

Separation Enhancement of Mechanical Filters by Adding Negative Air Ions

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Abstract: The purpose of this work is to combine negative air ions (NAIs) and mechanical filters for removal of indoor suspended particulates. Various factors, including aerosol size (0.05-0.45 μm), face velocity (10 and 20 cm/s), species of aerosol (potassium chloride and dioctyl phthalate), relative humidity (30% and 70%), and concentrations of NAIs (2×10^4 , 1×10^5 , and 2×10^5 NAIs/cm³) were considered to evaluate their effects on the aerosol collection characteristics of filters. Results show that the aerosol penetration through the mechanical filter is higher than that through the mechanical filters cooperated with NAIs. This finding implies that the aerosol removal efficiency of mechanical filters can be improved by NAIs. Furthermore, the aerosol penetration through the mechanical filters increased with the aerosol size when NAIs were added. That is due to that the aerosol is easier to be charged when its size gets larger. The results also indicate the aerosol penetration decreased with the NAIs concentration increased. Reversely, aerosol penetration through the mechanical filters increased with the face velocity under the influence of NAIs. The aerosol penetration through the filter with NAIs was no affected with relative humidity. Finally, The penetration through the filter with NAIs against solid aerosol was lower than that against liquid aerosol.

Keywords: Negative air ions, Filtration, Aerosol penetration, Mechanical filter.

1. INTRODUCTION

On average, people spend as much as 87.2% of their time in indoor environment [1]. Hence indoor air quality has become an increasingly important problem. Indoor suspended particulates play a major role in indoor air quality because they cause many respiratory diseases [2-4]. Therefore, more and more air-cleaning technologies have been used to remove the indoor particulates.

Air filtration is an effective technique for removing aerosols from a gas stream. The key collection mechanism between particles and filters is the mechanical force. Traditionally, mechanical filters are often used in a heating, ventilating and air-conditioning (HVAC) system to remove indoor particulates. The mechanisms of mechanical filters for particle removal are only interception, inertial impaction, diffusion and gravitational settling.

Recently, the electrostatic capture forces, including dielectrophoretic, coulombic, and image capture forces [5], were applied in the filtration processes for increasing the aerosol collection efficiency. Several researches had investigated the electrostatic collection characteristics and filtration mechanism of electret

filters [6-12]. Luckner *et al.* [13] and Lee *et al.* [14] used an external electric field on the filter to increase the electrostatic force for removal of aerosols. Mermelstein *et al.* [15] observed that an external electric field added on the stainless steel filter provides the electrostatic capture capability for removal of aerosols. Yang and Lee [16] applied the surfactants coated on the surface of filter fibers to enhance the surface charges for raising the aerosol removal efficiency. Agranovski *et al.* [17] demonstrated that emission of air ions in the vicinity of a low-efficiency HVAC filter significantly improved the electrostatic capture force. All of these studies confirmed that coulombic and dielectrophoretic capture forces increased filtration efficiency of filters. However, the effect of the image capture force on the filtration is seldom studied.

Negative air ionizers have been applied to clean indoor air. Daniels [18] reported that negative air ions (NAIs) reduced aerosol particles, airborne microbes, odors and volatile organic compounds (VOCs). NAIs were of use to remove airborne particles [19-20]. Charging particles by emitted ions and electromigration was established as the removal mechanism supported by NAIs [21-22]. Interaction between charged particles and the electric field produced by electrical discharge increased the migration velocity towards the indoor surfaces, finally aerosols were deposited on various surfaces, such as wall surfaces [21-23]. However, the collected particles would stain the wall face.

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The purpose of this work is to combine NAIs and mechanical filters to eliminate indoor suspended particulates. NAIs caused the particles charged and provided the image capture force for mechanical filters to enhance their filtration capability. Charged aerosols are collected on the filters, and dirty surfaces cannot occur. Furthermore, the effects of face velocity, relative humidity, and the concentration of NAIs on the aerosol collection characteristics were also considered.

2. EXPERIMENTAL

2.1. Single-Fiber Efficiency Theory

The theoretical aerosol penetration through a filter, in terms of total single-fiber efficiency is [5]:

$$P = \exp\left(\frac{-4\alpha E_{\Sigma} m}{\pi d_f (1-\alpha)}\right), \quad (1)$$

where P is the aerosol penetration through the filter; E_{Σ} represents the total single-fiber efficiency; d_f is the mean fiber diameter; m is the filter thickness, and α is the fiber packing fraction. The total single-fiber efficiency of an electret filter is the sum of mechanical and electrostatic single-fiber efficiencies, expressed as

$$E_{\Sigma} = 1 - (1 - E_M)(1 - E_O)(1 - E_C)(1 - E_{IM}), \quad (2)$$

where E_M , E_O , E_C and E_{IM} are the single-fiber efficiency due to the total mechanical, dielectrophoretic, coulombic, and image capture mechanisms, respectively. The overall mechanical mechanism involves diffusion, interception, impaction, and gravitational settling. The mechanical mechanisms of an electret filter are insignificant, and thus the total mechanical mechanism represents the effect of all mechanical mechanisms. Equation (2) assumes independence of all mechanisms.

2.2. Test Filters

Polypropylene fibrous filters were employed in this study. The characteristics of the polypropylene fibrous filters were as follows: packing fraction 0.06; filter weight 56.0 g/m²; filter thickness 0.5 mm; mean fiber diameter 15.8 μm; the weight of filters were measured by the electronic scale. The fiber diameter of the untreated and surfactant pretreated filters was measured by the scanning electron micrograph (SEM) experiments. The filter thickness was measured by a ruler. The packing fraction were calculated by the empirical model of Davies [24].

$$\Delta p = \frac{vmUf(\alpha)}{r^2} \quad (3)$$

$$f(\alpha) = 64\alpha^{1.5}(1 + 56\alpha^3) \quad (4)$$

where Δp is the pressure drop across the filter; v is the air viscosity; m is the filter thickness; U is the face velocity; r is the fiber radius, and α is the packing fraction.

2.3. Aerosol Generation System

Figure 1 presents the experimental set up for the aerosol penetration test of the testing filters. It comprises a constant output atomizer (aerosol generator), a differential mobility analyzer, a neutralizer, a mixing column, a filter holder, a tested filter, an aerosol electrometer, a condensation particle counter used to sample the aerosol concentrations upstream and downstream across the filter, a pressure gauge to measure the pressure drop across the filter, and a flow meter.

Potassium chloride (KCl) and dioctyl phthalate (DOP) were selected as the solid and liquid test aerosols. These two aerosols were often used in several researches [25-28]. The test aerosols were generated in a polydisperse state using a constant output atomizer (model 3076, TSI Inc., USA). Then, the dried and neutralized polydisperse aerosol was electrically classified using a differential mobility analyzer (DMA, model 3080, TSI Inc., USA), to yield monodisperse, singly charged aerosols in the submicrometer-sized include 0.05, 0.07, 0.10, 0.20, 0.3 and 0.45 μm. The monodispersity and aerosol concentration of the generated particles were measured using a scanning mobility particle sizer (SMPS, model 3936, TSI Inc., USA). The geometric standard deviation (GSD) of these generated particles, based on particle counts varied from 1.10–1.15. The DOP aerosol concentrations are about 5×10^3 particles/cm³. The KCl aerosol concentration are about 4×10^3 particles/cm³. The aerosols from the DMA passed through a Kr-85 radioactive source (model 3077, TSI Inc., USA), which neutralized them to the Boltzmann charge equilibrium. Then, the tested aerosols were flowed into a mixing column, in which they were diluted with clean air. The diluted aerosol flow was drawn through the filter holder by using the flow meter and the pump.

2.4. Relative Humidity Control System

This study considered the effect of relative humidity (RH) on the filtration characteristics. The RH of the

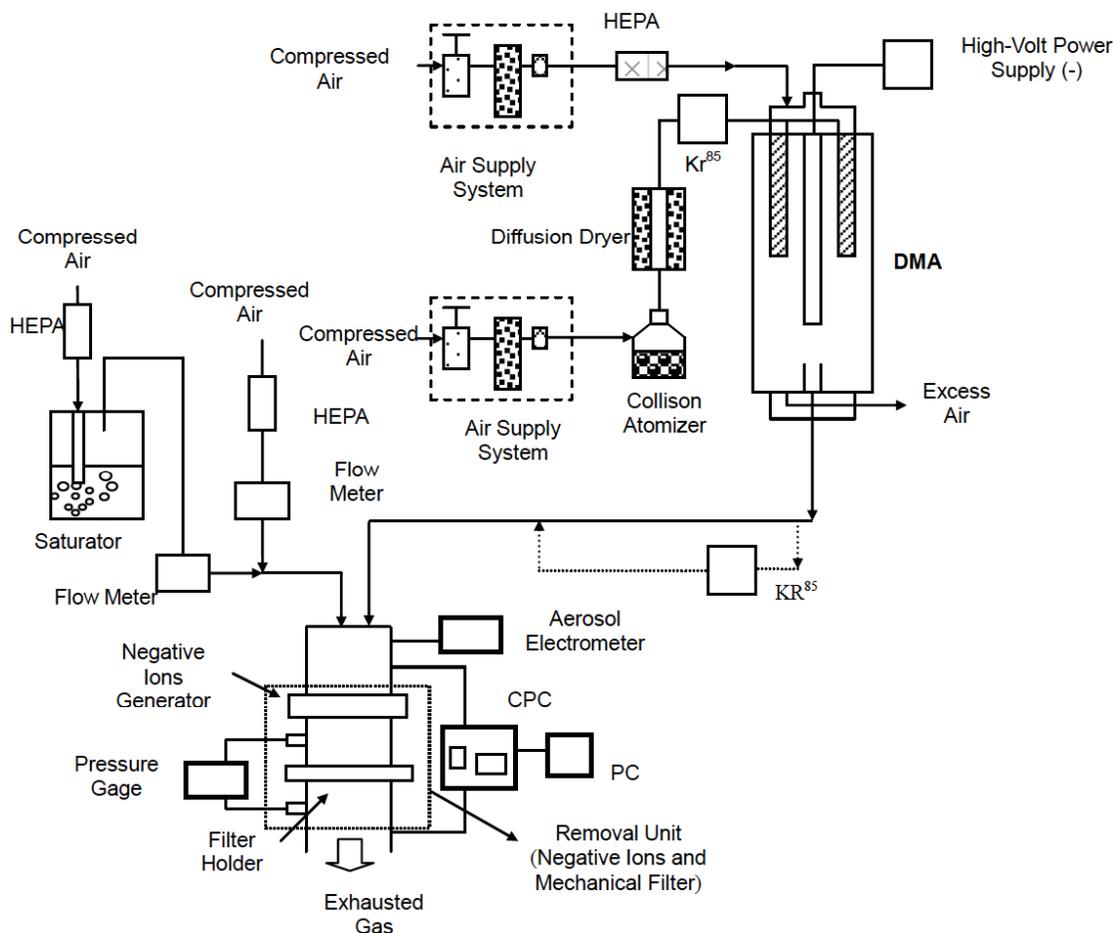


Figure 1: Schematic diagram of the experimental system.

aerosol-flow stream was modified by changing the ratio of the flow rate of the dry gas stream to that of the humidified gas stream generated by a water vapor saturator. The final RH of the aerosol-flow stream was measured using a hygrometer (model Hygromer A2, Rotronic Inc., Swiss). Two relative humidity, 30 and 70%, for experiments stood for dry and humid conditions, respectively.

2.5. Aerosol Removal Unit

The aerosol removal unit comprises a test column made by stainless steel, a negative air ion generator, a filter holder and the tested filter. The column was connected with a ground wire to avoid accumulating the negative air ions on its wall surface. The NAIs generator with a negative electric discharge was placed into the test chamber. The electrode of the generator was a cluster of copper needles. Its discharge voltage was controlled with a power supply (model SL300, Spellman Inc., USA) located outside the chamber. The NAIs concentrations of 2×10^4 , 1×10^5 , and 2×10^5 NAIs/cm³ were chosen in the work. The NAIs

concentration was detected with an ion counter (Model ITC-201A, ANDES, Japan).

2.6. Aerosol Penetration Measurements

The aerosol concentrations in upstream and downstream of the filter holder were measured using a condensation particle counter (CPC, model 3022, TSI Inc., USA). Therefore, the aerosol penetration through the removal unit was calculated. Each aerosol penetration test was performed in triplicate for a filter. The pressure drop across the test filter was measured using a pressure gauge (model 2000, Dwyer Instruments Inc., USA). The face velocity through the test filter was controlled using a flow meter and a pump.

2.7. Aerosol Penetration Calculation

The aerosol penetration through a filter is given by

$$P = \frac{C_{down}}{C_{up}}, \quad (5)$$

where C_{down} and C_{up} are the number concentrations measured downstream and upstream of the filter, respectively.

3. RESULTS AND DISCUSSION

3.1. Aerosol Penetration through Filters

When filters and NAIs were unemployed, 0.05 to 0.5 μm KCl monodisperse aerosols penetrating through the removal unit were sampled using a CPC to ensure that aerosol removal occurred only on the filter surface and not on the holder or any part of the test chamber. Its face velocity ranged from 10 to 20 cm/sec. Tests were performed at least in triplicate. Figure 2 clearly displays that losses of submicron aerosols through the holder are very small (<5%), verifying that background loss of aerosols can be ignored.

Figure 3 showed the aerosol penetration through the mechanical filters without and with NAIs when the face velocity and RH were maintained at 10 cm/s and 30%. For 0.3- μm aerosols, the aerosol penetration through the filter without NAIs was about 92%. The aerosol penetrations through the filters cooperated with 2×10^4 , 1×10^5 , and 2×10^5 NAIs/cm³ were around 79%, 52%, and 39%. Obviously, NAIs are able to enhance the capture effect on aerosols. It is due to that the NAIs would first contact with the particles and cause the particles charged. Then the mechanical filter would collect the charged particles easier. That is working by image electrostatic force (image attracting force is between charged particles and uncharged filter). For understanding the effect of NAIs, the factor ($\text{penetration}_{\text{with NAIs}}/\text{penetration}_{\text{without NAIs}}$) was applying to

calculate the enhancement of the penetration through the filter with using NAIs. The results show that when mechanical filter combining with NAI concentrations of 2×10^4 , 1×10^5 , and 2×10^5 NAI/cm³, the overall enhancement factors range of 1.01 to 1.18, 1.33 to 1.80 and 1.59 to 2.42 from the aerosol size from 0.05 to 0.45 μm . It is indicating that the variation of the aerosol penetration through the filter between with and without using NAIs increased with the aerosol size increasing. That is due to that the aerosol was charged with more NAIs when aerosol size was getting larger. This phenomenon is consistent with the results from pervious studies by White [29].

According to these results in Figure 3, aerosol penetration through the filters with NAIs was decreasing when NAI concentrations was increasing. When mechanical filter combining with NAI concentrations of 2×10^4 , 1×10^5 , and 2×10^5 NAI/cm³, the enhancement factors of 0.3- μm challenging aerosol were 1.16, 1.77 and 2.36, respectively. It is because of that the image electrostatic force raised with the aerosols charges increasing. During the filtration process, when the NAIs concentration was increasing, the aerosols have more chances to collide with NAIs. Thus, testing with higher NAI concentration would cause the charges on the aerosol increased. This phenomenon agreed with the results from previous studies by White [29].

3.2. Effect of Face Velocity on Aerosol Penetration

Figure 4 depicts aerosol penetration against aerosol size for the KCl aerosol at various face velocities (10

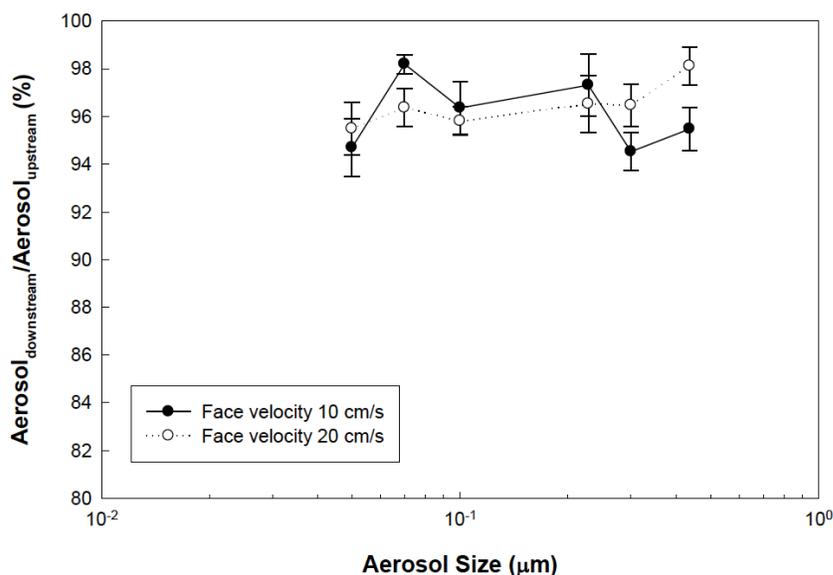


Figure 2: Evaluation of aerosol losses through the test chamber and filter holder.

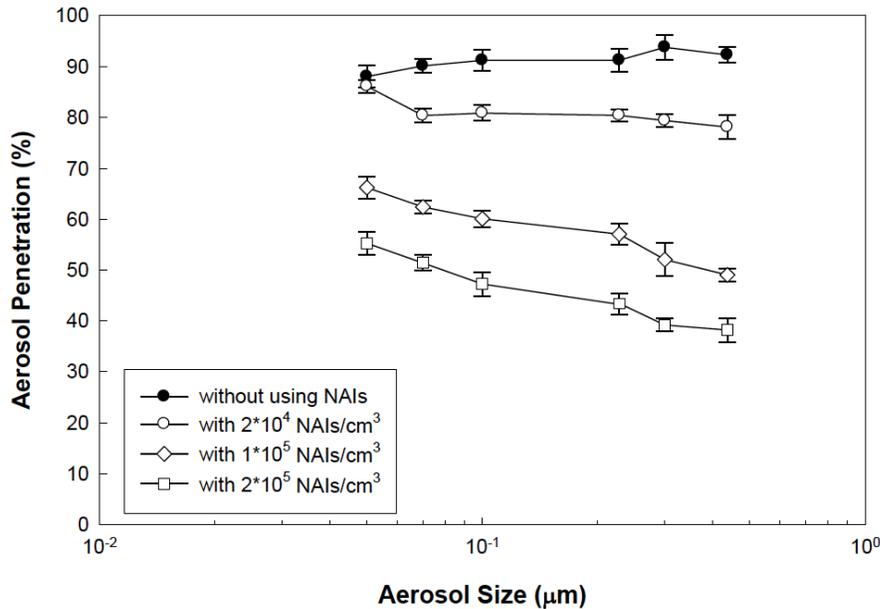


Figure 3: Aerosol Penetration through the filters with negative air ions.

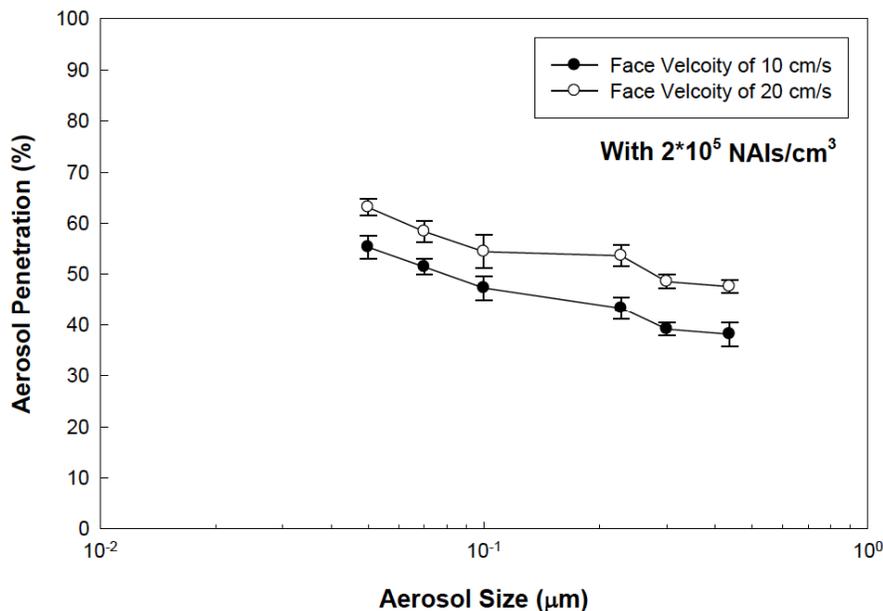


Figure 4: Aerosol Penetration through the filters with NAI at different face velocities.

and 20 cm/s), through the filter with 2×10^5 NAI/cm³. The result reveals an increase in the penetration of 0.3 μm-aerosol through the filter with 2×10^5 NAI/cm³ from approximately 39% to 49% as the face velocity increases from 10 to 20 cm/s. This result follows from the fact that the principal mechanisms between the submicron charged aerosols and uncharged filter is image electrostatic attraction and diffusion. A higher face velocity leads to a shorter residence time associated with aerosol deposition by electrostatic attraction and diffusion.

3.3. Effect of Relative Humidity on Aerosol Penetration

Figure 5 plots the aerosol penetration through the filter with 2×10^5 NAI/cm³ versus aerosol size at two values of RH (30% and 70%). The results reveals the penetration of 0.3 μm-aerosol through the filter with 2×10^5 NAI/cm³ in RH of 30% and 70% were approximately 39% and 42%. The paired t-test was used to determine the difference of the data for two RHs. A comparison of data for two RHs identified insignificant variation ($P > 0.05$). The analysis results

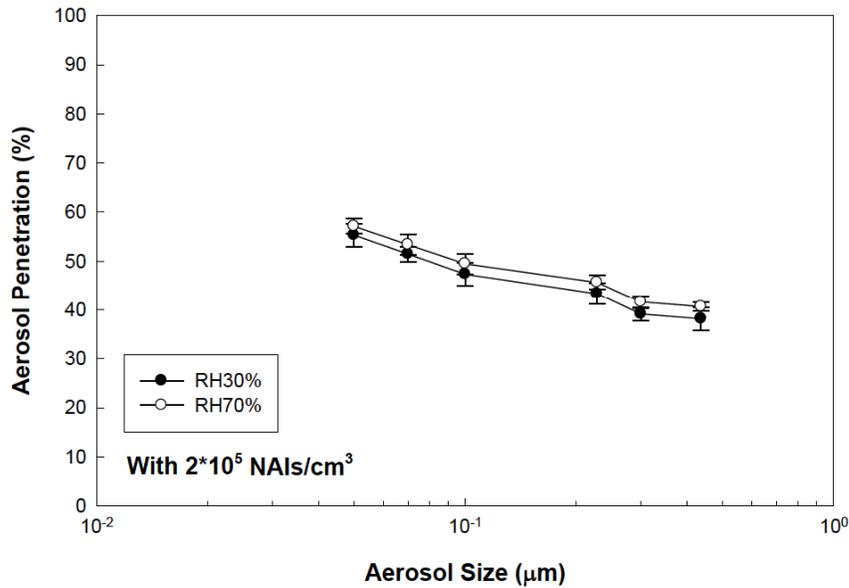


Figure 5: Aerosol Penetration through the filters with NAI at different RHs.

indicate that the penetrations through the filter with NAI were nearly no affected by difference RHs.

3.4. Effect of Aerosol Type on Aerosol Penetration

Figure 6 plots aerosol penetration versus aerosol size for filters with 2×10^5 NAI/cm³ at a face velocity of 10 cm/s. The penetrations of the 0.3 μm KCl and DOP aerosol were 39% and 51%. The experimental results reveal that the penetration through the filter with NAIs against solid aerosol was lower than that against liquid aerosol. This finding is consistent with those of John *et al.* [30] which demonstrated that the penetration of liquid aerosols through the filter exceeds that of solid

aerosols because aerosol-bouncing effect promotes the penetration of solid aerosols. The bouncing effect is probably the main reason why the penetration of solid aerosols through filters exceeds that of liquid aerosols.

3.5. Comparison of the Effect of Different Parameters on Aerosol Penetration

A regression equation was used to identify the effects of different parameters on aerosol penetration. The penetrations of the solid and liquid aerosols are quite different. Hence, the type of aerosol cannot be quantified nor regressed in the equation. The regression equation considered the most significant

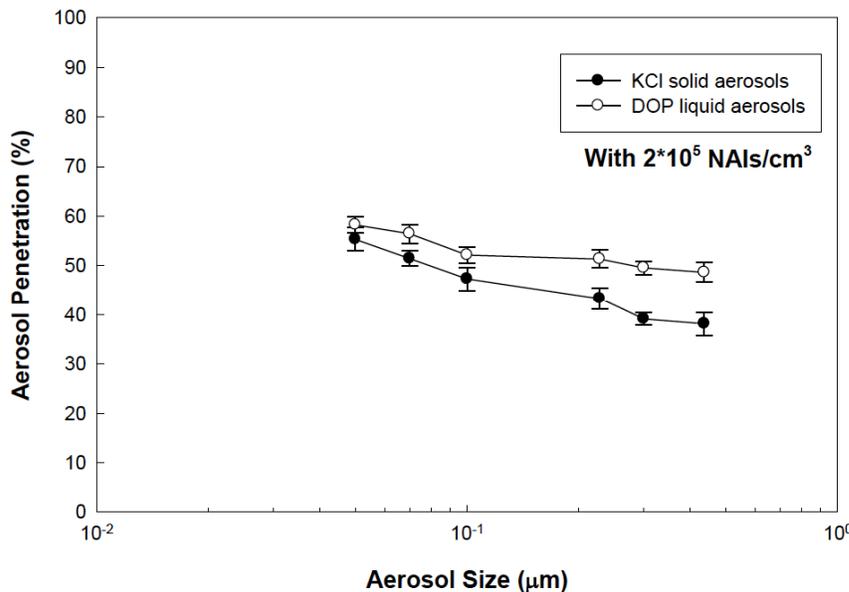


Figure 6: Aerosol Penetration through the filters with NAI against NaCl and corn oil aerosols.

parameters, including aerosol size (0.05–0.45 μm), NAI concentrations of 2×10^4 , 1×10^5 , and 2×10^5 NAI/cm³, face velocity (10 and 20 cm/s), and RH (30% and 70%). The experimental results can be fit to the following equation:

$$P = ad_p^b N^c U^d R^e \quad (5)$$

where a, b, c, d, and e are constants, P denotes aerosol penetration, d_p represents aerosol size, N is the concentration of NAIs, U denotes the face velocity, and R represents the relative humidity. The regression analysis yields the following regression equation:

$$P = 0.53d_p^{-0.53} N^{-0.87} U^{0.46} R^{0.38} \quad (6)$$

As demonstrated by the regression analysis, the correlation coefficient R^2 is approximately 0.914. Comparison of the coefficients (b, c, d, and e) revealed the effects of different parameters on aerosol penetration. According to the regression equation, the results show that the largest value is c, indicating that the concentration of NAIs exerts the strongest influence on aerosol penetration. Moreover, the second highest coefficient value is for b, followed sequentially c, and d. Thus, aerosol size is the second strongest influence on aerosol penetration, followed by face velocity, and RH has the smallest effect on penetration. An optimal condition could be obtained from the regression equation in the range of this experiment. In this study, the optimal condition is that when aerosol size is 0.05 μm , a concentration of NAIs is 2×10^5 NAIs/cm³, face velocity is 0.1 m/s, and RH is 30%.

4. CONCLUSIONS

The aerosol penetration of 0.3 μm aerosol through the filter without NAI was about 92%. The 0.3- μm aerosol penetrations through the filter with 2×10^4 , 1×10^5 , and 2×10^5 NAI/cm³ were around 79%, 52%, and 39%. It indicates that combing mechanical filter with NAIs could decrease the aerosol penetration during the filtration process. The results also indicate that the variation of the aerosol penetration through the mechanical filter with NAIs increased with the aerosol size. That is due to that the aerosol was easier to be charged when aerosol size was getting larger. The aerosol penetration through the filters with NAIs was decreasing when NAI concentrations was increasing. It is because of that the image electrostatic force raised with the aerosols charges increasing. The result reveals an increase in the penetration of 0.3 μm -aerosol through the filter with 2×10^5 NAI/cm³ from

approximately 39% to 49% as the face velocity increases from 10 to 20 cm/s. Moreover, result implies an increase in the penetration of 0.3 μm -aerosol through the filter with 2×10^5 NAI/cm³ from approximately 39% to 42% as the RH increases from 30% to 70%. The experimental results indicate that the penetrations through the filter with NAIs are getting a slight increase when test RH was raising. The aerosol penetration versus aerosol size for filters with 2×10^5 NAI/cm³ at a face velocity of 10 cm/s against 0.3 μm KCl and corn oil aerosol were 39% and 50%. The experimental results reveal that the penetration through the filter with NAI against solid aerosol was lower than that against liquid aerosol.

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