Aftertreatment of Carbon Particle Emitted by Diesel Engine Using Combination of Corona and Dielectric Barrier Discharge

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***Abstract*— The collection and incineration mechanisms in the particulate matter (PM) aftertreatment technique proposed by the author were investigated. An experiment for actual exhaust gas was performed by sampling 10 NL/min of exhaust gas from the flue gas from a stationary diesel engine generator. The reactor for PM aftertreatment had a glass tube that could be positively charged at the surface using surface electrodes and corona needles that discharge negative charges surrounding it. Various combinations of voltages applied to each of the corona needles and the surface electrodes were compared. The results enhanced the hypothesis that negatively charged PM is attracted by the dielectric surface, which is positively charged by positive ions supplied by the surface electrode.**

I. Introduction

Fine particles, especially those with diameters smaller than 2.5 μm ($PM_{2.5}$) and 0.1 μm ($PM_{0.1}$), can penetrate deeply into the lungs and cause damage to human health through the respiratory system. Anthropogenic particles constitute the majority of $PM_{2.5}$ because particles from natural sources are usually larger than 10 μm [1]. Therefore, eliminating PM emission is a significant subject for diesel engines, because diesel engines are crucially useful for reducing CO_2 emissions due to their high thermal efficiency and omnivorousness of fuel consumption, which includes various kinds of biofuels. At present, diesel particulate filters (DPF) made of porous ceramic are widely used. However, periodic incineration of the collected PM by heating is needed to keep the pressure loss at an acceptable level. The incineration process requires an additional fuel consumption.

Electrostatic precipitation is one of the promising technologies for PM reduction because it consumes little energy and has low pressure loss. However, there is the problem that collected PM detaches easily because of the high electrical conductivity of carbon particles through induction charging [2-4]. In addition, the collected PM needs to be taken out of

the device regularly. These problems have led to novel approaches, including cyclic alternation of the polarities of the collection electrodes [2] and utilizing electrohydrodynamic (EHD) flow [3-5].

Nonthermal plasma (NTP) generated in air creates active species including ozone, atomic oxygen, and hydroxyl radicals that can decompose many kinds of persistent substances [6-10]. This feature has been applied to decomposition of PM emitted by diesel engines[5, 11-16] , and some studies have discussed ozone injection to DPF to decompose accumulated PM [17, 18].

The author has been working toward a simpler technique that can both collect and decompose carbon particles from combustion equipment and has partially proved its feasibility [19]. The basic strategy is the collection of negatively charged PM by a dielectric surface that is positively charged by the effect of AC high voltage with positive offset. It has already been proven by surface potential measurement that the offset polarity determines the polarity of the charging of the dielectric surface [19]. Because the dielectric surface does not lead to induction charging, re-entrainment of the collected PM is expected to be suppressed. Moreover, this system would be able to decompose the PM on the dielectric surface by using NTP generated by dielectric barrier discharge (DBD). In this study, the author attempted to describe the collection mechanisms of PM.

II. Experimental Methods

Figure 1 show a reactor used for PM aftertreatment [19]. The reactor has a quartz glass tube on which surface PM is collected and decomposed. The quartz glass tube is 26.5 mm in outer diameter with a wall thickness of 2 mm and provided with 5-mm-wide discharge electrodes made of copper tape with an interval of 120 ° on its outer surface. A copper tape as a ground was attached to the inner surface. The part where the discharge electrodes and the ground electrode face each other is 70 mm in axial length. This glass tube is set at the center of an acrylic casing that is 39 mm in inner diameter. Needles as corona electrodes extends inward from the inner surface of the acrylic pipe. The tips of the corona needles are 2.5 mm away from the glass surface. Also, an acrylic casing without the corona needles were used for comparison. In PM treatment processes, AC high voltage with or without positive offset (V_{ac}) was applied to the surface electrodes, while a negative DC high voltage (V_{dc}) was applied to the corona needles. V_{ac} and V_{dc} were measured as against the ground electrode. V_{ac} was generated with an AC power supply manufactured by the Rogy Electronics, Co. Ltd., (LHV-13AC, f = 12–15 kHz). The waveform was not symmetry with respect to 0 V but had a larger amplitude in positive half cycles than in negative half cycles. The offset was provided so that the lowest value became zero as against the ground as seen in **Fig. 2**. V_{dc} was generated by rectifying an AC high voltage from an inverter neon transformer (Lecip Corp., M-5). Currents, I_c and I_d, were measured by measuring the voltage at resistors of 1kΩ and 10 Ω, respectively inserted between each the power supply and the ground. The capacitor was connected in parallel at the 1-kΩ resistor to eliminate the AC components from detected current. The power P_{dc} was defined by Equation 1. When the effective AC power at the reactor (P_{ac}) was determined, the power dissipation at high voltage cables was considered as described in Equation 2.

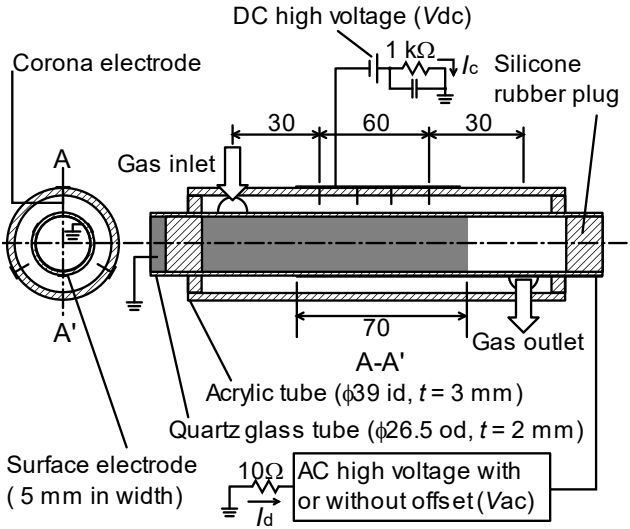

Fig. 1. Reactor for the collection and decomposition of the particulate matters (PM) in exhaust gas from a diesel engine (lengths are all in mm)

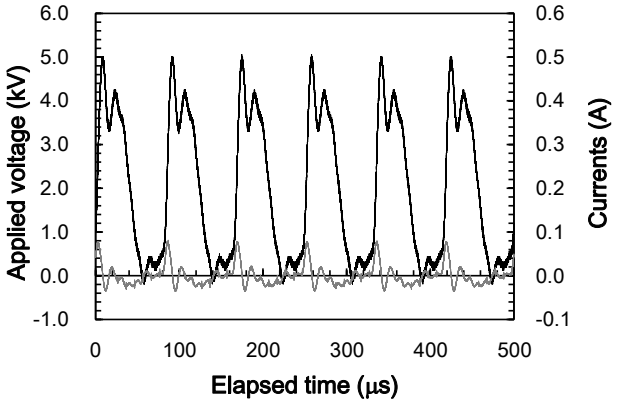

Fig. 2. Typical waveform of applied AC voltage (thick and thin lines indicate V_{ac} and I_d, respectively)

$$P_{dc} = V_{dc} I_c \tag{1}$$

$$P_{ac} = \left(\frac{1}{nT} \int_0^{nT} V_{ac} I_d dt \right)_W - \left(\frac{1}{nT} \int_0^{nT} V_{ac} I_d dt \right)_{WO} \tag{2}$$

(T: the period of V_{ac}, n: the number of periods, and subscriptions W: the reactor was connected and WO: the reactor was not connected)

Figure 3 shows an experimental system for PM aftertreatment. 10 NL / min of exhaust gas was sampled from the flue gas of a stationary diesel engine generator (Yanmar, Co. Ltd., YDG-200VS, rating load = 2 kW, rotating rate = 3600 rpm, displacement = 219 mL with a single cylinder) loaded with 1 kW through a pipe that is maintained at 90 °C to the

reactor placed in a thermostatic chamber kept at 70 °C. The PM at the downstream of the reactor were caught at a glass fiber filter (Advantec, Co. Ltd., GF-75, filtration efficiency at 0.3 um particle diameter > 99.999%). The effect of the reactor could be found by comparing the collected PM amounts on the glass fiber filter between the power on and off. The exhaust gas was constituted by NO of 230–270 ppm, NO_2 of 45–60 ppm, CO of 460–490 ppm, O_2 of 13.8 vol%, and others including about 10 vol% of water vapor and hydrocarbons when 1 kW was loaded.

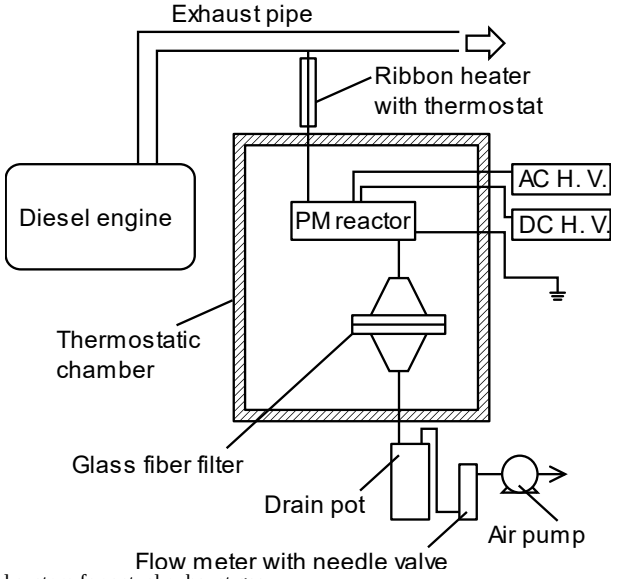

Fig. 3. Experimental system for actual exhaust gas

III. Results and Discussion

PM reduction efficiency (η) was defined by Equation 3.

$$\eta = 1 - C_1/C_0 \tag{3}$$

(C: the PM concentration at the downstream of the reactor, subscription 0 indicates the case where the reactor did not operate, and 1 indicates the case where the reactor operated) **Figure 4** shows η and C_0 during the PM reduction experiment. C_0, which can almost be translated as PM concentration in untreated exhaust gas, showed the average value of approximately 10 mg/m^2. Two operation modes (temporarily noted as A and B) are indicated in this graph. Mode A indicates an operating condition: V_{ac} = 5.2 kV_{pp} with a positive offset and V_{dc} = −3 kV, and mode B indicates a condition: V_{ac} = 8.0 kV_{pp} with no offset and V_{dc} = 0 kV. Mode B were specifically expected to regenerate the glass surface by decomposing the collected PM.

The glass fiber filter was exchanged every 20 min during mode A, and every 10 min during mode B to measure C_1. C_0 was measured at a regular interval in each the mode,

spending 20 min. The time when the reactor did not operate for C_0 measurement was excluded from the elapsed time indicated in **Fig. 4**.

The reduction efficiency η in mode A has been fluctuating around 0.4 for 400 minutes, not showing monotonous increase or decrease. The result indicates that the reduction efficiency decreased extremely slowly or as is discussed later, oxidative decomposition of the collected PM suppressed the decrease in η also in mode A. For this reason, the effect of performing mode B was not significant. C_0 tended to increase with elapsed time, but no significant correlation with the PM reduction efficiency was observed, which point will also be discussed later.

The negative value of η seen in mode B indicates that some amount of the collected PM on the glass surface detached probably because of the ionic wind created by the DBD. However, at the same time, the collected PM was supposed to be decomposed by oxidation.

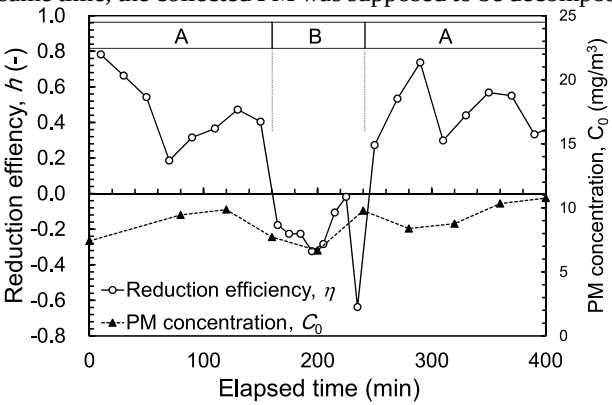

Fig. 4. PM reduction efficiency and C_0 with respect to elapsed time (two operation modes were performed; mode A: V_{ac} = 5.2 kV_{pp} with offset and V_{dc} = −3.0 kV, and mode B: V_{ac} = 8.0 kV_{pp} with no offset and V_{dc} = 0 V)

Figure 5 is the photo of the glass tube that was taken out of the reactor at an elapsed time of 160 min in **Fig. 4**. The accumulation of PM is observed at areas which are more than 1–3 mm apart from the edge of the surface electrodes. The spots where little PM adhered were right below the corona needles. Band-like regions more densely adhered by PM can be observed from near the corona needles toward the surface electrode edges. These observations suggest that PM that were negatively charged near the corona needles were attracted to the glass surface where positive ions spread from the surface electrodes. The PM-adhered area, which is expected to be the area where positive ions spread, was approximately consistent with the former measurement [19].

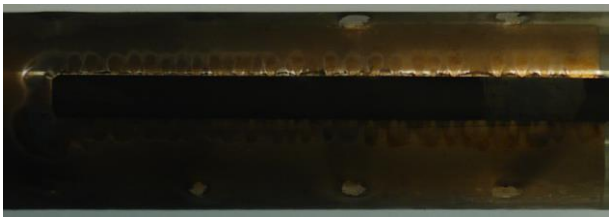

Fig. 5. Photo of the glass tube surface taken after 160 min of operation shown in Fig. 5 (the center horizontal strip seen is one of the surface discharge electrodes)

Figure 6 represents an assumption on the currents and the behaviors of PM in the reactor. I_c was approximately 30 μA, which had the same order of magnitude of that in the case where V_{dc} = −3 kV and V_{ac} = 0, therefore this current is supposed to be composed of negative charges. I_c must have had two components: I_{c1} and I_{c2} —I_{c1} is the current formed by the encounter of negative charges (ions and negatively charged PM) and the positive ions from the surface electrode, while I_{c2} is formed by the absorption of negative charges by the surface electrode.

Application of V_{dc} alone offered the reduction efficiency less than 0.1. The reactor that its corona needles were removed from showed η as small as 0.03. Those results suggest that only I_{c1} substantially contributed to the PM reduction. The negatively charged PM, which were attracted by the positively charged surface, would be partially neutralized and adhere to the surface with dispersion forces. Some region where the collected PM worked as a conducting channel, PM at its edge could be positively charged and given a force toward the corona needle as is illustrated in **Fig.6**. Although this force induces detaching, the small spots observed in **Fig. 5** suggest that this detachment phenomenon was minor in a whole process of the PM reduction.

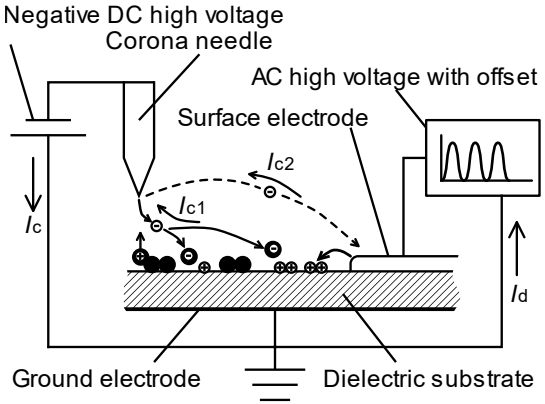

Fig. 6. Currents and behaviors of PM in the PM reactor (Ic1: the current that contributes to PM reduction and formed by the encounter of negative charges from the corona needle and the positive ions from the surface electrode, Ic2: the current formed by the absorption of negative ions by the surface electrode)

The power consumption at the I_c loop (P_{dc}) ranged from 0.09 W when V_{dc} = −3.0 kV, while P_{ac} was between 0.24 and 0.76 W, where the variation was due to the variation of the power dissipation at high voltage cables. The energy efficiency of PM reduction (the required energy for the reduction of PM of a unit mass) is calculated to be 5.2 g(PM)/kWh (calculated using its average of the measured powers). This is a quite good value, comparing a value acquired with the ozone injection technique [18], 2.7 g(PM)/kWh. However,

it must be confirmed that reduction efficiency would maintain for a longer period in future studies.

IV. Conclusion

1) This work enhanced the hypothesis about the PM collection mechanism: negatively charged PM is attracted by positive ions supplied on the dielectric surface.

2) The PM collecting area is few mm away from the edge of the discharge electrode, which is almost coincide with the region where positive ions are supplied by the discharge electrode.

3) When the collected PM formed a conducting layer on the surface, positive charges would be induced at the end of the conducting layer near the corona needle, causing detachment of the PM. However, this phenomenon is minor in the whole collection process.

Acknowledgement

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