Experimental study on precipitation of aerosol particulates under combined external fields

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Abstract. Electrostatic and ultrasonic precipitators have been put to good use in many industries in the manufacture of iron, cement, nonferrous metals, petrochemicals, cellulose, etc. However, the efficiency of using dust collectors based on externally applied fields (electrostatic and ultrasonic) varies widely with physicochemical behaviour of an airborne particulate system. The capture efficiency of airborne particulates of different type is influenced by the precipitation device design. The fact that suspended aerosol particles are polydisperse and their precipitation rate in the air stream is different, also poses a special difficulty. In these days, the capture efficiency of aerosol particulates is under improvement through combining several kinds of exposure applied to aerosol particulates at a time.

1. Introduction

Outdoor and indoor ultrafine particulates drastically affect the human organism, increasing the incidence of respiratory, ophthalmological and dermal diseases. For instance, roadway emissions were shown to comprise 70% suspended asphalt particles of 0.35 to 2.8 µm in size with the mean below 0.7 µm [1]. The analysis of the particulate matter size distribution in the air on a moderate traffic highway revealed 3800 to 6900 tire fragments present in each cubic meter of the air, over 58% of which were less than 10 µm in size. Toxic emissions also originate from subway train braking and operation [2]. Such concentrations of harmful aerosol can provoke the progression of allergic and oncological diseases.

Brisk growth and activities of industrial enterprises entail the generation of unhealthful micron-sized particulates which accumulate indoors of manufacturing shop floors and of material laydown and storage areas. An example is construction, metallurgical and mining companies and those in other industrial sectors [3]. Dust particulate matter varies in size from 0.01 to 40 µm and is chemically composed of poisonous carcinogenic substances detrimental to the respiratory system [4].

Apart from fighting solid airborne particulates, there remains an equally important issue of settling down liquid aerosols of harmful compounds such as sulfuric acid, alkaline liquors [5], petrochemicals [6], and other oily liquids [7]. Hence, the topical challenge is to remove toxic aerosol emissions of different chemical composition and particle size, especially in indoor conditions. One of the ways to enhance the efficacy of capturing polydisperse particles of different composition is to combine a few aerosol settling techniques. For instance, diffusional deposition coupled with an electrostatic precipitator is applied to remove particulates below 0.1 µm in size (efficacy over 99%) [8, 9]. Electrocyclones are utilized to collect fly ash particulates [10]. Besides, wet electrostatic precipitators to remove organic liquid droplets in the submicron range are gaining increasing popularity [8, 11].
Preliminary charging the filtering medium and aerosol generates an induced electrostatic charge and enhances the capture efficiency of fine aerosol particulates. Such an effect is exploited to cleanse the air stream of exhaust products [12].

It has been proposed that the dust suppression effectiveness be improved by sprinkling, which implies capturing and enlarging dust particles by wetting their surface with droplets, followed by sedimentation of the resultant particles [3]. The ultrasonic exposure when incorporating an additional dispersed phase (sprinkling) helped considerably increase the sedimentation rate of most of the fine solid aerosols [13].

However, the air environment polluted with volatile complex organic compounds (say, tobacco smoke) requires stepwise purification by combining a few kinds of exposure [14]. For instance, the acoustic field in addition to a centrifugal agglomerator can massively increase particle sizes through means of complementary agglomeration and ensure the capture efficiency of airborne particulates having a density of 2000 kg/m³ and the following dispersion attributes: 75% particles of up to 1 µm, 53% particles of up to 0.5 µm, 37% particles of up to 0.2 µm, and 28% particles of up to 0.1 µm [15].

Among the ways to accelerate the precipitation of aerosol pollutants is combining the acoustic source with the electrostatic filter [16, 17]. Combining particularly the ultrasound-assisted particle agglomeration with the electrostatic precipitation reduces the ultrasonic exposure time and enhances the filtration capacity, which in turn cuts down on capital costs and ultrasonic device energy consumption [18].

Enlarging the initial fine aerosol particles to a 2–4 µm size by intensive acoustic coagulation increases steeply the effectiveness of electrostatic filters. Yet, it is unadvisable to enlarge the particles up to 10–15 µm because this does not improve the device performance [19].

Experimental studies demonstrated that residual dustiness after using the electrostatic filter decreased by 15–17 times when the particles were enlarged 10-fold by the acoustic coagulation [19]. The aggregates formed in the acoustic field by the electrostatic precipitation do not break down. A dust scrubbing technique was suggested that involves applying acoustic and electrostatic fields to the dust gas stream at a time [20].

Thus, theoretical and experimental research on the precipitation efficiency of different composition aerosols under electric and acoustic fields is a topical challenge. The use of externally applied fields allows a range of useful properties to be achieved from the viewpoint of enhancing the efficacy of toxic aerosol scrubbing in indoor conditions:

- the ultrasonic field makes for particle coagulation and enlargement whereby coarse particles settle down faster. The acoustic coagulation effect is dependent on acoustic radiation pressure, frequency and intensity and on the particle interaction under hydrodynamic forces;
- the ultrasonic technique is more applicable to cleansing the air of particles with high concentrations and large sizes (1–10 µm wide);
- the electric field causes avalanche ionization to occur whereby the ordered motion of aerosol particles takes place towards precipitation electrodes of the electrostatic precipitator. The electrofilter performance depends largely on its design parameters;
- the electrostatic technique is commonly used to precipitate fine particulates with a size below 5 µm and compounds having an average electrical resistivity (10⁴ to 10⁵ Ωm·cm) to avoid particle bounce or ejection by back corona [21].

The present study aimed to examine the precipitation efficiency of suspended particulates with different physicochemical composition, particle size and concentration in the air environment under the combined physical fields (ultrasound and electrostatic) in a confined test space.

2. Experimental description and methodology
Photographs of powders under test and bar charts of particle size distributions were obtained by an OMEC particle image processor (PIP 9.0). The initial particle size distribution is constituted of the following parameters:

- mass mean particle diameter \( D_{4,3} \);
- arithmetic-mean particle diameter \( D_{1,6} \);
- median diameter \( D_{50} \);
- smallest particle diameter \( D_{105} \).
• largest particle diameter $D_{90}$;
• specific surface area $[\text{m}^2/\text{cm}^3]$.

The measurement range was between 0.5 and 3000 µm.

A set of experiments to measure the airborne particulate concentration over time were performed. For this, a LID-2M laser measuring setup was employed that is based on the modified small-angle scattering method which estimates the distribution function by solving a series of direct problems in aerosol optics and compares calculated data with the experimental [22].

The small-angle scattering method can technically be implemented by using different optical schematics. One of the classical variations of the schematic for measuring the small-angle scattering is illustrated in Figure 1. The LID-2M hardware enables aerosols to be tested from their origination moment until their complete disappearance due to the aerosol evolution.

![Figure 1. Optical schematic for small-angle scattering measurement](image)

The particle mass concentration $C_m$ is an important parameter to describe the aerosol sedimentation process and can be determined by using the LID-2M instrument. A pneumatic atomizer was used as an atomizing device in the experiments [23]. The acoustic exposure was generated by a Solovey UZAGS-0.6/22-O ultrasonic device having a noise level of at least 144 dB and a frequency of 22 kHz [24]. The design parameters of the electrofilter were as follows: 1000 mm$^2$ precipitation area; 0.085 m corona element length, active zone length; 0.01 m distance between corona electrodes; 0.005 m distance between the planes of corona and collecting electrodes; 0.004 m corona electrode radius; and 8000 V average voltage [25].

![Figure 2. Test chambers without and with externally applied fields: (a) no external fields applied, (b) under electrostatic field, (d) under ultrasonic field, (e) combined electrostatic and ultrasonic fields. 1. test chamber; 2. atomizer; 3. laser measuring system; 4. electrostatic precipitator; 5. ultrasonic radiator.](image)
All the experiments were run in a confined test volume under normal ambient environment conditions. A 3-atm nitrogen gas cylinder was used to supply and maintain the required atomizer pressure.

Four experiments were performed with each test powder:
- gravitational sedimentation with no external field applied to aerosol particulates (Figure 2a);
- electrostatic field applied after aerosol formation (Figure 2b) (the source was located at the upper corner of the test chamber) [26];
- ultrasonic field applied after atomization (Figure 2d);
- ultrasound coupled with electrostatics (Figure 2e).

The initial ambient environment conditions in the experiments were 25°C and 50 % humidity. For the initial 30 sec was recorded the background, and a fine powder was thereafter atomized in order to generate a thick aerosol cloud with a high concentration of 1 to 6 g/m³. The precipitating devices were enabled immediately after a test substance was atomized, with an exposure time of 60 to 90 min.

Figure 3. Bar chart of the particle size distribution obtained using the PIP 9.0 instrument for (a) talcum, (b) chalk and (c) wood meal powders.
3. Test powders
Fine powders with different physicochemical compositions were used herein as airborne particulate matter:

- talcum powder: \( D(4.3)=11.13 \, \mu m, 2.8 \, g/cm^3 \) density, and \( 10^9 \, \text{ohm}\cdot\text{m} \) electric resistivity (Figure 3a);
- PKMMS-15 chalk: \( D(4.3)=3.44 \, \mu m, 2.2 \, g/cm^3 \) density, and \( 60 \, \text{ohm}\cdot\text{m} \) electric resistivity (Figure 3b);
- MD-E wood meal: \( D(4.3)=21.01 \, \mu m, 0.4 \, g/cm^3 \) density, and \( 10^{11} \, \text{ohm}\cdot\text{m} \) electric resistivity (Figure 3c).

4. Experimental results and discussion
In the experiments with a talcum aerosol to examine the actions of external fields in a test volume, the talcum powder was atomized for 30–40 sec; the atomized powder weight was 5 g. The experimental results for the talcum powder (Figure 4) showed that it took more than 1000 sec for the concentration to drop to zero in all cases, except the case of the combined electrostatic and ultrasonic fields (Figure 5, Table 1). Talcum falls within substances that have the average resistivity of \( 10^9 \, \text{ohm}\cdot\text{m} \), so the electrostatic field exposure was highly effective towards talcum, resulting in doubled precipitation rate of the aerosol particulates. The ultrasonic exposure promoted the particle coagulation and somewhat accelerated the precipitation as compared to the control. Under the combined electrostatic and ultrasonic fields, the precipitation rate was the highest and the relative concentration reduced to zero within about 900 sec (Table 1).

| Substance   | Precipitation time (sec) |
|-------------|--------------------------|
|             | No exposure | Ultrasound | Electrostatics | Combined |
| Talcum      | 3300        | 2700       | 1950          | 900       |
| Chalk       | 6000        | 4300       | 1500          | 1300      |
| Wood meal   | 4000        | 3300       | 2600          | 2150      |

Table 1. Experimental precipitation times of aerosols in test chamber

Figure 4. Time course of the relative talcum aerosol concentration without and with different externally applied physical fields: 1. no exposure; 2. ultrasonic field; 3. electrostatic field; 4. combined electrostatic and ultrasonic fields

The weights of the other fine powders dispersed in the test chamber were 4 g within 8 sec for chalk and 1 g within 10 sec for wood meal. The time course of the concentration change of the said substances during the aerosol evolution is displayed in Figure 5.
The chalk aerosol particles were at most 10 µm in size (Figure 3b), so they kept being suspended inside the measuring chamber for long – more than 80 min (Figure 5a, curve 1, Table 1), with a concentration of up to 4 g/m³. The chalk aerosol particle size being such, the particle coagulation under the ultrasonic field was taking place long, and the aerosol precipitation rate was only about 20% faster (Table 1). The electrostatic precipitator provided a higher precipitation rate — the relative chalk particle concentration was tending to zero for 1500 sec (Figure 5a, curve 3, Table 1) — despite the low electric resistivity provoking the chalk aerosol particles to bounce off the collecting electrodes. The precipitation time when the ultrasonic and electrostatic fields were applied together was about that when the electric field was applied alone (Figure 5a, curve 4, Table 1). This is explained by the electrostatic device collecting the small chalk particles sooner than they have time to coagulate under the ultrasound. So, it can be inferred that the ultrasound applied to fine particles (up to 10 µm) is not as effective as the electrostatic field. On the other hand, if the particle concentration was higher, the ultrasonic exposure could be more efficient because the coagulation rate is proportional to the number concentration of particles.

Out of the airborne particulate matters studied herein, the wood meal had coarser particles. This substance also distinguishes itself by a high electric resistivity of $10^{11}$ ohm·m. Figure 5b, curve 2, demonstrates an increased precipitation rate of the suspended wood meal particles with a size of 1–20 µm in the air under the ultrasound, despite their small concentration in the measuring chamber (below 1g/m³). This is on a par with the preliminary calculated estimates for the precipitation time of coarse particles under the ultrasound, meaning that the ultrasonic coagulation is
effective for such particles [27]. Irrespective of the wood meal aerosol particle concentration in the test volume, and despite the high electric resistivity of the wood meal (10^{11} \text{ ohm}\cdot\text{m}), the electric field impact doubled the precipitation rate of this matter (Figure 5b, curve 3, Table 1) as compared to the wood meal atomized under no exposure (Figure 5b, curve 1). The combined fields even more accelerated the particle coagulation (Figure 5b, curve 4, Table 1).

It follows from Table 1 that the relative concentrations of the airborne particulates under test were the longest persistent in the air environment when no exposure was applied, as demonstrated by the experiments. The ultrasound made a faster precipitation of the particulates, especially of coarser particles like wood meal. In all the cases, the electrostatic field was more effective than the ultrasound (Table 1). The good purification efficiency exhibited by the electrostatic precipitator used in these experiments is attributed to its specific design parameters. Because the test chamber had no powerful air stream inside, the low-resistivity chalk particulates could not fly out beyond the collecting electrodes. As to the wood meal, its low-concentration high-resistivity suspended particles were not enough to induce the back corona discharge. The fastest and most complete precipitation was achieved by applying the ultrasonic and electrostatic fields together.

5. Conclusion
The combination of different precipitation methods and their joint actions can substantially improve the performance of cleaning devices. Such an approach is fairly effective in terms of capturing complex compounds of different chemical composition. Here we examined some commonly found chemicals with detailed dispersion characteristics. The concentration of aerosols in a confined volume was measured by the small-angle laser radiation technique. The experiments have shown the precipitation rate and efficiency of either method towards aerosols depend measurably on the nature, particle size and concentration of a compound in the air environment. For instance, at small concentrations and particle sizes (below 10 \mu m), the ultrasound is less effective than the electrostatics. For coarser particles, the ultrasound works better. To speed up the aerosol precipitation, an ultrasound radiation source operating at over 22 kHz and at least 120–140 dB is needed. Regardless of the electric resistivity of the particulate matters studied, the electrostatic field exhibited a high performance in cleansing the air environment. The smaller the aerosol particles, the faster the complete precipitation occurs under the electrostatic field.

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