Influence of Duty Ratio on Collection Efficiency in a Rectangular AC Energized Electrostatic Precipitator

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Abstract—Collection of low resistive particulate matter (PM) emitted from automobile and marine diesel engines or diesel generators have been known to be difficult by conventional electrostatic precipitators (ESPs). A two-stage ESP utilizing AC high voltage significantly suppresses 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 as well as tunnels or underground parking. Therefore, it is very important to suppress the re-entrainment.

Fujimura et al. determined the relation between the particle size distribution and the optical density. They concluded that this was 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. Recently, an electrohydrodynamically assisted ESP was proposed for preventing the re-entrainment [13].

A two-stage ESP employing the charging section by DC field, followed by the collection section by low frequency AC field including the rectangular waveforms in the range of 0.1 to 20 Hz has been investigated for the collection of diesel particles in tunnels [14], while the conventional ESP utilizes DC high voltage. The ESP utilizing AC high voltage significantly suppresses particle re-entrainment.

In this paper, the influence of duty ratio on collection efficiency in a rectangular AC energized ESP is investigated. The ESP consists of the pre-charger and the collector. The pre-charger consists of wire electrodes and grounded plate electrodes. A negative DC voltage of 10.5 kV is applied. The collector has a parallel-plates configuration and the spacing between the adjacent plates is 9 mm. Rectangular AC high voltages are applied to the collector. The rectangular AC waveform is 7.8 kV in voltage, with a cycle of 1 s including 0.05–0.5 s of positive high voltage time. The negative DC high voltage is also applied to the collector. The gas flow velocity is 9 m/s. The particle concentrations on the upstream and downstream sides of ESP are measured by particle counters (RION, KC-01D), and collection efficiencies are calculated.

The result has demonstrated that the effect of suppressing the particle re-entrainment is not influenced by the duty ratio of the rectangular AC high voltage.

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 as well as tunnels or underground parking. Therefore, it is very important to suppress the re-entrainment.

Fujimura et al. determined 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]. 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 was due to the decreased re-entrainment [6].

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

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II. EXPERIMENTAL METHOD

A. Summary of Experimental System

The experiments were carried out using two systems which were type-A and type-B. Two systems are basically same. The schematic of the experimental system used in the present work is shown in Fig. 1. The exhaust gases from the diesel engine are diluted with air in the mixing chamber, then boosted by the fan and introduced into the ESP system. The gases cleaned by the ESP pass through an induced fan, to be eventually discharged. The gas velocity in the ESP is approximately 9 m/s, and the gas flow rate is approximately 0.8 m³/s.

B. ESP Arrangement and Sampling Location

The structure of the ESP is shown in Fig. 2. The two-stage type ESP consists of the pre-charger and the collector. The pre-charger includes tungsten wires of 0.26 mm in diameter and aluminum plates. The collector has a parallel-plates configuration and the spacing between the adjacent plates is 9 mm. The length of the electrodes are 824 mm in type-A. The length of the grounded electrode is 900 mm and that of the high voltage electrode is 827 mm in type-B.

A -10.5kV DC voltage (corona current was 2.1 mA, current density was 5.8 mA/m²) was applied to the pre-charger, and -7.8 kV DC or 7.8 kV rectangular AC voltage was applied to the collector. Two modes of rectangular AC high voltages as shown in Fig. 3 were used. In one mode, the time of positive high voltage was changed between 0.05 and 0.5 s, with a fixed period of 1.0 s, to investigate the influence of that change on the effect of preventing the re-entrainment as shown in Fig. 3-a. In the other mode, the period was changed between 1.0 and 4.5 s with a fixed time of positive high voltage as shown in Fig. 3-b.

The particle size-dependent number densities were determined by the particle counter (PC; RION, model KC-01C) for the particle size larger than 300 nm, and the particle weight concentration were measured using the digital dust monitor before and after ESP (AP-632T, SHIBATA) as shown in Fig. 2. The collection efficiency \( \eta \) was calculated by equation (1):

\[
\eta = \left\{ 1 - \frac{N_D}{N_U} \right\} \times 100
\]

(1)

where \( N_U \) is the particle concentration on the upstream side of ESP, and \( N_D \) on the downstream side.

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![Fig. 1. Schematic of the experimental system.](image)

![Fig. 2. Structure of ESP.](image)
III. RESULTS

A. Effect of AC Operation

The effect of AC operation was investigated using the experimental system of type-A. The particle size distribution in ESP utilizing DC high voltage, measured by PC, is shown in Fig. 4. The size distribution is indicated in log-normal scale, where $N$ is the number concentration of particles of diameter $d$. The number concentration was measured for the particle size between 300 nm and 5000 nm. The upstream and downstream distributions are indicated. The total upstream number concentration is approximately $1 \times 10^8$ part/m$^3$. The number concentration is highest at a particle diameter of 300 nm, and decreases with increasing particle diameter on both the upstream and downstream sides. The downstream particle concentration is lower than the upstream value due to the effect of collection. However, the decreasing rate for the particle size between 1,000 nm and 5,000 nm is lower than between 300 nm and 1,000 nm.

The time-dependent number density collection efficiency, when the DC high voltage was applied to the collector, measured by PC, is shown in Fig. 5. The collection efficiencies of particles with a diameter of 300 to 500 nm and 500 to 1,000 nm were almost constant with time. The collection efficiencies of particles with a diameter of 1,000 to 2,000 nm and 2,000 to 5,000 nm were greater than 85% for 6 min after operation. However, they decreased with elapsing time due to particle re-entrainment. The collected particles on the grounded electrode formed dendrite due to agglomeration in the electrostatic field. 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, thus decreasing the collection efficiency. Therefore, the decreasing rate for the particle size between 1,000 nm

![Fig. 3. Rectangular AC high voltage waveform.](image)

$T_+$: Time of positive high voltage [s]. $T$: Period time [s].

![Fig. 4. The particle size distribution in ESP utilizing DC high voltage, measured by PC.](image)

![Fig. 5. The time-dependent number density collection efficiency in ESP utilizing DC high voltage, measured by PC.](image)
and 5,000 nm is lower than between 300 nm and 1,000 nm as shown in Fig. 4.

The particle size distribution in ESP utilizing rectangular AC high voltage with a period of 4.5 s including 0.1 s for applying the positive high voltage, measured by PC, is shown in Fig. 6. The general tendency is the same as the particle size distribution in ESP utilizing DC high voltage as shown in Fig. 4. However, it is clear that the decreasing rate for the particle size of 1,000 nm to 5,000 nm is greater than the rate for 300 nm to 1,000 nm in comparison with Fig. 4.

The time-dependent number density collection efficiency in ESP utilizing rectangular AC high voltage with a period of 4.5 s including 0.1 s for applying positive high voltage, measured by PC is shown in Fig. 7. The collection efficiencies for all particle diameters are at high levels between 80 and 95%, and almost constant with time in comparison with the characteristic of ESP utilizing DC high voltage as shown in Fig. 5.

The collection efficiency as a function of particle diameter for various operation modes, measured by PC, is shown in Fig. 8. The average collection efficiency of DC operation before re-entrainment for 6 min is almost the same as AC operation. However, the large particle collection efficiency between 6 and 50 min is lower than in the case of the AC operation due to the particle re-entrainment. It is clear that the particle re-entrainment is suppressed due to AC operation. The collected particles formed dendrite due to agglomeration on the electrode in the collector. When the electric field changes, the shape of the dendrite form particles becomes spherical. The spherical particles have a large contact area between the particles and the electrode and thereby increase the adhesion force between the particles and the electrode. As a result, the particle re-entrainment is assuredly prevented in comparison with DC operation.

B. Influence of Duty Ratio of AC High Voltage

The influence of duty ratio of AC high voltage was investigated using the experimental system of type-A. The collection efficiency as a function of particle diameter for various duty ratios in ESP utilizing rectangular AC high voltage, measured by PC, is shown in Fig. 9. The period of AC high voltage is 1 s, with the time of positive high voltage between 0.05 and 0.5 s, i.e., 0.05 to 0.5 in duty ratio. The collection efficiencies increase with increasing particle diameter due to the suppressed particle re-entrainment. The collection efficiency with the positive time of 0.25 s is approximately 5% less than the other conditions. This is probably due to the influences of the temperature, the humidity or the particle concentration. We consider that the collection efficiencies are roughly the same at all duty ratios, so that the tendencies of three conditions, which are the positive times of 0.5, 0.1 and 0.05 s, are the same. It is clear that the effect of rectangular AC high voltage for preventing particle re-entrainment does not depend on the duty ratio. This result also indicates that
Particle weight concentrations were measured using Digital dust monitor (AP-632T, SHIBATA). Particle weight concentrations were measured using Digital dust monitor (AP-632T, SHIBATA). The collection efficiency as a function of particle diameter was obtained by equation (2).

\[ \eta_t = (\eta_+^T_+ + \eta_-^T_-) / T \]  

where \( \eta_t \) is the collection efficiency of 90% at the duty ratio of 0, \( \eta_+ \) is the collection efficiency of 38% at the duty ratio of 1, \( T_+ \) is the time of positive high voltage which is between 0 to 4.5 s, \( T_-(T = 4.5 - T_+) \) is the time of negative high voltage, and \( T \) is the period time (\( T_+ + T_- \)) of 4.5 s.

The collection efficiency as a function of the duty ratio is shown in Fig. 11. The experimental collection efficiency is 90% at the duty ratio of 0, which means applying the negative DC high voltage. On the other hand, the collection efficiency is 38% at the duty ratio of 1, which means applying the positive DC high voltage. This cause is that dust is put on the surface of the high voltage electrode in the collector before starting experiment. The particles are negatively charged in the pre-charger, and they are collected on the positive polarity electrode in the collector. The negatively charged particles are collected on the high voltage electrode at the duty ratio of 1. Therefore, the collection efficiency becomes low so that particles cannot be collected on the surface of the high voltage electrode. It is also the reason that the electrode length applied high voltage is shorter than the grounded electrode.

The collection efficiency increases with decreasing duty ratio. Especially, the collection efficiencies at the duty ratios of 0.02 and 0.1 are almost the same as that at 0.05 s.

The collection efficiency as a function of particle diameter for various periods of AC high voltage applied to the collector, measured by PC, is shown in Fig. 10. The particles are negatively charged in the pre-charger, and they are collected on the positive polarity electrode in the collector. The negatively charged particles are collected on the high voltage electrode at the duty ratio of 1. Therefore, the collection efficiency becomes low so that particles cannot be collected on the surface of the high voltage electrode. It is also the reason that the electrode length applied high voltage is shorter than the grounded electrode.

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Collection Efficiency

\[ \eta \times (T_+ + T_-) / T \]

where \( \eta \) is the collection efficiency of 90\% at the duty ratio of 0, \( \eta_+ \) is the collection efficiency of 38\% at the duty ratio of 1, \( T_+ \) is the time of positive high voltage which is between 0 to 4.5 s, \( T_- (T = 4.5 - T_+) \) is the time of negative high voltage, and \( T \) is the period time (\( T_+ + T_- \)) of 4.5 s.

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the duty ratio of 0. The experimental tendency is the same as the calculation value. Therefore, it is indicated that the high collection efficiency and high re-entrainment prevention capability can be kept by controlling the duty ratio of the rectangular AC high voltage as shown in Figs. 7 and 11.

IV. CONCLUSION

The influence of duty ratio on collection efficiency in ESP utilizing rectangular AC high voltage was investigated. The results showed that the collection efficiency in rectangular AC energized ESP was significantly higher in comparison with DC energized ESP due to the suppressed particle re-entrainment. The effect of suppressing the particle re-entrainment was not influenced by the duty ratio of the rectangular AC high voltage. The particle re-entrainment was prevented when the duty ratio of the rectangular AC high voltage was between 0.02 and 0.5. It was indicated that the effect of rectangular AC high voltage was not influenced by the period between 1 and 4.5 s. The high collection efficiency and high re-entrainment prevention capability were kept by controlling the duty ratio of the rectangular AC high voltage in the case where the high voltage electrode was shorter than the grounded electrode.

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REFERENCES


