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 2.3 L and 3.2 L diesel 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°C to 280°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 demonstrated a significantly high collection efficiency even at high gas flow velocities in comparison with the conventional ESP.

Keywords—electrohydrodynamics, ESP, reentrainment. diesel particulates, low resistive particulates

I. 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 collected are detached from the collection plate, i.e. the electrostatic repulsion force due to induction charge and electrohydrodynamic shear stress exceeds particle adhesion force. 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 Tier-2 by 2011 and Tier-3 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 did not utilize 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 was exposed to zero electric field, so that no electrostatic repulsion force due to induction charge takes place. This is the major contribution 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 on the pocket, which release the pressure buildup inside of the pocket to minimize the recirculation inside 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 engines. 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.

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Presented at the 12th International Conference of Electrostatic Precipitation, ICESP, in May 2011 (Nuremberg, Germany)

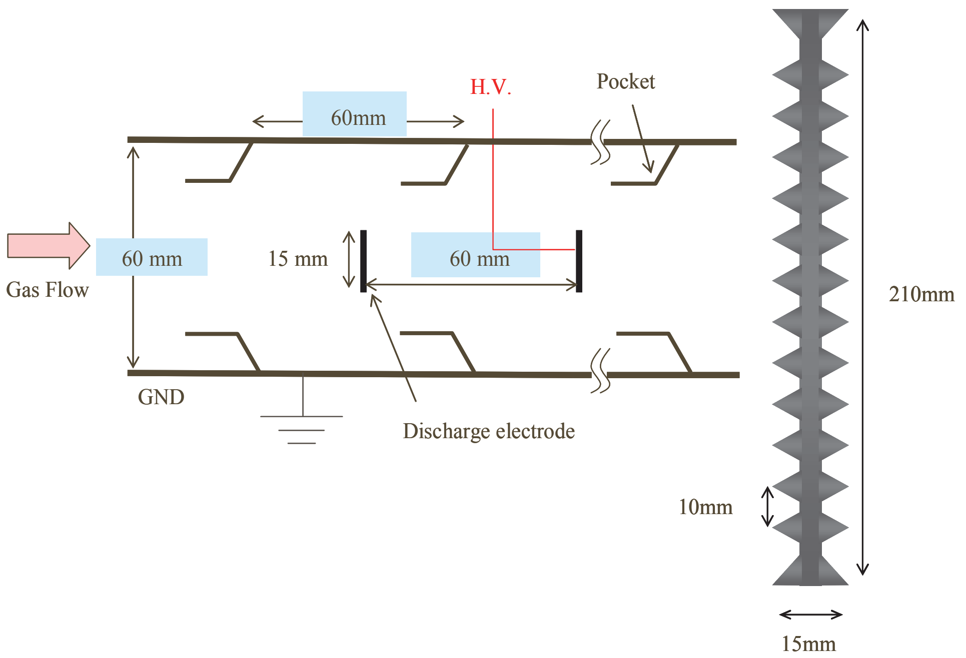


Fig. 1. EHD assisted ESP configuration.

II. Experimental Setup

A 2.3 L diesel engine using heavy oil A (Hokuetsu Kogyo, PDS175S) with a constant speed of 2,000 rpm and a 3.2 L diesel engine (Komatsu, 4D95LE-2) with various engine speed were used to investigate even higher gas flow velocity and load 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 ESP were determined by the SMPS (Scanning Mobility Particle Sizer, Model 3034) for the particle size ranged 20-800 nm and the PC (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 varied 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 two collection plates with six pockets each, 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 saws 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 previous 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 through the transition where 50% opening perforated plates were placed to achieve a uniform flow in the ESP.

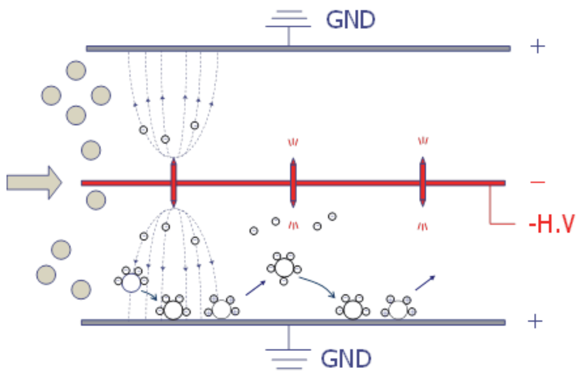


Fig. 2. Concept for low resistive particle reentrainment.

III. Results and Discussion

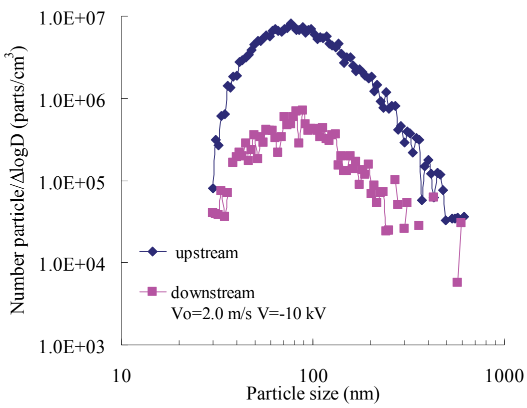
Particle reentrainment occurs when the particle resistivity is below 10^5 ohm-cm like diesel particles. Particles are charged under the electric field and move towards the collection plate by Coulomb force. The negative charges on particles with negative DC discharge were drained off to the ground electrode 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 [13, 14]. When the electrostatic repulsion force combined with electrohydrodybnamic shear stress 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 particles are escaped from the ESP without collection, i.e., particle reentrainment as shown in Fig. 2. The detained theoretical investigation including the electrohydrodynamic repulsion was reported earlier [13].

A. Experimental Results using 2.3L Engine with Grade A Heavy Oil

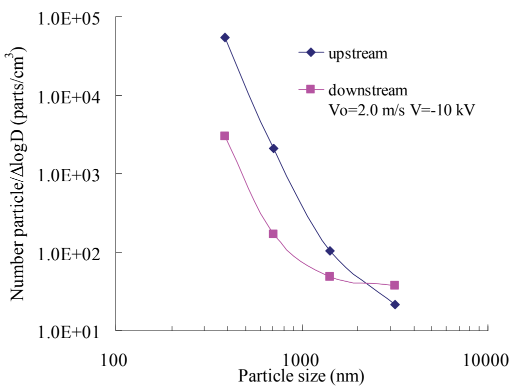
Grade A heavy oil was used for 2.3 L diesel engine, which was used for compressor operation. The engine was run at 2,000 rpm and the load was not able to change for this application. The gas velocity was measured at 2.0 m/s for the EHD ESP and 1.35 m/s for the conventional ESP (EHD ESP without pocket). 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 for particle number density 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 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 average 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. Note that the conventional ESP showed negative collection efficiency beyond particle size of 1,000 nm [13, 14].

Fig. 4(a) shows the particle size-dependent mass-density distribution using 2.3 L diesel engine with $V = -10$ kV and $V_0 = 2.0$ 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% with measured particle density of 0.886 g/cm^3. Fig. 4(b) shows the particle size-dependent mass density distribution 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 overall collection efficiency was 92.7%, implying that the overall efficiency was dominated by the small particle size due to higher number density. The experimental error was within 5.0%.

The ESP has two roles: one is particle precipitation

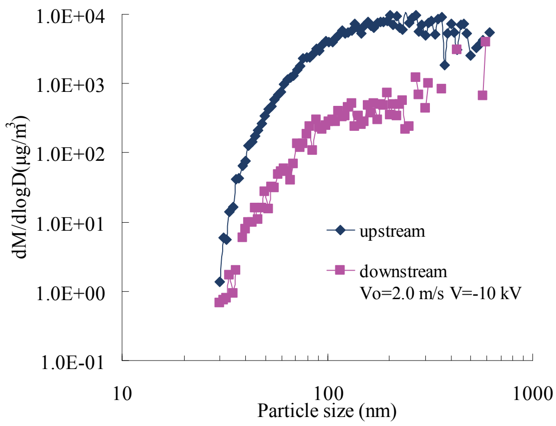


(a) Measured by SMPS

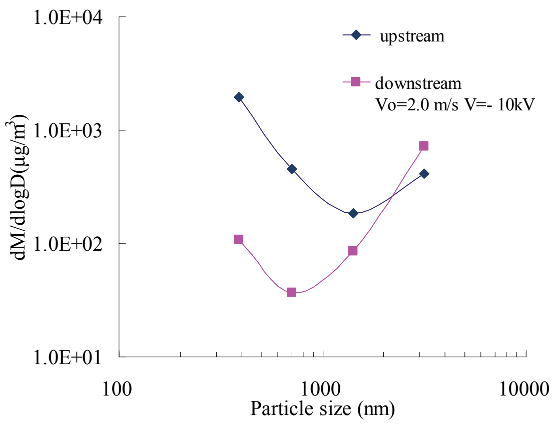


(b) Measured by PC

Fig. 3. Particle-size-dependent number density using 2.3 L diesel engine for the EHD ESP ($V = -10$ kV and $V_0 = 2.0$ m/s). (a) measured by SMPS, (b) measured by PC



(a) Measured by SMPS (calculated mass collection efficiency of 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 $V_0 = 2.0$ m/s). (a) measured by SMPS (92.9%), (b) measured by PC (calculated mass collection efficiency of 68.7% and the overall collection efficiency of 92.7%)

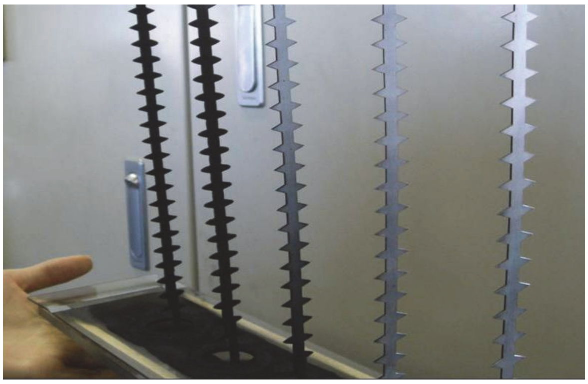


Fig. 5. View of particle collection on discharge electrodes, looking upstream from the EHD-ESP outlet.

and the other is particle agglomeration. 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 electrohydrodynamic shear stress on the particle layer. This was attributed to low number density for large particle size. Note that we do not have data for the conventional ESP at present.

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 precipitated on the discharge electrodes after third electrodes, indicating no distinct particle reentrainment occurred as shown in Fig. 5.

B. 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 achieve 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^{o}C with 0% load, 150^{o}C with 25% load, 220^{o}C with 50% load. Also, particulate concentration 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, while maintaining the same gas volume for both ESP operation.

The previous 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. Therefore, 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 density collection efficiency was in the range of 70% for particle size of 300-500 nm, 80% for 500-1,000 nm, 88% for 1,000-2,000 nm, and 95% for 2,000-5,000 nm over 20 min operation. The collection

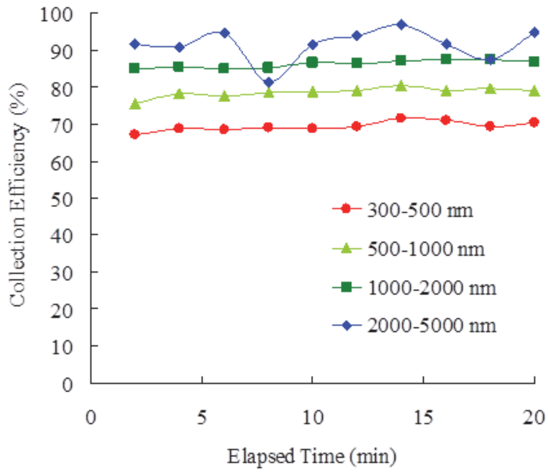


Fig. 6. The time-dependent number density collection efficiency as a function of particle size measured by PC for the EHD ESP when the load is 0%.

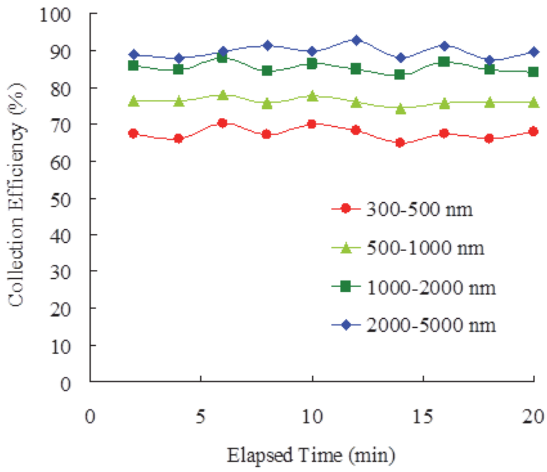


Fig. 7. The time-dependent number density collection efficiency as a function of particle size measured by PC for the conventional ESP when the load is 0%

efficiency was increased with increased particle size which follows the classical electrostatic theory, indicating less reentrainment. This was attributed to increased adhesion force by soluble organic compounds (SOFs) and moisture condensation due to low gas temperature (105^{o}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 300-500 nm, 77% for 500-1,000 nm, 86% for 1,000-2,000 nm, and 88% for 2,000-5,000 nm 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.

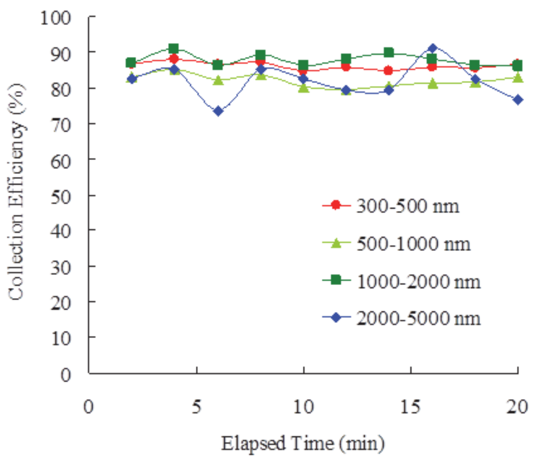


Fig. 8. The time-dependent number density collection efficiency as a function of particle size measured by PC for the EHD ESP when the load is 25%.

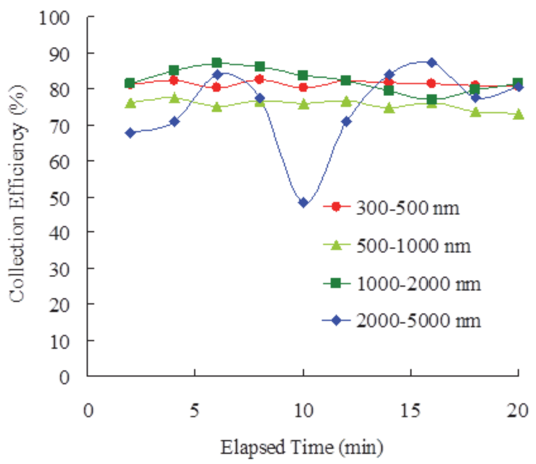


Fig. 9. The time-dependent number density collection efficiency as a function of particle size measured by the PC for the conventional ESP when the load was 25%.

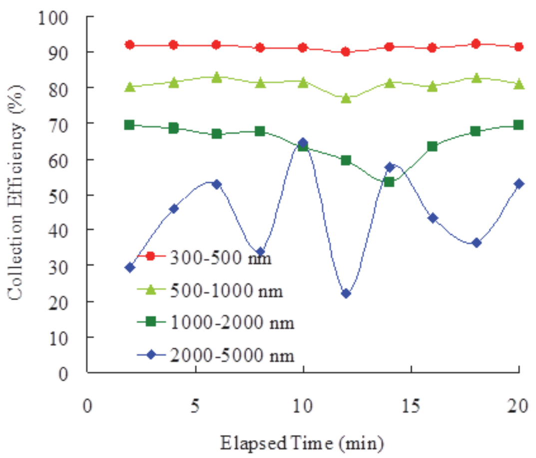


Fig. 10. The time-dependent number density collection efficiency measured by the PC as a function of particle size for the EHD ESP when the load is 50%.

Fig. 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 300-500 nm, 80% in average for 500-1,000 nm, and 90% for 1,000-2,000 nm. However, the collection efficiency fluctuated a little 72-90% for 2,000-5,000 nm. More fluctuation of particle collection efficiency was observed for large particles. This was attributed to higher gas temperature (150°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 300-500 nm, 77% for 500-1,000 nm, 82% for 1,000-2,000 nm, and 50~87% for 2,000-5,000 nm over 20 min operation. The overall collection efficiency was again higher for the EHD ESP despite of higher gas flow velocity: 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 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 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 300-500 nm, 82% in average for 500-1,000 nm, and 62-80% for 1,000-2,000 nm. However, the collection efficiency was fluctuated more in the range of 20~60% for 2,000-5,000 nm. This was attributed to some reentrainment due to higher velocity (7.3 m/s) and less adhesion force due to higher gas temperature (220°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 significantly 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 conventional 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.

IV. 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. The adhesion force was dominated due to SOF and moisture content in the flue gas over electrostatic repulsion force, which results in little particle reentrainment. For the high load or high gas temperature operation, reentrainment was significantly suppressed and good 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 Science and the Ocean Policy Research Foundation (OPRF).

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