Diesel Exhaust Particle Reduction using Electrostatic Precipitator

H. Kawakami¹, A. Zukeran², K. Yasumoto¹, M. Kuboshima³, Y. Ehara³, and T. Yamamoto³
¹Road Systems Engineering Department, Fuji Electric Co., Ltd., Japan
²Department of Electronic & Electrical Engineering, Kanagawa Institute of Technology, Japan
³Department of Electrical & Electronic Engineering, Tokyo City University, Japan

Abstract—Electrostatic precipitators (ESPs) are used to decontaminate polluted environment. Conventional ESPs have high collection efficiency but still have a problem in that their collection efficiency decreases due to particle re-entrainment for collection of low resistive diesel particulates such as marine engines. In this study, the effect of electrode configuration on collection performance of diesel particulates was investigated using one-stage and two-stage ESPs. The particle concentration for the particle-size range of 20 to 5,000 nm was measured using a scanning mobility particle sizer (SMPS) and a particle counter (PC). The collected particles on electrodes were observed using a scanning electron microscope (SEM). The collection efficiencies as a function of the electrode length and the particle diameter were estimated. As a result, the particle re-entrainment was suppressed with increasing number of discharge electrodes in the one-stage type ESP and increasing collection electrode length of the collecting section in the two-stage type ESP.

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

I. INTRODUCTION

Electrostatic precipitators (ESPs) have been extensively used for the cleaning of industrial process flue gases, combustion flue gases, and ventilation flue gases of road tunnels, etc. Conventional ESPs have high collection efficiency but still have a problem in that their collection efficiency decreases due to particle re-entrainment. The collection of 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 stress on the collection electrode. This phenomenon has been known as particle re-entrainment. These particles are emitted from various sources such as marine engines, diesel automobiles, power generation engines, and tunnel or underground parking. Therefore, it is very important to suppress the re-entrainment.

Fujimura et al. measured the relation between the particle size distribution and the optical density. They studied the influence of the re-entrainment on the visibility in road tunnels [1]. Takahashi et al. studied the influence of the re-entrainment on the particle deposition on a wall [2]. Re-entrained particle charging polarity and the particle behavior after re-entrainment were investigated [3]. H. Masuda et al. suggested that charged particles were more easily re-entrained than uncharged particles [4] and the frequency of the re-entrainment depended on the structure of the electrode surface, the gas velocity and the particle size [5]. Felder et al. noted that collection electrodes covered with particles exhibited higher efficiency than uncovered collection electrodes. They concluded that this is due to the decreased re-entrainment [6]. Several ideas that have been proposed to suppress re-entrainment are as follows;

1) collection electrode coated with a dielectric sheet [7],
2) mixing water mist with gases [8],
3) using an ESP as an agglomerator [9, 10]
4) silent discharge type ESP [11]
5) application of gradient force [12]

However, these concepts achieved only limited success for minimizing the re-entrainment and investigation of the fundamental collection characteristic for low resistivity particles was not enough at the high dust loading and the high gas temperature. An ESP using low frequency rectangular AC field has been used to suppress the particle re-entrainment for road tunnels [13]. It also achieved only limited success in the high dust-loading condition. An electrohydrodynamically assisted ESP was proposed in this condition [14].

In this paper, the fundamental collection characteristics under high dust-loading and high gas temperature conditions were investigated for one-stage and two-stage ESPs. The influences of the number of discharge electrodes, the collection electrode length and the engine load on the particle size–dependent collection efficiency were investigated using a 199-cc engine. The particle concentration for the particle-size range of 20 to 5,000 nm was measured using a scanning mobility particle sizer (SMPS) and a particle counter (PC). The collected particles on the electrodes were observed using a scanning electron microscope (SEM).

II. EXPERIMENTAL SETUP

A schematic diagram of the experimental system is shown in Fig. 1. Emissions from small diesel engine generator (Yammer Co., Ltd., YDG200A-5E, direct injection type for a single cylinder, displacement volume of 199-cc, maximum electric power output of 1.7 kW) using light oil with 3000 rpm were used to create a high dust-loading and high gas temperature condition in the ESP. In order to determine the particle number density in the ESP, the flue gas was diluted approximately 100

Corresponding author: Akinori Zukeran
Corresponding author: Akinori Zukeran
Corresponding author: Akinori Zukeran
e-mail address:
e-mail address:
e-mail address:
zukeran-akinori@ele.kanagawa-it.ac.jp
zukeran-akinori@ele.kanagawa-it.ac.jp
zukeran-akinori@ele.kanagawa-it.ac.jp

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times by the dilution machine (MD19-3E, Matter) and the particle size-dependent number densities before and after the ESPs were determined by the Scanning Mobility Particle Sizer (SMPS, Model3080, TSI) for the particle-size range of 20-300 nm and the Particle Counter (KC01-E, RION) for the particle-size range of 300-5,000 nm, respectively. The collected particles on the collection electrode were observed using a scanning electron microscope (SEM). The exhaust gas temperature was 130-200°C. The gas velocity in the ESP was approximately 1.3 m/s. The engine load was set to 30, 60 and 90%. The collection efficiency ψ was calculated by equation (1): 

$$\psi = \left[ 1 - \frac{N_d}{N_u} \right] \times 100 \quad [\%]$$  

(1)

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

The one-stage type ESP configuration was as shown in Fig. 2. The one-stage type ESP consisted of grounded plate electrodes and discharge electrodes. The length of the grounded plate electrode was 150, 300 and 450 mm. The discharge electrode has saw-toothed edges on upstream and downstream sides to increase particle charge. The length of the discharge electrode was 130 mm. The spacing between the adjacent plates was 9 mm. -7.5 kV DC was applied to the one-stage type ESP. Aluminium foils were attached to the electrodes to observe collected particles using SEM as shown in Fig. 2 (b).

The two-stage type ESP configuration was as shown in Fig. 3. The two-stage type ESP consisted of the pre-charger and the collecting section. The pre-charger was the same as the one-stage type ESP shown in Fig. 2. However, the length of the grounded plate electrode was 150 mm. The collecting section had a parallel plate configuration and the spacing between each plate was 9 mm. The length of the electrode was 150, 300 and 450 mm. -7.5 kV DC was applied to the pre-charger and -8 kV DC was applied to the collecting section. Aluminium foils were attached on each grounded electrode in the collecting section to observe collected particles by SEM.

The particle-size dependent number density upstream of the ESP for various engine loads was as shown in Fig.4. A maximum value at particle diameter approximately 70 nm was observed for the engine load of
30%. The peak of number density shifted to larger particle sizes with increasing engine load. The maximum value also increased with the engine load.

The particle-size dependent mass density upstream of the ESP for various engine loads was as shown in Fig. 5. The peaks of mass density were found at larger particle sizes than the peaks of the particle number density shown in Fig. 4. The total mass densities were 1.5 mg/m³ at the engine load of 30%, 15.4 mg/m³ at 60% and 85 mg/m³ at 90%.

III. RESULTS AND DISCUSSION

A. Collection for One-Stage ESP

The particle size distributions upstream and downstream of the ESP at the engine loads of 30, 60 and 90% were as shown in Fig. 6-8. The number distribution and the mass distribution were indicated in Figures. The number density downstream of the ESP was lower than upstream of the ESP due to particle collection in all cases. Fig. 9 shows the particle-size dependent collection efficiency for various engine loads when the electrode length was 450 mm. The collection efficiency within the particle-size range of 300-5,000 nm for the engine load of 90% decreased with increasing particle diameter. The collection of low resistive particles such as diesel exhaust particles are detached from the collection plate where the
electrostatic repulsion force due to induction charge exceeds particle adhesion force and electrohydrodynamic shear stress on the collection electrode. This phenomenon has been known as particle re-entrainment [3]. The collection efficiency for particle sizes larger than 1,000 nm increased with decreasing engine load. This was attributed to an increased adhesion force by soluble organic compounds (SOFs) due to the decrease in the engine load [15].

Fig. 10 shows the particle-size dependent collection efficiency for various electrode lengths in the one-stage type ESP, where the engines load was 90% which was easy to re-entrain. The collection efficiency within the particle-size range of 20-300 nm was greater than almost 90% for all electrode lengths. The collection efficiency within the particle-size range of 300-5,000 nm for the electrode length of 150 mm decreased with increasing particle size. The collection efficiency at particle sizes greater than 2,000 nm had negative values. The negative collection efficiency indicated that the downstream particle density was greater than upstream particle density due to particle re-entrainment. The collection efficiency within the particle-size range of 300-5,000 nm increased with the electrode length. The collection efficiency at the electrode length greater than 300 mm had positive values due to the suppressed particle re-entrainment.

The collected particles on the surface of electrodes were observed to investigate the mechanism of suppressing particle re-entrainment. Pieces of aluminium foil were attached on the grounded electrode surfaces to sample particles as shown in Fig. 2 (b). The pieces were prepared for the SEM. Typical SEM images of the collected particles for various sampling locations are shown in Fig. 11. Many large agglomerations of particles were observed on the electrode surface under the saw-toothed edge as shown in Fig. 11 (a). The particles were pressed down by wind pressure of corona wind. Therefore, the particles were spherical in shape, which increased the contact area between the particles and the electrodes and made the particles difficult to be re-entrained from area under the saw-toothed edge. The particles at the middle position of the grounded electrode formed dendrite due to agglomeration in electrostatic field as shown in Fig. 11 (b). The charges on the particles were drained off to the grounded electrode and the positive charges were accumulated on the particles due to the induction charge, resulting in the dendrite form. The dendrite-formed particle was easy to be re-entrained due to the aerodynamic force when exposed to the gas stream.
The area under the saw-toothed edge, where the particles were difficult to be re-entrained, increased with the discharge electrode length, resulting in a further suppression of the re-entrainment.

B. Collection for Two-Stage ESP

Fig. 12 shows the particle-size dependent collection efficiency for various collecting electrode lengths for the two-stage type ESP when the electrode length of the precharger was 150 mm and the engine load was 60% which was average load of marine engine [17]. The collection efficiency within the particle-size range of 20-300 nm was greater than 90% for all electrode lengths. The collection efficiency within the particle-size range of 300-5,000 nm for the electrode length of 150 mm decreased with increasing particle size. The collection efficiency for particle sizes greater than 2,000 nm had negative values due to particle re-entrainment. The collection efficiency within the particle-size range of 300-5,000 nm increased with the electrode length. The collection efficiency at the electrode length of 450 mm had positive values due to the suppressed re-entrainment.

The collected particles on the surface of electrodes were observed to investigate the mechanism of suppressing re-entrainment for the two-stage type ESP. Pieces of aluminium foil were attached on the grounded electrode surfaces to sample particles as shown in Fig. 3. Typical SEM images of the collected particles for various sampling locations for two-stage type ESP are shown in Fig. 13. Many large agglomerations of particles were observed on the electrode surface at the positions of 75 mm and 225 mm as shown in Fig. 13 (a) and (b). The agglomeration particles formed dendrite which was easy to be re-entrained. The spherical agglomerations of particles, which were difficult to be re-entrained, were observed on the electrode surface of 375 mm as shown in Fig. 13 (c). The positively charged re-entrainment particle from the grounded electrode was re-collected on the negative high voltage electrode. The re-collected particle on the negative high voltage electrode was charged positively due to induction charge and re-entrained again. These processes were repeated and the particle was changed to a spherical shape, which impeded further re-entrainment.

IV. CONCLUSION

The effect of the electrode configuration on the collection performance of diesel particulates was investigated using one-stage and two-stage ESPs. The collection efficiency for the electrode length of 150 mm decreased with increasing particle size in the one-stage type ESP due to particle re-entrainment. The
area under the saw-toothed edge increased with the discharge electrode length, resulting in further suppression of re-entrainment.

The collection efficiency for the collection electrode length of 150 mm decreased with increasing particle size in the two-stage type ESP due to re-entrainment. The particle re-entrainment became suppressed with increasing collection electrode length.

It is clear that particle re-entrainment was suppressed by increasing the collection electrode length in this study. It needs further consideration for the comparison of the performances in the one-stage type ESP and the two-stage type ESP.

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