EFFECT OF THE NUMBER OF PAIRS OF DIELECTRIC BARRIER DISCHARGE REACTOR ON DIESEL PARTICULATE MATTER REMOVAL AND PRESSURE DROP

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Abstract

Worldwide emission regulations on diesel particulate matter (PM) into the atmosphere have become more stringent. In Japan a new vehicular emission regulation, so called “post new long term regulation”, will be introduced since 2009. In this regulation, PM emission rate is should be less than 0.005 g/km.

We have developed an uneven type of dielectric barrier discharge (DBD) reactor, which consists of uneven alumina plates and uneven stainless steel plates, to comply with the regulation. PM emitted from a diesel engine (4-cycle, direct Injection, 2 liter) was oxidized by some active oxygen species produced by the corona discharges. The PM emission rate under conditions with or without corona discharges was measured. The pressure drop in the DBD reactor was measured at the inlet of the DBD reactor.

The energy efficiency and pressure drop are very important. In this study, we investigated the effect of the number of pairs of the alumina plate and stainless steel plate on the performance of the reactor because the rise in the number of the pairs of the uneven alumina and stainless steel plates can be generally considered to increase the energy efficiency and decrease the pressure drop.

When the engine output was 3.0 kW, PM removal ratio and energy efficiency using 20 pairs were 47-84% and 2.9-0.85 g-PM/kWh, respectively, in the range of injection energy of 84-340 W. When 50 pairs were used, the energy efficiency was greatly increased to 13.7-3.6 g-PM/kWh. PM removal ratio was 86% at the injection energy of 87 W and reached 94% at 250 W. The rise in the number of pairs from 20 to 30 or 50 increases the opening space and discharge (reaction) area of the reactor. Thus, the increase in PM removal ratio and energy efficiency is due to the increase in the discharge area. The pressure drop was 6.8 and 4.3 kPa when 20 or 30 pairs were used. The pressure drop was reduced to 2.3 kPa, which corresponds to the 2.9% energy loss, by using 50 pairs by the increase of opening space of the reactor. It was found that the energy efficiency of PM removal is inversely proportional to the approximately 1.6 power of the space velocity and that the pressure drop is proportional to the 1.2 power of the space velocity. Based on the regression curve, it was found that 56 pairs of the uneven alumina and stainless plates can provide an energy loss due to pressure drop smaller than 2 %.

Introduction

Reduction in emission of diesel particulate matter (PM) into the atmosphere is a very important thing from environmental and human health viewpoints[1-3]. In Japan a new vehicular emission regulation, so called “post new long term regulation”, will be introduced from 2009. In this regulation, PM emission rate is required to be less than 0.005 g/km. So far, many aftertreatment systems to decrease PM emission have been developed such as diesel particulate filters (DPF), catalyst-based DPF (CB-DPF)[4-7] and diesel particulate-NO_x reduction (DPNR)[8]. However, the use of these systems results in a rise in the exhaust gas pressure because the filter is clogged with PM. In addition, these systems require additional fuel injection to burn off the trapped PM.

The plasma technology is promising to reduce PM emission from a diesel engine by oxidation[9-22] because the energy consumption is low and this technology can work from ambient temperature. Recently, we have developed an uneven dielectric barrier discharge (DBD) reactor driven by a pulsed corona discharge for removal of PM in exhaust gas from a diesel engine [23-25]. Corona discharges uniformly take place in each gap between uneven alumina and uneven electrode. PM was oxidized by some active oxygen species produced by the corona discharges. The initial PM removal ratio and pressure drop was 88% at 230 W injection energy and 3.7 kPa, respectively although the PM removal ratio decreased to 65% and the pressure drop increased to 15.9 kPa at 14 h [25].

The energy efficiency and pressure drop are very important. For practical use, the energy consumption for PM removal should be less than 100 W [26] and the energy loss due to pressure drop (=rise in exhaust gas pressure) should be less than 2%. Since PM removal ratio and exhaust gas pressure drop are strongly dependent on space velocity, in this paper we investigated the influence of the space velocity by changing the number of the pairs of the uneven alumina and stainless steel plates on PM removal ratio and pressure drop.

Experimental

The details of the experimental system were described elsewhere[24,25]. The experimental system comprised of a diesel engine (Toyota, 2 liter, 4-cycle, direct injection), a hydro dynamometer test cell, an uneven DBD reactor, a pulse power supply, and PM emission monitoring system. The operating conditions of the engine were 1200 rpm and 3.0 kW. The uneven DBD reactor is installed in the exhaust pipeline 1.5 m downstream of the exhaust point of the engine. The temperature of the exhaust gas from the engine was measured with a thermocouple 0.05 m upstream of the reactor. The flow rate of total exhaust gas was monitored at the end of the exhaust pipe and recorded with a personal computer. The pressure at the inlet of the DBD reactor (P_1) was measured with a pressure sensor (VPRN, 0-100 kPa, Valcom). In addition, the pressure at the inlet of a straight pipe without the uneven alumina or stainless steel plates (P_2) was also measured. The pressure drop ($=P_1-P_2$) resulting from the use of the DBD reactor was calculated by subtracting the pressure at the inlet of the straight pipe from that of the DBD reactor. A portion of the exhaust gas from 0.05 m downstream of the DBD reactor was diluted with air at 150 °C and the air-diluted exhaust gas was sent to a PM mass monitor (TEOM 1105; Repperecht & Patashnick) to measure the PM emission rate (g/h). The flow rates of the heated air and the diluted exhaust gas were controlled to 2.28 and 2.50 L/min, respectively. The main property of the diesel fuel (Idemitsu Kosan, Japan) was specific gravity at 15 °C: 0.8270 g/cm^3, cetane number: 56.7, flash point: 64.0 °C, and sulfur: 5ppmwt.

Basic arrangement and structure of the DBD reactor are shown in Figures 1 and 2, respectively. Uneven alumina plates and uneven stainless steel plates were assembled alternately. The grooves of the stainless steel plates (electrodes) were put parallel to the exhaust gas flow and those of the alumina plates (dielectrics) were put perpendicularly to the exhaust gas flow. In this study, 20, 30, or 50 pairs of uneven alumina plates and uneven stainless steel plates were used. Alumina spacers were used to control all exhaust gases passing through the grooves and to inhibit electric shorts between high voltage electrode and earth electrode or the wall of the reactor frame made of stainless steel. The stainless steel plates were connected alternately and half of them were connected with the high voltage output of a pulse power supply (Pulse Electric Engineering Co., Ltd. (PEEC)) and another half of them were connected with earth. The pulse power supply, which is driven by a direct current (DC) power supply (Matsusada Precision Inc.), generated positive-negative pulse voltage with a rise (fall) time of approximately 12 µs (10% to 90%), a half-width time 15 µs, absolute peak voltage 10 kV at maximum, and pulse repetition frequency 10 to 500 Hz. The discharge voltage was measured with a voltage probe (EP-50K, PEEC). The discharge currents of the high voltage electrode and earth electrode were measured with two current transformers (Model 2-1.0, Strangenes). The analogue signals from the voltage probe and current transformers were recorded with a digital phosphor oscilloscope (TDS 7104, Tektronix).

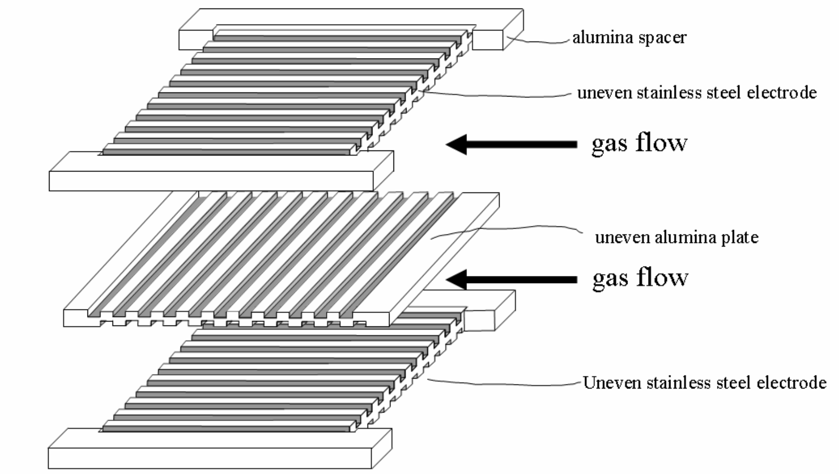

Figure 1 Basic arrangement of uneven alumina plate and stainless steel plate

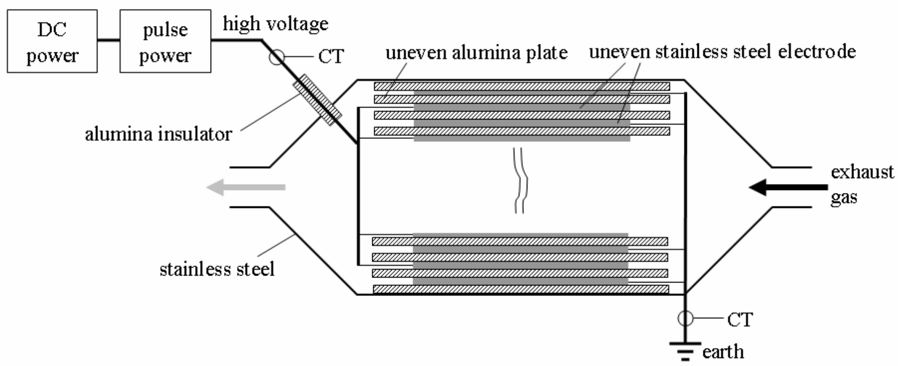

Figure 2 Structure of uneven DBD reactor

The power input P_t (W) to the pulse power was calculated from the product of the output voltage (12 V) and current of the DC power supply. The injection energy P_d (W) from the pulse power supply to the DBD reactor was calculated from the waveforms of voltage and current using Eq.1

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

where F is pulse repetition frequency (Hz); V_i and I_{ci} are voltage (V) and current (A) of high voltage electrode, respectively, at discharge time t_i (s).

PM removal ratio X (%) was calculated using Eq. 2.

$$PM\ removal\, ratio\ X\ (\%)$$
$$= \frac{PM\ emission\, rate\ without\ plasma\ (g/h) - PM\ emission\, rate\ with\ plasma\ (g/h)}{PM\ emission\, rate\ without\ plasma\ (g/h)} \times 100 \tag{2}$$

The energy efficiency of PM removal (g-PM/kWh) based on P_d was calculated using Eq. 3.

$$Energy\ effeiciency\ of\ PM\ removal\ (g - PM/kWh)$$
$$= \frac{PM\ emission\ rate\ without\ plasma\ (g/h) \times PM\ removal\ ratio\ X(\%) \div 100}{P_d(W) \div 1000} \tag{3}$$

We calculated the space velocity [h^{-1}] as the division of the exhaust gas flow rate [L/h] by the net reactor volume [L]. Discharge area [cm^2] was the summation of the gap area of the alumina and stainless steel plates. The residence time [ms] was calculated as the division of total discharge volume (=volume of grooves) [L] by the exhaust gas flow rate [m^3/s].

Results and discussion

PM removal ratio and the energy efficiency of PM removal

Figures 3 and 4 show ratios of PM removal and its energy efficiency, respectively, as a function of injection energy (P_d). PM removal ratio and energy efficiency using 20 pairs were 47-84% and 2.9-0.85 g-PM/kWh, respectively, in injection energy range of 84-340 W. The PM removal ratio increased and the energy efficiency decreased with increasing the injection energy. The PM removal ratio and the injection energy using 30 pairs were substantially increased to 74-93% and 6.0-1.8 g-PM/kWh, respectively, with the injection energy of 80-333 W. When 50 pairs were used, the energy efficiency was increased further to 13.7-3.6 g/kWh. PM removal ratio was 86%, of which corresponding PM emission rate was 0.0046 g/km, at the injection energy of 87 W. This indicates that the PM emission rate and the energy consumption are less than the regulated values by using 50 pairs of this uneven DBD reactor in this engine conditions. The maximum PM removal ratio reached 94% (=0.0018 g/km emission rate) at 250 W.

Table 1 summarizes the characteristics of the DBD reactor. The discharge area, where PM oxidation reaction takes place and residence time increase with the rise in the number of pairs. Thus, the increase in PM removal ratio and the energy efficiency of PM removal are due to the increase of discharge area and residence time.

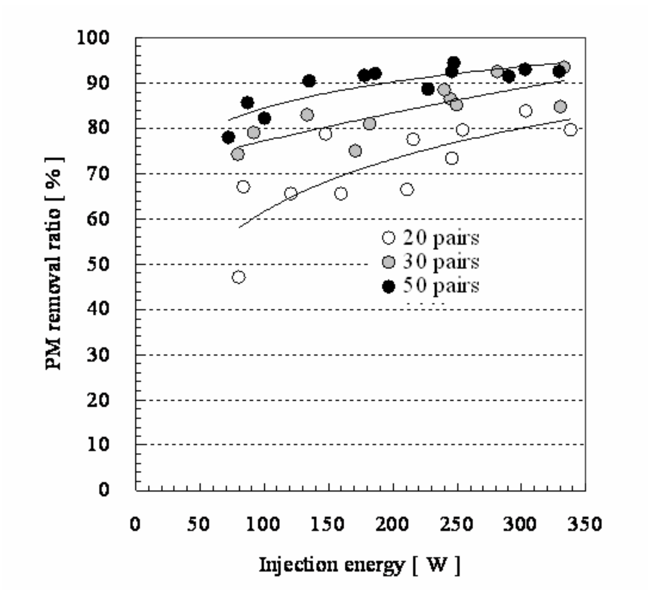

Figure 3 PM removal ratio as a function of injection energy (P_d)

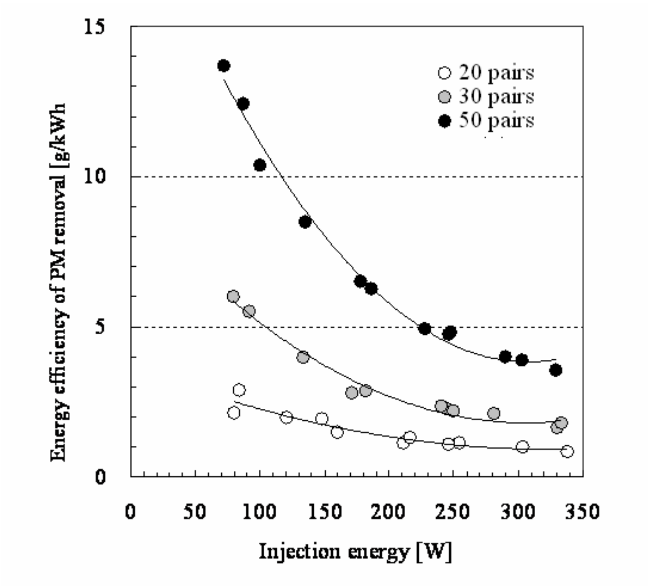

Figure 4 Energy efficiency of PM removal as a function of injection energy (P_d)

Table 1 Characteristics of the DBD reactor (at 460 K)

Number of pairs	Space velocity [h^{-1}]	Discharge area [cm^2]	Residence time [ms]
20	14.7×10^4	6.5×10^3	4.5
30	9.9×10^4	9.7×10^3	6.7
50	5.9×10^4	16.1×10^3	11.2

Next we calculated the relationship between energy efficiency of PM removal and space velocity at the injection energy (P_d) of 100, 200 and 300 W (Figure 5). It was found that the energy efficiency of PM removal is inversely proportional to the approximately 1.6 power of the space velocity.

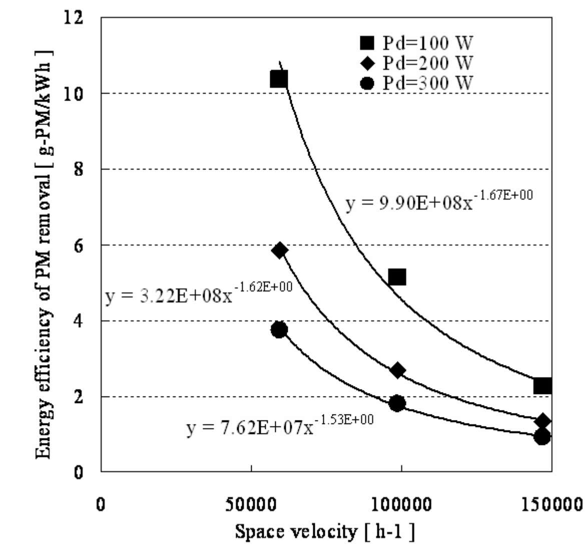

Figure 5 Relationship between energy efficiency of PM removal and space velocity

Figure 6 shows the PM removal rate per pair and injection energy per pair. The PM removal rate per pair is also increased as the rise in the number of pairs. This indicates that the PM removal reaction on each plate is also promoted by the increase of residence time. In the case of 20 and 30 pairs, the PM removal rate per pair gradually increased with the increase in the injection energy. However, when 50 pairs were used, the PM removal rate per pair increases up to approximately 0.024 g/h and saturated at an energy injection per pair is higher than 3 W.

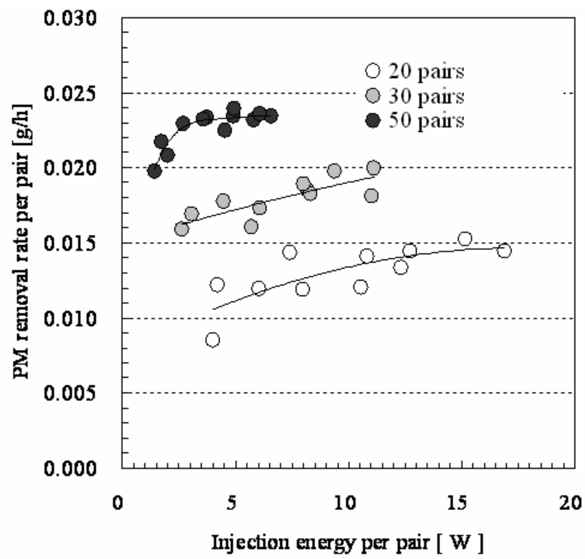

Figure 6 PM removal rate per pair as a function of energy injection to each pair

As we previously reported[27], the reaction mechanism of PM removal is considered to be three steps:

1) Adsorption of PM on surface of alumina plate.
2) Production of active oxygen species by plasma.
3) Oxidation of PM by the active oxygen species.

In addition, it is known that the production of active oxygen species by plasma (excitation and dissociation by electron collision) is an extremely fast reaction[28]. Thus, the rate-determining step should be either adsorption of PM on the alumina plate (step 1) or oxidation of PM by the active oxidation species (step 3). When oxidation of PM (step 3) is rate-determining step, the PM removal rate per pair should become larger as injection energy per pair increases. Hence, it is considered that the oxidation of PM by the active oxygen species is rate-determining step when 20 or 30 pairs are used. On the other hand, the PM adsorption on the surface of alumina (and stainless steel) plate is rate-determining step because of the decrease in PM adsorption rate per pair by increasing the number of pairs. Besides, longer residence time is also considered to promote the oxidation of PM by the active oxygen species.

Pressure drop

Figure 7 shows the pressure drop of the DBD reactor when 20, 30 and 50 pairs were used. The abscissa is the elapsed time after the engine start. The pressure drop at 5 min, when rapid rise in pressure due to the engine start stopped, was 6.8 kPa in the case of 20 pairs. However, the pressure drop at the same time was decreased to 4.3 or 2.3 kPa by using 30 or 50 pairs by the increase of opening space of the DBD reactor (Table 2). The corresponding energy loss due to pressure drop is also shown in Table 2. As can be seen, the energy loss is still larger than the required value (2%). The pressure drop should be less than 2 kPa to meet the requirements.

The pressure drop monotonically increased independent of the number of pairs. This indicates that the adsorbed PM is accumulated on the surface of alumina and/or stainless steel plates.

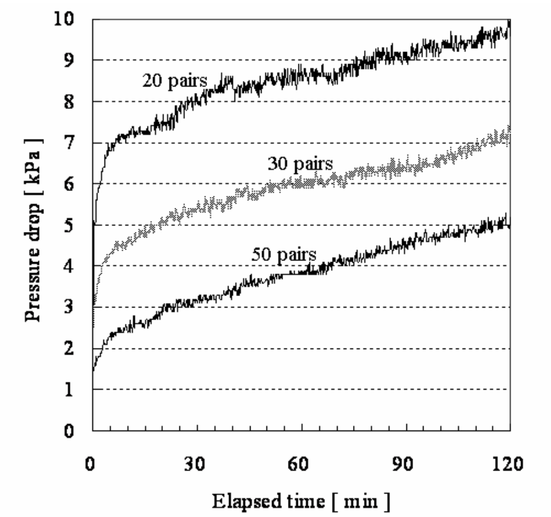

Figure 7 Pressure drop of the uneven DBD reactor.

Next we calculated Reynolds number by assuming that the exhaust gas is air at 423 K. Note that the characteristic length of the reactor (d_H) [m] was calculated as follows[29];

$$d_H = \frac{4 \times (cross\ section\ of\ groove)}{perimeter\ of\ groove} = 4 \times (hydraulic\ radius) \quad (4)$$

The results are also shown in Table 2. It suggests that the conditions are laminar flow in all three cases.

Table 2 Characteristics of DBD reactor after 5 min of engine start (at 423 K)

Number of pairs	Opening space [cm^2]	Pressure drop at 5 min [kPa]	Energy loss [% of engine output]	Flow velocity [m/s]	Reynolds number [-]
20	8.0	6.8	8.5	43	584
30	12.0	4.3	5.4	29	390
50	20.0	2.3	2.9	17	234

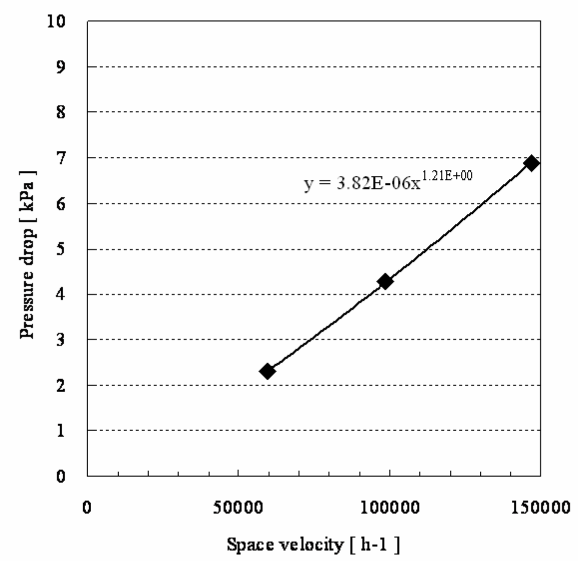

Figure 8 Pressure drop as a function of space velocity

Next we calculated the relationship between pressure drop and space velocity. The results are shown in Figure 8. It was found that the pressure drop is proportional to the 1.2 power of the space velocity. By using this regression curve, we estimated the required number of the pairs to reduce energy loss smaller than 2% of engine output. The result shows that at least 56 pairs are necessary to meet the requirements.

Conclusion

The effect of number of pairs of uneven alumina and stainless steel plates in a DBD reactor on PM removal ratio and pressure drop was measured when the engine output was 3.0 kW. The rise in the number of the pairs substantially increases the ratios of PM removal and its energy efficiency by the increase of discharge area and residence time. PM removal ratio using 50 pairs was 86% at the injection energy of 87 W. The maximum PM removal ratio reached 94% at 250 W. The pressure drop decreased with increasing the number of pairs by the increase of opening space. The pressure drop increases with time, indicating that the adsorbed PM is accumulated on the surface of alumina or stainless steel plates. It was found that the energy efficiency of PM removal is inversely proportional to the approximately 1.6 power of the space velocity and that the pressure drop is proportional to the 1.2 power of space velocity. Based on the regression curve, it was found that 56 pairs of the uneven alumina and stainless plates can give the pressure drop smaller than 2 kPa.

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