EHD-assisted plasma electrostatic precipitator for simultaneous PM collection and incineration

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Abstract. The electrohydrodynamically-assisted (EHD) plasma electrostatic precipitator (called plasma ESP hereafter) was developed not only to collect low-resistive fine particles generated from diesel engine but also to incinerate captured particulates within the same reactor. The plasma ESP is to utilize EHD to transport the charged particles effectively into the low electrostatic field region where electrostatic repulsion force acting on particles by induction charge is very small, resulting in suppression of PM reentrainment. At the same time, collected particulates are incinerated by ozone and oxidation product of NO2 in the flue gas by the surface discharge plasma in the same unit so that no particle storage and handling device are required. The particle-size dependent collection efficiency and particle incineration were evaluated by the Scanning Mobility Particle Sizer (SMPS) for particle size of 20-500 nm and the particle counter (PC) for particle size of 300-5,000 nm. The results indicated that the plasma ESP was able to collect more than 90 % collection efficiency and no reentrainment occurred for all particle size measured. The plasma ESP leads to more economical and compact ESP feasible. No PM handling device and storage are required and therefore has high potential for marine engine and automobiles.

1. Introduction
The particulate matters (PMs) emitted from diesel engine exhaust are low resistive and extremely small in the range of 70~100 nanometers (nm). These particles are penetrated into alveolus and extremely harmful to human health. These particles are generated from various emission sources such as diesel automobiles, marine engines, power generation engines and construction machines. The use of diesel particulate filter (DPF) was widely used for the collection of automobile diesel PM but was not cost effective, especially for marine engine emission where PM concentration is often higher than 100 mg m⁻³. The collection of low resistive PM has been known to be extremely difficult by the conventional electrostatic precipitators (ESPs). The low resistive diesel engine particles are detached from the collection plate where the electrostatic repulsion force due to induction charge exceeds particle adhesion force on the collection

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electrode. These PMs were escaped without collection in the ESP. This phenomenon has been known as particle reentrainment or resuspension, resulting in poor collection efficiency.

There are many references for controlling high resistive particles but few literatures for controlling low resistive particles [1-8]. Two-stage ESP employing charging section by DC field, followed by the collection section by low frequency AC field including the trapezoidal waveforms in the range of 1~20 Hz has been investigated for the collection of diesel particles in tunnel [9-11], while the conventional ESP utilizes DC high voltage. Various collection plate designs such as corrugated collection plates were employed but were exposed to high electric field or not taken into account electrohydrodynamics (EHD) to transport the charged particles into mechanically trapping zone in the ESP. These concepts have limited success for minimizing the particle reentrainment. Recently, electrostatic flocking filter on the collection electrode was developed to capture fine diesel particles [12]. The combination of diesel particulate filter (DPF) combined with sliding discharge was developed to incinerate the captured particles [13]. The wet ESP was another strong candidate for this application but it creates water treatment as opposed to dry process.

Based on fundamentals of reentrainment theory, the new electrohydrodynamically-assisted electrostatic precipitator (EHD ESP) was developed to overcome the reentrainment in the conventional ESP [14, 15]. The EHD ESP, which utilizes the ionic wind to transport the charged particles effectively into the zero electrostatic field zone or pocket zone attached to the collection plate. The captured particles are trapped in the pocket where particles captured in the pocket zone were exposed to zero electric field, so that no electrostatic repulsion force on the particles due to induction charge was taken place. This is the major factor for reduction of particle reentrainment.

As an extension of the EHD ESP, the new EHD-assisted plasma ESP was developed. The low resistive diesel PM is effectively captured in the low electric field region and at the same time, collected particulates are incinerated by ozone and oxidation product of NO2 in the flue gas by the surface discharge plasma in a single unit so that no particle handling device is required. This novel device is called EHD-assisted plasma electrostatic precipitator (abbreviated as plasma ESP hereafter). Note that the carbon particle incineration by ozone is effective when the flue gas temperature is above room temperature but NO2 incineration as reaction product becomes effective when the flue gas temperature exceeds 250 °C [16]. When DC and surface discharge for the plasma ESP are operated at the same time within the same reactor, the small carbon particles can be incinerated during the collection process. The particle-size dependent number density and mass collection efficiency, and particle incineration were evaluated by Scanning Mobility Particle Sizer (SMPS) and particle counter (PC). This device is particularly attractive for automobile and marine diesel engine emission control because no additional particle handling device is required.

2. Concept of plasma ESP
The plasma ESP used for this experiment was shown in figure 1 (a)-(b) for cross section views from flue gas inlet and reactor frontal side and 1(c) for three dimensional view. The discharge electrode consists of 6.35 mm in diameter rod and 416 mm long tube where 18 mm diameter star electrode was equally spaced with every 34 mm interval, a total of 12 star electrodes, denoted as the center electrode. The inner electrode was 53 mm in diameter with the thickness of 1 mm, where 30 mm×30 mm square holes were punched every 10 mm spacing. The outer electrode was punched with 30 mm and 13 mm square holes every 4 mm spacing, which was attached to 70 mm OD and 65 mm ID dielectric quartz tube. The dielectric quartz tube was covered by the most outer ground electrode tube. All components were made of stainless steel. Their dimensions were designated in the figures. The minimum distance between the star electrode and the inner electrode was set at 20 mm.

The plasma ESP has two mode operations as mode (A) and (B). As mode (A) operation (DC on and AC off for particle collection), the center electrode was energized as negative DC high voltage, while all inner and outer electrodes as well as the most outer electrodes were grounded. Ionic wind is generated
towards inner electrode but charged particles are escaped from small area of inner electrode and accelerated to move towards outer electrode by EHD action. Majority of particles are collected on the outer electrode and quartz tube surface, and small fraction of particles were collected on the inner electrode on both sides.

The ions for collected charged particles are drained off as soon as particles touch the ground plate for conductive particles or low resistivity particles such as diesel particles. Opposite polarity of charge as positive ions are immediately accumulated on the particles due to the induction charge, which experiences the particle repulsion force, resulting in particle reentrainment. This force is proportional to the square of the electric field and particle diameter [14]. When the repulsion force exceeds the particle adhesion force, particles are detached from the surface and transported into the inter-electrode space, where negative ions exist. Particle are again charged negatively and attracted to the collection plate. These processes are repeated and finally go through the ESP without collection, i.e., particle reentrainment. The detained theoretical investigation including the electrohydrodynamics on particle reentrainment was reported earlier [14].

![Figure 1](image_url)

**Figure 1.** (a) Cross section view for the plasma ESP; (b) Cross section view for the plasma ESP; (c) Three-dimensional view of the plasma ESP.

As for incineration process as mode (A) operation, the surface discharge (6 kV with 10 kHz and 60 mA) was applied between the outer electrode and the most outer electrode, while the inner electrode and the center electrode were grounded for mode (A) operation. Ozone was generated and diffused into the inner and outer electrode surface for particle incineration. When the gas temperature is higher than 250 °C, NO in the flue gas is oxidized to form NO₂ by ozone and O radical and carbon particles can be incinerated.
The chemical reaction for particle incineration are as follows, where \( T_g \) = gas temperature: \( \text{NO} + \text{O} \rightarrow \text{NO}_2 + \text{O}_2 \) (\( T_g > 20 \) °C), C + 2NO\(_2\) \( \rightarrow \) \( \text{CO}_2 + 2\text{NO} \) (\( T_g > 250 \) °C), C + O\(_3\) \( \rightarrow \) \( \text{CO}_2 + \frac{1}{2}\text{O}_2 \) (\( T_g > 20 \) °C). The speed of particle incineration depends on particle size and concentration and ozone concentration. Two stages of plasma ESP are required for continuous diesel emission control for mode (A) operation: one operation is for particle capture and the other is for particle incineration so that two plasma ESPs are required for the continuous emission control.

On the other hand, as for mode (B) operation (DC on and AC on) for the purpose of simultaneous particle collection and incineration, particles collected to the inner and outer electrodes are incinerated by the surface discharge. Small particle may incinerate before reaching to the electrodes, which depends on particle size and ozone concentration. For both mode (A) and (B) operation, particle handing device is totally eliminated. This operation mode may be applicable to light loading at present level. In both cases, particle storage and handling device are totally eliminated so that it is particularly attractive such as automobile and marine engine applications. In the present paper, the results of mode (A) were reported.

3. Experimental setup
A diesel engine generator (Yammer Co., Ltd., YDG200A-5E, direct injection type for a single cylinder, displacement volume of 200 cc, maximum electric power output of 1.7 kW) using light oil was used. The constituents of the diesel PM measured were 99 % of C, 0.1 % of Si, 0.07 % of Fe, 0.1 % of Ca, 0.4 % of S, and 0.03 % of Zn. In order to determine the number particle density in the ESP, the flue gas was diluted approximately 100 times by ambient air and particle size-dependent number densities before and after the ESP was determined by the Scanning Mobility Particle Sizer (SMPS, Model 3034) for the particle size ranged 20-800 nm and the particle counter (PC, Rion KC-01C) for the particle size of 300-5,000 nm, respectively. The exhaust gas temperatures were measured at the plasma ESP inlet and outlet by thermocouples. The gas velocity was measured by the hot wire anemometer (Kanomax). Ozone concentration was measured by ozone monitor (Ebara Jitsugyo. EG-2001). Figure 2 shows the experimental setup for evaluation of the plasma ESP.

![Experimental Setup for the plasma ESP evaluation.](image)

4. Results and discussion
The voltage and current relationship for the plasma ESP was shown in figure 3. The onset voltage was 6.0 kV and the spark-over voltage was 18 kV with 4.2 mA at room temperature before particles were introduced. When the load was 0.5 kW which was 25 % load, the flue gas temperature was 135 °C at the ESP inlet and 65 °C at the plasma ESP outlet so that the gas velocity of the plasma ESP was 1.9 m s\(^{-1}\).
based on the average gas temperature.

Figure 4 shows the particle-size dependent number density for the plasma ESP, which was measured by SMPS when the applied voltage was modest \( V = -10 \text{ kV} \) with \( I = 0.5 \text{ mA} \). The maximum number density was \( 10^8 \) particles \( \text{cm}^{-3} \) at particle size of 70 nm. One order of magnitude reduction of number density was achieved for particle size of 20-500 nm.

Figure 3. Voltage and current relationship for the plasma ESP.

Figure 4. Particle-size dependent number density distributions by the SMPS when the load is 0.5 kW and gas velocity is 1.9 m s\(^{-1}\).

Figure 5. Particle-size dependent number-density distribution for the plasma ESP measured by the PC when the load of 0.5 kW and gas velocity of 1.9 m s\(^{-1}\).

Figure 6. Time-elapsed number density collection efficiency for the plasma ESP measured by PC when the load is 0.5 kW and gas velocity is 1.9 m s\(^{-1}\).

The particle size-dependent collection efficiency for particle size in the range of 300-5,000 nm measured by the PC was shown in figure 5. Again, one order magnitude particle number density reduction was achieved for 300-500 nm and further reduction was observed with increased particle size.

Particle reentrainment occurs for the particle size of greater than 1,000 nm based on previous
Figure 7. Particle-size dependent mass-base density distribution measured by SMPS for the plasma ESP ($\eta=86.6\%$).

Figure 8. Particle-size dependent mass-base density distribution measured by PC for the plasma ESP ($\eta=93.0\%$, $\eta_t=90.0\%$).

Experimental results [15] so that the time-dependent number density collection efficiency as a function of particle size was evaluated for 300-5,000 nm when the load is 25% as shown in figure 6. The number collection efficiency was greater than 95% for particle size ranging of 500-5,000 nm and 80-85% for 300-500 nm during 20 min operation. The collection efficiency was increased with increased particle size and minimum for 300 nm range which implies the classical electrostatic charging theory, indicating no particle reentrainment occurred during 20 min operation. This was attributed to increased adhesion force by moisture content, that is, capillary condensation associated with the contact between particle and the surface, due to low gas temperature when the load was 25%. Also, the particle surface resistivity becomes more affected over the volume resistivity.

Note that when treating the marine diesel engine emission, A and C grade heavy oil used for diesel emission contains large fraction of soluble organic fractions (SOFs) as well as particulates. When particulates were collected at higher temperature, SOFs and other vapor phase compounds were escaped from PM collection device. SOFs are condensed and converted to solid particulates at lower temperature. For this reason, it is difficult to obtain good collection efficiency when the ESP is operated at higher temperature for treating the marine diesel engine emission. Hence, it is important to remove gas-phase SOFs using nonthermal plasma or other means before the ESP or to operate the ESP at lower temperature (possibly less than 90 °C) to ensure to capture SOFs, bound H₂O, and sulfate as liquid or solids phase because ESP cannot collect gas phase substances. Tsukamoto [17] was also indirectly suggested the similar operation.

Figure 7 and 8 show the corresponding particle-size dependent mass-base collection efficiency for particle size ranging from 20-500 nm measured by SMPS and 300-5,000 nm by PC. The distribution of particle-size dependent mass collection efficiency was significantly changed over particle number density distribution as shown in figure 4 and 5. The collection efficiency ($\eta$) was 86.6% for 20-500 nm and 93.0% for 300-5,000 nm. The overall mass collection efficiency ($\eta_t$) was 90.0%. Although the collection efficiency was predominantly determined by small particle size range based on previous findings [15], the collection efficiency was not significantly affected by small particle size for this case.

When the load is 1.0 kW (50% load), the flue gas temperature was increased to 182 °C at the ESP inlet and 70 °C at the ESP outlet so that the average gas velocity was 2.1 m s⁻¹ based on the average gas temperature. Figure 9 shows the particle-size dependent number density, measured by SMPS. When the voltage was applied, the peak number density increased to 200 nm, primarily due to particle agglomeration. Two orders of magnitude reduction of collection efficiency were obtained for particle size...
less than 100 nm. However, the collection efficiency became minimum at 200–300 nm ranges.

**Figure 9.** Particle-size dependent number density distribution by the SMPS when the load is 1.0 kW (50 % load) and gas velocity is 2.1 m s⁻¹.

**Figure 10.** Particle-size dependent number density distributions by the PC when the load is 1.0 kW (50 % load).

**Figure 11.** Time-elapsed number density collection efficiency for the plasma ESP when the load is 1.0 kW.

**Figure 12.** Particle-size dependent mass-base density distribution measured by SMPS for the plasma ESP (η=95.0 %).

The particle size-dependent collection efficiency for particle size in the range of 300–5,000 nm measured by the PC was shown in figure 10. The collection efficiency was lower between 200–500 nm ranges but one order magnitude reduction of particle number density was observed for particle size greater than 500 nm. The increased collection efficiency with increased particle size indicated that the collection efficiency becomes minimum at 200–300 nm by classical charging theory and no reentrainment occurred even for higher load or flue gas temperature.

Figure 11 shows the time-dependent number density collection efficiency as a function of particle size of 300–5,000 nm when the load is 50 %. The number collection efficiency was in the range of 20–85 % for particle size of 300-500 nm 80 % for 500–1,000 nm, 80–90 % for 1,000–2,000 nm, and 90–95 % for 2,000–5,000 nm over 15 min operation. The collection efficiency was increased with increased particle size which again ascribed by the classical electrostatic theory, indicating no reentrainment occurred.
Figure 13. Particle-size dependent mass-base density distribution measured by PC for the plasma ESP ($\eta=81.5 \%, \eta_t=88.3 \%)$.

This was ascribed by classical charging theory for field and diffusion charging regime and increased adhesion force by moisture condensation due to low gas temperature operation or increased particle surface resistivity when the load is even 50%.

Figure 12 and 13 show the corresponding mass-base collection efficiency for particle size ranging 20–500 nm measured by SMPS and 300–5,000 nm by PC. The collection efficiency was 95.0 % for 20-500 nm and 81.5 % for 300-5,000 nm. The overall collection efficiency was 88.3 %. The collection efficiency was affected by small particle size range owing to high number density. The difference of collection efficiency was due to increased mass loading, gas temperature and primary gas flow velocity.

In order to incinerate the collected diesel particles, surface discharge plasma was induced with the applied AC voltage of 6.0 kV and the total current of 60 mA, whole all other electrodes were grounded for the operation mode (A). The ozone was generated on the surface of the outer electrode and ozone concentration of 47 ppm was obtained during 20 min operation. The amount of ozone generated during 20 min operation was 471 mg, which is able to incinerate 118 mg of carbon particles as described earlier. PM concentration and generation rate during 20 min operation with different load levels are as follows. When the load is 0.5, 1.0 and 1.5 kW, PM concentrations are 1.5, 15.4, and 85.0 mg m$^{-3}$, and PM generation rate are 8.95, 91.9, and 507 mg during 20 min operation, respectively. Based on the results, the plasma device is able to incinerate PM up to 75 % load with continuous plasma operation. Our plasma device is self-designed reactor and the outer electrode cylinder was not perfectly attached to the dielectric barrier quartz tube, which plasma was generated only at good contact point between the outer electrode and dielectric quartz tube so that strong plasma was not uniformly generated in the plasma reactor. The commercially available surface discharge reactor is able to generate significantly higher ozone generation. However, the fundamental concept of the EHD-assisted plasma ESP was successfully demonstrated. The development of the plasma ESP is particularity important for automobile and marine diesel engine emission control, where no particle storage is required.

Figure 14(a)-(b) show the pictures of the outer electrode before and after incineration and figure 15(a)-(b) also show the pictures of the dielectric quartz tube before 15(a) and after 20 min operation by the surface discharge. It was clear that diesel PM collected on outer and inner electrodes as well as quartz tube surface were perfectly incinerated by ozone during 20 min operation. The concept of plasma ESP was successfully demonstrated for collection of low resistive diesel PM collection as well as incineration, which reentrainment can be minimized.
5. Summary
The novel EHD-assisted plasma ESP was developed to collect low resistive particles generated from diesel engines and simultaneously incinerate collected particles using a single reactor. The plasma ESP showed more than 90% collection efficiency for low and medium load conditions when the gas velocity was in the range of 1.9-2.1 m s⁻¹. No reentrainment was observed due to low flue gas temperature, where adhesion force was dominated due to high moisture contents over electrostatic repulsion force. The collected particles were incinerated with ozone generated by the surface discharge. The plasma ESP leads to more economical and compact ESP feasible. No PM handling device and storage are required and therefore has a wide range of diesel emission control such as marine engine and automobiles.

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