Diesel PM Incineration for Marine Emissions Using Dielectric Barrier Discharge Type Electrostatic Precipitator

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***Abstract*—This research has been developed an after treatment system for removal of particulate matter (PM) emissions from a diesel engine. The PM was collected by electrostatic precipitator (ESP) using a high-frequency dielectric barrier discharge (DBD). The ESP using DBD were composed by a parallel plate electrode. Both electrodes were covered by the dielectric glass plate. In the DBD, the air is activated by discharge and produces ozone, oxygen radical and nitrogen radical. Therefore, the diesel particulates are oxidized and incinerated under low temperature condition.**

I. INTRODUCTION

The particulate matters (PMs) emitted from marine diesel engine exhaust during the combustion process have low resistivity and extremely small in the range of 70-120nm. These particles cause a various human health and environment impacts. After MARPOL

73/78 Convention Revised Annex VI entered into force on 1st of July 2010, shipping-induced NOx and SOx, PM emissions are regulated stricter.

The 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 50 mg/m^3. The collection of low resistive PM has been known to be extremely difficult by the conventional electrostatic precipitators (ESPs). PMs are easy to be re-entrained [1, 2]. The low resistive particles cause particle detachment from the collection plate by induction charge, i.e. PM re-entrainment, resulting in poor collection efficiency. Therefore, it is very important to prevent the particles from being re-entrained. Authors have been studying the technology of the re-entrainment inhibition in ESP. The particle re-entrainment was prevented by AC-ESP [3]. AC-ESP with hole-punched electrode was suggested to improve the nano particle collection efficiency and suppress particle re-entrainment [4].

Many methods were applied to control mass concentration of PM from diesel exhaust gas. Many studies of ESP were reported to collect low resistive particles generated from diesel engine [5, 6]. Authors confirmed that a collection was possible in PM by a dielectric barrier discharge (DBD) type ESP [7, 8]. In barrier discharge space, since non-thermal plasma is formed, the particles which pass a charging section are charged in positive and negative polarity. Therefore, the collection of the PM is carried out to both of a high voltage and a grand electrode [9]. In the DBD type ESP, the PM is collected densely on the dielectric material compared with the corona discharge type ESP, there is almost no re-entrainment for the particles of the large diameter. Therefore, the re-entrainment phenomena are prevented due to the thin dust layer on electrode [10].

This research has been developed an after treatment system for removal of PM emissions from a diesel engine. The system is composed of ESP and a high-frequency DBD reactor. A single stage type of ESP was used in this research. The objective is to investigate experimentally DBD type ESP performance on removal of diesel particulate. In the DBD, the air is activated by discharge and produces ozone, oxygen radical and nitrogen radical. Therefore, the diesel particulates are oxidized and incinerated under low temperature condition.

II. Experimental Setup

A. Confirmation of PM Incineration by DBD reactor

The DBD reactor used for this experiment was shown in Figs. 1. The high voltage electrode consisted of 6 cm in diameter cylinder and the ground electrode was plate. The dielectric glass plate was covered by the high voltage electrode. The discharge gap length was 4mm. 20mg of PM collected in the diesel exhaust were placed on the grand electrode of this reactor. A high-frequency power supply (Matsusada Precision Inc., HEOPT-20B10) was used to energize the DBD reactor. The power consumption of the DBD reactor was evaluated by the Lissajous figures method. AC high voltage was applied between the electrodes and the discharge was generated between gaps for 30min. Then, the weights of PM which remained on the electrode were measured. The amount of PM removal by discharge was calculated.

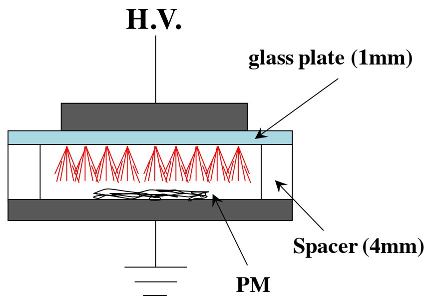


Fig.1. Dielectric barrier discharge reactor.

B. PM Incineration using DBD type ESP

The schematic diagram of the experimental setup for DBD type ESP was shown in Fig.2. Diesel engine generator (Yammer Co., Ltd., YDG500VS-5E, direct injection type for a single cylinder, displacement volume of 435cc, maximum electric power output of 4.0 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, TSI Model 3080L) for the particle size ranged 20-800 nm and the particle counter (PC, Rion KC-01E) for the particle size of 300-5,000 nm, respectively. The gas velocity was 13m/s.

The electrode configuration of the DBD type ESP used for this experiment was shown in Figs. 3. The DBD type ESP was composed by a parallel plate electrode. Both electrodes were covered by the dielectric glass plate. The discharge gap length was 3.5mm. The discharge power was measured by Lissajous figures method.

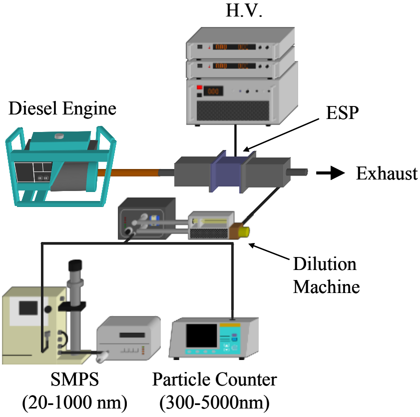


Fig.2. Schematic diagram of the experimental setup for DBD type ESP.

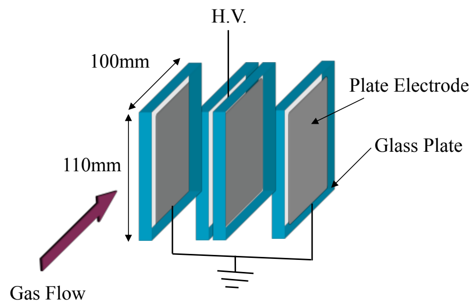


Fig.3. Electrode configuration of the DBD type ESP.

III. MECHANISM OF PM INCINERATION

Dielectric barrier discharges are characterized by the presence of one or more insulating layers (dielectric barrier) in the current path between metal electrodes in addition to the discharge space. Discharges are initiated in discharge gap due to strong electric fields. The presence of the dielectric precludes dc operation. Although DBD configurations can be operated between line frequency and microwave frequencies the typical operating range for most technical DBD applications lies between 500 Hz and 500 kHz.

For industrial purposes ozone is exclusively generated in large installations using DBDs [11, 12]. Local electrical breakdown in narrow discharge gaps leads to micro-discharge formation and short current pulses. The following neutral particle reactions in oxygen as well as in air show that mainly the electrons are important for ozone formation. Ozone is formed almost exclusively from oxygen atoms, a process which, at atmospheric pressure, takes about 10 μs in oxygen and about 100 μs in air.

$$O_2 + e \rightarrow 2O + e \quad \cdots\cdots \quad (1)$$
$$O_2 + O + M \rightarrow O_3 + M \quad \cdots\cdots \quad (2)$$

In air naturally also nitrogen molecules are subjected to electron collisions which results in excitation and subsequent energy transfer to O_2 molecules or direct dissociation and subsequent reaction:

$$N_2 + e \rightarrow 2N + e \quad \cdots\cdots \quad (3)$$
$$N + O_2 \rightarrow NO + O \quad \cdots\cdots \quad (4)$$
$$NO + O \rightarrow NO_2 + M \quad \cdots\cdots \quad (5)$$
$$NO + O_3 \rightarrow NO_2 + O_2 \quad \cdots\cdots \quad (6)$$

When the gas temperature is higher than 250°C, NO in the flue gas is oxidized to form NO_2 by ozone and O radical, then carbon particles can be incinerated. The chemical reactions for particle incineration are as follows:

$$C + 2O_3 \rightarrow CO_2 + 2O_2 \quad \cdots\cdots \quad (7)$$
$$C + 2NO_2 \rightarrow CO_2 + 2NO \quad \cdots\cdots \quad (8)$$
$$C + NO_2 \rightarrow CO + NO \quad \cdots\cdots \quad (9)$$
$$C + 1/2O_2 + NO_2 \rightarrow CO_2 + NO \quad \cdots\cdots \quad (10)$$

IV. RESULTS AND DISCUSSION

The particle-size dependent number density from the diesel engine particulates was shown in Fig. 4 when the engine was 25% load (1.0kW), 60% load (2.4kW) and 90% load (3.6kW), respectively. The particle size-dependent number densities were determined by the SMPS for the particle size ranged 40-250 nm, and the PC for the particle size ranged 390-3000 nm. The maximum number density was 6×10^{12} particles/m^3 at particle size of 50 nm with 25% load. The maximum number density was 8×10^{12} particles/m^3 at particle size of

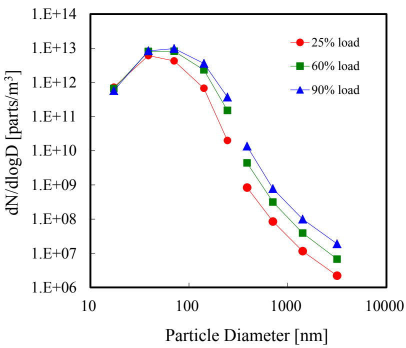


Fig. 4. The particle-size dependent number density from the diesel engine particulates.

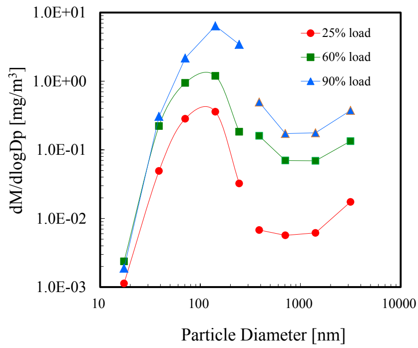


Fig. 5. Particle-size dependent mass-base density from the diesel engine particulates.

70 nm with 60% load and 1×10^{13} particles/m^3 at particle size of 70 nm with 90% load.

Figs. 5 shows the particle-size dependent mass-base densities with various engine load for particle size ranging 40-250nm measured by SMPS and 390~3,000nm measured by PC. The maximum mass-base density was 0.3 mg/m^3 at particle size of 140 nm with 25% load. The maximum mass-base density was 1.2 mg/m^3 at particle size of 140 nm with 60% load and 6.4 mg/m^3 at particle size of 140 nm with 90% load. Table 1 shows the total amount of PM generation with different load levels. The total amount of PM generation was 0.8 mg/m^3 with 1.0kW load, 3.0 mg/m^3 with 2.4kW load, and 13.5mg/m^3 with 3.6kW load respectively.

Table 1. Total amount of PM generation with various loads

Load [kW]	PM concentration [mg/m^3]
1.0	0.8
2.4	3.0
3.6	13.5

As mentioned above, it is conceded that the particle number density and mass-base density from the diesel exhaust increased with increasing the engine load.

In order to understand the PM incineration properties, PM were oxidized using DBD reactor. Fig. 6 shows the time-dependent amount of PM removal as a function of the discharge power. The discharge power was measured by Lissajous figures method. The initial weight of PM was 20mg. The amount of PM removal increased with increasing the incineration time. The incineration velocity was fast for 5 minutes after applied voltage, and then it was decreasing gently. Based on the PM incineration properties, it is indicated that more than 80% of the whole PM incinerates by DBD for 30 minutes over 67W.

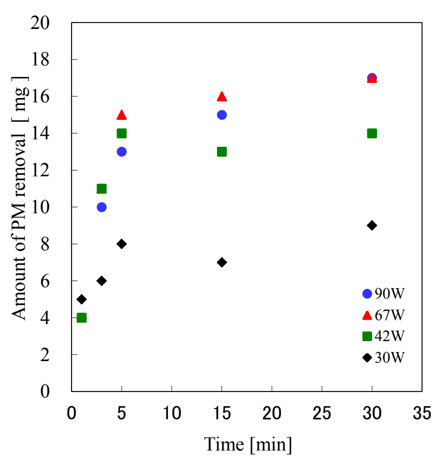
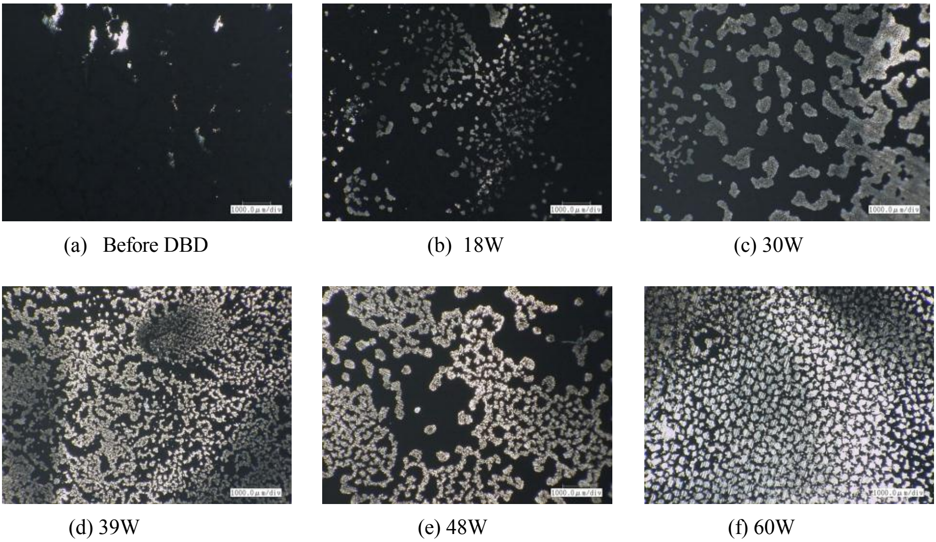


Fig. 6. Time-dependent the amount of PM removal as a function of the discharge power.

Subsequently, the picture of the electrode surface after 20min DBD operation was shown in Fig. 7. (a) is before DBD, (b) (c) (d) (e) and (f) is 18W, 30W, 39W, 48W, and 60W respect-



Figs.7. The picture of the electrode surface after 20min DBD operation loads.

tively. A black division is retained layer of collecting particles and a white division is an electrode surface. It was conceded that the removal of PM by DBD increased with increasing the discharge power. It was clear that diesel PMs were perfectly incinerated by ozone during 20 minutes operation.

In this research, the diesel engine generator using light oil was used. When the load was 3.6 kW (90 % load), the amount of exhaust gas was 650 L/min and the amount of PM generation was 13.5 mg/m^3. The required quantity of the ozone removed per 1g of PM is about 8g according to the expression (7). Based on the results, the DBD reactor which has 108 mg/m^3 of ozone concentration is able to incinerate PM up to 90% load with continuous discharge operation.

In order to understand the performance of DBD type ESP, the collection efficiency was measured at 5, 10, 15and 20W, respectively. Fig.8 shows the particle-size dependent collection efficiency as a function of the discharge power of 5-20W when 435cc diesel engine with the engine load of 60% was used. The collection efficiency of large particles was higher than that of small particles. The collection efficiency increased with increasing the discharge power. The maximum collection efficiency was 22% at particle size of 3,200nm with 5W discharge power. The maximum collection efficiency was 68% at particle size of 1,400nm with 20W discharge power. The ESP using DBD has high potential especially for highly concentrated marine diesel engine emission control.

Figures 9 (a) and (b) show the pictures of the dielectric glass after 60 minutes operation by DBD. In the discharge power of 5W, the dielectric glass surface had a lot of soot compared with 20W. However, the collection efficiency of high discharge power was higher than that of low discharge power as shown in Fig. 8. It was clear that the collected particles were incinerated with ozone generated by DBD.

In order to understand the amount of PM incineration, the weight of PM on the

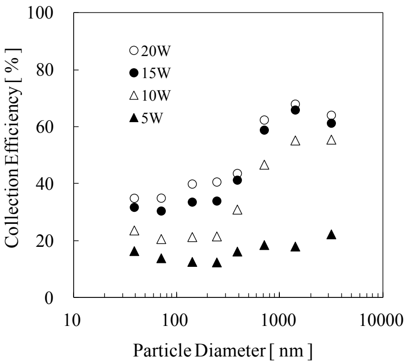
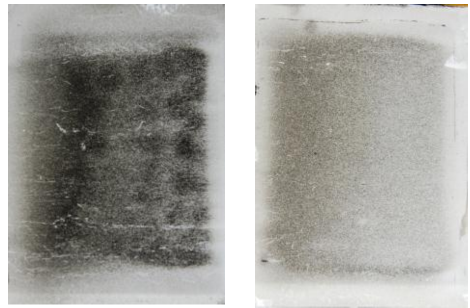


Fig. 8. Particle-size dependent collection efficiency as a function of the discharge power of 5-20 W.



(a) 5 W (b) 20 W

Figs. 9. The picture of the dielectric glass after 60 min DBD type ESP operation.

dielectric glass was measured. DBD type ESP was operated 30 minutes with 20W, 435cc diesel engine with the engine load of 60% was used. The total amount of PM in the exhaust gas for 30 minutes was 120 mg. The total collection efficiency was 58%, and it means that the collection of PMs was calculated 70 mg. The weight of PM on the dielectric glass was 32mg after 30 minutes DBD ESP operation. Therefore, it was estimated that the incineration of PM was approximately 54%.

As mentioned above, it was confirmed that the effectiveness of the self-clean technology which performs collection and oxidation treatment of PM continuously by DBD. The DBD type ESP is particularity important for marine diesel engine emission control, where no particle storage is required.

V. Conclusions

Development of DBD type ESP for continuous removal of diesel particulate matter was able to achieve an extremely cost effective and compact diesel emission control. The DBD reactor showed more than 80% of the PM incineration efficiency for 30 minutes with 67W. The collected particles were incinerated with ozone generated by DBD. The DBD type ESP was successfully demonstrated to achieve high collection and incineration efficiency using 435cc diesel engine, and has high potential especially for highly concentrated marine diesel engine emission control.

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