Air cleaning performance of a novel electrostatic air purifier using activated carbon fiber filter for passenger cars

Hak-Joon Kim[1)], Bangwoo Han[1)], Changgyu Woo[1)], Yong-Jin Kim[1)],
Gi-Taek Lim[1), 2)] and Weon Gyu Shin[2)]
1) Dept. of Eco-machinery System 2) Dept. of Mechanical Engineering
Korea Institute of Machinery & Materials Chungnam National University
phone: (82) 10-5175-9220
e-mail: diayolk@kimm.re.kr

***Abstract*—A novel electrostatic type air purifier using an activated carbon fiber filter to apply electrostatic force to charged particles toward a collection rod and to adsorb gas at the same time was developed for indoor air quality of passenger vehicles. The cylindrical air purifier with the diameter of 100 mm and the length of 185 mm was composed of a conductive brush type charger and an electrostatic collection rod for particle removal, and an activated carbon fiber filter for gas removal. The flow rate of the device was approximately 300 L/min. The novel purifier was tested in a chamber of 1 m^3 with 0.3 micrometer particles, and three gases such as ammonia, acetic acid, and acetaldehyde. The gas cleaning performance of the purifier was compared to a commercial purifier with a HEPA filter and activated carbon pellets. A clean air delivery rate of the novel electrostatic air cleaner was 0.219 m^3/min, which is 35% higher than that of a HEAP filter type. In addition, gas degradation ratio by the operation of the electrostatic purifier against acetic and acetaldehyde was 80% after 10 min of the continuous operation, while 45% with the commercial one after the same operation time.**

I. INTRODUCTION

A number of studies have been devoted to assessing commuters' exposure inside public or private transportation vehicles[1]. Despite the short average commuting time (1.3 h/day), in cabin exposure alone accounts for up to 45−50% of the total daily exposure to UFPs [2]. Solutions to improve IAQ in vehicles are to ventilate air periodically and to operate an air conditioner equipped with a cabin air filter. Increasing ventilation rates, the most common solution, is limited by intake of contaminants from outdoor air, and using an air conditioner in a passenger car is energy-consuming method due to its high air flow rate and pressure drop through a high efficient cabin air filter. These days, in China and Korea, market of air cleaners for indoor air quality in vehicles is dramatically increasing due to citizens' concern on health risk by PM2.5, yellow dusts, and smog. Air cleaning type of most of the air cleaner is HEPA filter and ion generation types, and the market share of the two types is over 90%, especially 60% by a filter type air cleaner. The filter type air cleaners are

equipped with a HEPA filter and activated carbon filter, which remove a variety of contaminants including ultrafine particles and harmful gases however frequent replacement by contamination and high pressure drop is necessary. An ionizer type air cleaner is very small and easy to use however its air cleaning capacity is very low during a short term operation against particles and especially none against gases.
In this study, we developed a novel electrostatic type air cleaner with carbon fiber brush charger, and an activated carbon fiber sheet as a high voltage electrode and gas absorption media. The air cleaning performance was investigated with various parameters for carbon fiber charger and activated carbon fiber sheet, and compared to those of a commercialized filter type air cleaner.

II. EXPERIMENTAL SET UP

Figure 1 shows a schematic diagram of the ESP air cleaner with a cylindrical geometry used in this study, consisting of a charging and particle collection stage with a carbon fiber charger, a gas adsorption and particle collection stage with an activated carbon fiber sheet and a metallic rod, and a centrifugal fan for suctioning polluted air. The first stage (Ø 100 mm × 33 mm) was made of a carbon fiber brush as a high voltage electrode and a stainless steel ring as a grounded electrode, and the second stage was made of a hollow aluminum rod (Ø 30mm × 100 mm) as a grounded electrode and an activated carbon filter rolled at diameter of 60 mm as a high voltage electrode. This formation is to separate gas to the activated carbon filter and charged particles to the collection rod by electrostatic force. A high voltage supply was used to supply - 10 kV to both of the carbon brush and the activated carbon filter while the metallic ring and rod were grounded.

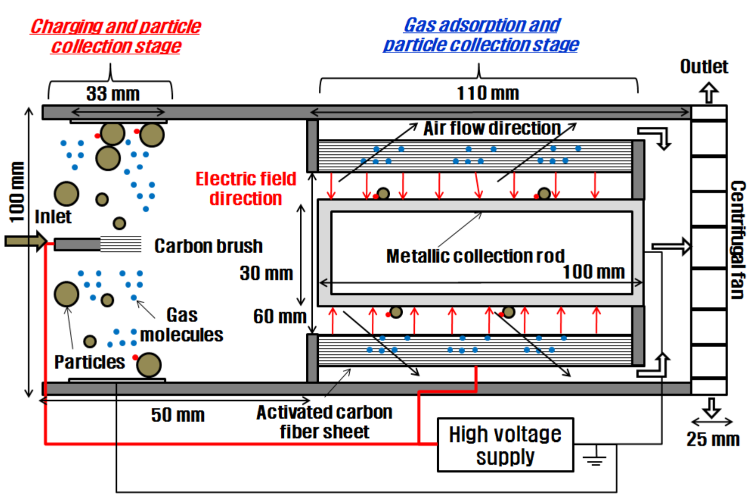

Fig. 1. A schematic of an electrostatic air cleaner used in this study.

Figure 2 shows the experimental set up for particle and gas cleaning performance tests in this study. The test procedure used in this study was Korean and Japanese standard test methods for an air cleaner except type of particles and size range, and chamber size [3],[4].

A blower which was connected to the HEPA filtration system was operated until the concentration of residual particles in the test chamber (1 m^3) decreased to less than 10^5 #/m^3. When the background level of particles in the test chamber fell below this limit, a circulation fan was operated to ensure particle mixing. Uncharged KCl particles generated from a constant output atomizer (Model 3076: TSI Inc.) were introduced to the chamber with clean compressed air at a rate of 2 L/min until the initial concentration of the test particles ranged between 10^8 and 10^9 #/m^3. When the required concentration was reached, the circulation fan was turned off, the air cleaner was turned on, and particle concentrations were recorded at 1-min intervals for a 30 min period.

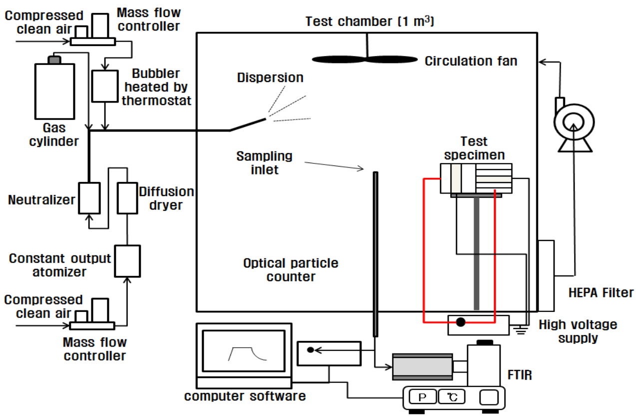

Fig. 2. A Experimental set up in this study.

With the chamber test, particle collection efficiency (η) of air cleaners was also measured by comparing the outlet particle number concentration (N_o) with the inlet number concentration (N_i) of particles 0.3 μm in diameter, using the laser aerosol spectrometer and the following equation:

$$\eta\ (\%) = (1 - N_i/N_o) \times 100 \qquad (1)$$

Two gases were selected for the gas-removal performance tests: acetic acid (CH_3COOH) and acetaldehyde (CH_3CHO) ; the two are also used in the Korea Air Cleaning Association (KACA) and Japan Electrical Manufacturers' Association (JEMA) standards, and are sources of malodorous indoor irritants. An FTIR spectrometer (Model I4000, Midac, USA) with a 20-m cell was used to measure the concentrations of acetaldehyde and acetic acid in the chamber. When the test chamber background level fell below the measurement limit of 0 ppm, gases from a bubbled or a cylinder were introduced to the chamber in clean compressed air at a rate of 2 L/min until the initial concentration of the test gas ranged between 8 and 13 ppm. This concentration was intentionally higher than actual field concentrations of the gas, so that the concentration decay curve could be accurately measured before it fell below the instrument detection limit. When the required initial concentration was reached, the test specimen was turned on, and gas concentration data form the FTIR spectrometer were acquired at 20-s intervals for 30 min.

The particle decay-measured CADRs (Clean Air Delivery Rate) of the ESP air cleaner under different operating conditions in the test chamber were calculated using the AHAM method [5].

Theoretically, the regression of particle concentration follows a first-order decay model:

$$C_t = C_0\, e^{-kt} \qquad (2)$$

where

C_t = concentration at time t (#/m^3)

C_0 = initial concentration at t = 0 (#/m^3)

k = decay constant (t^{-1})

t = time (min)

The time-resolved decay constant k is calculated statistically by a linear regression of ln*Ct* and *t*.

Using equation (3), the method for calculating CADR, a performance metric based on an air cleaner's ability to reduce airborne particles in a closed chamber is ;

$$CADR = V \times k \qquad (3)$$

where

CADR = Clean Air Delivery Rate (m^3/min)

V = chamber volume (m^3)

k = decay constant (min^{-1})

Finally, the gas removal performance was measured by a normalized concentration of C_t/C_o for tested gases during a continuous operation of an air cleaner which is used in KACA and JEMA test methods.

III. RESULTS AND DISCUSSION

Figure 3 shows the variation in single-pass collection efficiency of the particles at the different voltages applied to the activated carbon fiber sheet in the gas adsorption and particle collection stage of the ESP air cleaner for different flow rates. The voltage applied to the carbon brush charger was maintained at -10 kV, while the voltage applied to the second stage was varied from 0 to -10 kV and the flow rate from 210 to 363L/min. The single-pass collection efficiency against 0.3 μm and total particles increased linearly with the increase in voltage applied to the activated carbon sheet because of the higher electric field strength [6]. The proportion constant was decreased 2.0 to 1.5 as flow rate increased. The collection efficiency for 0.3 μm particles was approximately 5 % higher than those for total particles because the size range is known to be hardly collected by an ESP [6]. Without applied voltage to the activated carbon fiber sheet (3 mm thickness), the efficiency with only the charger and activated carbon filter without electrostatic force was ranged 48 to 63 %. By the way, with applied voltage to the sheet, the efficiency of the ESP air cleaner was enhanced up to 90% at 210 L/min which is far higher than the minimum efficiency required for certification by the KACA [3]. This result indicated that additional collection in the novel ESP air cleaner is possible by applying high voltage to an activated carbon filter sheet which is activated carbon but conductive.

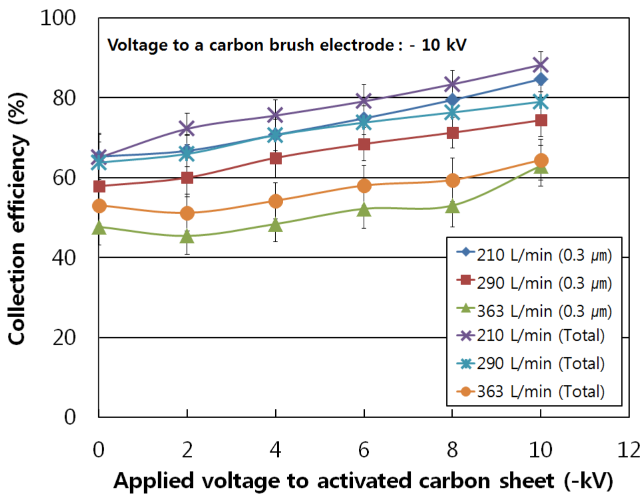

Fig. 3. Variation in single-pass collection efficiency of particles for different applied voltages to the an activated carbon sheet at set flow rates of 210, 290, 363 L/min

Figure 4 shows the variation in single-pass collection efficiency of the particles with different flow rates through the ESP air cleaner with different voltage conditions to the collection electrode and an activated carbon sheet. The flow rate ranged between 210 and 363 L /min. The applied voltage to the charger was set at -10 kV, and + 10 kV was applied to a collection rod to compare the case of voltage condition of - 10 kV to the activated carbon sheet, which is the same potential between the rod and the activated carbon sheet. The single-pass collection efficiency of the particles decreased linearly with an increase in the air flow rate of the air cleaner under the same experimental conditions because of a decrease in the residence time in both the two regions [6]. Constants of proportionality for different applied voltages to ionizers and collection plates were similar: -0.18 %/L/min.

Figure 5 also shows the variation in decay-measured CADRs of the ESP air cleaner for the particles. The same voltages of -10 kV were applied to the carbon brush charger and the activated carbon fiber filter sheet, and the flow rate were varied from 210 to 363 L/min, while changing the thickness of an activated carbon sheet from 1 to 3 mm. the decay-measured CADRs with increase of flow rate showed linear increase with flow rate in spite of the negative proportionality of the collection efficiency to the flow rate shown in Figure 4. This is contributable to the fact that linear increase of flow rate of an air cleaner increases cleaning number linearly. In Figure 4, the collection efficiency decreased only 20%, while increasing flow rate by 170%. Therefore, for the ESP air cleaner in this study, the CADRs were mainly dependent on flow rate. Also, the CADR increased as the thickness of an activated carbon filter increased because the particles which were not collected by electrostatic mechanisms in this study could be collected on the activated carbon filter.

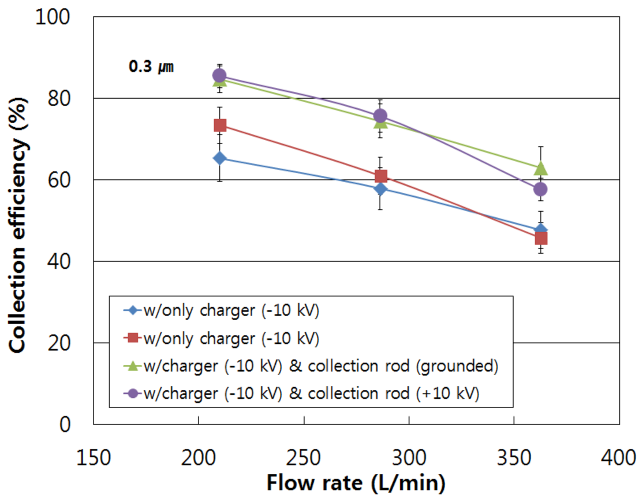

Fig. 4. Variation in single-pass collection efficiency of particles for different applied voltages to the an activated carbon sheet at set flow rates of 210, 290, 363 L/min

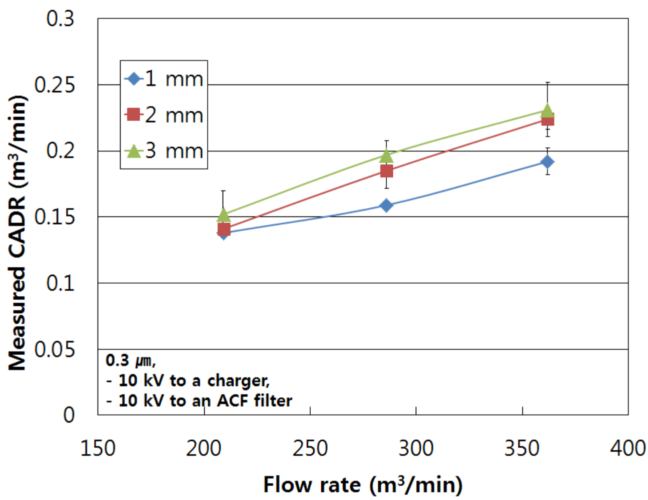

Fig. 5. Variation in CADRs of the ESP air cleaner for particles for different thickness of a carbon fiber sheet at set flow rates of 210, 290, 363 L/min.

Figure 6 shows the relationship of decay-measured CADRs and collection efficiencies multiplying flow rates for the ESP air cleaner used in this study. Both of them were linearly proportional to each other. These results showed that the required CADR for the ESP air cleaner developed in this study can be determined by simply measuring the single-pass collection efficiency and the flow rate. Moreover, the CADR, 0.219 m^3/min with -10 kV of applied voltage was achieved which was approximately 35% higher than 0.17 with a commercial filter type air cleaner which is the most efficient air cleaner reported in Korean and Chinese air cleaner market for vehicles.

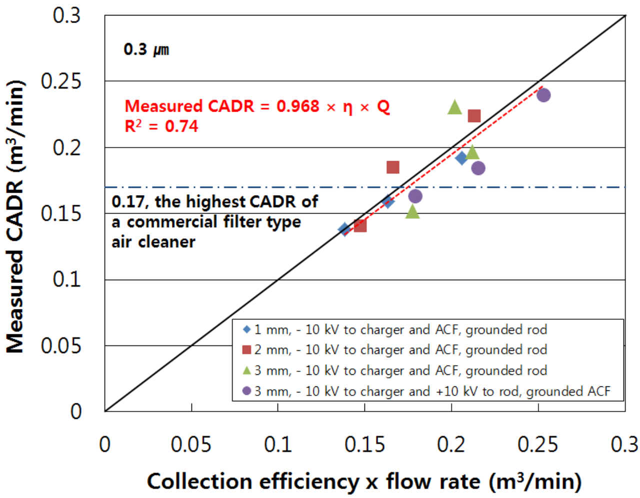

Fig. 6. Relationship between the decay-measured CADRs, and the values of multipying collection efficiency and flow rate

Figure7 and Figure 8 show the comparison of performances between using the ESP with 7.3 g of an activated carbon sheet in this study and using a filter type air cleaner (180 × 180 × 80 mm) with a HEPA filter and activated carbon pellets of 49g, which showed the CADR of 0.17 m^3/min with using 0.3-μm KCl particles. The performance was evaluated with decay of gas concentration divided by initial gas concentration in a test chamber. The gas degradation ratio by the operation of the electrostatic air cleaner against acetic and acetaldehyde was approximately 80% after 10 min of the continuous operation, while approximately 45% with the commercial one after the same operation time.

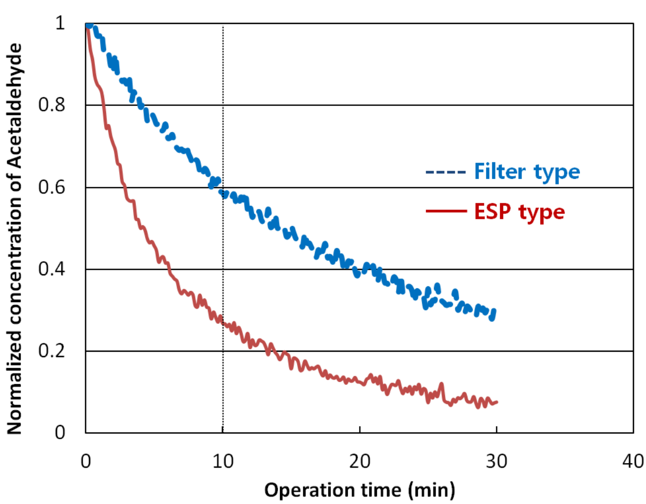

Fig. 7. Normalized acetaldehyde gas concentration as a function of time for the ESP type in this study and the commertial filter type air cleaners

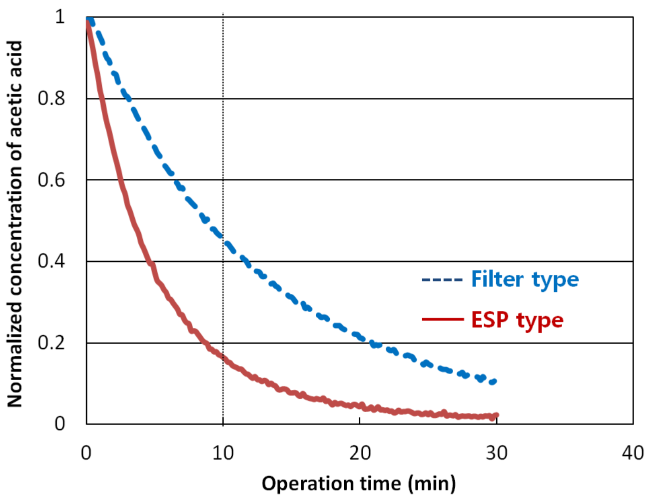

Fig. 8. Normalized acetic acid gas concentration as a function of time for the ESP type in this study and the commertial filter type air cleaners

IV. Conclusion

This results indicate that the air cleaner with the ESP (Ø 100 × 190 mm) air cleaner with a carbon brush charger and a activated carbon fiber sheet (7.3g) in this study could achieve a higher CADR and faster gas removal performance than those of an air cleaner (180 × 180 × 80 mm) with a HEPA filter and activated carbon pellets (49g), thus this technology could be very useful especially for air cleaning devices indoors for passenger vehicles.

V. Acknowledgement

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