

Pilot-Scale Combined Reduction of Accumulated Particulate Matter and NO_x Using Nonthermal Plasma for Marine Diesel Engine

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Abstract— An effective NO_x-reduction aftertreatment system for a marine diesel engine that employs combined nonthermal plasma (NTP) and adsorption is investigated. The NO_x reduction comprises repeated adsorption and desorption flow processes using NTP combined with NO_x adsorbents. In view of a practical use, experiments in larger number of cycles are carried out. The amount of adsorbents is varied to be 80 and 105 kg. In the balanced state of adsorption and desorption amounts of NO_x in adsorbents, NO_x reduction efficiency by NTP is higher than our previous study, and it is greater at the higher amount of adsorbents due to higher NO_x desorption. This aftertreatment system demonstrates an excellent energy efficiency of 115 g(NO₂)/kWh. The present aftertreatment could generate a synergistic effect of PM and NO_x reduction.

INTRODUCTION

Diesel engines have the advantages of low CO₂ emissions, compact size, and higher fuel efficiency with respect to output power. However, their emissions contain harmful particulate matter (PM) and NO_x (i.e., NO and NO₂), and aftertreatment technologies are required for their removal. Such technologies have been extensively developed in recent years, as reported in our previous paper [1, 2], and are the most effective means for emission purification.

For the removal of PM, diesel particulate filters (DPFs) made using plates of metal, SiC, or cordierite ceramics have been widely employed in automobiles and construction machines. For the removal or incineration of the deposited soot from the DPF (regeneration of DPF), the use of NO₂ oxidation-catalyst incineration (CRT, continuous regeneration trap [3]) has been investigated. The CRT method is effective for use in automobiles but cannot be used for marine diesel engines because sulfur in the emissions damages the oxidation catalysts. We previously proposed a continuous DPF regeneration technology using nonthermal plasma (NTP)-induced radicals, and analyzed the regeneration mechanism [4]. For marine diesel engines, PM emission is a large issue as well [5, 6]. In the use of DPFs, an innovative method for removing deposited soot from the DPF should be considered. We previously proposed and achieved high-performance continuous DPF regeneration technology using nonthermal plasma-induced radicals, which is catalyst free and self-sustaining [7, 8].

For NO_x emissions from diesel engines that are difficult to treat, emissions requirements have become increasingly stringent in recent years. An improvement of fuel injection in diesel engine are investigated [9]. For reducing NO_x emissions in oxygen (O₂)-rich environments in automobiles and construction machines, selective catalytic reduction (SCR) using urea or ammonia, which has been used for stationary emission sources such as incinerators and power generation plants, has been applied [10–16]. There are combined SCR methods with NTP [17–21]. The SCR method, however, has the following issues: a high temperature of 300°C is required for catalyst activation, the possible production of nanoparticles, leakage of harmful ammonia, the use of harmful heavy-metal SCR catalysts, and the necessity for storage of the urea solution.

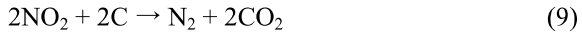
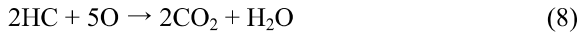
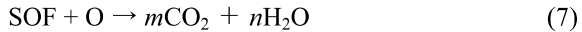
Because regulations regarding emission from automobiles are already implemented in western countries, marine diesel engines are the next target. In view of these circumstances surrounding marine diesel emissions, the issue of NO_x treatment as well as the removal of PM must be addressed urgently [22–24]. For NO_x reduction, although urea-SCR technology is presently the most promising approach, it requires large urea storage tanks inside the vessels.

In this study, an aftertreatment system of NO_x reduction and PM treatment using NTP for a marine diesel engine is developed based on our previous studies on NO_x reduction using NTP combined with an adsorption process, and DPF regeneration using plasma-induced ozone in a laboratory-scale experiment [25, 26]. In view of a practical use, experiments in larger number of cycles are carried out. The amount of adsorbents is varied to be 80 and 105 kg. Compared with selective catalytic reduction (SCR), this technology offers the advantages of not requiring urea solution or harmful heavy-metal catalysts and low operating temperatures of less than 150°C. In this paper, based on our previous experimental results [1, 2] on NO_x reduction, the effect of combined reduction of accumulated particulate matter and NO_x in a balanced state of adsorption and desorption amounts of NO_x in adsorbents, and the amount of adsorbents is varied to be 80 and 105 kg. The present aftertreatment could generate a synergistic effect of PM and NO_x reduction.

OPERATING PRINCIPLE OF AFTERTREATMENT SYSTEM ON SIMULTANEOUS PM AND NO_x
REDUCTION

A. PM reduction

The DPF where the PM is collected is regenerated. Diesel emission PM mostly consists of dry soot (carbon, C), a soluble organic fraction (SOF), hydrocarbon compounds (HCs), and sulfates. In particular, exhaust gas from marine diesel engines operated with marine diesel oil includes a larger SOF than those operated with light oil. In the proposed method, these PMs are first captured by a wall-flow-type DPF. Next, NTP-induced O₃ is injected before the exhaust gas passes through the DPF. The captured PMs are then oxidized to gaseous CO_x (CO + CO₂) by oxygen radicals, which are induced mainly by the thermal decomposition of O₃ and NO₂. The chemical reactions in this process are as follows:



where m and n are integers. The typical reaction temperature is 200–300°C. As shown in these reactions, NO₂ and O₃ originally contribute to the oxidation of the PM. Note that the present method avoids the problem of catalyst degradation by sulfur because it does not use a catalyst. In addition, it was reported in [4] that all kinds of diesel PM can be removed by the O₃ injection, appearing in reactions (1)–(10). In the simultaneous DPF regeneration with NO_x reduction, as a synergistic effect, NO in exhaust gas could enhance PM oxidation by reaction (6) that shows NO reduction as well.

B. NO_x reduction

In the previously developed technology [25, 26], since NO_x cannot be reduced efficiently by the direct application of NTP under oxygen-rich conditions, it is first adsorbed under oxygen-rich conditions. After adsorption, NO_x is desorbed periodically by heating under an oxygen-lean (O₂ < 2% is desirable) and fuel-rich (CO and hydrocarbon rich) gaseous condition. Switching between the different processes is accomplished by changing the paths of the exhaust gas and using a waste-heat recovery system from the engine. The high-concentration desorbed NO_x is effectively reduced by NTP to nitrogen gas (N₂) and nitrogen (N) radicals. Oxygen-lean or N₂ gaseous conditions can be achieved using an oxygen penetration membrane or by controlling the engine operation mode

(fuel-injection mode) to have a fuel-rich condition. The chemical reaction for NO_x reduction with an oxygen-lean NTP is given by



NTP can be turned off during adsorption and should only be turned on when high concentrations of NO_x are desorbed and only during the short desorption period, thus further reducing the required plasma energy. Laboratory-scale experiments based on this procedure, in which NO_x is treated with high energy efficiency, have been reported in our previous papers [27–30], including a patent [31].

Figure 1 shows the process diagrams of the PM and NO_x simultaneous reduction system for a marine diesel engine. The system primarily consists of the diesel engine, DPFs, adsorption chamber, and NTP reactors. PM reduction is carried out with a pair of DPFs regenerated by ozone injection and the following NO_x reduction is realized by two flow processes: adsorption followed by desorption combined with the NTP reaction. Continuous NO_x reduction is performed by the sequential application of these two processes in the same adsorption chamber. In the adsorption process, as illustrated in **Fig. 1(a)**, the exhaust gas first passes through one of twin DPFs where PM such as carbon soot is removed. The flow velocity is measured by a set of Pitot tubes to determine the flow rate of the exhaust gas. Subsequently, after the gas is cooled by a water-cooling type cooler, it passes through an adsorption chamber where NO_x is adsorbed. Some CO_2 , hydrocarbons (HCs), and water vapor are also adsorbed in this process. The NO_x concentrations are measured at the inlet and outlet of the chamber using a NO_x analyzer. In the desorption process, as illustrated in **Fig. 1(b)**, the exhaust gas passes through one of twin DPFs and a heat exchanger integrated into the adsorption chamber. The exchanged waste heat is added to the adsorbent pellets through the heat exchanger and induces thermal desorption of NO_x . Simultaneously, oxygen-lean air or nitrogen gas ($11.8 \text{ Nm}^3/\text{h}$) flows over the packed

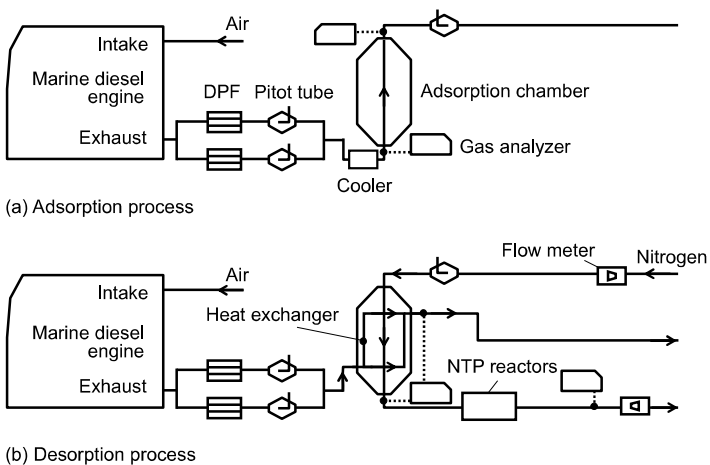


Fig. 1. Process diagrams of the NO_x -reduction system for a marine diesel engine

adsorbent pellets, and consequently, high concentrations (typically 4000 ppm) of NO_x are eluted from the chamber. The eluted NO_x is treated and reduced in the NTP reactor. These are the principle of simultaneous reduction of PM and NO_x . In the next section, experimental apparatus and results are presented.

EXPERIMENTAL APPARATUS

Experiments were carried out using electrical sub power generation marine engine (6DK-20e, Daihatsu Diesel MFG Co. Ltd., Japan) bench in the laboratory. The specifications of the engine are as follows: a maximum or 100% output power of 1071 kW, four cycles, six cylinders with a cylinder bore of 200 mm and a stroke of 300 mm, a constant rotation rate of 900 rpm, and the total mass of the engine and dynamo of 16 ton. Marine diesel oil (A-heavy oil, sulfur = 0.075 mass%, nitrogen = 0.01 mass%, heat quantity = 45.4 MJ/kg) is used as the fuel. The exhaust flow rate is 3920 Nm^3/h for 50% load or output power, 5526 Nm^3/h for 75%, and 6815 Nm^3/h for 100% (N denotes the standard state of 0°C, 0.1 MPa). The raw or untreated exhaust gas components such as NO_x , CO, CO_2 , O_2 , and HCs in C1-based total hydrocarbon from the targeted diesel engine at different engine loads are measured as a specification of the engine itself using a marine-diesel exhaust gas measuring system (MEXA-1600DS, Horiba, Ltd., Japan). All aftertreatment experiments are performed either at engine loads of 50 or 75%. At an engine load of 50%, the typical concentrations of NO_x , CO, CO_2 , O_2 , and HCs are 660 ppm, 33 ppm, 4.8% (= 48000 ppm), 14.4%, and 120 ppm, respectively, and at an engine load of 75%, they are 710 ppm, 63 ppm, 4.9%, 14.2%, and 120 ppm, respectively.

Figure 2 shows the experimental setup for the aftertreatment system for the marine diesel engine. The exhaust gas emitted from the engine is first separated and approximately 16% of the bypassed gas, whose flow rate is controlled by a flow regulation valve, passes through a set of ceramic DPFs, where most PM is removed. After the gas passes through the DPFs, the flow velocity is measured by a set of Pitot tubes (L type, FV-21A, OKANO WORKS, Ltd. Japan). The size of the pipe for the bypassed flow is 150 A (in Japanese Industrial Standards; inner diameter = 155.2 mm). The DPF (material: SiC, TYK Corporation, Japan) has the following specifications: a diameter of 190.5 mm, a length of 100 mm, a cell density of 169 cells/in², and a wall thickness of 16 mil (= 0.406 mm). The accumulated PM in the DPF is treated by nonthermal plasma-induced ozone (O_3) injection technology, as we previously reported [8] for a marine diesel engine. O_3 is generated by an ozonizer (EW-90Z, Ebara Jitsugyo Co. Ltd., Japan, O_3 = 90 g/h, input power = 3.1 kW) equipped with a pressure swing absorption (PSA) oxygen generator. O_3 is injected when the pressure difference Δp reaches to around 3.0 kPa, and a simultaneous treatment of PM and NO_x is carried out. From cycle 24, O_3 is injected in the adsorption process when the pressure difference Δp = 0.8 kPa. After the PM removal, NO_x in the exhaust gas is treated by NTP combined with adsorption and desorption processes. The NO_x reduction process is realized by switching valves and controlling the flows of the adsorption and desorption processes. For the effective adsorption of NO_x to the adsorbents, the exhaust gas is cooled from 270°C to approximately 45°C with a water-cooling type cooler. In the chamber containing the adsorbents, a maximum of 92% of the NO_x is adsorbed. Before the gas passes through the chamber the concentration of untreated NO_x come from the engine is 400–760 ppm, and the ratio of NO_2 to NO_x is approximately 15%. Finally, the exhaust gas

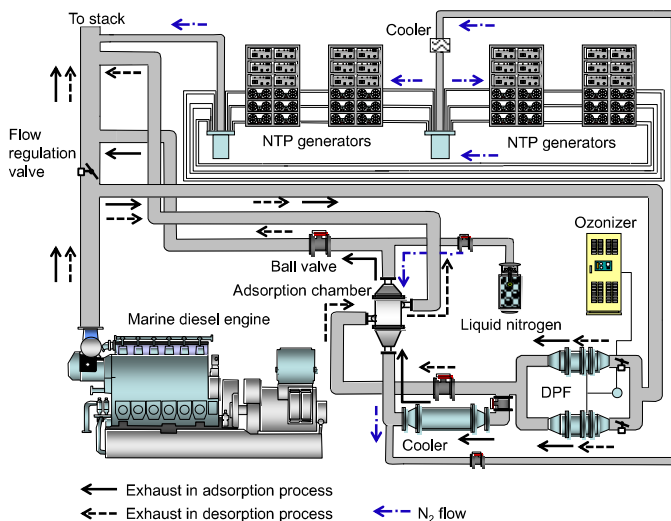


Fig. 2. Schematic of experimental setup for exhaust gas aftertreatment in marine diesel engine system

flows out from a stack. In the desorption process, after the valves have been switched accordingly, N₂ gas at a lower flow rate of 11.8 Nm³/h (200 L/min at 5°C) from a liquid N₂ cylinder passes through the chamber. The direction of the N₂ gas is opposite to that of the exhaust gas during adsorption. Simultaneously, the chamber is heated by waste heat from the exhaust gas. The remarkable point is that the desorbed NO_x concentration is high. As a result, much higher concentration (typically 3660–25000 ppm) NO_x than that (typically 4000 ppm) in the previous experiment [1] flows out of the chamber and enters the NTP reactors with a total energy consumption of 12.0 kW. NO_x is reduced and purified according to reaction (10). The concentrations of NO_x, NO, CO, and O₂ after adsorption and after NTP treatment are measured using a gaseous analyzer (PG-235, NO_x chemiluminescence-type, Horiba, Ltd., Japan). N₂O concentration after NTP treatment is measured using a gaseous analyzer (VIA-510, infrared-type, Horiba, Ltd., Japan) through a sampling unit (ES-510, Horiba, Ltd., Japan) and a catalyzer unit (Horiba, Ltd., Japan). The total NO_x and O₂ concentrations before adsorption and after desorption are measured using another NO_x and O₂ analyzer (NOA-7000, Shimadzu Corporation, Japan). For high-concentration desorbed NO_x more than 2500 ppm which is the upper imitation of the analyzer, the gas is diluted with atmospheric air and the real NO_x concentration is estimated by comparing the oxygen concentration of the diluted exhaust gas with that of the raw exhaust. All aftertreatment experiments are performed either at engine loads of 50 or 75%. As shown in the figure, at an engine load of 50%, the typical concentrations of NO_x, CO, CO₂, O₂, and HCs are 660 ppm, 33 ppm, 4.8% (= 48000 ppm), 14.4%, and 120 ppm, respectively, and at an engine load of 75%, they are 710 ppm, 63 ppm, 4.9%, 14.2%, and 120 ppm, respectively [1].

Figure 3 shows the adsorption chamber equipped with a waste heat exchanger specially designed and manufactured by Sumitomo Precision Products Co. Ltd. (type: XS6083) The

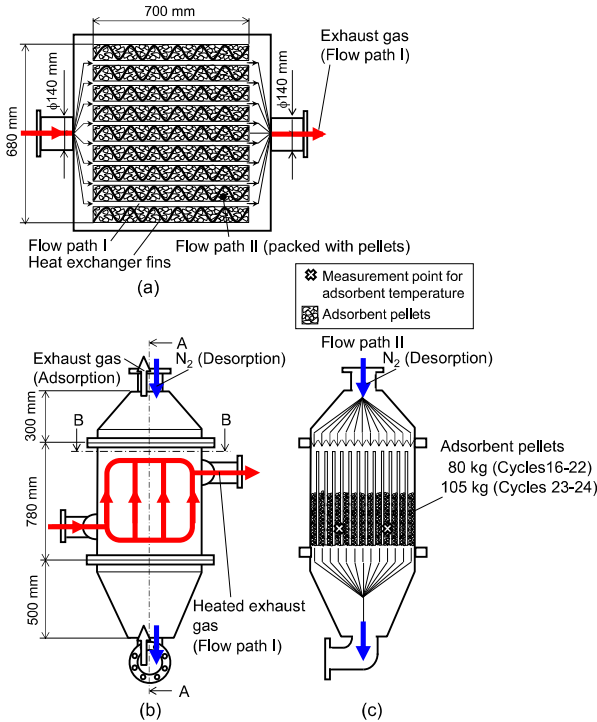


Fig. 3. Schematic representation of adsorption chamber containing adsorbents with gas flows in desorption process

directions of gas flows and the dimensions are shown in the figure. The same chamber as the previous experiment is used [1]. However, the amount of packed adsorbent pellets is varied in the present experiment. The amounts are 80 kg in cycles 16-22 and 105 kg in cycles 23-24. In comparison with the previous study [2], the dimensions of the chamber are different and the amount of packed adsorbent pellets is larger. **Fig. 3(a)** shows a cross-section of the chamber with two types of flow paths, namely, flow path I and flow path II, alternately stacked inside. Flow path I (the number is 47 and each gap is 3.2 mm), is empty and flow path II (the number is 48 and each gap is 8.9 mm), is packed with adsorbent pellets to a height of 270 mm, as shown in **Fig. 3(c)**. The thickness of the plates between path I and II is 1 mm. Corrugated stainless-steel heat exchanger fins are placed in flow path II in order to enhance heat transfer. In the adsorption process, exhaust gas flows from the bottom inlet to the top outlet of flow path II, and NO_x is adsorbed to the adsorbent pellets. In the desorption process, heated exhaust gas passes through flow path I in order to heat the adsorbent pellets, and simultaneously a low flow rate of nitrogen gas or oxygen-lean gas flows from the top inlet to the bottom outlet of flow path II, as shown in **Figs. 3(b)** and **(c)**. In order to switch between these two processes, the gas flow directions are changed by opening and shutting the ball valves. The adsorbent used in this study is a MnO_x-CuO oxidative compound (N-140, 1.2–2.4 mm-sized granular pellets, Süd-Chemie Catalysts

Japan, Inc.). The temperatures of the adsorbents are measured using thermocouples at the points shown in **Fig. 3(c)**.

The NTP reactor used for NO_x reduction in the desorption process consists of a surface discharge element (ET-OC70G-C, Masuda Research Inc., Japan), air-cooling fins, and a flange to fix the discharge element to the frame. Tungsten discharge electrodes are on the inner alumina ceramic wall of the discharge element. As shown in the figure, NO_x in N_2 gas flow on the surface discharge element. NO_x is reduced into clean gases of N_2 and O_2 with the surface discharge plasma. The surface discharge element is cooled with air-cooling fan. The specifications of one unit of the NTP generator that includes the power supplies and the NTP reactors are as follows: Two of these reactors are powered by a single pulse high-voltage (maximum peak-to-peak voltage = 10 kV, frequency = 10 kHz, and maximum input power = $450 \times 2 = 900$ W) power supply (HCII-70/2, Masuda Research Inc.). A unit of NTP generators (HCII-OC70 \times 12) consists of 12 NTP reactors and 6 power supplies. The total input power of a unit is $900 \text{ W} \times 6 = 5.4 \text{ kW}$ and the discharge power is 5.0 kW. The electrical conversion efficiency is $5.0/5.4 \times 100 = 93\%$. The capacity of N_2 flow rate is $60 \text{ m}^3/\text{h}$. The power consumption per one reactor is 9 kVA where the voltage is 200 V. In the experiment, 4 NTP generator units (total input power is $5.4 \times 4 = 21.6 \text{ kW}$) connected in three parallel separate flow lines are used. The flow rate of each line is $3.9 \text{ Nm}^3/\text{h}$ and the total is $11.8 \text{ Nm}^3/\text{h}$. When high-concentration desorbed NO_x in N_2 flows into the inlet of the reactor, the NO_x reduced by the NTP flows out of the reactor outlet as a clean gaseous mixture of N_2 and O_2 .

III. RESULTS AND DISCUSSION

C. Reduction of NO_x for cycles 16–19

Experiments were carried out for 24 cycles in total to evaluate the NO_x -reduction performance in the aftertreatment system. It is noted that engine operation was stopped once during each process. The mass concentration of PM in the untreated exhaust gas is 14–16 mg/Nm^3 . Before the exhaust gas passes through the adsorption chamber, it is treated by two DPFs and more than 95% of particulates larger than 20 nm are removed.

Figure 4 shows the time-dependent NO_x emissions before and after the gas passes through the aftertreatment system for operation cycles 16–19. Cycles 16–19 are transition of adsorbent from unsteady to steady states. The engine load is set to 75% for all adsorption processes, 50% for the all desorption processes. The engine loads are set by regarding exhaust gas temperatures suitable for the adsorption and desorption of NO_x . The amount of adsorbent pellets in the adsorption chamber is 80 kg. In this figure, the mass flow rate for NO_x shown on the vertical axis is evaluated based on the molecular mass of NO_2 with the unit of $\text{g}(\text{NO}_2)/\text{h}$. Furthermore, untreated NO_x is indicated by white circles with lines in the adsorption process. Treated NO_x is indicated by black circles with lines. NTP is applied only in the desorption processes, and the input power to the NTP generator is 12.0 kW. The mass flow rate of NO_x in the untreated exhaust gas is 1330–1500 $\text{g}(\text{NO}_2)/\text{h}$ in a steady state of engine operation. It is noted that the engine operation is stopped at $t = 3900$ min in adsorption process of cycle 17 and at $t = 4192$ min in adsorption process of cycle 18 because the engine is stopped for about a half day due to the schedule of the experiment. As a result of the adsorption processes, the mass flow rate of NO_x decreases to 970–1280

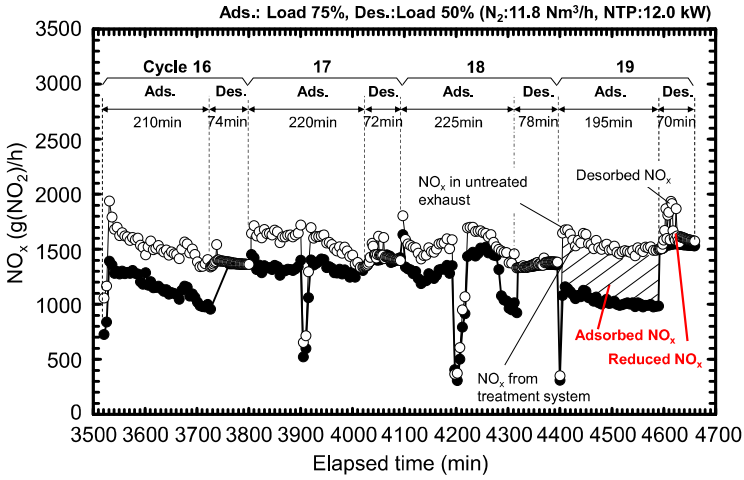


Fig. 4. Schematic representation of adsorption chamber containing 105 kg of adsorbents with gas flows in desorption process

$g(NO_2)/h$. In the desorption processes, the characteristics of NO_x desorption is that the concentration drastically increases and reaches to the maximum. The maximum concentrations of desorbed NO_x are 8180 ppm, 11380 ppm, 3660 ppm, and 17830 ppm in cycles 16–19, respectively. On average 49% of the desorbed NO_x is reduced by the NTP generators. For example, in cycle 19 shown in the graph, the hatched area surrounded by white and black symbols represents the total mass of adsorbed NO_x , and the area in the desorption process represents the total mass of NO_x reduced by the NTP. As a result, the desorption of NO_x is enhanced in cycle 19.

Table 1 shows the adsorbed, desorbed, reduced, and treated amounts of NO_x together with the gaseous flow rates and energy efficiencies of NO_x removal by the NTP and the entire system in cycles 16–19. The adsorbed mass of NO_x , W_a , ranges from 855 to 1651 $g(NO_2)$. The desorbed mass of NO_x , W_d , ranges from 41.4 to 160 $g(NO_2)$. The mass of NO_x reduced by the application of NTP, W_{NTP} , is in the range 17.3–113.6 $g(NO_2)$. The total amount of NO_x removed by the system is calculated as

$$W_{\text{system}} = W_a - W_d + W_{NTP} \quad (12)$$

The energy efficiency of the NTP treatment itself is calculated as

$$\eta_{NTP} = \frac{W_{NTP}}{E_{NTP}} \quad (13)$$

where E_{NTP} is the applied NTP energy. η_{NTP} is found to be 1.11–8.11 $g(NO_2)/kWh$. The NO_x removal energy efficiency of the system is calculated as

$$\eta_{\text{system}} = \frac{W_{\text{system}}}{E_{NTP}} \quad (14)$$

Table 1: Resulting treated NO_x amount and removal energy efficiency (g(NO₂)/kWh) in each cycle (cycles 16–19, 23,24)

	Unit	Cycle 16	17	18	19	23	24
Averaged flow rate of exhaust gas	Nm ³ /h	944	999	948	946	804	913
(1) Adsorbed, W_a	g(NO ₂)	1248	855	937	1651	1740	1260
(2) Desorbed, W_d	g(NO ₂)	49.9	113	41.4	160	337	405
(3) Reduced by NTP, W_{NTP}	g(NO ₂)	26.0	35.4	17.3	114	237	340
(4) Removed in system, $W_{system} = W_a - W_d + W_{NTP}$	g(NO ₂)	1224	777	913	1605	1640	1195
NTP power	kW	12.0	12.0	12.0	12.0	12.0	12.0
NTP energy, E_{NTP}	kWh	14.8	14.4	15.6	14.0	14.4	14.8
$\eta_{NTP} = W_{NTP} / E_{NTP}$	g(NO ₂)/kWh	1.76	2.46	1.11	8.14	16.5	23.0
$\eta_{system} = W_{system} / E_{NTP}$	g(NO ₂)/kWh	83	54	59	115	114	81

The highest system energy efficiency, $\eta_{system} = 115$ g(NO₂)/kWh, is achieved in cycle 19. This result indicates that the lower NTP power of 12.0 kW is sufficient for NO_x reduction under these conditions. It is noted that in the adsorption process of cycle 19, the typical concentrations of gaseous NO₂, NO, CO, and O₂ downstream of the adsorption chamber are 100 ppm, 430 ppm, 69 ppm, and 13.9%, respectively. In the desorption process of cycle 19, the NO_x concentrations upstream and downstream of the NTP generator are 5610 ppm and 1620 ppm, respectively.

D. Combined reduction of PM and NO_x for cycles 23 and 24

DPF regenerations are carried out in cycles 23 and 24 with the injection of O₃. **Figure 5** shows photographs of DPF (a) unused before experiment, and (b) after regeneration. The four white parts on the DPF after regeneration are observed because four ozone injection tubes are placed in front of DPF. DPF is partially regenerated. An effective regeneration is achieved in the present study. In the simultaneous DPF regeneration with NO_x reduction, NO in exhaust gas could enhance PM oxidation by reaction (6) that shows NO reduction as well. It could generate a synergistic effect of PM and NO_x reduction.

Table 1 shows the adsorbed, desorbed, reduced, and treated amounts of NO_x together with the gaseous flow rates and energy efficiencies of NO_x removal by the NTP and the entire system in cycles 23 and 24. At cycle 23, $W_a = 1740$ g(NO₂), $W_d = 337$ g(NO₂), $W_{NTP} = 237$ g(NO₂), and $E_{NTP} = 14.4$ kWh; therefore, the highest system energy efficiency of $\eta_{system} = 114$ g(NO₂)/kWh is recorded for this cycle. It is noted that in the adsorption process of cycle 23, the typical concentrations of gaseous NO₂, NO, CO, and O₂ downstream of the adsorption chamber are 80 ppm, 400 ppm, 70 ppm, and 13.9%, respectively. In the desorption process of cycle 23, the NO_x concentrations upstream and downstream of the NTP generator are 11660 ppm and 3190 ppm, respectively.

The system energy efficiency of $\eta_{system} = 115$ g(NO₂)/kWh is lower than $\eta_{system} = 161$ g(NO₂)/kWh recorded in the previous study [1]. This is because the previous one is

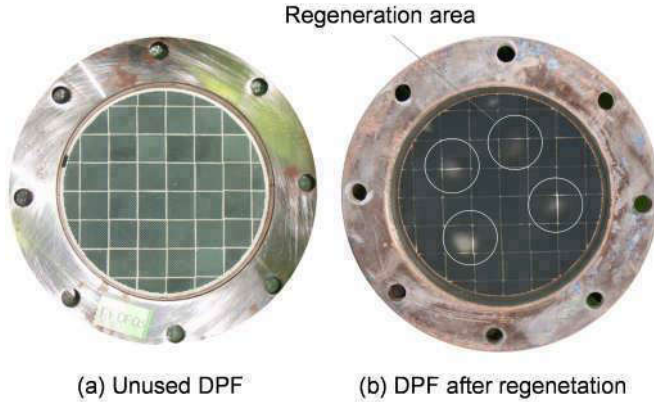


Fig. 5. Photographs of DPF (a) unused before experiment, (b) after regeneration

recorded with help from high-adsorption performance of the relatively new adsorbents, but the present study is carried out in the balanced steady state of adsorption and desorption amounts of NO_x where adsorption performance decreases. However, the desorption performance is greater and NO_x reduction efficiency by NTP is higher than the our previous study. The IMO emission standards from Tier II to III for a marine diesel engine with a rotating speed of 900 rpm requires NO_x emissions to be reduced by 6.89 g/kWh. The recorded system energy efficiency of $\eta_{\text{system}} = 115 \text{ g}(\text{NO}_2)/\text{kWh}$ in terms of the IMO emission standards from Tier II to III corresponds to only 6.0% ($= 6.89/115 \times 100$) of the engine output power. This high performance aftertreatment fulfills the most recent IMO emission standards for 2016 using present-day technology.

In this experiment, the maximum system energy efficiency, η_{system} of 115 g(NO_2)/kWh is obtained in cycle 19. In the present combined pilot-scale aftertreatment system of NO_x reduction and PM treatment, the pressure difference and the resistance coefficient in DPF can be reduced with plasma-induced O_3 injection, that is, DPF regeneration is achieved.

CONCLUSION

An combined pilot-scale aftertreatment system of NO_x reduction and PM treatment for marine diesel exhaust gas is developed. An experiment using a pilot-scale aftertreatment system for a marine diesel engine with an output power of 1 MW has been carried out using an NTP generator with a power of 12.0 kW. The characteristics of NO_x adsorption/desorption and NO_x reduction by NTP are analyzed using the experimental data. DPF regeneration with plasma-induced O_3 injection is achieved, simultaneously. Finally, the energy efficiency of NO_x reduction by NTP is evaluated. The present aftertreatment could generate a synergistic effect of PM and NO_x reduction. The system energy efficiency of $\eta_{\text{system}} = 115 \text{ g}(\text{NO}_2)/\text{kWh}$ is lower than $\eta_{\text{system}} = 161 \text{ g}(\text{NO}_2)/\text{kWh}$ recorded in the previous study [1]. This is because the previous one is recorded with help from high-adsorption performance of the relatively new adsorbents, but the present study is carried out in the balanced steady state of adsorption and desorption amounts of NO_x

where adsorption performance decreases. NO_x reduction efficiency by NTP is higher than the our previous study, and it is greater at the higher amount of adsorbents due to higher NO_x desorption. This system demonstrates an excellent system energy efficiency for NO_x removal of 115 g(NO_2)/kWh. Because high-concentration NO_x is treated by NTP with the help of NO_x adsorption and desorption, the present aftertreatment system can achieve higher energy efficiency. This remarkable efficiency fulfills the most recent requirement of the IMO emission standards from Tier II to III that is reduction of 6.89 g/kWh for engine rotating speed of 900 rpm for a marine diesel engine, requiring only 6.0% of the engine output power when the engine rotating speed is 900 rpm. The present aftertreatment system can fulfill the same-level requirement in future. This system does not use any rare or precious metal catalysts, harmful ammonia, or urea solution. Therefore, this method has significant advantages over conventional exhaust gas treatments such as the marine SCR method, which requires a urea solution storage tank inside the ship.

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