Collection of diesel exhaust particle using electrostatic charging prior to mechanical filtration

H. Hayashi, M. Kimura, K. Kawahara, Y. Takasaki, K. Takashima and A. Mizuno

***Abstract*—After treatment systems consisting of new catalyst technologies and particulate filters will be indispensable to meet increasingly stringent global regulations limiting particulate matter (PM) and NOx emissions from heavy duty and light duty diesel vehicles. Diesel particulate filter (DPF) has been established as a key technology in reducing diesel particulate emission. However, pressure drop, durability and insufficient collection efficiency for nano-particles call for technological improvements. Electrostatic Precipitation (ESP) is another leading technology used in exhaust treatment but it is currently limited to applications for factories. In this paper we have proven that concurrent use of DPF and ESP show synergetic effects with very high collection efficiency and slower rise up of the pressure drop. The number density of particles observed downstream of the combined system was 98 % less compared with that of DPF only. In addition, it was confirmed that increase in the pressure drop of the DPF was slower. In this study, filter that exposed exhaust gas was observed by using SEM (Scanning Electron Microscope). In addition, the electrical impact with the electrification particle on the surface of the filter was considered with a sucking type Faraday cage. The influence that the diesel particulate exerted on DPF by such an experiment was able to be clarified.**

***Index Terms*— Plasma, electrostatic precipitator, diesel engine**

I. Introduction

THE demand for more efficient automobiles has risen due to the sharp increase in oil price. At the meantime, strong economic growth in several countries has caused serious air pollution due to exhaust from vehicles. SPM and NO_x are main pollutants. SPM are particles smaller than 10 μm suspended in the atmosphere for a long time [1-4]. DPF has been widely used [5,6] to prevent emission of SPM. Although this method has high PM collection efficiency, it still has many problems such as high pressure drop and durability during regeneration of collected soot by combustion.

Another technology for particle removal is ESP that has been used satisfactory for cleaning of flue gas from large-capacity factories, combustion furnaces and thermal power plants. In ESP, SPMs agglomerate to large particles [7]. However a problem with ESP is an abnormal dust re-entrainment. The agglomerated particles repeat jumping and emitted outside an ESP. To combine an ESP and DPF, collection efficiency could be improved and increase in the pressure drop can be slower due to agglomeration. In this paper, characteristics of an ESP-DPF combined system are reported. In addition, the situation was confirmed by catching the particle, and using SEM for a mock filter to consider the influence that the particle electrified by ESP exerted on the surface of DPF, and the electrical impact was observed with a Faraday cage.

II. Experimental Setup

Figure 1 shows the schematic diagram of the experimental setup. The exhaust gas from a diesel engine generator (FUJI HEAVY INDUSTRIES Ltd., SGD3000S-Ⅲ) of 3 kW was used with a high load of 2.6 kW in order to reduce the ratio of Soluble Organic Fraction (SOF). SOF consists of unburned fuel and lubricant. The number density of particles measured with the quartz filter was about 20 mg/m^3 in the exhaust gas. 250 L/min of exhaust gas was passed through the precipitator. The gas from the precipitator was analyzed with an Engine Exhaust Particle Seizer (EEPS) (TSI Ltd, 3090). EEPS is a measurement device for engine exhaust, monitoring in real time (every 0.1 seconds) the number density and the size distribution of particles. The EEPS spectrometer displays measurements in 32 channels (16 channels per decade). It operates over a wide particle number density range, measuring as low as 200 $particles/cm^3$.

The ESP used a negative polarity D.C. high voltage power supply to generate corona discharge. The efficiency was evaluated by measuring the particle number density and size distribution using EEPS and the pressure drop with the pressure gauge. For the measurement, the exhaust sample was diluted 1:50 with nitrogen gas from the cylinder (12 L/min).

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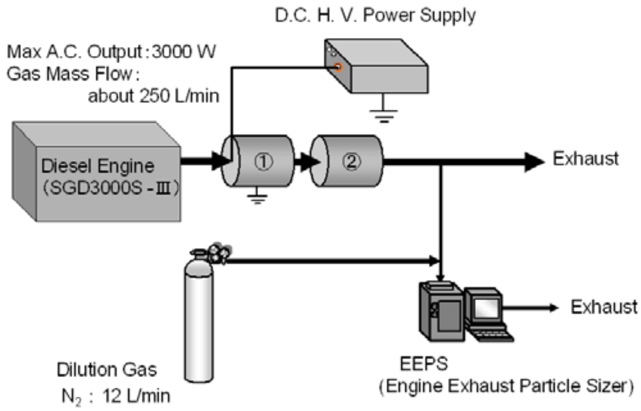


Fig. 1. Experimental Setup for the combined ESP (1) and DPF (2) system.

Figure 2 shows the precipitator outline chart. The discharge electrode was energized with a negative D.C. high voltage to the corona wire (ϕ =0.2 mm). A stainless steel pipe (36 mm inside diameter, 38 mm outside diameter) was used as a collection electrode. A ceramic tube (43.1 mm inside diameter, 50 mm outside diameter) was used as insulator. In the ESP, the length of the discharge area is 100 mm, the gas residence time was 0.024 seconds, and the temperature of the exhaust was 70 ℃. The precipitator was installed in front of the DPF (diameter 50 mm, length 128 mm.).

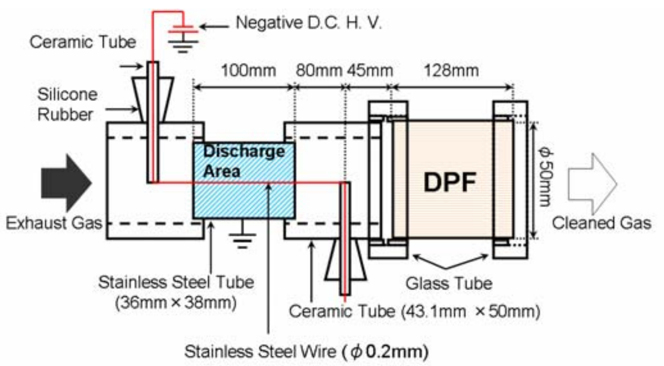


Fig. 2. Combined ESP and DPF system.

Figure 3 shows the experimental setup to measure the charge carried to the filter. After the DPF, an ESP and a Faracay cage were connected The line from the ESP to the Faraday cage was heated so that the temperature did not decrease. In this experiment, the measured voltage of the electrometer was stabilized by connecting the capacitor of 0.1 μ F with the electrometer. When ESP was not used, 1200 pF was connected instead. EEPS was used to confirm the change in the particle number with the ion removal device.

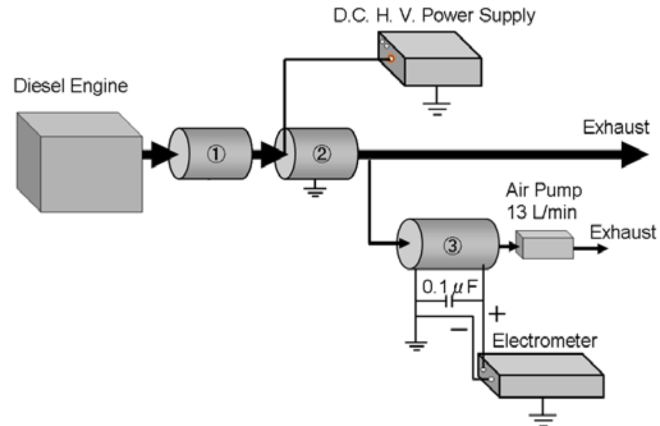


Fig. 3. Experimental Setup to measure voltage on surface of filter (①:DPF, ②: ESP, ③: Sucking type Faraday cage.)

Figure 4 shows a detail of sucking type Faraday cage. Teflon(4mm in thickness) was used as insulator between the electrode on the filter side and the electrode on a ground side. The electrical charge that exhaust gas carried to the filter can be measured.

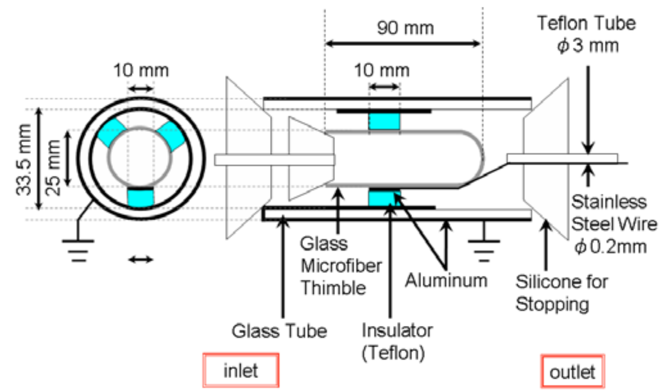


Fig. 4. Detail of sucking type Faraday cage.

In addition, the caught particle was observed with SEM the filter in this study. The Experimental Setup was the same one as Fig.3. However, DPF(①) is not installed. The filter fixed with a Faraday cage, and caught the particle.

III. Results and Discussions

Figure 5 shows the number density and mass distribution of the SPM when ESP is not used. The number density of particles(number of particles in cubic cm) is shown in the left axis and the mass distribution (micro-gram in m^3) is shown in the right axis. The highest number of particles was observed at 69.8 nm diameter and the highest mass at 124.1 nm.

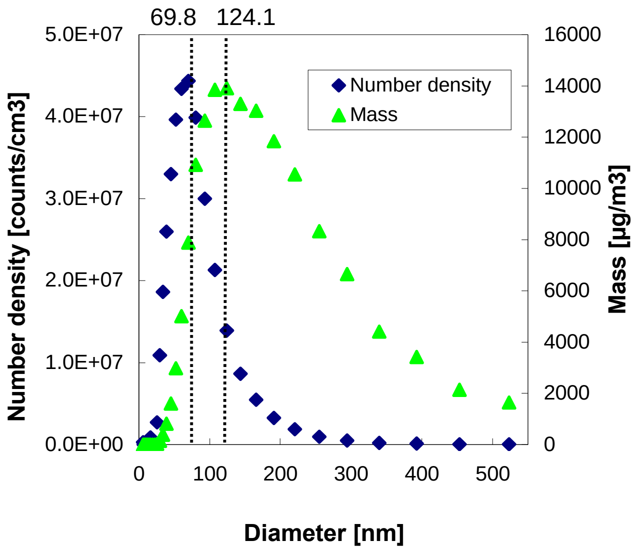


Fig. 5. Number density and mass distribution of exhaust particles.

Figure 6 is the V-I characteristic of the ESP. The corona onset voltage was -6.5 kV and the current gradually increased with a quadratic function of the voltage. At -17 kV, spark took place.

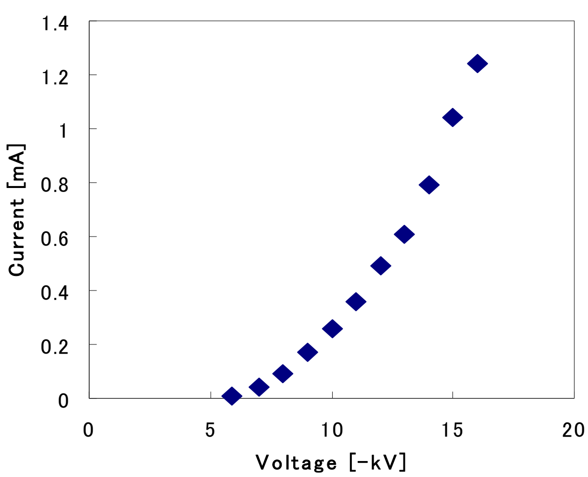


Fig. 6. V-I characteristic of the wire cylinder ESP.

Figure 7 shows the particle collection efficiency of the ESP alone. Length of the discharge electrode was 100 mm. ESP was operated with the applied voltage of -12.5 kV, and current between 0.45 mA ~ 1.25 mA. The measurement was carried out from 3 min. after the discharge was on for 80 minutes.

The collection efficiency was calculated by counting particles with and without the corona. Figure 7 shows that the collection efficiency was about 90 % or more in each particle diameter range. Especially, the collection efficiency of larger particles of 523.3 nm was high (almost 100 %).

Figure 8 shows the collection efficiency when DPF was added after the ESP and corona was switched on and off. The applied voltage was -12.5 kV and current was 0.5 mA ~ 1.2 mA. This graph shows that the collection efficiency of the particles with the corona on was almost 100 %.

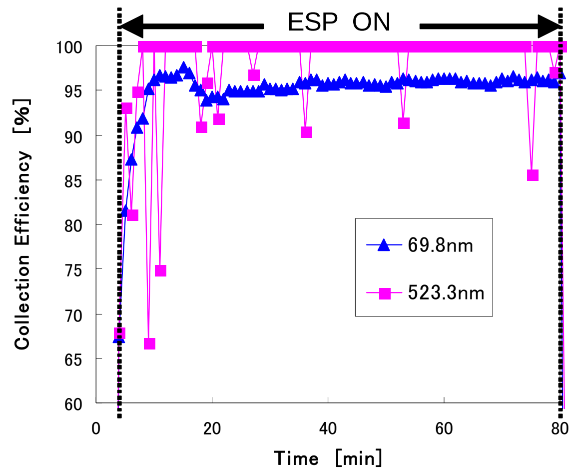


Fig. 7. The change in particles collection efficiency when ESP was used.

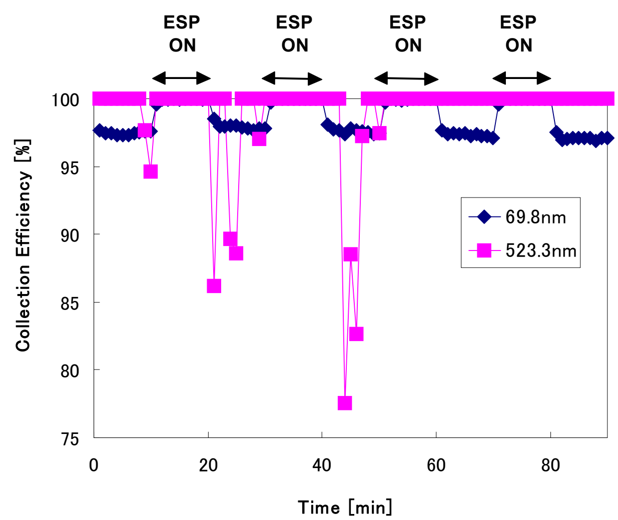


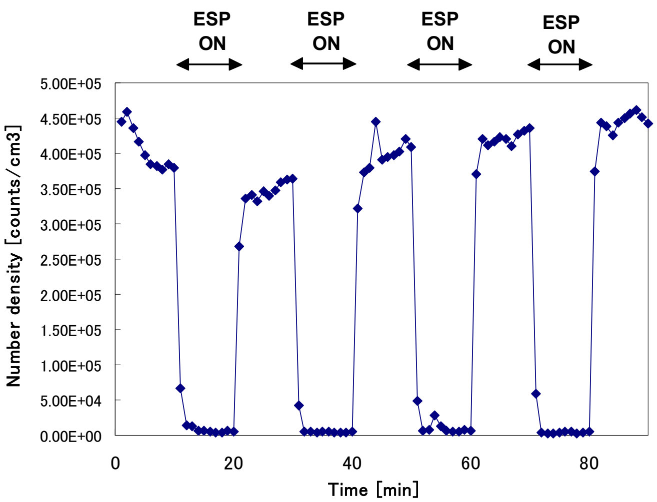
Fig. 8. The particle collection efficiency when DPF is installed

When Figure 7 and 8 are compared, it is clear that the collection efficiency of the particles is higher in Fig.8. One reason is particle agglomeration in the ESP [7]. Particles agglomerate, and become easy to be caught by DPF.

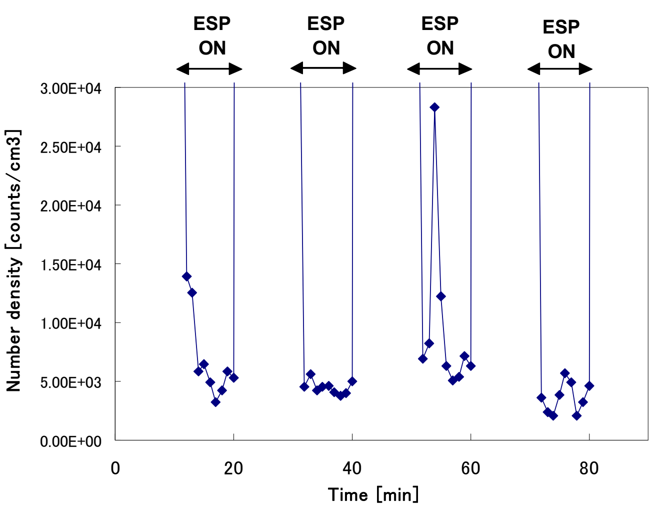
When the graphs in Fig.8 are compared, the collection efficiency of the particles in the range of 523.3 nm was not stable. This could be due to errors associated to a very small number of counted particles within the range.

Figure 9(a) shows the change in particle number density when the ESP was turned on and off in front of a DPF. The number density was 17,500,000 counts/cm^3 at the inlet. The collection efficiency of the DPF was about 98 %, and the total number density is decreased to about 350,000 to 450,000 counts/cm^3. With the ESP on, the count decreased sharply.

Fig.9(b) shows the count of particles with ESP on. In combination of ESP and DPF, the total number density decreased to 2000 counts/cm^3 to 7000 counts/cm^3, indicating the collection efficiency more than 99.9 %. This density is near the measurement limit of EEPS. The result confirms an ability to remove the particles effectively using the combination of ESP and DPF.



(a) ESP + DPF



(b) ESP + DPF with magnified counting scale

Fig. 9. The change in total number density of particles.

Figure 10 is a time change of the pressure drop of the DPF with and without the energization of the ESP. The applied voltage was -12.5 kV, current 0.65 mA ~ 0.87 mA and the temperature of the exhaust gas in the precipitator is about 70 ℃. From Fig. 7 the pressure drop increased after the engine was on. Without ESP operation, the pressure drop increased more rapidly and reached to about 35 kPa in 9 minutes. In the case of combined use of ESP and DPF, the pressure drop rose significantly slower. The cause of this phenomenon is the trapping of particles in the ESP, as well as the difference of the deposition of agglomerated particles on the wall of DPF.

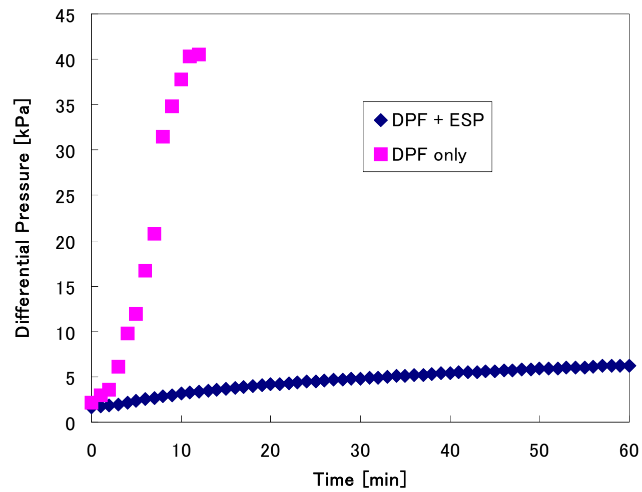


Fig. 10. Pressure drop comparison between DPF and combined ESP/DPF.

Using SEM the state of the particles collected on the glass fiber filter set after the ESP was observed with the applied voltage of -12.5kV (and current was 0.70mA).

Figure 11 is a clean filter. In Figure 12, many particles can be confirm existing in round massiveness. With higher magnification as shown in (b), fibers with adhesion of many particle were not observed. Moreover, the particles seems to block the spacing of the filter. Figure13 shows a filter, sampled after the ESP. The ESP was operated with about 95% particle collection efficiency. With higher magnification, chained particles adheres to the filter and grown like hair. This is a phenomenon not seen in Fig.12. This could be due to electrical force. This comparison shows the effectiveness of charging particles prior to mechanical filtration.

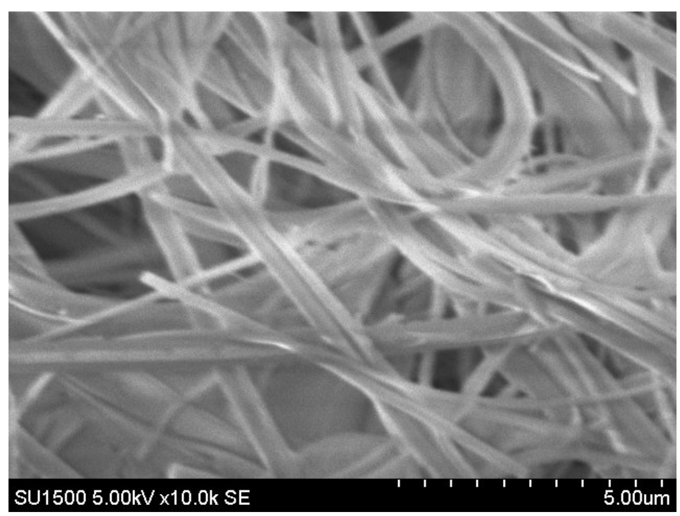
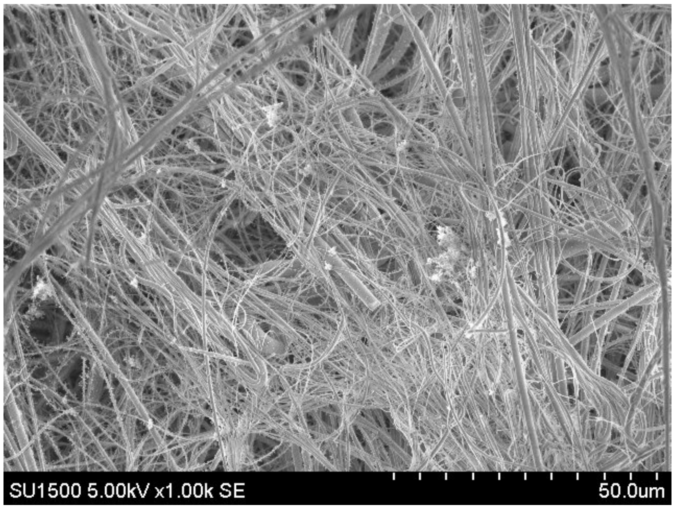
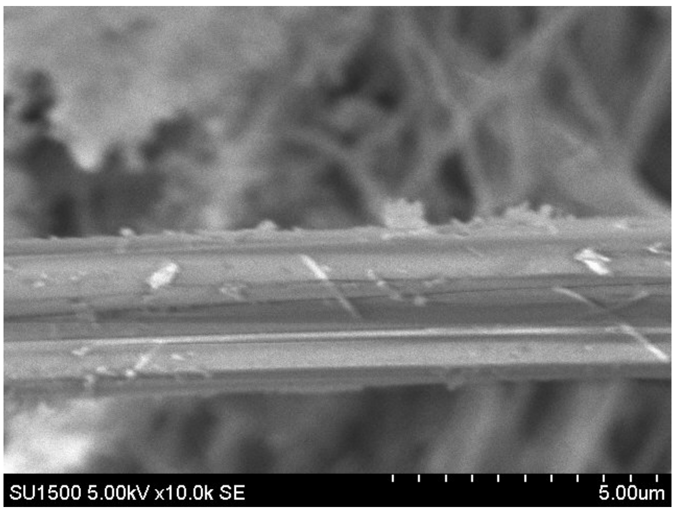


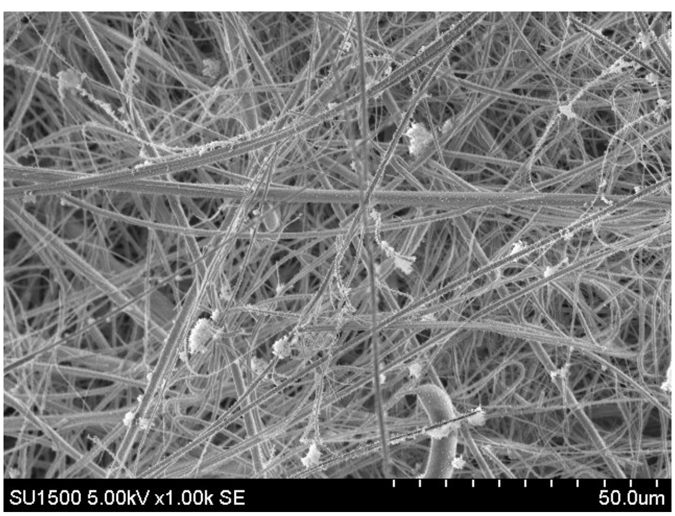
Fig. 11. Filter before exhaust gas is exposed. The magnification is 10,000.



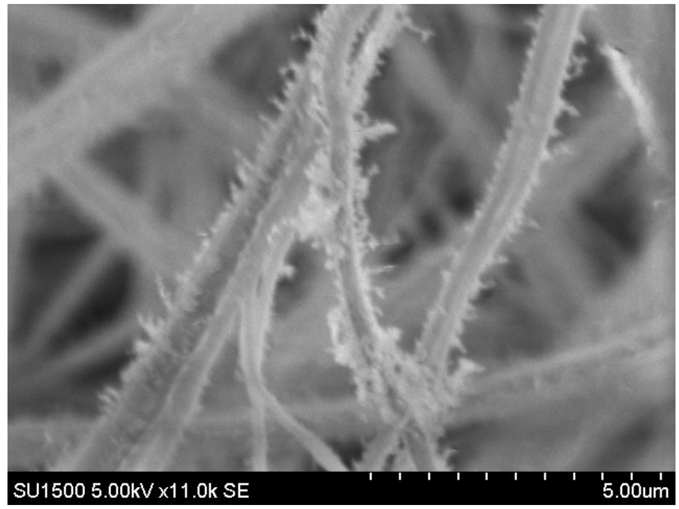
(a) The magnification is 1,000.



(b) The magnification is 10,000.
Fig. 12. Particles on filter with ESP off. Exposure time 3 min.



(a) The magnification is 1,000.



(b) The magnification is 11,000.
Fig. 13. Particles on filter with ESP on. Exposure time 3 min.

Then, the charge on the filter was examined using the Faraday cage shown in Fig.3 and 4. Figure14 shows of the voltage of the Faraday cage when exhaust gas is not passed through ESP nor DPF. The voltage increases towards positive as time passes,. The value of the voltage, however, was almost 1/100 of the experiments shown in Fig.15.

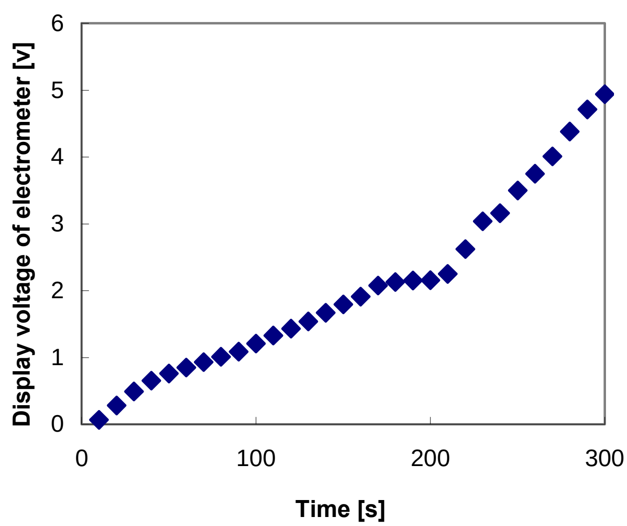


Fig. 14 Time change of the voltage of the filter when not used ESP. Capacitor is 1200 pF.

Figure 15 shows the time change of the voltage of the filter. When only ESP is used, the electrification should be caused by the charged particles and the ions exhausted from the ESP. When the DPF was inserted prior to the ESP, the voltage change should mainly be caused by the ions exhausted from the ESP.

From the result shown in Fig.15, the voltage of about 5.3 times more than that with DPF was observed. However, the voltage greatly depends on ambient temperature and the humidity.

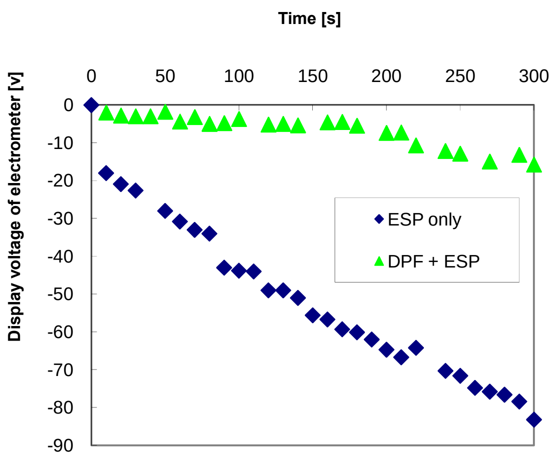


Fig. 15. Time change of the voltage of the Faraday cage with and without the DPF prior to the ESP (The capacitor of the cage was 0.1 μF).

IV. Conclusion

The combination of ESP and DPF is proved to be very effective for collecting nano-particles. Increase of the pressure drop of the DPF is slower with the combination. DPF can be charged by charged particles exhausted from the preceeding ESP. Therefore, The electron microscopic observation of a glass fiber filter after an ESP shows pearl-chain formation of the particles, and the attachment of fiber-like chained particles vertical to the filter fibers. This adhesion characteristics could be a reason for the slow rise of the pressure drop.

Acknowledgement

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