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Diesel emission control system using combined process of nonthermal plasma and exhaust gas components' recirculation

Keiichiro Yoshida [a], Tomoyuki Kuroki [b], Masaaki Okubo [b,*]

[a] Osaka Institute of Technology, 5-16-1, Omiya, Asahi-ku, Osaka 535-8585, Japan
[b] Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai 599-8531, Japan

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ABSTRACT

A NO_x aftertreatment system, using nonthermal plasma (NTP) reduction and exhaust gas components' recirculation, is investigated. A pilot-scale system is applied to a stationary diesel engine. In this system, NO_x is first removed by adsorption, and subsequently, the adsorbent is regenerated by thermal desorption. NO_x desorbed is reduced by using nitrogen NTP. Moreover, NO_x, CO_2, and water vapor recirculated into the engine intake reduce NO_x. In this study, approximately 57% of the NO_x of the exhaust (NO_x: 240–325 ppm, flow rate = 300 NL/min) can be continuously treated for 58 h. A system energy efficiency of 120 g (NO_2)/kWh is obtained.

1. Introduction

A diesel engine is widely used in automobiles, construction machines, electric generators, ships, etc. because these engines reduce CO_2 emission due to high thermal efficiencies. However, these engines emit nitrogen oxides (NO_x), mainly nitrogen monoxides (NO); these oxides are one of the most critical environmental pollutants. Currently, selective catalytic reduction (SCR) [1–13] and lean NO_x trap (LNT) [14,15] are used as the representative and most effective NO_x aftertreatment technologies. SCR is a technique in which NO_x is reduced by a catalyst with the help of reducing additives such as ammonia [1–5] or hydrocarbons (HCs) [6–13]. However, the technique that uses ammonia has certain problems with respect to the requisite infrastructure for the supply of urea solution, ammonia slips, the formation of ammonium particles, heavy metal spills, and so on. In the case of the technique that uses HCs, there are problems such as deactivation of the catalyst by the condensation of fuel on the catalyst surface [13] because the fuel is injected as a reducing agent in the system. On the other hand, in the case of LNT [14,15], in which NO_x is stored during a lean condition and reduced during a rich-burn condition, the problem is that sulfur oxides strongly adhere to the catalyst and deactivate it. Therefore, the abovementioned technologies do not yield satisfactory results at this stage, and further study is required for achieving an ideal aftertreatment of NO_x.

Fig. 1 shows the conception diagram of the authors' system. Hot exhaust gas from the engine first heats adsorption chamber 1, in which the adsorbent is regenerated by thermal desorption, and the gas subsequently enters adsorption chamber 2, where NO_x is removed by adsorption. Nitrogen gas that is flowed through adsorption chamber 1 elutes the desorbed NO_x from the chamber. This NO_x is subsequently reduced by using a nonthermal plasma (NTP) reactor. The adsorption and regeneration processes are interchanged between the two chambers. This system does not use catalysts or special reducing agents but uses an oxygen-deficient gas that can be produced by pressure swing adsorption or by a selective O_2 permeation membrane or by controlling the engine combustion condition. Another advantage of this system is that the NTP is not affected by the sulfur present in the exhaust gas. The feasibility of this system was evaluated by carrying out experiments that treated up to 90 NL/min of exhaust gas at a system energy efficiency of 15.8 g (NO_2)/kWh [16].

The most important improvement conducted in the present study is the employment of the cooling process between the regeneration process and the next adsorption process. During the cooling process, atmospheric air is introduced into the section packed with adsorbent pellets in order to lower the section's temperature so that the adsorbent can adsorb NO_x in the next adsorption process. The air that has passed through the adsorbent section includes a considerable amount of NO_x, CO_2, and water vapor and is introduced into the engine intake. One of the expected effects of such a cooling process is the decomposition of NO_x during engine combustion. Another is the reduction in NO_x production in the engine due to the inhalation of CO_2 and water vapor. This reduction has already been investigated earlier, and its significant effect has been demonstrated [17]. However, gas

* Corresponding author. Tel./fax: +81 72 254 9230.
E-mail address: mokubo@me.osakafu-u.ac.jp (M. Okubo).

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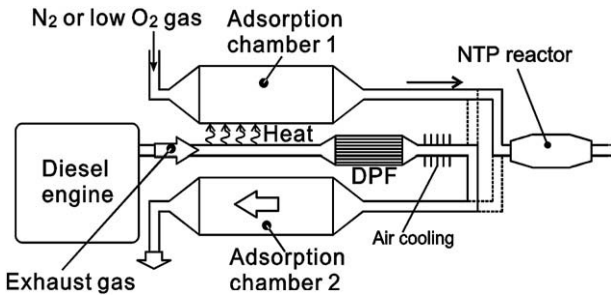

Fig. 1. Concept of NO_x aftertreatment system.

recirculation tends to increase the particulate matter (PM) in the exhaust gas [17]. Moreover, we have not found studies on the combined use of gas recirculation, NO_x adsorption, and NTP. Therefore, the aim of this study is to investigate the impact of the abovementioned combination on NO_x treatment performance. In addition, reduction of highly concentrated NO (more than 5000 ppm) by NTP is performed in this study. The report of NO reduction by NTP is difficult to find in such high concentration region.

2. Experimental apparatus and methods

The engine under investigation is a diesel engine generator (maximum load = 2 kW, displacement = 219 cc, cylinder number = 1 and rotation rate = 3600 rpm; YDG200VS, YANMAR Co., Ltd.). The flow rate of the exhaust gas is approximately 300 NL/min (N implies standard state) when the engine is operated with a 1-kW load (an electric heater) connected to the power output terminal. The exhaust gas includes 240–325 ppm of NO_x ($NO + NO_2$), 160–220 ppm of CO, 4 vol.% of CO_2, 130–190 ppm of HCs in C_1-based total hydrocarbon (THC), and 7 vol.% of water vapor.

The experiment in this study focuses on one of the two chambers in Fig. 1. Fig. 2 shows the gas flows of the NO_x aftertreatment system tested in this study with its photo. It comprises three flow processes: (a) adsorption, (b) heating, and (c) cooling processes. The heating process corresponds to the regeneration process shown in Fig. 1. These processes are repeatedly carried out in the following order: (a), (b), and (c).

In an adsorption process, as shown in Fig. 2a, the exhaust gas first passes through a diesel particulate filter (DPF) where PM such as carbon soot is removed. Subsequently, after the gas is cooled by an air-cooling heat radiator (not described in the figure), it passes through an adsorption chamber where NO_x is removed by adsorption. Some amount of CO_2, HCs, and water vapor is also adsorbed in this process. The mass flow rate of these gases is measured at the exit of the chamber by using a NO_x analyzer (PG-235, Horiba, Ltd.).

Fig. 2b shows the gas flows in a heating process. The exhaust gas first passes through a heat exchanger integrated into the adsorption chamber and heats the surrounding adsorbent pellets in order to induce the thermal desorption of NO_x. Simultaneously, nitrogen gas (5.2 NL/min) is supplied to the zone packed with the adsorbent pellets. Then, the NO_x is eluted. The nitrogen gas is circulated with an air pump not shown in the figure. The total flow rate of the gas passing through the chamber is 40.2 NL/min because of the circulation. This circulation enhances thermal desorption by enhancing the heat exchange between the exhaust gas and the adsorbent. The NO_x eluted by the nitrogen gas is subsequently reduced to nitrogen with an NTP reactor. NO_x concentration is measured after the confluence of the engine exhaust gas and the reduced gas.

Fig. 2c shows the gas flows in a cooling process. Ambient air (approximately 150 NL/min) is introduced into the zone packed with adsorbent pellets with the help of the negative gauge pressure of the engine intake. This air cools the adsorbent pellets that have been heated in the preceding heating process. However, because the temperature of the adsorbent is high immediately after the heating process, the thermal desorption of NO_x, CO_2, and water vapor still takes place. Therefore, these components are circulated through the engine. The mass flow rate of these components is measured at both the inlet and the outlet of the engine. In addition, the gas temperature, T_{in}, is measured at the engine intake in all processes.

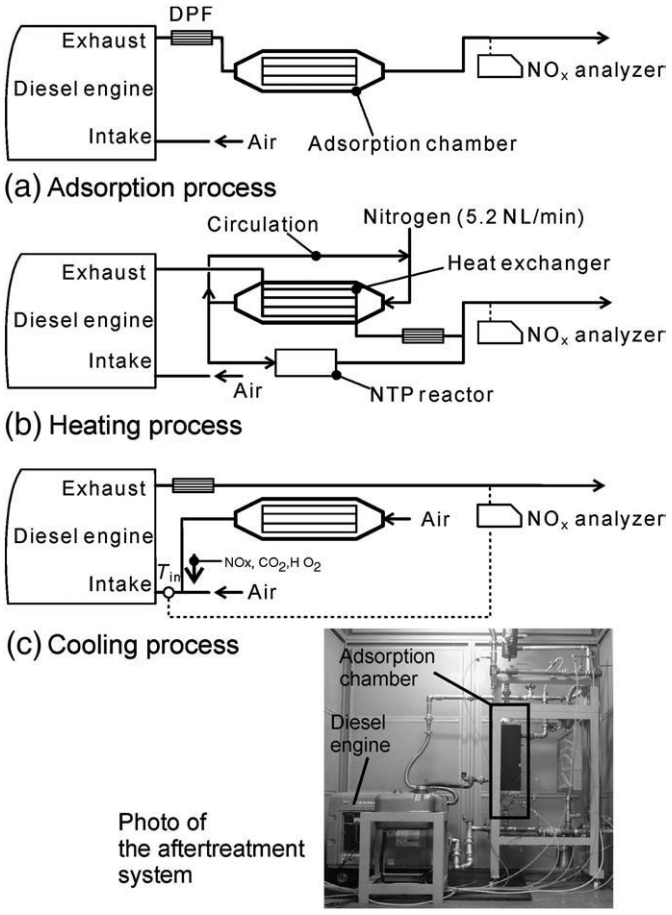

Fig. 2. Exhaust and nitrogen gas flows in each process: a) adsorption process, b) heating process, and c) cooling process.

Fig. 3 shows the structure of the adsorption chamber. The gas flows in a heating process are shown in this figure. Two types of flow paths, flow path I and flow path II, are alternately stacked to form the chamber. Flow path I is empty and path II is packed with adsorbent pellets. Corrugated fins are placed in path II in order to enhance heat transfer. In a heating process, hot exhaust gas passes through path I in order to heat the adsorbent pellets, while nitrogen gas flows from the top inlet to the bottom outlet of path II. In an adsorption process, the exhaust gas passes through path II. The dimensions of the section packed with adsorbent pellets are $120 \times 130 \times 400$ mm.

The adsorbent tested in this study is a CuO–MnO_x complex oxide (N-140; 1.2–2.4-mm granular pellets; Süd-Chemie Catalysts Japan, Inc.) impregnated with 1 wt.% of ruthenium. The packed mass is 2.7 kg. The temperature of the adsorbent (T_1 and T_2) is measured by using thermocouples.

Fig. 4 shows the NTP reactor. This reactor is an aluminum duct in which 12 surface discharge elements are placed in a series. The surface discharge element (OC-002, Masuda Research Inc.) is a ceramic tube (outer diameter: 13 mm) on which surface NTP is generated by applying a high voltage between the inside and the outer surface of the ceramic wall (for a detailed description, refer to ref. [16]). Aluminum blocks surround each element so that the gas stream passes through the region near the surface of the elements where the NTP is generated, as shown in Fig. 4b. The gap formed by the blocks is 1 mm. By