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Effect of turbulence intensity and particle characteristics on the deposition of submicron particles enhanced by the ionic air purifier

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ABSTRACT

A negative air ionizer (NAI) is a common indoor air purifier for aerosol particles. The turbulence intensity can influence the performance of NAI. Besides, the dielectric constants (p) of particles can affect the electric mobility and deposition of particles in the electric field. Hence, this study aims to exam the difference between the deposition rate of NaCl ($p = 6.1$) and sucrose ($p = 3.3$) submicron particles when an NAI is operating under various turbulence intensities.

The experiments were conducted in a stainless steel chamber under 50% relative humidity. Polydisperse submicron particles (PSPs) of 30–300 nm and monodisperse submicron particles (MSPs) of 30, 50, 100, 170 and 300 nm were used for testing. In the experiments of particle deposition, the aerosol particle number concentration and size distribution were monitored continuously by a Scanning Mobility Particle Sizer. The decay constant of particle concentration (k) and effective cleaning rate (ECR) were determined from the time profiles of particle concentration.

When the NAI was off, k of NaCl and sucrose particles was similar. However, when the NAI was operating, the deposition rate of NaCl particles was higher than that of sucrose particles and the NAI performed better under lower turbulence intensity. Because the coagulation coefficient of PSP was larger than MSP, the decay constant of PSP was superior to that of MSP. The ECR was negatively correlated with particle size and was higher under lower turbulence intensity.

Conclusively, the NAI is more efficient in charging particles with higher dielectric constants and performance better under lower turbulence intensity.

1. Introduction

Modern people spend about 87% of their time indoors, and thus most of their exposure to particulate matters (PM) occurs in indoor environments. To remove aerosol particles, negative air ionizers (NAIs) have been a prevalent air purifier. For instance, Grabarczyk [1] employed corona ionizers as the indoor air purifier for dust particles of 0.3–2.5 μm in a 50-m^3office room. Grinshpun's group at the University of Cincinnati utilized the continuous emission of unipolar ions to remove fine and ultrafine aerosol particles and bioaerosols (virus and bacteria) from indoor environments [2,3]. They also used an ionic air cleaner to reduce respirable particles concentration in confined indoor spaces [4]. Hu's group at the National Taipei University of Technology exploited negative air ionic cleaner to remove submicron particles in an industrial mini environment for the Integrated Circuit manufacturing processes and the clean rooms [5,6]. An NAI can charge aerosol particles and enhance their deposition owing to the electrostatic effect. Besides, some studies successfully improved the filtration efficiency by charging the particles with an NAI [7,8]. Moreover, several studies used the ion generator to remove microbial contamination, including influenza particles and *Escherichia coli* and *Staphylococcus epidermidis* and to manage infection transmission [9–11]. Abidin and Ming [12] applied a commercial negative air ionizer to kill house dust mites (*Dermatophagoides pteronyssinus* and *Dermatophagoides farinae*). Furthermore, NAIs have been proved to be efficient in diminishing the activity concentrations caused by radon and thoron (^{220}Rn) decay products [13].

Many factors can influence the effectiveness of NAI on the deposition of the particles. Wu et al. [14] investigated the effect of wall surface materials on the deposition of particles enhanced by an operating NAI. The net effectiveness of the NAI on the removal of 0.03-μm and 0.3-μm particles followed the order of wood > PVC

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and cement paint > wallpaper > stainless steel; wood > PVC > wallpaper > stainless steel > cement paint, respectively. These orders were roughly consistent with the order of surface electrical resistivity of the wall materials. Lee et al. [2] and our previous study have demonstrated that the deposition rate of the particles can be enhanced by increasing the ion concentration. However, the ion concentration decreased with the distance from the NAI, and thus the effectiveness of NAI on the particle deposition would decrease with the hypothetical room size [15]. Furthermore, because the particle charging efficiency of the NAI is a function of particle diameter and dielectric constant [2,16,17], the particle deposition rate enhanced by the NAI is also influenced by these two factors. Besides, NAIs may emit ozone, which reacts with terpenoids to produce ultrafine secondary organic aerosols, carbonyls, carboxylic acids, and free radicals. Waring and Siegel [18] demonstrated that in a residential room the simultaneous use of the air ionizer and the air freshener (with terpenoids) resulted in increases in ultrafine particles, as well as formaldehyde and nonanal.

It is well known that the turbulence intensity can significantly affect the particle deposition rate onto the surface without the NAI operating [19,20]. However, there is few study regarding the effect of turbulence intensity on the particle deposition enhanced by the operating NAI. Therefore, we would like to investigate how turbulence intensity influences the particle deposition when the NAI is operating. Moreover, aerosol particles in the real world are polydisperse. However, the experimental results of monodisperse particles are more possibly to be proven by the theoretical model. In this study, the experiments were conducted with both monodisperse submicron particles (MSPs) and polydisperse submicron particles (PSPs) to compare the differences between the deposition of MSP and PSP.

2. Methodologies

2.1. Particle deposition enhanced by the NAI

The schematic diagram of the experimental setup to conduct the particle deposition experiments is shown in Fig. 1(a) and (b). This setup contains a zero air supply system, a test aerosol generation system, and a polished stainless steel test chamber (60 cm × 60 cm × 60 cm) equipped with a negative air ionizer (NAI) (Model STR-11, Rayuan Co. Ltd.) to charge the particles. The strength of electrostatic field and concentration of negative air ions produced by the NAI were measured by an Electrostatic Field Meter (EFM 231, Kleinwächter Ltd.) and an Air Ion Counter (AIC-20M, AlphaLab, Inc., USA), respectively.

The zero air supply system included an oil-free air compressor (ORSO), a homemade diffusion dryer, an active carbon capsule, and an HEPA filter (HEPA Capsule, Part Number 12144, PALL Corporation, USA). The relative humidity (RH) of the experimental system was controlled by the flow rate ratio of saturated air to dry air and maintained at 50% ± 3% throughout each experiment. A metal fan in the test chamber provided the freestream air velocity (FAV) of 0.56, 1.2 and 2.0 m/s (were defined as low, medium and high FAVs, respectively) to explore the effect of turbulence intensity (expressed as FAV) on the deposition of particles. The FAV, RH, temperature, and CO_2 concentrations (tracer gas for mixing level measurement) in the test chamber were measured by a Q-Trak® indoor air quality monitor (model 7565-X, TSI Inc.) throughout each experiment.

The "test aerosol generation system" produced both polydisperse submicron particles (PSPs) and monodisperse submicron particles (MSPs) for the experiments and we investigated the effect of particle size distribution on the deposition of particles. The PSPs were produced from the Aerosol Generator Model 3076 (TSI Inc., USA). The MSPs with the diameter of 30, 50, 100, 170 and 300 nm were generated by passing the PSPs through the Differential Mobility Analyzer (DMA, Model 3081, TSI Inc., USA). Before being introduced into the test chamber, all the test aerosol particles were neutralized by an Aerosol Neutralizer Model 3077, (TSI Inc., USA) to eliminate the effect of polarized charges on the particle deposition.

To investigate the effect of aerosol particles' relative permittivity (p) on the deposition of particles, we used two kinds of aerosol particles: sucrose (p = 3.3) and NaCl (p = 6.1) to carry out the experiments.

Before each experiment got started, the aerosol particles in the chamber would be cleaned up by purging the chamber with zero air and operating the NAI until the aerosol particle concentration in the chamber decreased to less than 100 particles/cm^3. In the experimental system shown in Fig. 1(a), the test aerosol particles were introduced into the chamber until the particle number concentration achieved $C(d_p,t=0)$. Then the particles size distribution and decay of number concentration were continuously recorded by the Scanning Mobility Particle Sizer (SMPS, Model 3936L76, TSI Inc., USA). In general, the decay of particle number concentration follows the equation below:

$$C(d_p,t) = C(d_p,t=0) \times \exp[-t \times (k_a \text{ or } k_n)] \quad (1)$$

where, $C(d_p,t)$is the number concentration of particles with diameter d_p at time t; $C(d_p,t=0)$ is the initial number concentration of particles with diameter d_p; k_a represents the decay constant of the particle number concentration when the NAI is operating; k_n stands for the decay constant of particle number concentration when the NAI is off. The particle removal efficiency (*PRE*) is given by:

$$PRE = 1 - \frac{C(d_p,t)}{C(d_p,t=0)} = 1 - \exp[-t \times (k_a \text{or} k_n)] \quad (2)$$

Rearranging Equation (2), we have:

$$\ln[1/(1-PRE)] = t \times (k_a \text{ or } k_n) \quad (3)$$

The decay constant (k_a or k_n) can be determined from the slope of the plot of ln [1/(1-*PRE*)] versus t.

2.2. Theoretical model for particle deposition

It is widely believed that there is a particle-concentration gradient within the boundary layer over the wall surface. We assumed that there was no particle rebounds or resuspension from the surface, and the generation and decay of particles within the boundary layer were negligible. As a result, the particle flux, J, through the near-wall particle concentration boundary layer can be expressed as by the Fick's first law:

$$J = -(D + \varepsilon_p)\frac{\partial C}{\partial y} \quad (4)$$

where D is the particle Brownian diffusivity; ε_p is the particle turbulent (eddy) diffusivity; C is the number concentration of aerosol particle; y is the distance from the surface of the chamber wall. The particle eddy diffusivity is a function of turbulence intensity and the distance from the surface (y) [20]: