagulation only.

Finally, the study findings suggest that for the acoustic sedimentation of fine aerosols, the sound radiation sources have to be located above the aerosol cloud. The sound level should be at least 125 dB (the higher the level, the smaller the particle size).

Acknowledgments

Authors would like to thank Dr. V. Khmelev from Biysk Technological Institute (branch) of the AltSTU for support in the research. The acoustic source was kindly provided by Acoustic Processes & Devices lab.

References

1. ANTONNIKOVA A.A., KOROVINA N.V., KUDRYASHOVA O.B., AKHMADEEV I.R. (2013), *Experimental Study of the Processes of Aerosol Transformation under Ultrasonic Impact*, Atmospheric and Oceanic Optics, **1**, 57–59.

2. ANTONNIKOVA A.A., KUDRYASHOVA O.B., SHALUNOVA K.V. (2012), *Application of Ultrasound to Settle sub-micron Aerosols*, Proceedings of International Conference EDM 2012, pp. 87–89, Biysk, Russia.
3. CZYZ H. (1997), *On the relation between the inertial coagulation and the amplitudial effect*, Archives of Acoustics, **22**, 4, 437–444.
4. KOROVINA N.V., ANTONNIKOVA A.A., KUDRYASHOVA O.B. (2013), *Sedimentation of Superfine Aerosol by Means of Ultrasound*, Open Journal of Acoustics, **3A**, 16–20.
5. KUDRYASHOVA O., PAVLENKO A., VOROZHTSOV B., TITOV S., ARKHIPOV V., BONDARCHUK S., MAKSIMENKO E., AKHMADEEV I., MURAVLEV E. (2012), *Remote optical diagnostics of nonstationary aerosol media in a wide range of particle sizes*, [in:] *Photodetectors*, pp. 341–364, InTech, Rijeka, Croatia.
6. MEDNIKOV E. (1966), *Acoustic coagulation and precipitation of aerosols*, Consultants Bureau, New York.
7. SMOLUCHOWSKI M. (1916), *Three reports on diffusion, Brownian molecular movement and coagulation of colloid particles* [in German], Physik. Z., **17**, 557–571, 585–599.
8. WYRZYKOWSKI R. (1969), *A theory of acoustic coagulation* [in Polish], University of Rzeszow, **1**, 125–135.
9. WYRZYKOWSKI R. (1956), *Sonic agglomeration of aerosols*, Proceedings of II Conference on Ultrasonic, PWN, Warszawa, 103–109.