Novel EHD-Assisted ESP for Collection of Low Resistive Diesel Particulates

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Abstract:

The novel electrohydrodynamically-assisted electrostatic precipitator (EHD ESP) was developed to suppress particle reentrainment for collection of low resistive diesel particulates. The collection efficiency was compared between the EHD ESP and the conventional ESP using two large diesel engines; 2.3 L and 3.2 L engines. The gas velocity was varied in the range of 1.35 to 7.3 m/s and the load was set at 0, 25 and 50%, where the operating gas temperatures were varied from 120 ^{o}C to 280^{o}C for 3.2 L engine. The particle size dependent collection efficiency was evaluated for the particle size ranging in 20 to 5,000 nm using a scanning mobility particle sizer (SMPS) and a particle counter (PC). The EHD ESP showed excellent suppression of particle reentrainment and collection efficiency even for high gas flow velocities in comparison with the conventional ESP.

1 Introduction

The particulate matters (PMs) emitted from diesel engine exhaust are low resistive in nature and extremely small in the range of 70~120 nanometers (nm) in average. These particles are penetrated into alveolus and extremely harmful to human health. These particles are generated from various emissions such as diesel automobiles, marine engines, power generation engines, and construction machines. The use of diesel particulate filter (DPF) was widely employed for the collection of automobile diesel PM, but was not cost effective, especially for marine engine emission where PM concentration is usually more than 50 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 particles are detached from the collection plate where the electrostatic repulsion force due to induction charge exceeds particle adhesion force and electrohydrodynamic shear streee on the collection electrode. This phenomenon has been known as particle reentrainment or resuspension, resulting in poor collection efficiency.

The regulation for automobile diesel PM emission was 0.01 g/kWh and NOx was 0.7 g/kWh by the year 2009. On the other hand, the marine engine regulation was much less restrictive by MARPOL treaty in 2005. More stringent regulations are forced by TEER-3 by 2011 and TEER-4 by 2016 (80% of NOx reduction at the present level). There are many references for controlling high resistive particles but very few literatures describing the control of particle reentrainment were available [1-8].

Recently, 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. Several pocket design collection plates were reported but was not taken into account electrohydrodynamics (EHD) to transport the charged particles into the pocket zone. However, these concepts have limited success for minimizing the reentrainment. Recently, electrostatic flocking filter on the collection electrode was developed to capture fine diesel particles [12]. 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 novel electrohydrodynamically-assisted ESP (EHD ESP) was developed to minimize the reentrainment in the ESP [13-14]. 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 particle captured in the pocket zone was exposed to zero electric field, so that no electrostatic repulsion force due to induction charge takes place. This is the major factor for the reduction of particle reentrainment. Obviously, particles exposed to electrostatic field such as between and above the pockets experiences the electrostatic repulsion force, which has to be minimized.

The latest EHD ESP design has holes inside of the pocket, which release the pressure buildup inside of the pocket to minimize the recirculation build up in the pocket, resulting in further reduction of reentrainment. In the present study, the EHD ESP and the conventional ESP were compared how significantly the collection efficiency or particle reentrainment can be minimized even with high gas flow velocities using both 2.3 L and 3.2 L diesel engine. The particle size-dependent collection efficiency and the mass-base collection efficiency were determined by Scanning Mobility Particle Sizer (SMPS TSI) with particle size in the range of 20-500 nm and particle counters (PC, RION) with particle size in the range of 300-5,000 nm.

2 EXPERIMENTAL SETUP

A 2.3 L diesel engine using heavy oil A (Hokuetsu Kogyo, PDS175S) with 2,000 rpm and 3.2 L diesel engine (Komatsu, 4D95LE-2) were used to achieve even higher gas flow velocity in the ESP. The constituents of the diesel PM 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 1,000 times by ambient air and particle size-dependent number densities before and after ESPs were determined by the SMPS (Scanning Mobility Particle Sizer, Model 3034) for the particle size ranged 20-800 nm and the particle counter (Rion KC-01C) for the article size of 300-5,000 nm, respectively. The load was varied from 0, 25, and 50% and exhaust gas temperature was changed accordingly. The gas velocity was measured by the hot wire anemometer (Kanomax).

The EHD ESP used for this experiment was shown in Fig. 1 for the EHD ESP. Their dimensions were designated in the figures, while the conventional ESP was the same dimension without pocket. When the gas was introduced into the ESP, the gas velocity was eventually lower for the conventional ESP. The EHD ESP consists of five teeth shaped electrodes and the collection plate with six pockets, while the conventional ESP does not have pockets. The channel width was 60 mm and its effective height was 200 mm. The 10 mm deep and 20 mm long pocket are attached to the collection plate with every 60 mm interval. The discharge electrode was the saw type, and their teeth were equally spaced with the interval of 10 mm. The distance between the discharge electrode and the upstream backside of the pocket was maintained at 20 mm, which was determined to be the optimum position by the preovious study [13]. The overall dimension of ESP section was 300 mm high and 420 mm wide without hopper and inlet and outlet transitions. The flue gas was connected to inlet and outlet of the ESP

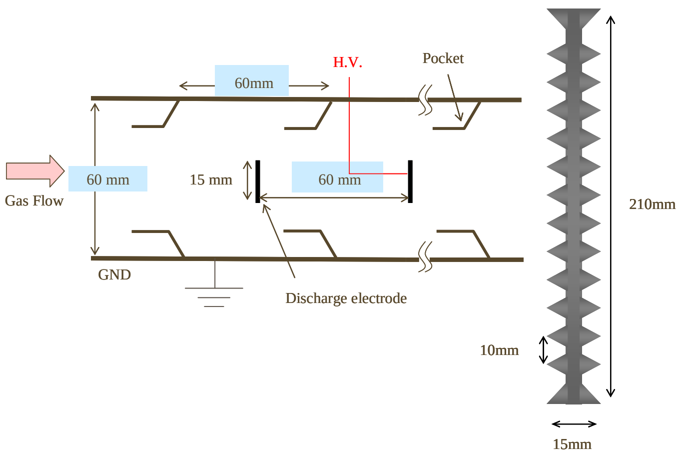


Fig. 1. EHD assisted ESP configuration

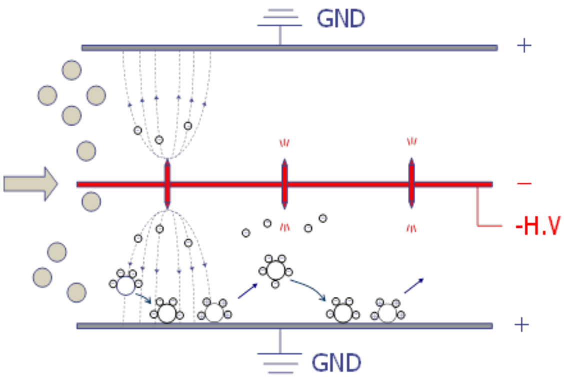


Fig. 2. Concept for low resistive particle reentrainment

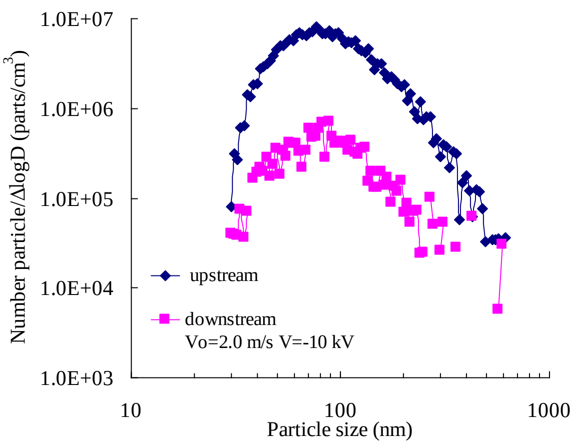
through the transition where 50% opening connected to inlet and outlet of the ESP through the transition where 50% opening perforated plates were placed to achieve a uniform flow in the ESP.

3 RESULTS and DISCUSSION

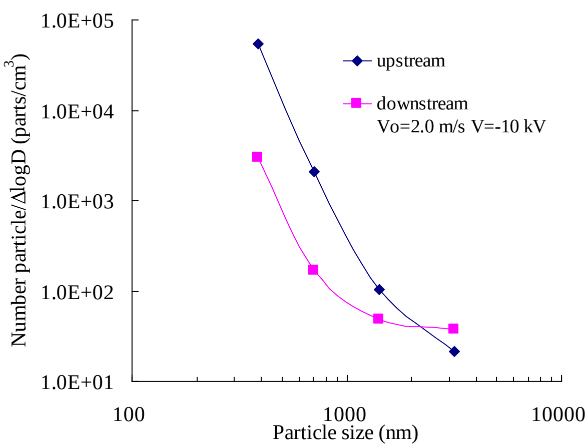
Particle reentrainment occurs when the particle resistivity is below 10^5 ohm-cm like diesel particles. Particles are charged under the electric field and move towards the collection plate by Coulomb force. The charges on particles were drained off to the ground plate and positive charges are immediately accumulated on the particle due to the induction charge, which experiences the particle repulsion force. This force is proportional to the square to the electric field and particle diameter. When the repulsion force exceeds the particle adhesion force, particles are detached from the surface and pushed back to 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 as shown in Fig. 2. The detained theoretical investigation including the electrohydrodynamics was reported earlier [13].

3.1 Experimental Results using 2.3L Engine with Heavy Oil of Grade A

A 2.3 L diesel engine using heavy oil of grade A was used. The engine used for compressor operation was run at 2,000 rpm and the load was not able to change for this experiment. The gas velocity was measured at 2.0 m/s for the EHD ESP and 1.35 m/s for the conventional ESP using 2.3 L engine. Fig. 3(a) shows the particle-size dependent number density for the EHD ESP, which was measured by SMPS when the applied voltage was modest V=-10 kV with I=0.5 mA, where the onset voltage was V=-6.0 kV and the spark over voltage was V=-17 kV with I=3.0 mA. One order of magnitude reduction was achieved for particle size of 300-500 nm. The particle size-dependent collection efficiency for particle size in the range of 300-5,000 nm measured by the



(a) Measured by SMPS

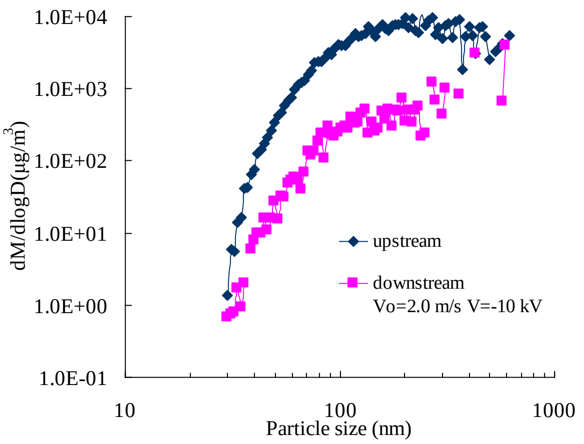


(b) Measured by PC

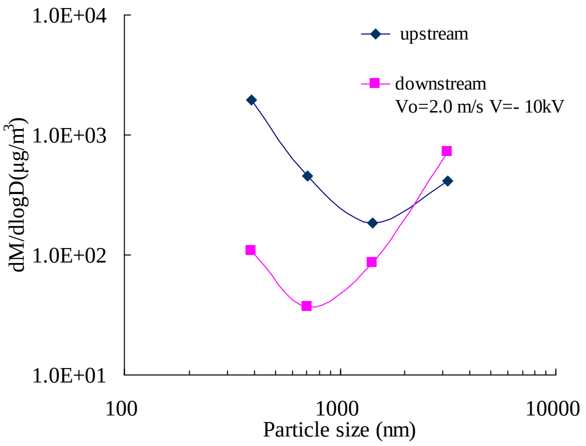
Fig. 3. Particle-size-dependent number density using 2.3 L diesel engine for the EHD ESP (V=-10 kV and V_o=2.0 m/s) (a) measured by SMPS,

PC was shown in Fig. 3(b). The collection efficiency was excellent up to 300-1,000 nm but decreased as particle size increased. At particle size of 3,000 nm, the collection efficiency was slightly negative, indicating some reentrainment for the EHD ESP. However, number density at 3,000-5,000 nm was less than 10 so that severe fluctuation was obvious.

Fig. 4(a) shows the particle size dependent mass-density distribution using 2.3 L diesel engine with V=-10 kV and V_o=2.0 m/s for the EHD ESP. The peak of mass density was shifted to larger particle size and the calculated mass collection efficiency for particle size of 30-500 nm was 92.9%. Fig. 4(b) shows the particle-size-dependent mass density in the range of 300-4,000 nm. The calculated mass collection efficiency for the particle size of 300-4,000 nm was 68.7%. The ESP has two roles: one is particle agglomeration and the other is particle capture. Negative collection efficiency indicated that the agglomerated large particles were reentained by the electrostatic repulsion force caused by induction charge. In addition, high flow velocity increased fluid dynamic shear stress on the particle layer of the collection plate. The overall mass collection efficiency for entire particle size range was 92.7%, which was dominated by the small particle size mass density. This was attributed to low number density for large particle size. Note that we do not have data for the conventional ESP at present.



(a) Measured by SMPS (92.9%)



(b) Measured by PC (68.7%)

Fig. 4 The particle size-dependent mass density using 2.3 L diesel engine for EHD ESP (V=-10 kV and Vo=2 m/s) (a) measured by SMPS (92.9%), (b) measured by PC (68.7% and the overall collection efficiency of 92.7%)

After 20 min of operation, majority of particles were collected for the first two stages of the EHD ESP and approximately 70% of particles were captured in the pockets. Based on observation of particle collection for the EHD ESP little particles are attached to the discharge electrodes after third electrodes, indicating no distinct particle reentrainment occurred as shown in Fig. 5.

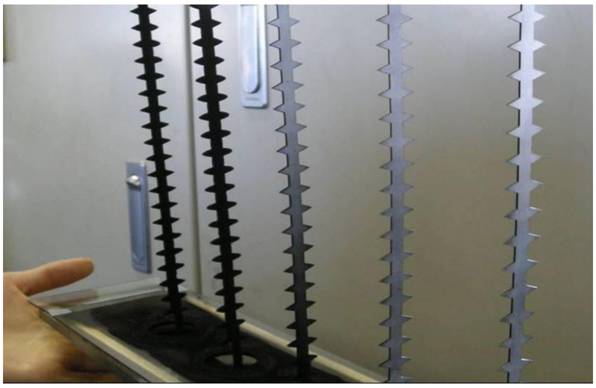


Fig. 5. View of particle collection on discharge electrodes, looking upstream from the EHD-ESP outlet

3.2 Experimental Results using 3.2 L Engine with Light Oil

A 3.2 L diesel engine using light oil was used as a follow-up experiment to achive a high gas velocity. The engine was run at 1,300 rpm and the load was varied at 0, 25, and 50%. The gas temperature at the ESP was increased with increased load: 105°C with 0% load, 150°C with 25% load, 220°C with 50% load. Also, particulate concentration was increased with increased load. The gas velocity for the EHD ESP and the conventional ESP was at 5.6 m/s and 3.7 m/s with 0% load, 6.4 m/s and 4.2 m/s with 25% load and 7.3 m/s and 4.9 m/s with 50% load, respectively.

The earlier EHD ESP was modified to add 40 of 3 mm holes on the pocket end the previous experiment in order to release the pressure buildup in the pocket so that the shear stress caused by the flow recirculation was minimized inside of the pocket, resulting in particle reentrainment. Fig. 6 shows the time-dependent number density collection efficiency as a function of particle size for the EHD ESP when the load is 0%. The number collection efficiency was in the range of 70% for particle size of 300-500nm, 80% for 500-1,000nm, 88% for 1,000-2,000nm, and 95% for 2,000-5,000nm over 20 min operation. The collection efficiency was increased with increased particle size which follows the classical electrostatic theory over 20 min operation, indicating less reentrainment. This was attributed to increased adhesion force by soluble organic compounds (SOFs) and moisture condensation due to low gas temperature (105°C) when the load is zero. Also, the particle surface resistivity could be more affected on over the volume surface resistivity.

Fig. 7 shows the time-dependent number density collection efficiency as a function of particle size for the conventional ESP when the load is 0%. The number density collection efficiency was in the range of 70% for particle size of 300-500nm, 77% for 500-1,000nm, 86% for 1,000-2,000nm, and 88% for 2,000-5,000nm over 20 min operation. The collection efficiency was maintained constant, indicating less reentrainment even for the conventional ESP. This was again due to increased adhesion force by low gas temperature. The overall collection efficiency was higher for the EHD ESP despite of higher gas flow velocity: 5.6 m/s for EHD ESP and 3.7 m/s for the conventional ESP.

Fig. 8 shows the time-dependent number density collection efficiency measured by the PC as a function of particle size for the EHD ESP when the load is 25%. The particle concentration increased with increased load. The number density collection efficiency was 85% in average over 20 min operation for particle size of 300-500nm, 80% in average for 500-1,000nm, and 90% for 1,000-2,000nm. However, the collection efficiency fluctuated a little 72-90% for 2,000-5,000nm. More fluctuation of particle collection efficiency was

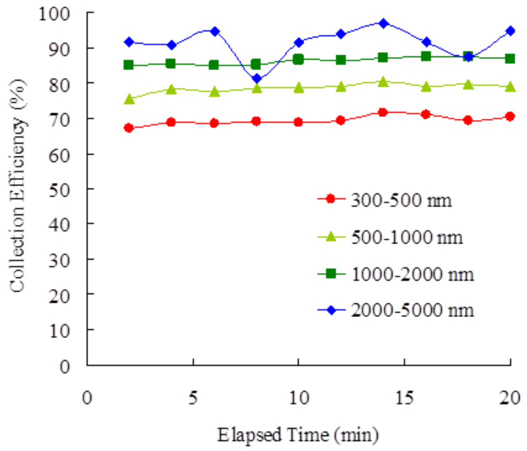


Fig. 6. The time-dependent number density collection efficiency as a function of particle size measured by PC for the EHD ESP when the load is 0%

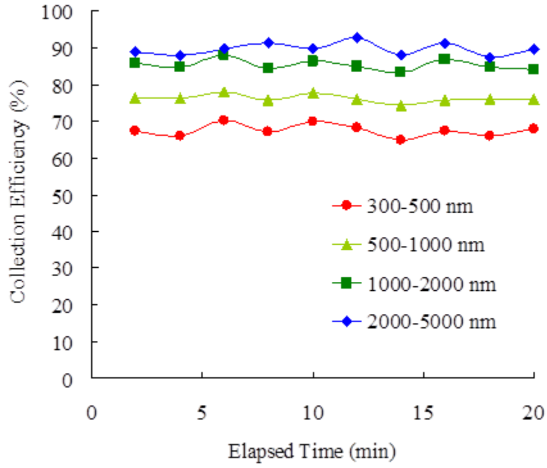


Fig. 7. The time-dependent number density collection efficiency as a function of particle size measured by PC for the conventional ESP when the load is 0%

observed for large particles. This was attributed to higher gas temperature (150^{o}C) and less adhesion force due to less SOF and moisture content. However, particle reentrainment was still small fraction.

Fig. 9 shows the time-dependent number density collection efficiency as a function of particle size for the conventional ESP when the load is 25%. The number collection efficiency was in the range of 80% for particle size of 300-500nm, 77% for 500-1,000nm, 82% for 1,000-2,000nm, and 50~87% for 2,000-5,000nm over 20 min operation. The overall collection efficiency was again higher for the EHD ESP despite of higher gas flow velocity:

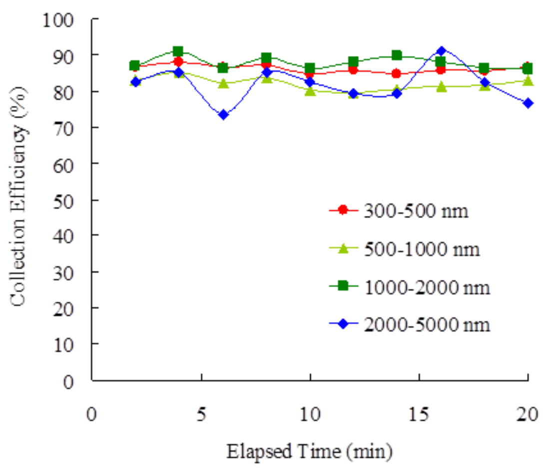


Fig. 8. The time-dependent number density collection efficiency as a function of particle size measured by PC for the EHD ESP when the load is 25%

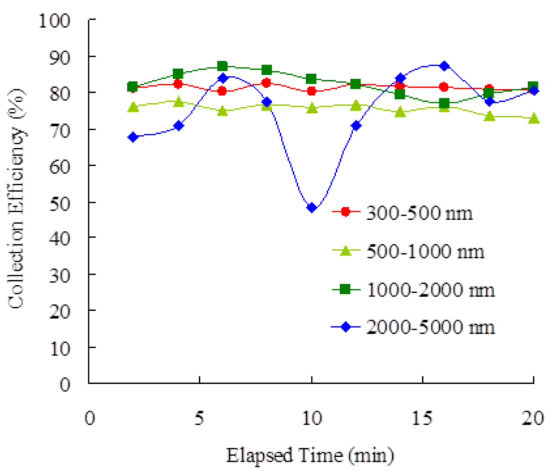


Fig. 9. The time-dependent number density collection efficiency as a function of particle size measured by the PC. for the conventional ESP when the load was 25%

6.4 m/s for the EHD ESP and 4.2 m/s for the conventional ESP. More fluctuation was observed for the conventional ESP in comparison with the EHD ESP, which results in more reentrainment despite of lower gas velocities.

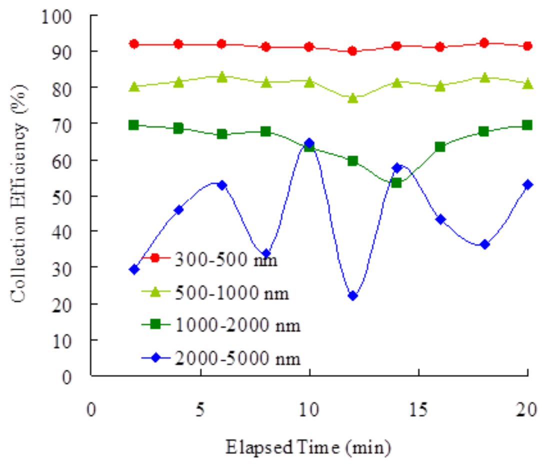


Fig. 10 The time-dependent number density collection efficiency measured by the PC as a function of particle size for the EHD ESP when the load is 50%

Fig. 10 shows the time-dependent number demnsity collection efficiency measured by the PC as a function of particle size for the EHD ESP when the load is 50%. The dust concentration and gas temperature was further increased with increased load. The number collection efficiency was more than 90% for particle size of 300-500nm, 82% in average for 500-1,000nm, and 62-80% for 1,000-2,000nm. However, the collection efficiency was fluctuated more in the range of 20~60% for 2,000-5,000nm. This was attributed to some reentrainment due to higher velocity (7.3 m/s) and less adhesion force due to higher gas temperature (220^{o}C). This fluctuation was also affected by less number density (less than 10^2 particles/cm^3) for this particle size range. The overall number collection efficiency was very high despite of higher gas velocity. No data was available for the conventional ESP. Also, SMPS data to measure nano particles are not available at present for 3.2 L engine. Also, lower collection efficiency achieved for particle size of 300-500nm for low load operation was not clear at present despite of increased adhesion force.

However, the EHD ESP showed a significant good collection efficacy over the conventional ESP despite of high gas velocities and demonstrated a reduction of reentrainment We are still looking for the detailed electrohydrodynamics of both EHD ESP and conventinoal ESP using Shlieren system and particles behavior using PIV system. This will lead to determine the optimum design for minimizing particle reentrainment with much higher gas velocities such as 20 m/s for the EHD ESP in order to achieve more compact and economical ESP for a wide range of diesel emission.

5 SUMMARY

The collection of low resistive particles generated from diesel engines was investigated using two large diesel engines. Both the conventional ESP and the EHD ESP showed a good collection efficiency for low load condition or low gas temperature, where adhesion force was dominated due to SOF and moisture content in the flue gas over electrostatic repulsion force, resulting in little particle reentrainment. For the high load or high gas temperature case, where the particle reentrainment is sevior, reentrainment was significantly supressed and excellent collection efficiency was obtained even for high gas velocities in the range of 7 m/s and for the EHD ESP in comparison with the conventional ESP. This leads to more economical and compact ESP feasible for a wide range of diesel emission control.

ACKNOWLEDGMENT

Authors wish to thank you for support by Grant-in-Aid for Scientific Research (B) of the Japanese Society for the Promotion of Scienceand the Ocean Policy Research Foundation (OPRF).

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