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Particles Removal by Negative ionic Air Purifier in Cleanroom

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ABSTRACT

This study investigated effectiveness of negative ionic air purifier in lowering the concentration of particles in a closed test chamber. The performance test was carried out in a closed test chamber under natural decay, as well as with an air mixing mechanism. Compared with natural decay, the air mixing mechanism could reduce particles concentration better (under the flow field condition). However, air change rate effect is limited in super cleanrooms that require suitable approaches to enhance control of particles concentration and to raise the effective cleaning rate of negative ionic air purifier. This study investigated the concentration gradient of particles at various heights and distances from the source of negative ions. Experiment results indicate that performance near the negative ionic purifier was better than in the rest of the cleanroom. In terms of height, the highest removal efficiency was observed at a height of 60 cm from the floor; it decreased substantially with increase in height. The empirical curves fit based for the concentration gradient of NAI generated was developed for estimating the NAI concentration at different heights and distances from the source of negative ionic air cleaner.

Keywords: Particle; Negative air ion; Air mixing; Removal efficiency; Air cleaning factor.

INTRODUCTION

The generation and storage of static charge during TFT-LCD production occurs primarily on the glass panels themselves, although other objects may also get charged. Neutralizing static charge on an insulator like glass requires the use of air or nitrogen gas ionization, particularly in cleanrooms required for TFT-LCD production. Air ionization is recognized as the most effective means of neutralizing static charge on glass panels and is widely used in TFT-LCD production facilities. Static charge levels during the production process are frequently higher. High production speeds are required to achieve profitability, often imply that ionizers must reduce the static potential in a very short period of time. To meet the requirements for neutralizing high levels of static charge in short periods of time, adequate quantity of high density negative air ions must be supplied.

Negative air ionizers are typically applied to clean air indoors. Daniels (2002) reported that negative air ions (NAIs) reduce aerosol particles, airborne microbes, odors and volatile organic compounds (VOCs) in indoor air. The removal of aerosol particles using NAIs is efficient (Grabarczyk, 2001; Wu and Lee, 2003). The operating principle of an ionic air cleaner is ion emission through corona discharge; the unipolar ions then electrically charges airborne particles, causing them to either repel each other or deposit on nearby surfaces through image charges or static electrification. In addition, some ionic cleaners act as electrostatic precipitators; directional ionic wind creates air and particles flow over precipitation plates and particles are charged and deposited onto these plates. Several studies have been conducted to test the ability of ionic cleaners to remove particles from the air (Grabarczyk, 2001; Grinshpun *et al*., 2001; Niu *et al*., 2001; Grinshpun *et al*., 2004, Lee *et al*., 2004; Grinshpun *et al*., 2005). These studies have detected and quantified large reductions in airborne particulate matter due to the presence of unipolar ions. Grabarczyk (2001) found that particles concentrations of between 0.4 and 2.5 μm underwent a 20-fold reduction after one hour of ionization in an unoccupied chamber of volume 50 m^3. A study examining wearable ionizers (Grinshpun *et al*., 2001) found that particle removal efficiency of the ionizer was 80% after 30 minutes and 100% after 1.5 hours in a 2 m^3 chamber. A later study by Grinshpun *et al*. (2005) tested commercially

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available ionic air cleaners in a 2.6 m^3 chamber and found that the unit which produced the most ions demonstrated 100% particulate matter removal within 10 to 12 minutes for particle sizes between 0.3 and 3.0 µm. Lee *et al*. (2004) tested commercially available ionic cleaners in a 24.3 m^3 test chamber and found that a 30 minute operation of the device, which produced the most ions, resulted in removal of about 95% of 1.0 µm particles from the air above, which was beyond the decay rate, due to particle settling. These studies clearly indicate that ions can facilitate reduction of airborne particulate matter. The limitation of the aforementioned studies, however, is that they have used uninhabited chamber environments to study the effect of ions on air quality, and have not challenged ionic air cleaners with real-life environments. Unlike in test chambers, in real indoor living spaces, airborne particles can be generated continuously by various activities of the inhabitants and infiltration of outdoor particles through the building envelope.

Common ionizers use ionization to decompose molecules in the air. This method not only produces negative ions, but also produces adjunctions like positive ions and ozone, etc. Negative ions occur commonly throughout nature and can create an overall sense of well-being. Positive ions are positively charged molecules (positively charged carbon dioxide) and are believed to have negative health effects on human health. Despite the positive influence of negative ions having already been understood by most people, applications have been limited. Negative ionic air purifiers using the Polymer Fusion Technology (PFT) to compound (fusion) the C_{60} series of carbon materials with other materials (like carbon/oxygen materials) changes physical, chemical and electric attributes of ionized particulate matter. More importantly, use of environment-friendly materials (excluding the eight major toxicant heavy metal pollutes), which can be decomposed after high-temperature heating, ensures compliance of global environment protection standards. The high or super-high molecular weight of chemosynthesised fullerene materials implies extraordinary properties unseen in physical and chemical research on delicate ions. Materials with such features have effective static reduction capabilities as they generate large amounts of pure OH^- electrons, commonly known as negative ions. The product reduces the static resulting from machine operation and operator motion. It quickly pushes airborne particles, dust, and residual spray paint toward the ground, and restricts airborne particles to a height of 10 cm from ground level. As a result, airborne particles will not continue to float, accumulate, and attach to each other. As large quantities of airborne particles are removed, defect rate in manufacturing can be decreased significantly.

The main objective of this study is to determine the particle (0.1–0.5 µm) removal efficiency of the negative ionic air purifier in a closed chamber that simulated a confined cleanroom environment. Effects of air mixing, height from the floor, and distance from the source of NAI generation in the chamber on the performance of the negative ionic air purifier will also be investigated.

MATERIALS AND METHODS

The tests were conducted in a closed chamber made of stainless steel (SUS-304), which was earthed. In the testing chamber a temperature of 24 ± 1°C and relative humidity of 45 ± 2% was maintained by an air-conditioning system. The geometry of the chamber and locations of devices and instrumentation were as shown in Fig. 1. The devices contained a fan to re-circulate chamber air through the negative ionic air purifier.

An ultrasonic nebulizer (Model: UN-808, Sigma Medical Supplies Corp. Tapei, Taiwan) was used to generate particles from polystyrene latex sphere (PSL), the particle source (injection velocity can be neglected); more than 75% of particles had diameter of 0.12 µm, and concentration at the source point was approximately 106 particles/ft3. PSL and deionized water were mixed in a concentration ratio of 50 mL per 1 gallon (3.8 liters). Negative ionic air purifier with an output rate of 2×10^6 ions/cm/sec (Average negative ion concentration was 6×10^5 ions/cm^3) was directed towards the middle of the chamber. The Specification of the negative ionic air purifier was shown in Table 1. Investigated the influence of air ionization at different distances (30, 50, 70, and 90 cm, from itself) and at different heights (60, 80, 100, and 120 cm) from the floor, on the filtration process. A multi-point laser particle counter (Model: Pacific Scientific Model Met One 2100.10, Ashtead Technology) was used to monitor particle concentration in the test chamber and the specification was shown in Table 2.

PRINCIPLE

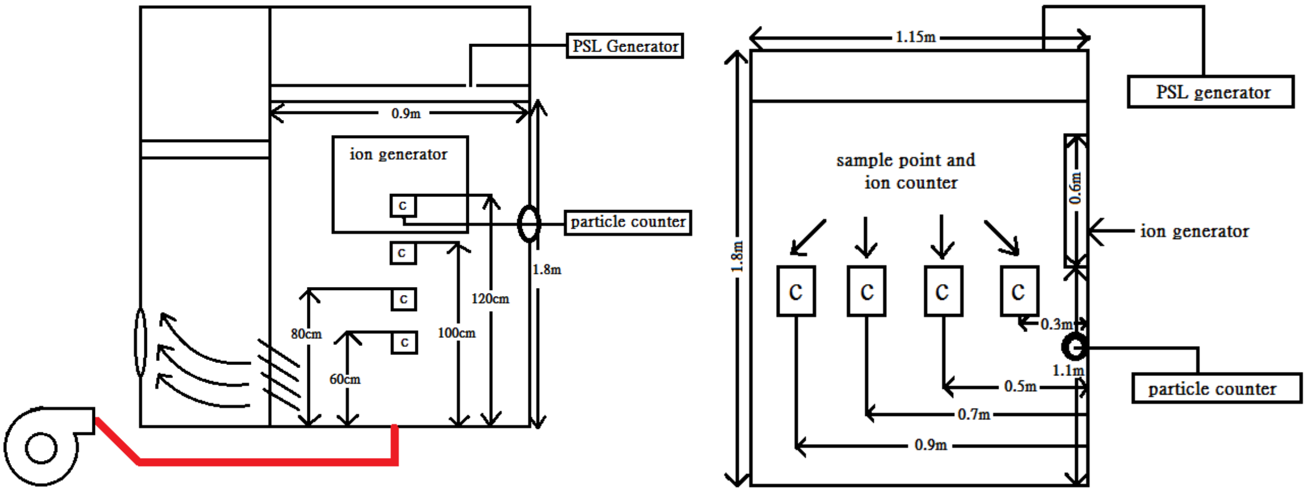
The negative ionic air purifier was as shown in Fig. 2. Used as the medium for generating negative ions, the conducting high polymer is made up of carbon nano-tubes and OH^-. A small amount of electricity flows through, the conducting high polymer creates molecular resonance with OH^-, generating large amounts of electrons. When the electrons bond with air molecules, negative ions are formed. Each generating mechanism releases up to two million negative ions per square centimetre.

First, the natural decay of particles concentration was determined. Prior to the test, particles were generated and mixed in the chamber for 30 min so that they were uniformly distributed. Then the particle counter began recording the data (t = 0) starting from the initial concentration C_0. It operated continuously for 1 h, and the aerosol concentration C_t was measured. Particle concentration decay was analyzed using the following equations: (Wu *et al*., 2006)

$$dC/dt = -kC \tag{1}$$

$$C_t = C_0 \exp(-kt), \quad k = k_n \text{ or } k_a \tag{2}$$

where C is particle concentration (number 1/ft^3); C_0 and C_t are initial concentration of target particles and concentration at time t, respectively (number 1/ft^3); t is the residence time (min); k is the decay coefficient of particle concentration (1/min); and, k_n and k_a are the decay coefficients of particle



(a) (b)

Fig. 1. Experimental set up.

Table. 1. Specifications of the negative ionic air purifier.

Power: AC 110 V or 220 V
Size: 60 × 60 × 6 cm
Power consumption: 8 W
Net weight: about 4 kilograms
Apparatus for negative ion generating mechanism: Four
Volume of negative ions generated: Each mechanism can generate more than two million ions/cm/sec
Location: Installed on the ceiling, above production line or to the side of production line

Table. 2. Specifications of the multi-point laser particle counter.

Title	Value
Size Channels	0.1, 0.2, 0.3, 0.5, 0.7, 1.0 µm
Flow Rate	1 cfm
Sample Time	1 second to 24 hours automatic, or manual start and stop
Hold Time	1 second to 24 hours
Data logging	500 samples
Output	Built-in printer, RS-232 port
Power	115 V
Dimensions	178 × 343 × 559 mm
Weight	19 kg

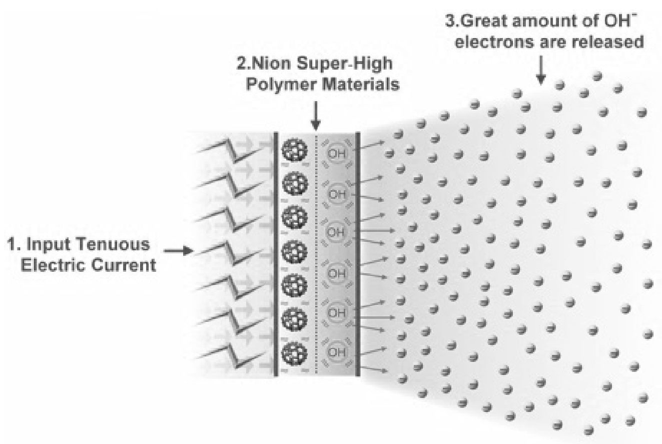


Fig. 2. The mechanism of the negative ionic air purifier.

concentration associated with natural decay and NAI, respectively (1/min). The coefficients of C_0, C_t and t were measured in each experiment. The decay coefficient (k) is a regression coefficient in an exponential regression analysis, specified by Eq. (2). Subscripts of k_n and k_a refer to natural decay and NAI, respectively.

Particle removal efficiency was determined as follows: (Grinshpun *et al*., 2005)

$$Particle\,removal\,efficiency = \frac{C(d_p, t=0) - C(d_p, t)}{C(d_p, t=0)} \tag{3}$$

Natural decay depends on air mixing conditions in the chamber. Therefore, the tests were conducted in calm air condition as well as with the re-circulation fan operating at flow rate of 0.682 m^3/s.

To quantify the efficiency of particle removal caused exclusively by ion emission, the air cleaning factor (ACF) was determined. For every particle size, ACF is defined as the ratio of concentration of particles at a specific time point during the natural decay process to concentration measured at the same time point when the ion emitter was operating (Lee *et al*., 2004):

$$ACF = \frac{C_{natural}(d_p, t)}{C_{ionizer}(d_p, t)} \tag{4}$$

RESULTS AND DISCUSSION

Natural Decay and Negative Air Ionization

Fig. 3 plots concentrations of 0.1 to 0.5 µm particles versus time under natural decay and NAI application below 6 hours. The results reveal that the reduction in particle concentrations when NAI was applied exceeded that associated with natural decay in Fig. 3. NAI of 0.1 to 0.5 µm particles was faster than that of natural decay of 0.1 to 0.5 µm particles.

Fig. 3 showed regression equations of particle concentration decay. Results of the regression analysis showed that all correlation coefficients for decay of particle concentration versus time exceeded 0.9975. Table 3 summarizes k_a and k_n for each size of particles. Each decay coefficient was an average over five repeats; standard deviations of decay coefficients were less than 10 %. The data showed that k_n values for natural decay of particles followed the order 0.5 µm > 0.3 µm > 0.2 µm > 0.1 µm. The order of decay coefficient (k_a) of the particles was 0.1 µm > 0.5 µm > 0.2 µm > 0.3 µm. Calculation of $k_a - k_n$ obtains the net effect of NAI application for each size of particles. The maximum net effect of NAI application for each size of particles was for 0.1 µm and the minimum net effect of NAI application was for 0.5 µm. The decay of particle concentration under NAI application was higher than that for natural decay (Wu *et al*., 2006).

Fig. 4 demonstrates how particle removal efficiency varies with particle size. It is seen that removal efficiency provided by the negative air purifier increases by as much as two times compared with no ion emission in case of smaller particles of size ~0.3 µm, and approaches 95% when the particle size reaches ~0.5 µm, with as well as without ion emission.

The particle removal efficiency of natural decay and negative air ionization as a function of particle size is shown in Fig. 5. Removal efficiencies greater than 90% were accomplished for particles smaller than 0.1 µm and larger than 0.5 µm, and decreased to about 65–90% for particles 0.2–0.4 µm. These results imply that particles 0.2–0.4 µm, which have been traditionally difficult to charge by means of natural decay and negative air ionization, can be effectively charged and collected in both case of larger particle 0.5 µm. The loss in efficiency at smaller sizes (0.2–0.4 µm) in Fig. 5 is due to they require higher number of charges per particle to acquire comparable electrical mobility.

Fig. 6 shows the overall particle removal efficiency as a function of time for natural decay, and negative ionic air purifier, when operating in calm air. Particle removal efficiency for natural decay increased gradually from 9–50% at t = 210 min to about 50–67% at t = 330 min. The data demonstrate that air cleaning provided by the negative ionic air purifier reached considerable levels after it had continuously operated for more than one hour; particle concentration in the chamber decreased by a factor of 2 (removal efficiency = 50%) after 80 min and almost fivefold (removal efficiency = 80%) after 150 min.

The negative ion emission produced by the ionic air purifier significantly cleaned the air of particles of size ~0.3 µm, but for particles of size ~0.5 µm ACF-values were not so high (see Table 4). The difference between the data obtained for sizes 0.3 µm and 0.5 µm was statistically insignificant.

Effect of Air Mixing

Fig. 7 showed that particle removal efficiency of negative ionic air purifier with air mixing was higher than under pure negative ionic air purifier condition. The time taken for achieving 90% particle removal efficiency was reduced from 240 to 80 min, from 310 to 90 min, from 310 to 90 min, and from 240 to 90 min, for particle sizes of 0.1, 0.2, 0.3, and 0.5 µm, respectively. The air currents intensify ion propagation in the chamber and enhance ion-particle interaction (Cyrys *et al*., 2004; Wallace *et al*., 2004; Grinshpun *et al*., 2005; Berry *et al*., 2007). This makes particle charging by air ions more efficient and consequently increases particle removal efficiency when air mixing is operational.

Effect of Distance from the Ion Source and the Height from the Floor

Vertical distribution of particle removal efficiency was determined by measuring particle concentration at varying heights; h = 60, 80, 100, and 120 cm (Fig. 8). The data indicate that height also plays a more important role in particle removal. The measurements indicate that particle removal efficiency by negative ionic air purifier substantially varies with its height from the floor, which has implications for its ability to effectively reduce

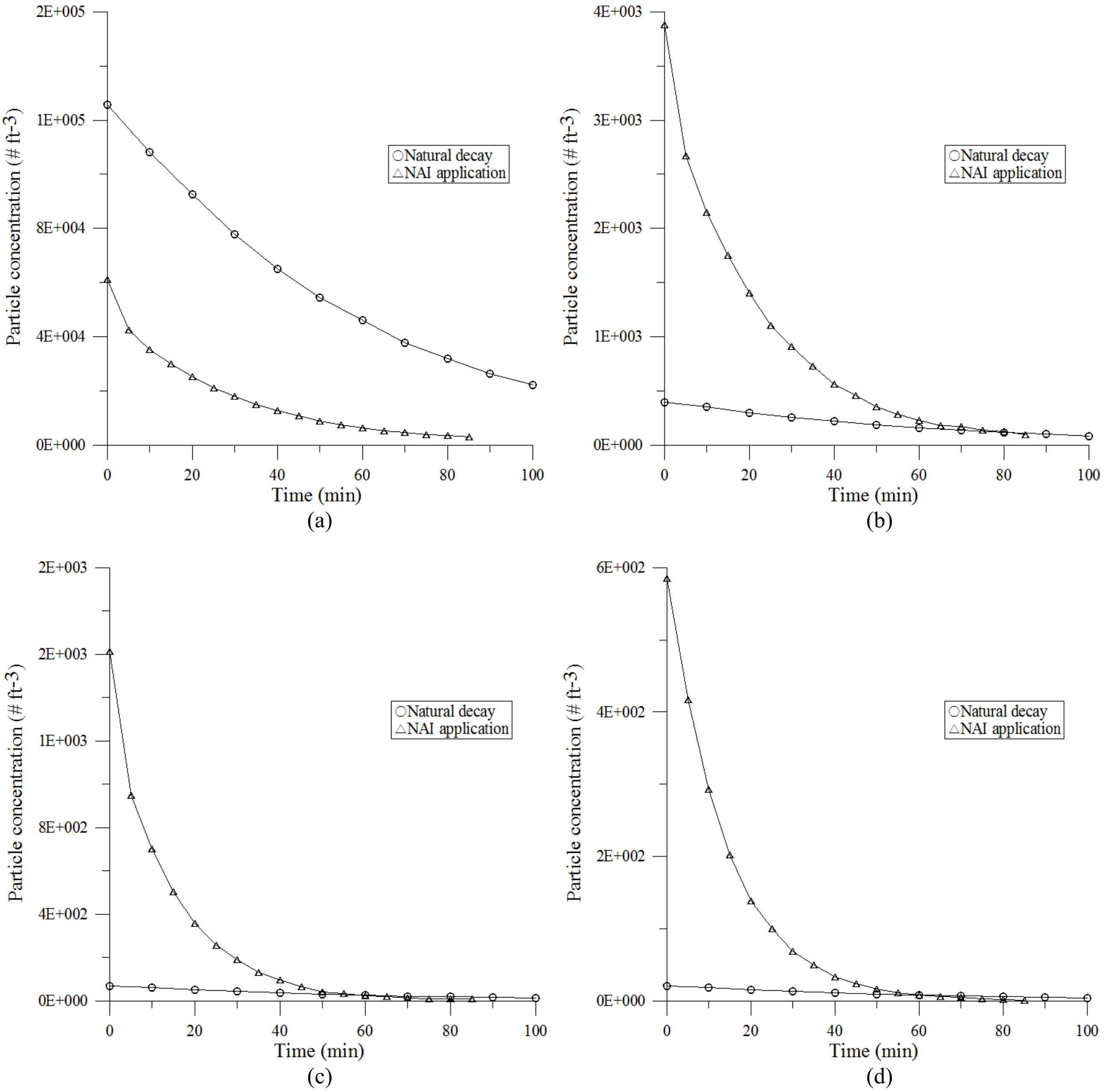


Fig. 3. Particle concentration (#/ft^3) for each size of particles with natural decay and NAI application (a) 0.1 μm, (b) 0.2 μm, (c) 0.3 μm, and (d) 0.5 μm. Note: #/ft^3 =35.3 #/m^3

Table 3. Decay coefficients (k) of each particle with natural decay and NAI application (k_a and k_n).

Particle diameter (μm)	Particle concentration vs time (t)	Decay coefficient (10^{-2}/hr)		
		k_a	k_n	k_a–k_n
Natural decay				
0.1	$y = 143482e^{-0.00337x}$, $R^2 = 0.9987$		0.337	0.685
0.2	$y = 955.49e^{-0.00356x}$, $R^2 = 0.9992$		0.356	0.384
0.3	$y = 124.13e^{-0.00568x}$, $R^2 = 0.9995$		0.568	0.089
0.5	$y = 42.54e^{-0.00893x}$, $R^2 = 0.9975$		0.893	0.077
Ion operation				
0.1	$y = 145634e^{-0.01022x}$, $R^2 = 0.9997$	1.022		
0.2	$y = 601.22e^{-0.0740x}$, $R^2 = 0.9993$	0.740		
0.3	$y = 107.83e^{-0.00657x}$, $R^2 = 0.9985$	0.657		
	$y = 39.39e^{-0.00970x}$, $R^2 = 0.9989$	0.970		

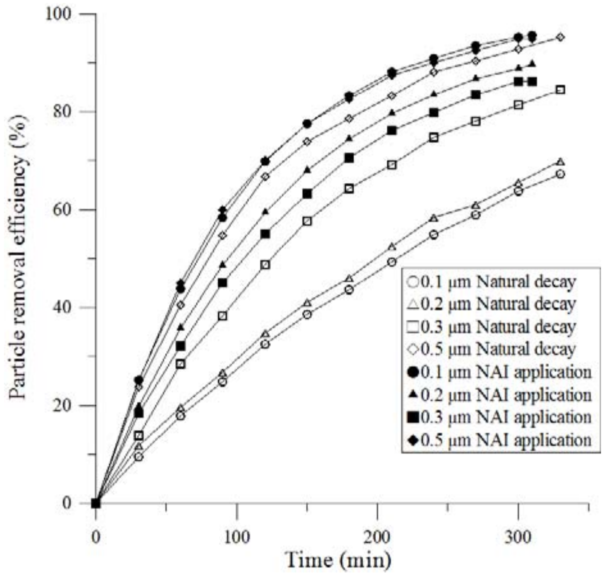


Fig. 4. The particle removal efficiency of natural decay and negative ionic air purifier at different particle size.

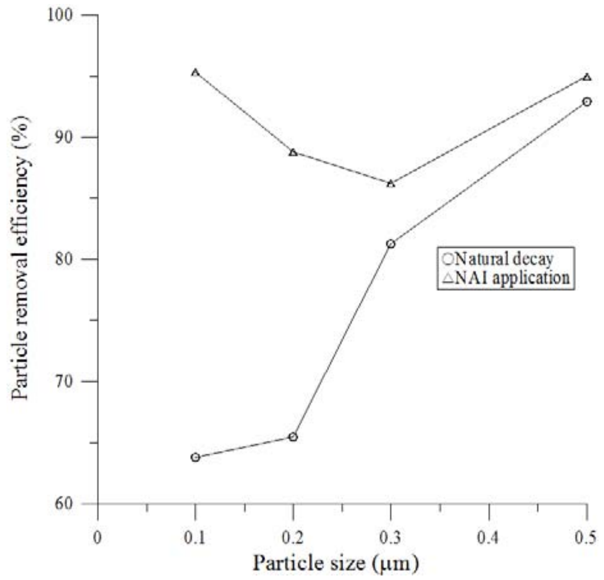


Fig. 5 Particle removal efficiency as a function of particle size.

airborne particulates at levels above its own height (60 cm). As seen in Fig. 8, particle removal efficiency decreased with increase in distance from negative ionic air purifier. We believe that this difference in particle removal efficiency is due to the difference in distance and the limited horizontal diffusion of ions. The data indicate that height has a greater impact on particle removal efficiency value than horizontal distance (Berry *et al*., 2007).

Table 5 depicts the average NAI concentration versus the distance from the ion source at different height from the floor. The concentration of NAI in the height between 60 cm and 120 cm decreased when the distance increased. The regression analysis of the average NAI concentration and the height from the floor showed that a exponent-

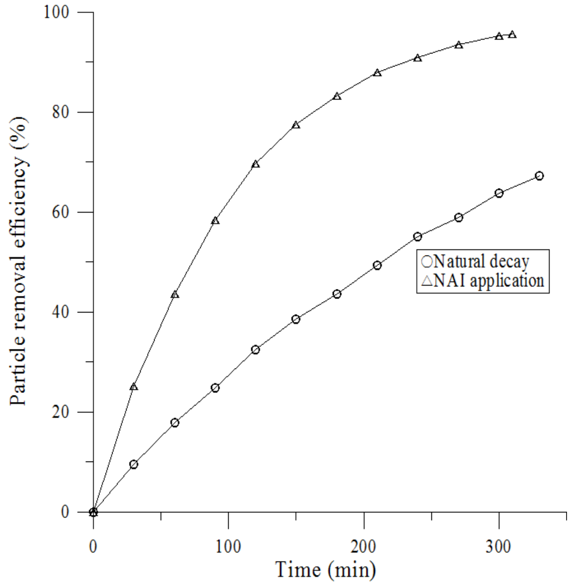


Fig. 6. Overall particle removal efficiency for natural decay and negative ionic air purifier.

Table. 4. The air cleaning factor (ACF) provided by continuous operation of the ionic air purifier.

Aerodynamic particle diameter	Air cleaning factor				
	60 min	120 min	180 min	240 min	300 min
0.1 μm	1.46	2.24	3.39	4.98	7.7
0.2 μm	1.97	2.54	3.32	3.94	4.85
0.3 μm	1.19	1.29	1.38	1.41	1.53
0.5 μm	1.14	1.17	1.29	1.25	1.5

linear regression line indicated a strong correlation between height and NAI concentration within a specific height. Regression results showed that the correlation coefficients (R^2) of the exponent-linear regression were 0.9926−0.9976 at different distance from the ion source (Wu *et al*., 2006; Berry *et al*., 2007). Also Table 5 depicts the average NAI concentration versus the height from the floor at different distance from the ion source. The concentration of NAI in the distance between 30 cm and 90 cm increased when the height increased. NAI concentration and the distance from the ion source showed that a exponent-linear regression line indicated a strong correlation between distance and NAI concentration within a specific distance. Regression results showed that the correlation coefficients (R^2) of the exponent-linear regression were 0.9933−0.9994 at height from the floor.

CONCLUSIONS

This study investigated effect of NAI on particles concentration in a test chamber. It was shown that continuous emission of negative air ions can efficiently control ultrafine aerosol pollutants in cleanrooms. The particles are charged primarily by the diffusion charging mechanism. Effects of air mixing and of distance from

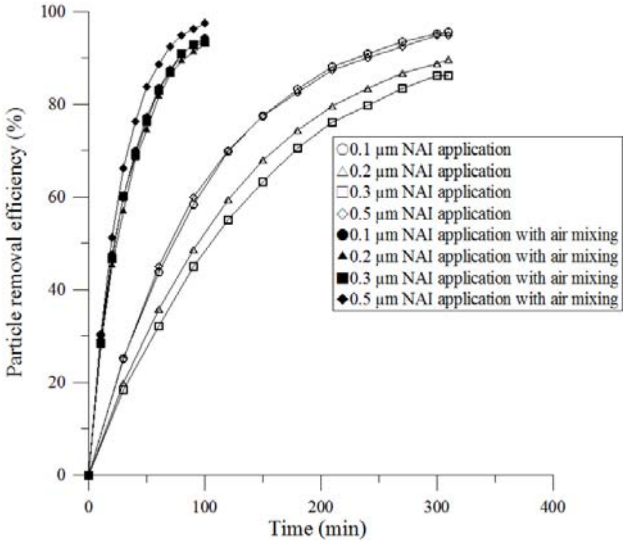


Fig. 7. Particle removal efficiency of negative ionic air purifier with air mixing.

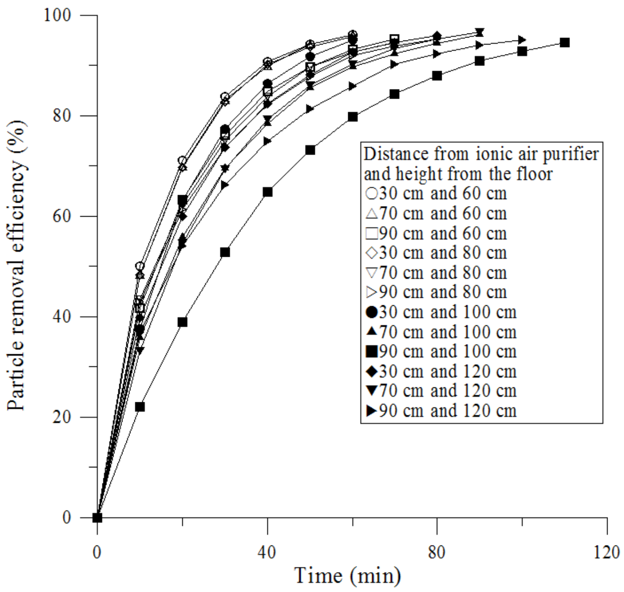


Fig. 8. Overall particle removal efficiency at different horizontal and vertical distances from the ionic air cleaner.

Table. 5. Average NAI concentration versus the distance from the ion source at different height from the floor and the height from the floor at different distance from the ion source.

Height (cm)	Average NAI concentration vs. Distance
120	$y = 1486.27e^{-0.02172x}$, $R^2 = 0.9927$
100	$y = 1004.89e^{-0.02167x}$, $R^2 = 0.9926$
80	$y = 528.71e^{-0.01745x}$, $R^2 = 0.9936$
60	$y = 322.78e^{-0.01593x}$, $R^2 = 0.9976$
Distance (cm)	**Average NAI concentration vs. Height**
30	$y = 52.19e^{0.02266x}$, $R^2 = 0.9989$
50	$y = 39.93e^{0.02152x}$, $R^2 = 0.9960$
70	$y = 36.30e^{0.01760x}$, $R^2 = 0.9994$
90	$y = 28.65e^{0.01677x}$, $R^2 = 0.9933$

negative ionic air purifier were studied. We found that there vertical diffusion of ions was limited. Experiments indicated that particles removal efficiency near the negative ionic air purifier was better in areas that were close to the negative ionic air purifier (in operational mode). Air mixing in the closed chamber enhanced the air cleaning effect. The highest particles removal efficiency was observed at a height of 60 cm from the floor. Considering the NAI concentration and two factors (height and distance), an empirical curve fit of concentration gradient of NAI was developed to estimate the concentration of NAI.

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REFERENCES

Berry, D., Mainelis, G., and Fennell, D. (2007). Effect of an Ionic Air Cleaner on Indoor/Outdoor Particle Ratios in a Residential Environment. *Aerosol Sci. Technol.* 41: 315–328.

Cyrys, J., Pitz, M., Bischof, W., Wichmann, H.E. and Heinrich, J. (2004). Relationship between Indoor and Outdoor Levels of Fine Particle Mass, Particle Number Concentrations and Black Smoke under different Ventilation Conditions. *J. Exposure Anal. Environ. Epidemiol.* 14: 275–283.

Daniels, S.L. (2002). On the Ionization of Air for Removal of Noxious Effluvia. *IEEE Trans. Plasma Sci.* 30: 1471–1481.

Grabarczyk, Z. (2001). Effectiveness of Indoor Air Cleaning with Corona Ionizers. *J. Electrostat.* 51–52: 278–283.

Grabarczyk, Z. (2001). Grabarczyk, Effectiveness of Indoor Air Cleaning with Corona Ionizers. *J. Electrostat.* 51–52: 278–283.

Grinshpun, S.A., Adhikari, A., Lee, B.U., Trunov, M., Mainelis, G., Yermakov, M. and Reponen, T. (2004). Indoor Air Pollution Control through Ionization. In *Air Pollution: Modeling, Monitoring and Management of Air Pollution*, Brebbia, C.A. (Ed.), WIT Press, Southampton, U.K, pp. 689–704.

Grinshpun, S.A., Mainelis, G., Reponen, T., Willeke, K., Trunov, M.A. and Adhikari, A. (2001). Effect of Wearable Ionizers on the Concentration of Respirable Airborne Particles and Microorganisms. *J. Aerosol Sci.* 32: S335–S336.

Grinshpun, S.A., Mainelis, G., Trunov, M., Adhikari, A., Reponen, T. and Willeke, K. (2005). Evaluation of Ionic Air Purifiers for reducing an Aerosol Exposure in Confined Indoor Spaces. *Indoor Air* 15: 235–245.

Hinds, W.C. (1999). *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, A Wiley-Interscience publication, New York (Chapter 1, 3, 9, 15).

Lee, B.U., Yermakov, M. and Grinshpun, S.A. (2004) Removal of Fine and Iltrafine Particles from Indoor Air Environments by the Unipolar Ion Emission. *Atmos. Environ.* 38: 4815–4823.

Lee, B.U., Yermakov, M. and Grishpun, S.A. (2004). Removal of Fine and Ultrafine Particles from Indoor Air Environments by the Unipolar Ion Emission. *Atmos. Environ.* 38: 4815–4823.

Niu, J.L., Tung, T.C.W. and Burnett, J. (2001). Quantification of Dust Removal and Ozone Emission of Ionizer Air-Cleaners by Chamber Testing. *J. Electrostat.* 51–52: 20–24.

Vincent, J.H. (1995). *Aerosol Science for Industrial Hygienists*, Elsevier Science Inc, New York, USA.

Wallace, L.A., Emmerich, S.J. and Howard-Reed, C. (2002). Continuous Measurements of Air Change Rates in an Occupied House for 1 Year: The Effect of Temperature, Wind, Fans, and Windows. *J. Exposure Anal. Environ. Epidemiol.* 12: 296–306.

Wu, C.C., and Lee, W.M. (2003). The Temporal Aerosol Size Distribution in Indoor Environment with Negative Electric Discharge. *J. Aerosol Sci.* 34: S999–S1000.

Wu, C.C., Lee, G.W.M., Cheng, P., Yang, S. and Yu, K.P. (2006). Effect of Wall Surface Materials on Deposition of Particles with the Aid of Negative Air Ions. *J. Aerosol Sci.* 37: 616–630.

Wu, C.C., Lee, G.W.M., Yang, S., Yu, K.P. and Lou, C.L. (2006). Influence of Air Humidity and the Distance from the Source on Negative Air Ion Concentration in Indoor Air. *Sci. Total Environ.* 370: 245–53.

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