Application of a Dielectric Barrier Discharge Reactor for Diesel PM Removal

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Abstract: An uneven DBD reactor driven by a pulse power supply for diesel particulate matter (PM) removal has been characterized using a diesel engine. The relations between energy injection, PM removal, space velocity and pressure loss are given.

Keywords: Uneven DBD reactor, diesel particulate matter, pulsed plasma, pressure loss, space velocity

1 INTRODUCTION

Plasma discharges are widely used in environmental controls such as VOC decomposition [1-7]. Recently, the authors developed a plasma discharge system for the removal of particulate matter (PM) from a diesel engine [8]. The plasma discharge system consists of mainly a dielectric barrier discharge (DBD) reactor driven by a high-voltage pulse power supply. PM is removed by oxidation to CO and CO_2 and by deposition [9,10]. The oxidation of PM is suggested by the reaction of carbon in PM with active oxygen species (such as O and OH) and by UV-light radiation, those oxygen species and UV lights are generated by plasma discharges. The deposition of PM is due to the electrostatic precipitation after charging PM by plasma discharges. The increase in the amount of PM deposition in the DBD reactor results in the increases in pressure loss on the DBD reactor; which then creates fuel penalty of the diesel vehicle. The plasma discharges within such a DBD reactor with deposited PM should be enhanced in order to keep its PM oxidative removal. After evaluation of several kinds of DBD reactors [11], an uneven type of DBD reactor capable of enhancement of uniform discharges even with deposited PM is finally selected for practice application. The PM emission from a light-duty diesel vehicle can satisfy the post new long-term regulation (PM emission limit: 0.005g/km) at the Japanese JC08 hot start mode, By using the uneven DBD reactor (21 electrode pairs) with an energy injection higher than 93 W. The fuel penalty using the uneven DBD reactor and pulse power supply is estimated to be 6.2% due to the pressure loss and additional fuel consumption for power (116 W $(=93\ \mathrm{W}\div 80\%)$ in total) generation. As the diesel vehicle is operated under non-constant conditions, it is difficult to estimate relations of PM removals, pressure loss and energy injections. In this study, the uneven DBD reactor has been characterized using a diesel engine operated under a constant condition.

2 EXPERIMENTAL SETUP

Fig. 1 shows the experimental system including a diesel engine (2C, 2-L, Toyota), an uneven DBD reactor, a pulse power supply (DP-15K03, Peec), a discharge measurement system, and a PM emission measurement system. The diesel engine was operated at 1190 rpm and 3.1 kW power outputs, with an exhaust gas flow rate of about 78 $\mathrm{Nm^3/h}$ (atmospheric pressure, 273 K). A part of the exhaust gas (F_1) was supplied to the DBD reactor.

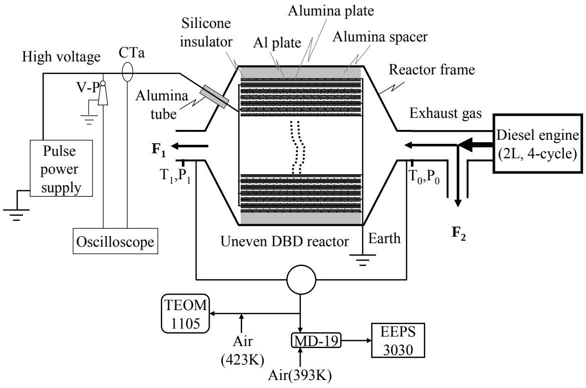

Fig. 1 Experimental setup for characterization of the DBD reactor

The uneven DBD reactor was installed in the exhaust pipe line 1.5 m downstream of the exhaust outlet of the engine. This uneven DBD reactor (21 electrode pairs) was mainly made of 80 pieces of uneven alumina plates and 41 pieces aluminum plates (Fig. 2). The volume (V_R) of filled parts was 2.58 L.

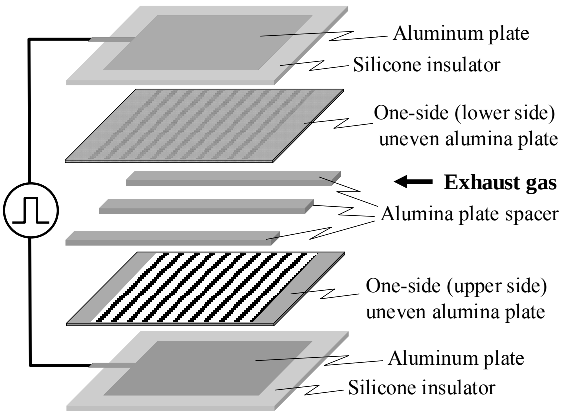

Fig. 2 Basic structure of the uneven DBD reactor

The discharge measurement system includes a voltage probe (V-P, EP-50K, Peec), a current transformer (CTa, Model 2-1.0, Strangenes), and a digital phosphor oscilloscope (WaveSurfer44Xs, LeCroy). The pulse power supply driven by a 12 V DC power supply (PQ15-80, Matsusada) was used to apply positive-negative pulse voltage to the uneven DBD reactor. The voltage probe and current transformer were used to measure the output waveforms of voltage and current, respectively. The peak value of pulse voltage and pulse frequency were adjusted in ranges of 0-9 kV and 50 Hz-250 Hz, respectively. The energy injection per pulse (P_d) in J/pulse and energy injection (P) in watts from the pulse power supply to the uneven DBD reactor were calculated using Eqs. 1 and 2 over one pulse discharge duration, respectively.

$$P_d = \sum_i [V_i I_i (t_{i+1} - t_i)] \tag{1}$$

$$P = F P_d \tag{2}$$

where, V_i and I_i are the pulse voltage in volts (V) and the current in amperes, respectively, at discharge time t_i in seconds. F is the pulse frequency in hertz (Hz).

The discharge energy injected into the uneven DBD reactor per liter gas volume was defined as the energy density (D_E) in J/L using Eq. 3.

$$D_E = \frac{P}{F_1 \cdot \frac{1000\,{}^{\mathrm{L}}\!/_{\mathrm{m^3}}}{3600\,{}^{\mathrm{s}}\!/_{\mathrm{h}}}} \tag{3}$$

where, F_1 is the gas flow rate of the exhaust gases in m^3/h at atmospheric pressure and average temperature of the temperatures measured at the inlet and outlet of the uneven DBD reactor.

Parts of the exhaust gases from the outlet or inlet of the uneven DBD reactor were diluted with air at 423 or 393 K. The air diluted exhaust gases were then sent to a PM mass monitor (TEOM 1105, R & P) for PM emission rate (in g/h) measurements and to a particle size spectrometer (EEPS 3090, from 5.6 to 560 nm, TSI) for PM size and number-concentration measurements.

PM removal (X_{TEOM}) based on TEOM measurements was calculated using Eq. 4.

$$X_{\mathrm{TEOM}} = \frac{m_0 - m}{m_0} \times 100\% \ . \tag{4}$$

where, m_0 and m are PM emission rates in g/h at the inlet and outlet of the uneven DBD reactor, respectively.

The PM removal (X_{EEPS}) based on the EEPS measurements was calculated as follows:

$$X_{\mathrm{EEPS}} = \frac{n_0 - n}{n_0} \times 100\% \tag{5}$$

where, n_0 and n are PM number-concentrations in particles/cm^3 at the inlet and outlet of the uneven DBD reactor, respectively.

The space velocity of the exhaust gases (SV) in h^{-1} was defined as

$$SV = \frac{F_1}{V_R} \times 1000 \quad \mathrm{L/m^3} \, . \tag{6}$$

The PM removal rate was the grams of PM removed per hour by plasma discharges. The pressure loss (ΔP) was the difference between pressures measured at points P_0 and P_1 (Fig. 1). The exhaust temperatures were measured at points T_0 and T_1 (Fig. 1).

All experiments were carried out within two days of about 9-hour elapsed times.

3 RESULTS AND DISCUSSION

3.1 Typical Waveforms of Voltage and Current

Typical waveforms of discharge voltage and current (CT_a) at an energy injection of 88.4 W were given in Fig. 3. The pulse voltage increased from zero to peak value of 5.7 kV in 20 μs, then decreased to -6 kV in 22 μs and finally returned to zero. The discharge current varied in a range of 10 A~-18 A.

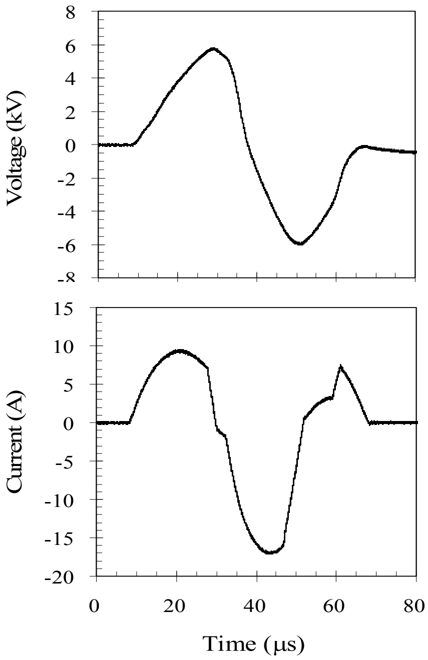

Fig. 3 Typical waveforms of discharge voltage and current.

3.2 Energy Injection Per Pulse

The energy injection per pulse (P_d) is shown in Fig. 4. The experiments were carried out in two days at various gas flow rates under different discharge conditions (various pulse frequencies and peak values of pulse voltage). P_d increases with increasing peak values of pulse voltage. P_d values in the two days' experiments are same; indicating that the discharge properties did not change even there was PM deposition on the surfaces of the uneven alumina plates which will be described later.

3.3 PM Removal

Fig. 5 shows PM removals as a function of energy injection. PM removal increases with the increase in energy injection. At an energy injection higher than 100 W, PM removal is higher than 80%. There are no obvious differences between TEOM and EEPS measurements, this finding suggested that both two measurement methods are useful for evaluating the PM removal properties by plasma discharges.

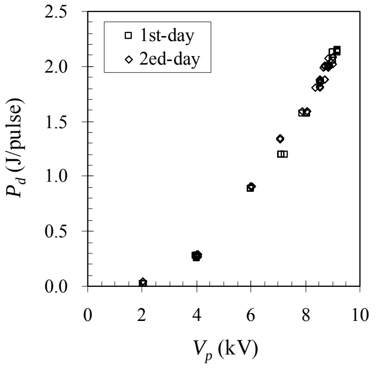

Fig. 4 Energy injections at various peak values of voltage

The relations of PM removal rates, energy injections and space velocities are illustrated in Figs. 6 and 7. PM removal rates are clearly mainly influenced by both energy injection and space velocity.

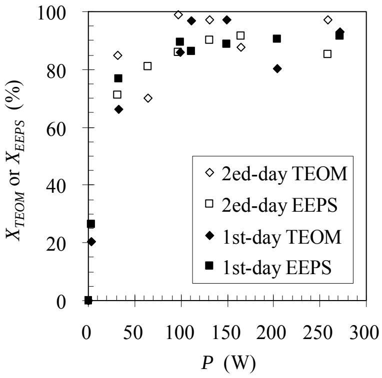

Fig. 5 PM removals as a function of energy injection

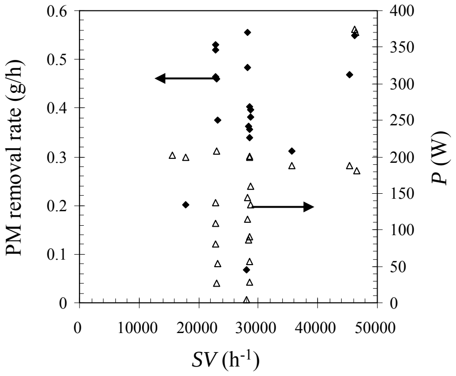

Fig. 6 PM removals at various energy injections as a function of SV

3.4 Pressure Loss

The pressure loss on the uneven DBD reactor creates fuel penalty, thus, the pressure loss at various elapsed times and various gas flow rates (F_1) are shown in Figs. 8 (first-day experiments) and 9 (second-day experiments). It has been found that the pressure loss increases with increasing elapsed time at a certain gas flow rate (Fig. 8); implied that the PM deposition in the uneven DBD reactor occurred. The deposition of PM in the uneven DBD reactor can be specified using the relation of pressure loss increase rate and gas flow rate. Fig. 10 shows such a relation calculated from results shown in Fig. 9. The pressure loss increase rate peaks at 100 m^3/h and decreases rapidly above 100 m^3/h. This finding suggested that lower gas flow rate enhances PM deposition in the uneven DBD reactor, but deposited PM can be blown off from the uneven DBD reactor at a higher gas flow rate.

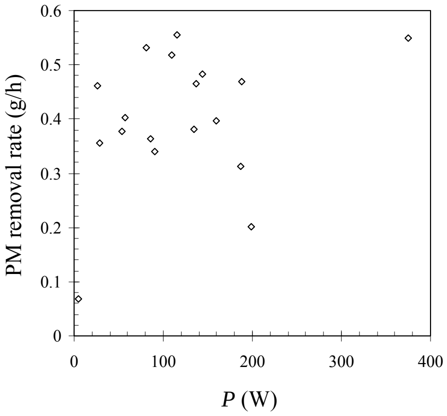

Fig. 7 PM removals as a function of energy injection in a SV range of 16,000~48,000 h^{-1}

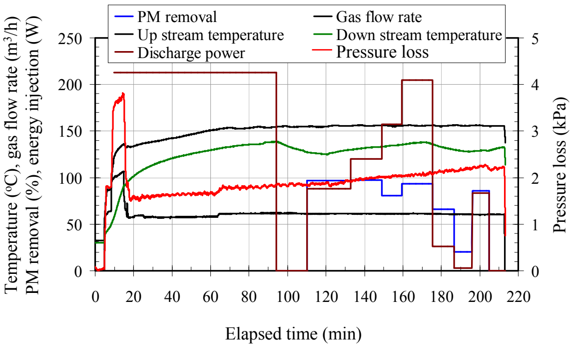

Fig. 8 Profiles of pressure loss, exhaust gas temperatures, gas flow rates, PM removals and energy injections at various elapsed times.

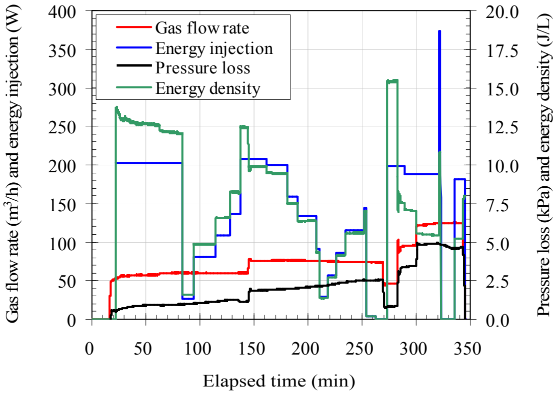

Fig. 9 Profiles of pressure loss, gas flow rates, PM removals and energy injections at various elapsed times

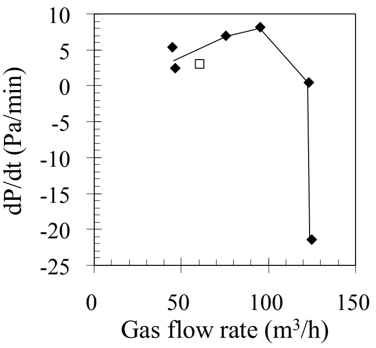

Fig. 10 Pressure loss increase rates as a function of gas flow rate. □: first-day experimental result; □: second-day experimental results

4 CONCLUSIONS

An uneven DBD reactor driven by a pulse power supply for PM removal from a diesel engine has been characterized. The results are summarized as follows:

1. The discharge properties do not change even there is PM deposition in the uneven DBD reactor.
2. PM removal increase with increasing energy injection. More than 80% PM can be removed by plasma discharges at an energy injection higher than 100 W.
3. PM removal rate is mainly influenced by energy injection and space velocity.
4. Pressure loss on the uneven DBD reactor is due to the PM deposition in the uneven DBD reactor. The deposited PM can be blown off when the gas flow rate is higher than 100 m^3/h.

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