ARCHIVES OF ACOUSTICS
Vol. **45**, No. 1, pp. 29–34 (2020)
DOI: 10.24425/aoa.2019.129739

Research Paper

Influence of Environment Conditions on Ultrasonic and Electrostatic Precipitation of Aerosols of Wood Flour

Maria STEPKINA, Olga KUDRYASHOVA*, Alexandra ANTONNIKOVA

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

(*received March 21, 2019; accepted October 7, 2019*)

The risk of human exposure to finely-dispersed aerosol particles being airborne indoors is determined by the size and the number concentration of particles, the intensity of an aerosol emission source, the air filtration and ventilation efficiency, etc. The emphasis in this article is on behaviour patterns of aerosol particles when exposed to ultrasonic and electrostatic fields in different conditions of air temperature and relative humidity. Wood flour having sizes of interest (characteristic particle diameter about 10 μm) is chosen as a model aerosol. The article considers a physical and mathematical model presenting the evolution of aerosol particles in external fields, taking into account the moisture content and the temperature of a dispersive medium. The efficiency of ultrasonic and electrostatic precipitation in different relative humidity and temperature conditions in an enclosed space was studied using optical measurement methods of particle size and concentration.

Keywords: dispersive medium; relative humidity; temperature; ultrasonic radiation; electrostatic field; finely-dispersed aerosol particles.

1. Introduction

Anthropogenic emissions of aerosol particles as a consequence of industrial processes significantly contribute to the air pollution. The actual labour conditions in many industrial environments vary depending on the seasonality and requirements to the manufacturing of raw materials. Thus, for example, the range of temperatures at a sawmill plant varies within 25–27°C in summer period and 15–17°C in winter at the average humidity of 50–60% indoors. The humidity at a furniture production varies within 85–93%. While the optimum operating conditions are 15–22°C during the warm season and 13–19°C during the cold season at a humidity of 40–60%.

This paper describes the effect of a medium viscosity on the speed of ultrasonic wave propagation (Kazys *et al.*, 2016). The theory of particle charging in an electric field is well described by various scientists: Pautenier and Moreau-Chano (1932), Fuchs (1947), Bricard (1949). Experimental and theoretical studies (Zhuang *et al.*, 2000) have found that the charge characteristics of an ultrafine particle depend largely on the parameters of ions, but there is a lack of description of the effect of dispersive air environment conditions and characteristics of a sprayed substance on the effectiveness of particle charge.

An electrostatic field exerts greater influence on the particle motion in a dry environment than in a humid environment. Higher humidity ($>80\%$) would enhance the ionization on the particle surface causing stronger electric interactions (He *et al.*, 2019). On the other hand, the effect of humidity on the agglomeration and coagulation of particles is not so evident (Guo *et al.*, 2012).

Riera *et al.* (2015) proposes an installation for removing solid-phase particles which is completed with a multi-frequency acoustic chamber and an electric precipitator. Such installation can be used in any industrial process where the agglomeration and the precipitation of finely-dispersed aerosol particles is required. It can also be used under high pressure, in high temperature and humidity conditions. The installation was tested in an environment with high humidity with additional spraying of a finely dispersed liquid-phase aerosol; it was succeeded thereby to enhance the effectiveness of the solid-phase aerosol particle agglomeration by 25% (Riera *et al.*, 2015).

Ultrasonic and electrostatic precipitators continue to be studied despite relatively wide experience in their usage. When developing such means of precipitating for removal of aerosol emissions indoors using external fields, one should take into account the environmental parameters (humidity, viscosity, temperature) with the object of ensuring the quickest ecological cleaning of work places and eliminating any potential risks to the human body (Wang *et al.*, 2017; Kim *et al.*, 2001).

The purpose of this paper is to determine the evolution patterns of disperse systems in changing the climatic variables (humidity and temperature) and with the use of ultrasonic and electrostatic effects. The major tasks of this paper include:

- a theoretical study aimed at introducing clarifications with regard to the physical and mathematical model taking into account varying environmental parameters (humidity, temperature) in calculating the particle sedimentation, the electrostatic and ultrasonic precipitations;
- obtaining the new experimental evidence on spatiotemporal properties of a simulative aerosol medium in different climatic conditions in a test volume in the presence and in the absence of external fields;
- an assessment of the effectiveness of sedimentation methods when exposed to ultrasonic and electrostatic fields, or their combination depending on the environmental conditions of a medium.

2. Mathematical model of coagulation among particles in an acoustic field and where the surface is charged

The settling of particles occurs under the effect of gravity. The drift rate of a particle in the gravity field not exposed to any electrical and ultrasonic fields will be determined by the following formula:

$$u_g = \frac{D^2 g \rho_p}{18\mu}, \tag{1}$$

where D – particle diameter, g – free-fall acceleration, ρ_p – particle density, μ – absolute viscosity of medium.

Ultrasonic exposure accelerates the process of settling owing to the coagulation among particles making them thus coarser and heavier. In theory, the coagulation process of aerosols is well described using the Smoluchowski balance equations. Such approach allows any changes in particle size and a reduction in particle concentration over time to be evaluated (Stepkina *et al.*, 2018; Kudryashova *et al.*, 2015).

Aerosol particles are coagulated with coarsening under the action of ultrasonic waves. The aerosol particles are entrained by a dispersive (gaseous) medium, oscillating in an ultrasonic field. The entrainment extent of particles depends on their size and weight. The particles, moving through a gaseous medium at different speeds, collide with each other and stick together. An orthokinetic coagulation which is inherent in polydisperse aerosols occurs. Obviously, the higher the particle concentration is and the stronger the effect is, the faster the particles coagulate.

The dispersive medium oscillation in an external field depends on the temperature. The higher the temperature of a medium is, the higher the gas molecule motion velocity is. According to the Einstein-Smoluchowski's equation, the diffusion coefficient of Brownian particles is proportional to the temperature and inversely proportional to the viscosity of a medium. The viscosity of humid air is higher than that of dry air. Therefore, the air molecular mobility decreases with decreasing temperature and reducing humidity regardless whether an ultrasonic field exists or not.

To describe the processes of ultrasonic coagulation we will use the Smoluchowski integral equation used to determine a change in the particle-size distribution vector-function over time $f(D,t)$ (Kudryashova *et al.*, 2015):

$$\frac{\partial f(D,t)}{\partial t} = I_1 + I_2, \tag{2}$$

where I_1 describes the reduction in number of particles having a diameter of D in unit time per unit volume due to the collision of a particle having a diameter of D and a particle having a diameter of D_1:

$$I_1 = -f(D,t) \int_0^{D_{\max}} K(D,D_1) f(D_1,t)\,\mathrm{d}t, \tag{3}$$

where $K(D,D_1)$ – probability of particle collision, $D_{\max} = (18\mu H/g\rho_p t)^{1/2}$, H – height of cloud top. All particles which weight exceeds the maximum value of $D_{\max}(t)$, are settled out and do not participate in further coagulation. The particle distribution at any given period of time t will be cut on the right-hand side due to the sedimentation of coarse particles; moreover, this border will gradually shift toward smaller and smaller particles.

The term I_2 describes the emergence of particles with a diameter of D due to the collision among particles with D_1 and D–D_1 diameters:

$$I_2 = -\frac{1}{2} \int_0^{D} K(D-D_1, D_1) f(D_1,t) f(D-D_1,t)\,\mathrm{d}t. \tag{4}$$

Initial conditions for the Eq. (1): at $t = t_0 f(D,t_0) = f_0(D)$ – the initial mass distribution of particles by sizes. Gamma distribution is usually used to describe the particle size-distribution function: $f_0(D) = aD^{\alpha}\exp(-bD)$, where b, α – distribution parameters, a – normalizing factor. The mean surface-volume diameter of particles (Sauter mean diameter) $D_{32} = (\alpha{+}3)/b$

is one of the statistic performance of the particle size-distribution function.

The probability of particle collision $K(D, D_1)$ plays a role of a kernel in the integral Eq. (1). The probability of particle collision determines the coagulation effectiveness: the higher it is, the faster the coagulation and aerosol sedimentation is. In the case of ultrasonic exposure, an expression for the probability of particle collision includes the frequency ω, the oscillation rate of particle motion (proportional to the amplitude) U_0, the Stokes relaxation time $\tau = \rho_p D^2/18\mu$:

$$K(D, D_1) = \frac{k_b n_0}{\mu}\left(D^2 + D_1^2\right)\left(1 + k_a\left(1 - \frac{1}{\sqrt{1+\omega^2\tau^2}}\right)\right), \tag{5}$$

where k_b, k_a – proportionality factors. Humidity dependence of μ is insignificant: the viscosity of air will increase by 1–2% with increasing the humidity from 40% to 75%. The viscosity of gas goes up with increasing temperature; it increases by about 15% within the test temperature range (10°C to 45°C).

We used in the calculations the Sutherland's law of viscosity versus temperature:

$$\mu(T) = \mu_0\left(\frac{T}{T_0}\right)^{3/2}\frac{T_0 + S}{T + S}, \tag{6}$$

where Sutherland's law coefficients are: $\mu_0 = 1.827 \cdot 10^{-5}$ Pa·s, $T_0 = 291.15$ K, $S = 120$ K.

The Stokes relaxation time τ will also depend on temperature, because this value is also inversely proportional to the viscosity of a medium. Temperature has also an effect on the value of k_b and k_a coefficients, which are responsible for the molecular mobility of a gaseous medium. The higher the temperature is, the higher k_b and k_a are.

An electric precipitator, while operating, creates an electrostatic field in space which makes the particles move and precipitate thereon. The following equation has been obtained for the drift rate of particles in an electric field (Uzhov, 1967):

$$u_e = \frac{0.118 \cdot 10^{-10} D E^2}{2\mu}, \tag{7}$$

where E – electric-field intensity.

As illustrated in the study (Uzhov, 1967; Sanaev, 2009), humidity and temperature have an effect on the value of the electric-field intensity created by the electric precipitator. The value of E increases with increasing temperature, and the increase in the medium humidity leads to the moderate decrease in the field intensity, and therefore, to the moderate decrease in the particle precipitation rate by the electric precipitator.

3. Experimental study

The powdered wood flour was used as a simulative aerosol. The mean surface-volume diameter of wood flour particles was $D_{32} = 10$ μm (parameters of the initial particle-size distribution: $\alpha = 2$, $b = 0.5$). The initial concentration of the sprayed wood flour powder in the test volume was 1 g/m^3, the time of aerosol cloud formation was 10 seconds (Stepkina, 2018).

A pneumatic spraying system was used to create an aerosol particle cloud. A climatic chamber KTKhV-10 was used to generate the required climatic conditions in the test volume. Therefore, the following climatic conditions of air medium were created in the test volume:

- low temperature (10–13°C) and normal humidity (40–45%);
- high temperature (40–45°C) and normal humidity;
- normal conditions: temperature 23–25°C, humidity 40–45%;
- normal temperature 23–25°C and high humidity 70–75%.

The created conditions are shown in Table 1.

Table 1. Variants of climatic conditions in the experiment.

Variant	Temperature [°C]	Relative humidity [%]
1	10–13	40–45
2	23–25	40–45
3	40–45	40–45
4	23–25	70–75

UZAGS-0.6/22-O sonicator of Solovey series was used to create a sonic field (sound level – 144 dB min; frequency – 22 kHz). The design parameters of an electric precipitator used are as follows: precipitation area 1000 mm^2; distance between the emitting and collecting electrode planes – 0.005 m; emitting electrode radius – 0.004 m; average voltage – 8000 V.

The following series of experiments were conducted:

1) At different air temperatures and normal humidity (variants 1–3):
    - with no exposure (gravitational sedimentation, Fig. 1),
    - when exposed to supersonic sound (Fig. 2),
    - when exposed to an electric field (an electric precipitator, Fig. 3),
    - under combined action of an electric precipitator and an ultrasonic field (Fig. 4).
2) At high humidity and normal temperature (variant 4): in the same way, under different kinds of action of external fields and without them (Fig. 5).

The dispersion characteristics and the concentration of aerosol in air with different parameters of climatic conditions were measured by means of LID-2M laser measuring installation which allows measurements with high timing resolution to be made. A version of optical method of low-angle scattering is implemented in the LID-2M installation, with is related to resolving a number of direct problems of aerosol optics in the laser beam scattering problem by a dispersive medium at low angles (Kudryashova, Pavlenko *et al.*, 2015).

4. Results and discussion

When exposed to an ultrasonic field and with slow gravitational settling, aerosol particles will coagulate with each other. In this case, the mathematical model (2)–(5) is applicable. The calculations were made with selecting free parameters of the model to ensure that the theoretical results agree with the experimental findings.

Figure 1 illustrates changes in the relative concentration of aerosol particles Cm with no exposure to external fields, taking into account different ranges of temperature and the relative humidity of 40–45%. The gravitational settling of wood flour with no exposure to external fields is a process for a very long time and takes more than 3,000 seconds. With a rise in temperature the settling occurs faster, which can be attributed to the acceleration of particle motion and rising in the probability of collision among them.

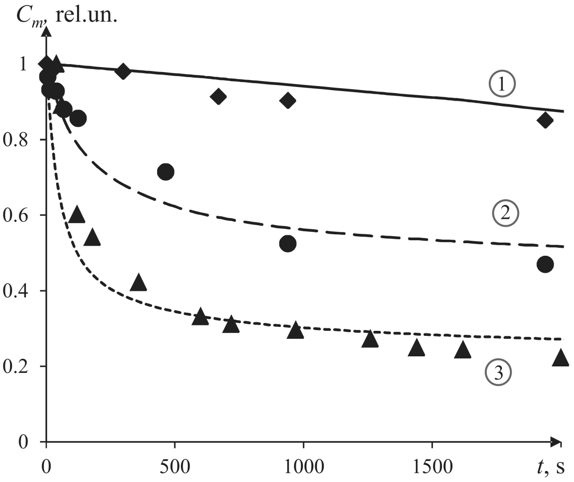

Fig. 1. Relation of the relative concentration of particles and the time of gravitational settling of wood flour particles at different temperature ranges and normal air humidity. Dots – experimental findings, lines – calculations based on the mathematical model (2)–(5).
1 – air medium temperature 10–13°C, 2 – air medium temperature 23–25°C, 3 – air medium temperature 40–45°C.

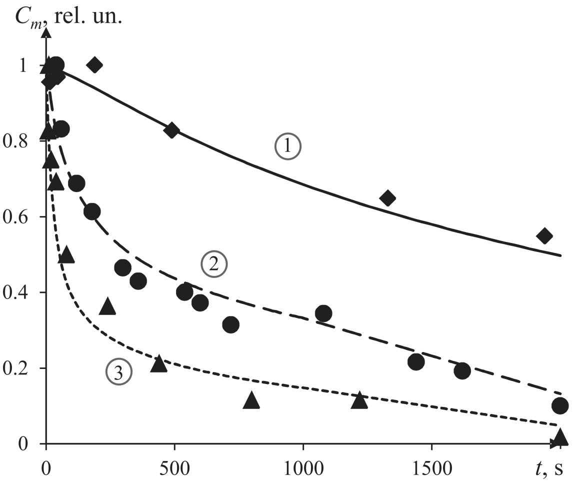

Fig. 2. Relation of the relative concentration of particles and the time of precipitation of wood flour particles when exposed to an ultrasonic field, at different temperature ranges and normal air humidity. Dots – experimental findings, lines – calculations based on the mathematical model (2)–(5).
1 – air medium temperature 10–13°C, 2 – air medium temperature 23–25°C, 3 – air medium temperature 40–45°C.

The next series of experiments were conducted on exposure to ultrasonic radiation (see Fig. 2). One can see in Fig. 2. that the ultrasonic coagulation is effective with increasing temperature up to 40–45°C ($C_m \to 0$ over the time of 3490 seconds), and the decrease in temperature to 10–13°C does not facilitate the coagulation and leads to the low sedimentation rate (C_m = 0.6 rel. units over the time of 2000 seconds).

The precipitation mechanism by the action of an electric field is not attributed to the coagulation of particles. The charged particles move toward a precipitating device with a speed to be determined using the Eq. (7). The results of the use of an electrostatic field for precipitating the finely-dispersed particles of wood flour are presented in Fig. 3. Electrostatic precipitation

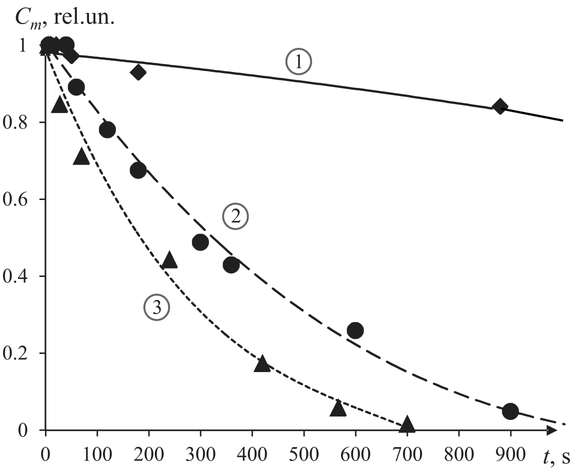

Fig. 3. Relation of the relative concentration of particles and the time of precipitation of wood flour particles when exposed to an electrostatic field, at different temperature ranges and normal air humidity. Dots – experimental findings, lines – polynomial interpolation.
1 – air medium temperature 10–13°C, 2 – air medium temperature 23–25°C, 3 – air medium temperature 40–45°C.

is effective with increasing temperature up to 40–45°C ($C_m \to 0$ over the time of 700 seconds); the decrease in temperature to 10–13°C does not promote fast precipitation: the relative concentration of particles C_m in the test volume is more than 0.8 for all the time of the experiment. The effect of temperature in this case can be attributed to the increase in the electric-field intensity E created by the electric precipitator, with increasing temperature (Sanaev, 2009).

There were also conducted the experiments on the precipitation of suspended particles of finely-dispersed wood flour using the combined action of ultrasonic and electric fields (see Fig. 4). As in previous cases, applying the combined action is less effective (precipitation occurs at a lower rate) with the decrease in temperature to 10–13°C (C_m = 0.6 over a time of 1000 seconds); the concentration decreases much faster at high temperature.

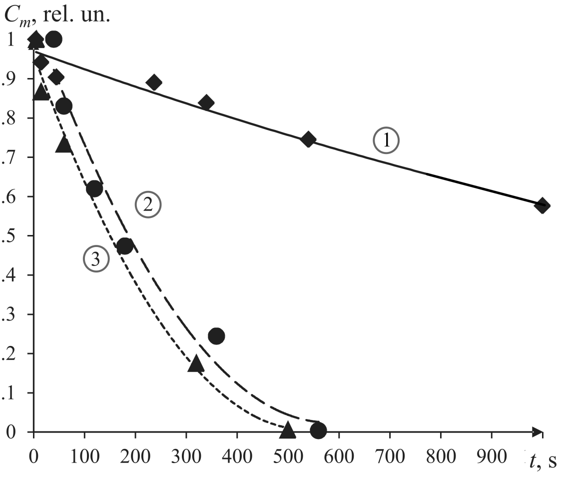

Fig. 4. Relation of the relative concentration of particles and the time of precipitation of wood flour particles with the combined action by ultrasonic and electrostatic fields, at different temperature ranges and normal air humidity. Dots – experimental findings, lines – polynomial interpolation.
1 – air medium temperature 10–13°C, 2 – air medium temperature 23–25°C, 3 – air medium temperature 40–45°C.

The last series of experiments were conducted in high humidity conditions (up to 75%) at normal values of temperature (23–25°C) for the following cases:

- with no exposure to external fields (gravitational settling, Fig. 5, Curve 1),
- when exposed to ultrasonic radiation (Fig. 5, Curve 2),
- when using an electric precipitating unit (Fig. 5, Curve 3),
- with the combined application of ultrasonic and electric fields (Fig. 5, Curve 4).

The analysis of Fig. 5 illustrates that in high humidity conditions the trend established for normal humidity continues: the lowest sedimentation rate is characteristic of an aerosol with no exposure to external fields; the ultrasonic sound accelerates the sedimentation; an electric precipitator accelerates it even more, and the combined action by external fields is the most efficient. Moreover, in most cases the sedimentation speed of particles in high humidity conditions is higher than that at normal humidity. This can be attributed to the absorption of moisture in air by wood flour particles, resulting in the increase in their size, weight, gravitational sedimentation speed, their coagulation and drift rate in an electric field.

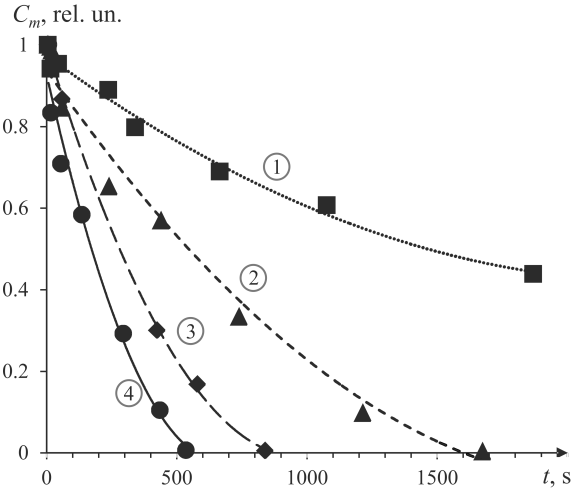

Fig. 5. Relation of the relative concentration of particles and the time of precipitation of wood flour particles with no exposure to and when exposed to external fields at normal air temperature and relative air humidity of 70–75%. Dots – experimental findings, lines – polynomial interpolation.
1 – gravitational sedimentation, 2 – ultrasonic exposure, 3 – electrostatic exposure, 4 – the combined action by ultrasonic and electrostatic fields.

Table 2 shows the settling time values of particles in the test conditions. Numbers of variants correspond to those specified in Table 1.

Table 2. Full settling time of particles of the wood flour aerosol (in seconds) for different climatic conditions and variants of external exposure.

Variants of climatic conditions	1	2	3	4
With no exposure	19600	12340	8218	3436
Ultrasonic field	5620	4860	3490	1610
Electric precipitator	4330	1010	700	830
Ultrasonic + electric fields	2360	550	500	520

Increasing temperature and humidity almost in all cases resulted in the acceleration of aerosol particle sedimentation. A single exception is that the electric precipitator operation in high humidity conditions was a little less efficient than at high temperature. In all the cases, an ultrasonic field, facilitating the coagulation, led to the acceleration of particle precipitation 2–3.5 times compared with the gravitational sedimentation. An electric field accelerates the process even more, i.e. more than 4 times, and the combined action by external fields – more than 6 times. The ultrasonic sound settles an aerosol faster in the high humidity conditions more than 3 times, but the usage of an electric precipitator in humid conditions is not more effective than in dry conditions.

5. Conclusions

The equations describing the coagulation among aerosol particles under the action of gravity, on ultrasonic exposure, the drift of particles in an electrostatic field, taking into account the environment conditions (temperature, viscosity) and the viscosity of a dispersive medium, have been analysed.

The experiments with the sedimentation of finely-dispersed particles of wood flour have been conducted at different initial values of air medium temperature and humidity. It was demonstrated that applying the ultrasonic and electrostatic effect separately or in combination with increasing temperature up to 40–45°C enhances the collection effectiveness of aerosol particles. Reducing temperature to 10–13°C considerably decelerates the sedimentation rate of the wood flour aerosol. High humidity promotes the particle coagulation and accelerates their natural settling, as well as sedimentation under the action of ultrasound, but, has almost no impact on the particle drift rate in an electrostatic field.

Acknowledgments

Instruments were provided by the Biysk Regional Center for Shared Use of Scientific Equipment of the SB RAS (IPCET SB RAS, Biysk).

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