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Complete regeneration characteristics of diesel particulate filter using ozone injection

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ABSTRACT

The regeneration of diesel particulate filters (DPFs) is a subject that has attracted considerable interest. Although the ozone injection method is effective, it is unclear whether it can be used to achieve complete DPF regeneration. From the applicative and fundamental points of view, the uncertainty is about whether the diesel particulates, which include nanoparticles, can be completely oxidized by means of plasma. In our study, the possibility of complete DPF regeneration by evaluating the difference between the inlet and outlet pressures of the DPF is investigated. The experimental results show that complete regeneration can be achieved using an ozone injection rate of 34.8 g/h for 2 h, after 2 h of PM collection. Furthermore, a theoretical analysis for the DPF regeneration based on the proposed chemical reactions is presented. Regeneration results agree well with the theoretical ones.

1. Introduction

Diesel engine is one of the significant energy conversion systems as it covers a wide range of applications. However, the treatment of the exhaust gas of diesel engines is currently one of the most significant environmental issues. Innovative technologies are needed to achieve the mitigation of environmental pollution in the emission from diesel engines. Combustion and emission in a system that includes a DPF was investigated under stoichiometric conditions by aiming for reducing pollution in the exhaust [1]. For more effective mitigation of the pollution, methods that utilize nonthermal plasma (NTP) can potentially be used for the comprehensive treatment of the exhaust [2,3]. Nevertheless, the use of a diesel particulate filter (DPF) is the most effective means of removing harmful particulate matter (PM), including nanoparticles, from the exhaust. The PM, however, clogs the DPF after long-term use and affects the operation of the engine. The clogging increases the back pressure that causes an energy loss. This has necessitated a technology for removing the PM – i.e., for DPF regeneration – to ensure the efficient long term operation of the engine.

Several studies have focused on DPF regeneration technologies [4–8] and a PM removal and incineration technology [9]. Methods that utilize NTP, including the use of an ozone injection or the indirect plasma method, have been reported [10–13]. The characteristics of the ozone jet have also been reported [14]. However, it is still unclear whether the ozone injection method can be used to achieve complete DPF regeneration, that is, whether all kinds of accumulated PM in a DPF can be oxidized by NTP, and whether the DPF can be restored to its original condition without PM. Moreover, the characteristics of the DPF regeneration process, which may be used to explain the PM oxidation mechanism, are yet to be analyzed in detail. These are important issues from both applicative and fundamental viewpoints, and should be investigated from the perspective of available technology and ongoing developments.

Against this background, we investigated the conditions that enable complete DPF regeneration by ozone injection. We accomplished this through an experimental and theoretical analysis of the difference between the pressures in the inlet and outlet pipes of a DPF. PM in diesel engine emission primarily consists of dry soot (carbon, C), soluble organic fractions (SOFs), hydrocarbon compounds (HCs), etc. In our proposed method of DPF regeneration, the PM is first captured using a wall-flow-type DPF. NTP-induced O_3 is then injected into the DPF before the exhaust gas passes through. Subsequently, the captured PM is oxidized to gaseous CO_x (= CO + CO_2) by means of oxygen radicals (O), which are mainly produced by the thermal decomposition of the O_3 and NO_2. The oxygen radicals and hydroxyl radicals (OH) contribute to the oxidation of the soot [15], and the oxygen radicals [16] particularly play an important role in our proposed method.

The chemical reactions of the above process are as follows:

$$O_3 \rightarrow O_2 + O \quad (1)$$

$$NO + O \rightarrow NO_2 \quad (2)$$

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$$NO_2 \rightarrow NO + O \quad (3)$$

$$C + 2O \rightarrow CO_2 \quad (4)$$

$$C + O \rightarrow CO \quad (5)$$

$$SOF + O \rightarrow mCO_2 + nH_2O \quad (m \text{ and } n \text{ are integers}) \quad (6)$$

$$2HC + 5O \rightarrow 2CO_2 + H_2O \quad (7)$$

$$2NO_2 + 2C \rightarrow N_2 + 2CO_2 \quad (8)$$

$$2NO_2 + 4C \rightarrow N_2 + 4CO \quad (9)$$

The typical reaction temperature is 200–300 °C, which is relatively lower than [17,18] that of DPF regeneration by thermal oxidization (typically 600 °C). As shown in the reactions, NO_2 and O_3 primarily contribute to the oxidation of the PM. Moreover, the proposed method is free from the problem of catalyst degradation by sulfur, since no catalyst is used.

2. Materials and methods

Fig. 1 shows a schematic of the experimental apparatus for the DPF regeneration using ozone injection. The investigated engine is a diesel engine generator (maximum load = 2 kW, displacement = 219 mL, single cylinder type, and rotation rate = 3600 rpm; YDG200VS-6E, YANMAR Co., Ltd.) that uses light diesel oil (sulfur concentration = 7 ppm) as fuel. During the experiment, the flow rate of the exhaust gas is maintained at 300 NL/min (where N denotes the standard or "normal" state of temperature and pressure) and a 1 kW electric heater load is connected to the power output terminal. Prior to the experiment, the engine is "warmed up" for 1 h with the exhaust gas emitted through flow channel 1. Immediately after the warming up, the experiment is performed by switching the exhaust flow via a valve from flow channel 1 to flow channel 2, in which a SiC DPF (diameter = 50 mm, length = 80 mm, cell density = 300 cpsi ≈ 46.5 cells/cm^2, and wall thickness = 12 mil ≈ 0.3 mm. material: SiC, TYK Corporation) is placed. The PM is initially captured in the DPF for some time. Then, without stopping the engine, O_3 generated by a plasma-induced ozonizer (surface discharge type, OZS-HC-70/W, Masuda Research Inc.), is injected at the inlet of the DPF for the regeneration. Table 1 shows the experimental conditions for the flow rate of supplied O_2 for the ozonizer, mass flow rates, and concentrations of O_3. O_3 is produced by supplying O_2 of 99.6% purity from a gas cylinder to the ozonizer with an input power of 370 W. The ozonizer produces and emits O_3 as a mixture of O_3 and O_2. The O_3 injection causes 1.5% increase of O_2 concentration. However, it is noted that this O_2 increase has little effect on the DPF regeneration. An ozone injection tube is installed at the center of the cross-section of the flow channel and 35 mm in front of the DPF inlet against the exhaust gas flow. O_3 is injected into the DPF apparatus in a direction opposite to the exhaust gas flow. The PM collection is set to 1–2 h; the DPF regeneration is set to 2–5.5 h; and the O_3 injection rate is 25.8–34.8 g(O_3)/h (the O_3 concentration after injection is 658–873 ppm) as shown in Table 1. During the PM collection, the injected flow rate of air is maintained equal to that of O_3 during DPF regeneration.

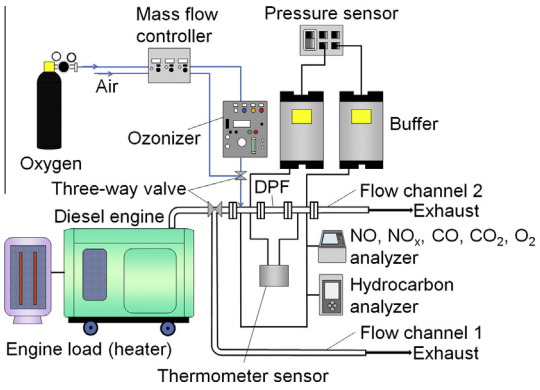

Fig. 1. Schematic of experimental apparatus for DPF regeneration.

Table 1
Experimental conditions for flow rate of supplied O_2 for the ozonizer, mass flow rates of O_3, and concentrations of O_3.

Volumetric flow rate of supplied O_2	L/min	5	8	10
Mass flow rate of O_3	g/h	25.8	32.9	34.8
Concentration of O_3 at outlet of ozonizer	%	4.10	3.25	2.74
Concentration of O_3 after injection	ppm	658	831	873

The engine load is set to 1.0 kW (50% of the maximum output power) for all the experimental trials. The pressures at the inlet and outlet of the DPF are measured using pressure sensors (amplifier AP-C40, sensor head AP-44, KEYENCE Co.). The pressure difference between the inlet and outlet channels is determined from the measured pressures. The pressure sensor has two resolutions – 0.02 and 0.1 kPa – for different pressure ranges. A resolution of 0.02 kPa is used at both the inlet and the outlet when $\Delta p \leqslant 14$ kPa, whereas 0.1 kPa is used at the inlet and 0.02 kPa is used at the outlet when $\Delta p > 14$ kPa. In addition, the exhaust gas temperatures upstream and downstream of the DPF are measured using thermocouples (type K) connected to a recorder (NR-1000, KEYENCE Co.). Gas components such as NO, NO_x (= NO + NO_2), CO, CO_2, O_2, and hydrocarbons (HCs) upstream and downstream of the DPF are also analyzed using gas analyzers (PG-240, HORIBA, Ltd., and VMS-100F, Shimadzu Co.). The measurement resolution is 1 ppm for NO, NO_x, CO and HCs. Those for CO_2 and O_2 are 0.1%. The precision of repeatability in NO, NO_x, and CO measurements are less than ±5 ppm. Those for CO_2, O_2, and HCs are less than ±0.20%, ±0.25%, and ±10 ppm, respectively. The response time in NO, NO_x, CO, CO_2, and O_2 measurements is less than 45 s. The response time in HCs measurement is less than 5 s. The measurements of the pressure and temperature and the gas sampling are taken at specified points, namely, 95 mm away from the DPF inlet pipe and 145 mm away from the outlet pipe.

When the pressure difference returns to the initial value before the PM collection, it is considered that the DPF has been completely regenerated; in other words, complete DPF regeneration has been achieved. It should be noted that the DPF and flow channel are covered with a thermal insulation material to minimize the effect of variations in the ambient temperature. To determine the masses of the collected and oxidized PM, the mass of the DPF is measured using an electromagnetic force balance (PFII-3000, Shinko Denshi Co., Ltd.; measurement accuracy = 10 mg) after it has been gradually cooled to between 18 and 19 °C.

3. Results and discussion

Figs. 2 and 3 show the resultant time-dependent pressure difference characteristics and exhaust gas flow rates during the DPF regeneration for O_3 injection rates of 25.8 g(O_3)/h and 25.8–34.8 g(O_3)/h, respectively. The pressure differences Δp are indicated by the white circles. The upstream and downstream gas temperatures T_{in} and T_{out} are indicated by the white and black triangles, respectively.

Fig. 2 shows the results of six DPF regeneration trials (one cycle of PM collection and DPF regeneration). Each of the first to fifth trials involved 2 h of PM collection and 5 h of regeneration, whereas