Diesel PM Collection for Marine Emissions Using Double Cylinder Type Electrostatic Precipitator

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Abstract—Low resistive particulate matter (PM) generated from marine engines or diesel generators has been known to be difficult to collect by the conventional electrostatic precipitators (ESP). In the present study, the double-cylinder type ESP (DC ESP) was developed to remove low resistive diesel exhaust particles. Two ESPs, namely, the conventional single-cylinder type ESP (SC ESP) and DC ESP were investigated using a 6728 cc engine. The particle size-dependent collection efficiency was obtained using a Scanning Mobility Particle Sizer (SMPS) for the particle-size range of 40-500 nm and an aerosol spectrometer (AS) for the particle-size range of 300-10,000 nm. The particle mass collection efficiency was obtained using a Low Volume Air Sampler (LVS). The effective of re-entrainment or collection efficiency for two ESPs was compared. As a result, the conventional SC ESP showed good collection efficiency for particle sizes less than 300 nm but showed severe re-entrainment for particle sizes greater than 1000 nm. The DC ESP also showed good collection efficiency for particle sizes less than 300 nm. However, the collection efficiency for particle sizes greater than 1000 nm was significantly improved due to particle capture between double cylinders i.e., suppression of particle re-entrainment. This result was also supported by the particle mass measurement and the filter colour detection by the LVS.

Keywords—Electrostatic precipitator, diesel exhaust particle, re-entrainment, collection efficiency, marine engine

I. INTRODUCTION

Electrostatic precipitators (ESPs) have been extensively used to decontaminate polluted gases exhausted from industrial plants and to clean air in buildings, etc., because of their high collection efficiency. However, the collection of these low resistivity particles by the conventional ESPs is known to be difficult. These particles are generated from various sources such as marine engines, diesel automobiles and power generation engines. The low resistivity particles cause particle detachment from a collection plate by an induction charge, i.e., dust re-entrainment, resulting in poor collection efficiency.

Several ideas that had been proposed to surpress re-entrainment are as follows;

1) Collection electrode coated with a dielectric sheet [1].
2) Mixing water mist with gases[2].
3) Using an ESP as an agglomerator [3-4]
4) Silent discharge type ESP [5]
5) Application of gradient force [6]
6) ESP by low frequency AC field [7]

However, these concepts achieved only limited success for minimizing the re-entrainment in the high dust-loading and high gas temperature condition.

The electrostatic cyclone DPF [8] and the DPF by means of high frequency induction heating [9] for marine engine were suggested. The seawater scrubber system was also proposed [10]. However, these concepts also achieved only limited success for small-sized system and low pressure drop. An electrohydrodynamically assisted ESP is proposed in this condition [11, 12].

The new double cylinder type ESP (DC ESP) was developed to overcome the re-entrainment [13]. In the previous report, the effect of the DC ESP was investigated by numerical simulation. The DC ESP utilized differential pressure to transport re-entrained particles effectively into the low gas velocity space from the high gas velocity space. The captured particles were trapped on the electrode in the low gas velocity space, where the hydrodynamic shear stress was low.

The purpose of this paper is that the effect of DC ESP on preventing re-entrainment is experimentally investigated. Two ESPs, namely, the conventional single cylinder type ESP (SC ESP) and DC ESP were investigated using a 6,728 cc engine. The particle size-dependent collection efficiency was obtained using a Scanning Mobility Particle Sizer (SMPS, TSI) for the particle-size range of 40-500 nm and an aerosol spectrometer (AS, Welas 2000, Palas) for the particle-size range of 300-10,000 nm. The particle mass collection efficiency was obtained using a Low Volume Air Sampler (Model 2000, R&P). The effective of re-entrainment or collection efficiency for the two ESPs was compared.

II. EXPERIMENTAL SETUP

A schematic diagram of experimental system is shown in Fig. 1. Emissions from a diesel engine compressor (Denyo, DIS-685SB, displacement volume of 6,278 cc, output of 140 kW) using heavy oil A (Exxon Mobile Corporation, FOA 01) with 1,200 rpm were used to create a high gas velocity and high gas temperature condition in the ESP. In order to determine the particle number density in the ESP, the flue gas was diluted

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approximately 17 times by the dilution system (KHG-2010, Palas) and the particle size-dependent number densities before and after the ESP were determined by the Scanning Mobility Particle Sizer (SMPS, Model3936L76-N, TSI) for the particle-size range of 40-500 nm and the aerosol spectrometer (AS, Welas 2000, Palas) for the particle-size range of 300-10,000 nm, respectively. The particle mass concentrations were determined by the Low Volume Air Sampler (LVS, Model 2000, R&P). The exhaust gas temperature was 220-334^{o}C. The gas velocity in the ESP was approximately 10 m/s. The collection efficiency η was calculated by equation (1):

$$\eta = \left(1 - \frac{N_d}{N_u}\right) \times 100 \quad [\%] \tag{1}$$

where N_u was the particle concentration upstream of the ESP and N_d was the particle concentration downstream of the ESP.

The DC ESP configuration was as shown in Fig. 2. The DC ESP consisted of a discharge electrode, hole-punched grounded electrode and grounding case. The upper and lower portions of the space between the grounded hole-punched electrode and the grounding case were closed. The flue gas was connected to upper portion between the discharge electrode and the grounded hole-punched electrode.

The SC ESP consisted of the discharge electrode and the grounded electrode substituted for the grounded hole-punched electrode in Fig. 2.

Negative DC high voltage of -4.8 - -6.1 kV was applied to the discharge electrode.

Concept of the DC ESP for particle collection is shown in Fig. 3. The space between the discharge electrode and the grounded hole-punched electrode is called "charging space" and the space between the grounded hole-punched electrode and the grounding case is called "collecting space". Particles in the flue gas are introduced to the charging space and negatively charged by corona discharge. The charged particles are collected on the grounded hole-punched electrode. The collected particles become positively charged by induction charge, so that the collected particles grow to be large particles by agglomeration [14]. The large particles are re-entrained by hydrodynamic repulsion force and introduced into the collecting space by differential pressure. The calculation value of average gas velocity in the collecting space is 1/3 or less of the charging space [13], so that the re-entrained particles are re-collected on the surface of the grounded hole-punched electrode and the grounding case in the collecting space.

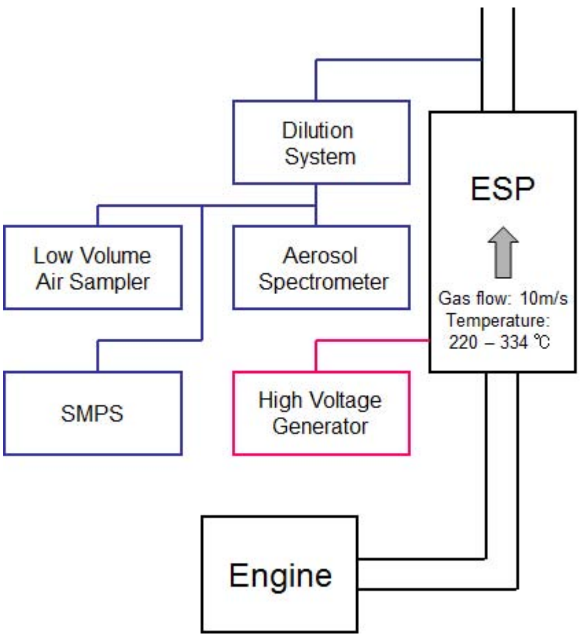

Fig. 1. Schematic diagram of the experimental system.

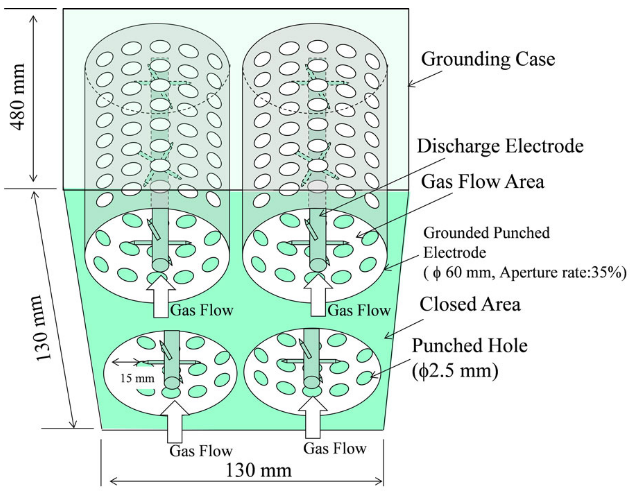

Fig. 2. DC ESP configuration.

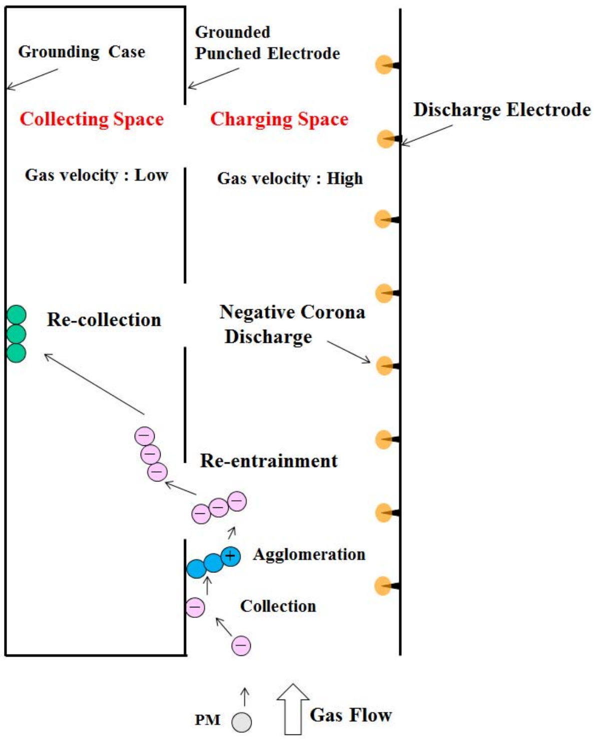

Fig. 3. Concept of the DC ESP for particle collection.

III. Results and Discussoion

A. *Collection Efficiency for Fine Particles*

The particle size distributions in the range of 40-500 nm in the SC ESP and the DC ESP were as shown in Figs. 4 and 5. The flue gas temperature was 250-275°C. The maximum value of the inlet distribution was at approximately 100 nm in diameter. In both case, the outlet particle density was always lower than the inlet particle density.

The particle size-dependent collection efficiency in the range of 40-300 nm for the two ESPs was as shown in Fig. 6. The minimum efficiency occurred at 150 nm in both ESPs. This was attributed to the lower charge on submicrometer particles and slip motion [15]. The collection efficiency at approximately 100 nm in the DC ESP was less than that in the SC ESP. This is because the surface area of the hole-punched electrode was smaller than that of the electrode in the SC ESP. However, we need more investigation for the fine particle collection. The collection efficiencies for particle sizes larger than 200 nm in the DC ESP were greater than that in the SC ESP due to the suppression of the particle re-entrainment. The collection efficiencies for particle sizes smaller than 80 nm were also greater than that in the SC ESP. This cause was that the electric field strength in the space near the punched hole edge was greater in the charging space [16].

B. *Collection Efficiency for Large Particles*

The particle size distributions in the range of 300-10,000 nm in the SC ESP and the DC ESP were as shown in Figs. 7 and 8. The flue gas temperature was 250-275°C. The particle concentration decreased with increasing particle diameter in both cases. The outlet particle concentration for particle sizes larger than 600 nm increased from the inlet concentration due to the particle re-entrainment [14].

The particle size-dependent collection efficiency in the range of 300-10,000 nm for the two ESPs was as shown in Fig. 9. Negative collection efficiency indicated that the agglomerated large particles captured at the electrostatic field exposed were detached and re-entrained by the repulsion force caused by the fluid dynamic shear stress. The collection efficiency decreased with increasing particle diameter. However, the collection efficiency for particle sizes larger than 1000 nm in the DC ESP was higher than in the SC ESP. These results indicated the effective of the DC ESP for the suppression of particle re-entrainment.

C. *Mass Collection Efficiency*

The collection efficiency was estimated from not only the particle number density, but also the particle mass density. The particle mass collection efficiency as a function of elapsed time for the two ESPs was as shown in Fig. 10. The flue gas temperature was 220-282°C. The particle mass collection efficiency in the SC ESP was

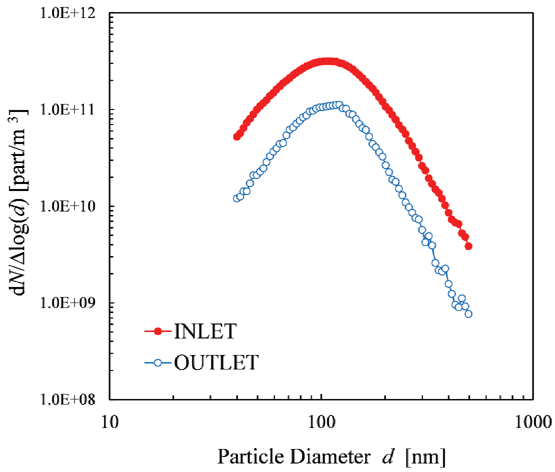

Fig. 4. Particle size distribution using SMPS in the range of 40-500 nm in the SC ESP.

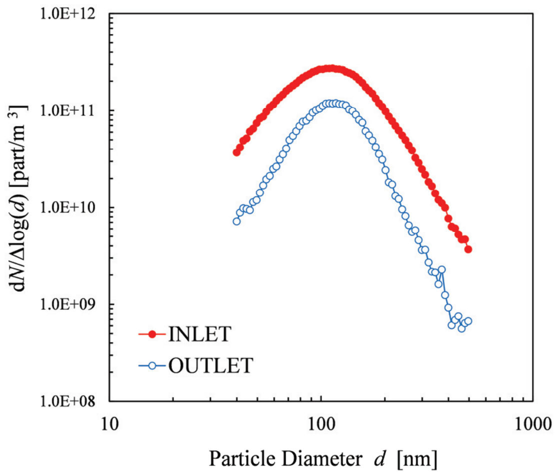

Fig. 5. Particle size distribution using SMPS in the range of 40-500 nm in the DC ESP.

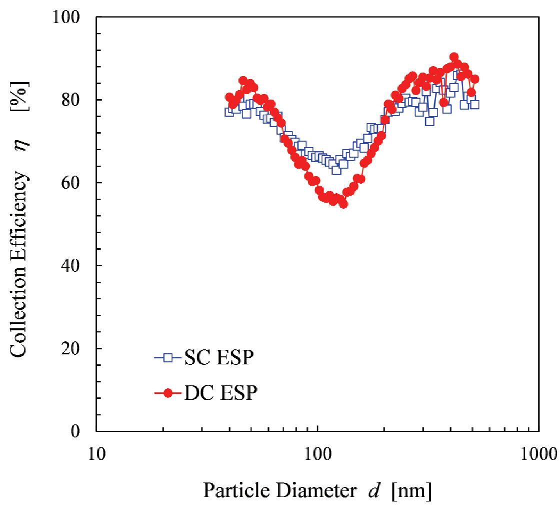

Fig. 6. Particle size-dependent collection efficiency using SMPS in the range of 40-500 nm for various ESPs.

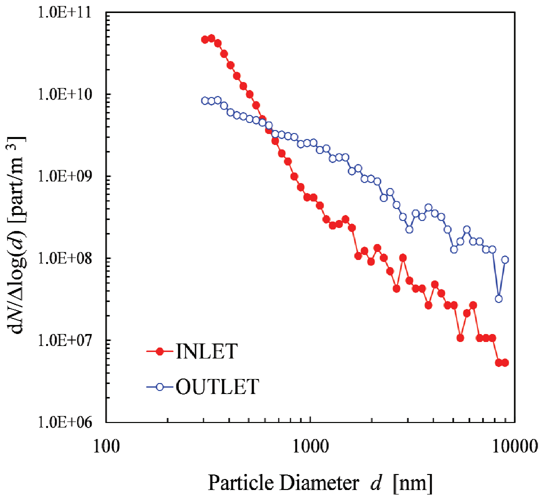

Fig. 7. Particle size distribution using AS in the range of 300-10,000 nm in the SC ESP.

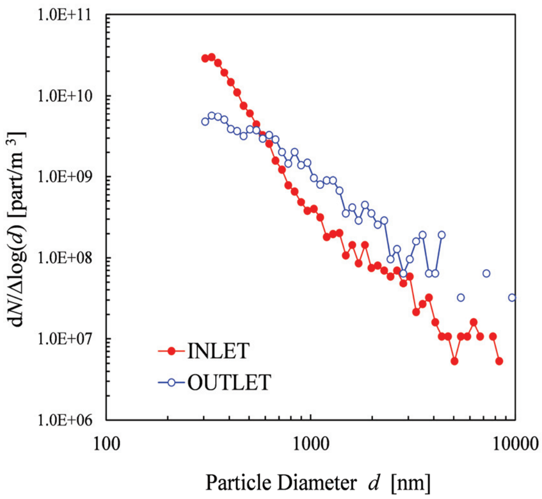

Fig. 8. Particle size distribution using AS in the range of 300-10,000 nm in the DC ESP.

34% at 15 minutes after the start of operation. However, the collection efficiency significantly decreased with increasing elapsed time due to particle re-entrainment. On the other hand, the collection efficiency in the DC ESP was higher than in the SC ESP, although the collection efficiency decreased with increasing elapsed time.

The filter color of LVS indicated particle concentration in 500-liter flue gas, as shown in Fig. 11. The particle concentration before treatment was higher than after treatment as indicated by the lighter color of the filter in the DC ESP. However, this tendency was not clear in the SC ESP. The inlet mass concentration in the SC ESP was 80 mg/m^3, that in the DC ESP was 83 mg/m^3, where mass concentration was included soot particles and soluble organic fraction (SOF). It needs further consideration for estimate mass concentrations of soot particles and SOF.

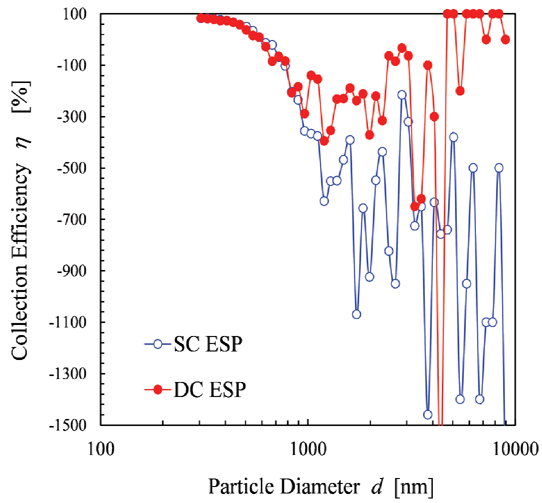

Fig. 9. Particle size-dependent collection efficiency using AS in the range of 300-10,000 nm for two ESPs.

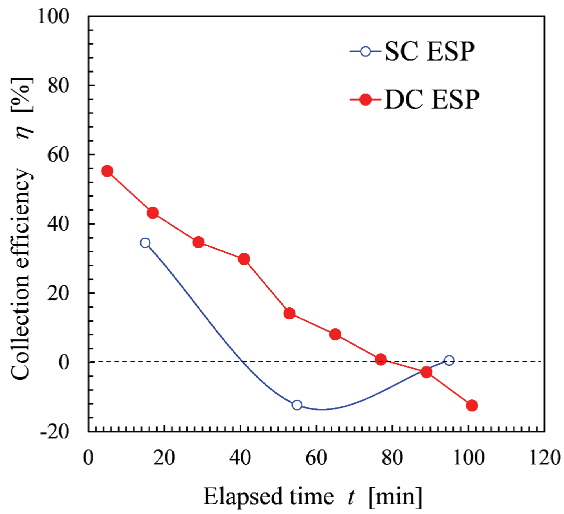

Fig. 10. Collection efficiency as a function of elapsed time using LVS for two ESPs.

IV. Conclusion

The collection of particles generated from marine and automobile engines was investigated using two types of ESPs, namely, the conventional single cylinder type ESP (SC ESP) and the double cylinder type ESP (DC ESP). The conventional SC ESP showed good collection efficiency for particle sizes less than 300 nm but showed severe re-entrainment for particle sizes greater than 1000 nm. The DC ESP also showed good collection efficiency for particle sizes less than 300 nm. Furthermore, the collection efficiency for particle sizes greater than 1000 nm was improved due to particle capture between double cylinders i.e., suppression of particle re-entrainment. This result was also supported by the particle mass measurement and the filter colour detection by the LVS. These results demonstrate the effectiveness of DC ESP

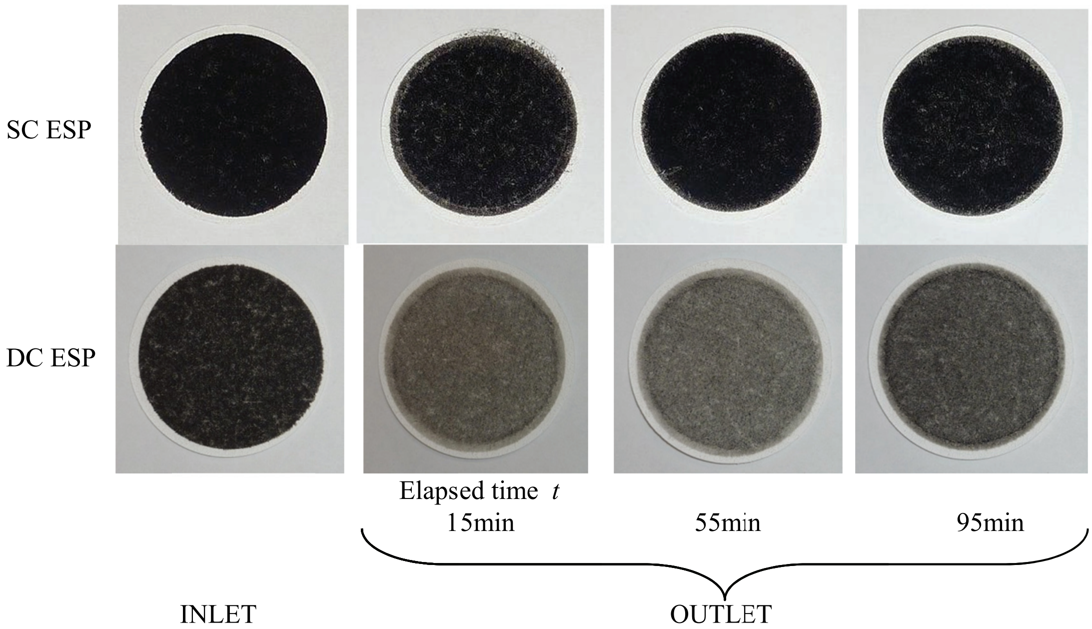

Fig. 11. Color of filter paper after used to take particle sample.

for collection of low resistive particle collection from exhaust gas treatment. However, we need further investigation to achieve much higher particle mass collection efficiency with long term operation.

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