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Original Paper

An experimental study on the air pollutant emission characteristics of high-speed diesel engine for small coastal ships according to the application of the LP EGR and DOC-DPF systems

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Abstract: High-speed diesel engines that are widely distributed in small coastal ships discharge nitrogen oxides (NOx) and other air pollutants. In this study, experimental investigations were conducted on the possibility of treating air pollutants when applying low-pressure exhaust gas recirculation (LP EGR), diesel oxidation catalyst (DOC), and diesel particulate filter (DPF), in accordance with the expectation of stricter regulations on ship-discharged air pollution. The experiment was conducted on a high-speed diesel engine for a 500 ps ship that uses diesel and consists of an EGR system that adopts an LP method for efficient air supply and cooling effect of exhaust gas. After the LP EGR, a DOC-DPF was additionally installed in the exhaust pipe to experiment on the treatment performance of other pollutants such as carbon monoxide (CO), hydrocarbon (HC), and smoke. The study demonstrated that NO_X emissions were reduced by 75.9%; from 7.56 g/kWh to 1.82 g/kWh, when LP EGR was operated at rates within the range of no output loss. This figure satisfies the International Maritime Organization (IMO) Tier III emission standard. Finally, when the DOC-DPF was additionally operated on the LP EGR, NO_X emissions could be reduced to 1.83 g/kWh and smoke concentration below 1%, and HC was reduced by up to 95% and CO by up to 94%.

Keywords: Diesel Engine, Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), Exhaust Gas Recirculation (EGR), Nitrogen Oxides (NO_X).

1. Introduction

Regulations to prevent air pollution driven by ship emissions are gradually being strengthened for both oceangoing ships and coastal ships **[1]**. According to the “2017 National Air Pollutants Mission (2020),” released by the National Institute of Environmental Research, air pollutant emissions from marine ships consist of 13.66% nitrogen oxide (NO_X) (162,514 tons), 3.79% particulate matter (PM)-10 (8,290 tons), 8.43% PM-2.5 (7,731 tons), and 12.50% carbon monoxide (CO) (102,179 tons) **[2]**.

Statistical data from the Ministry of Oceans and Fisheries indicate that fishing boats account for approximately 65,050 out of 73,949 registered powered ships, including fishing boats in Korea **[3]**. In the case of domestic fishing boats, outboard engines are generally used for those with less than 300 ps and diesel engines for more than 300 ps **[3]**.

Domestic ships’ discharge standard on NO_X was applied to ships built after 2006 and Tier II standard were applied for ships built after 2013. However, as of May 19, all ships built after 2006 were subject to Tier II standards when replacing institutions. In addition, with growing social concern regarding fine dust levels, measures have been adopted to reduce fine dust emissions in the port and ship sectors. Therefore, it is highly possible that additional regulations will be added and implemented to the current regulations for reducing air pollution generated by ships.

Diesel engines have the advantages of high fuel efficiency, high power, and excellent durability; therefore, they are widely utilized in small-and medium-sized domestic coastal ships. Pollutants discharged from diesel engines mainly include gaseous substances, such as NO_X, hydrocarbons (HC), CO, and PM, such as soot. NO_X discharged from diesel engines mainly consists of

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nitric oxide (NO) and nitrogen dioxide (NO_2), with more than 98% NO. NO released into the air oxidizes and becomes NO_2, and it reacts with HC to cause photochemical smog **[4]**. Several studies have investigated methods to reduce the emission of pollutants by focusing on fuel injection devices and their improvement in absorption and exhaust; however, additional measures for post-treatment technologies are required to satisfy the strengthened exhaust regulations.

To meet the new standards, it is necessary to either convert the existing fuels to clean fuels or apply an electric propulsion method. However, the transition to eco-friendly technology requires high initial investment and operational maintenance costs. Furthermore, the newly implemented regulations may not be sufficient for manufacturers to efficiently manufacture small ships and diesel engines in operation; hence, there is a demand for technologies to overcome these issues.

Methods for reducing NO_X include selective catalyst reduction (SCR), exhaust gas recirculation (EGR), and lean NOx traps (LNT). Among them, EGR is a technology that reduces the total amount of NO_X generated by suppressing the temperature owing to combustion gas in exhaust gas, and suppresses the generation of thermal NOx by lowering the excess air rate. In addition, the generation of NO_X is suppressed by replacing some of the air taken in with low-oxygen-concentration exhaust gas to reduce oxygen in the combustion chamber **[5][6]**.

EGR has a high-pressure (HP) loop type, low-pressure (LP) loop type, and dual loop type. HP EGR supplies high-pressure exhaust gas at the front of the turbine to the rear of the compressor. The length of the pipeline through which the EGR gas flows is relatively short; therefore, the system responsiveness is fast **[5]**. However, as the EGR rate increases, the turbine side flow rate decreases, which limits efficient turbine operation **[7]**.

LP EGR is a method of extracting exhaust gas from the rear of the turbine, by passing it through the EGR valve and cooler, and supplying it to the compressor front of the turbocharger. Because the LP EGR releases exhaust gas treated with pollutants that have passed through the diesel particulate filter (DPF), the gas pressures and temperatures are lower than those of the HP EGR, and the pressure at the front of the compressor is lower than that at the rear of the DPF **[8]**. Therefore, there is no difference in the exhaust gas flow rate on the turbine side of the turbocharger; subsequently, it is possible to maintain a higher supercharge pressure and supply a large amount of EGR while minimizing the reduction in the intake pressure **[7][9]**.

The dual loop EGR is a complex HP EGR and LP EGR, and HP or LP EGR may be selectively used depending on the driving condition. As a result, dual-loop EGR requires additional systems and its application has a difficulty because of the complexity of control and maintenance and high cost.

Therefore, to satisfy the IMO Tier III criteria, I applied the LP-based EGR that is with higher NO_X reduction efficiency compared to the HP method and a simple system configuration compared to the dual-loop EGR. The LP EGR system applied in this study consisted of major components, including the EGR V/V, back-pressure V/V, cooler, actuator, controller, and internal DPF.

The advantages of EGR include excellent reduction of NO_X without the need for catalysts and urea water and its applicability in limited spaces. However, EGR has the disadvantage of increasing the levels of smoke, CO, and HCs from incomplete combustion caused by excessive exhaust recirculation as the EGR rate increases **[10]**. To compensate these shortcomings, the system was constructed with an additional mounting diesel oxidation catalyst (DOC) and DPF at the rear of the engine exhaust pipe. A DOC is a device that removes HC, CO, and hydrocarbons adsorbed onto carbon particles **[11]**, and a DPF enables the reaction of CO and HC with an oxidation catalyst to purify them with CO_2 and H_2O and remove smoke through a filter **[12]**. When the DOC-DPF is applied, the first DOC removes HC, CO, etc., and then converts NO into NO_2. Thereafter, the DPF collects and continually oxidizes PM using NO_2 generated from DOC to reduce the emission of air pollutants **[11]**.

Overall, this study investigated the engine performance and exhaust emission characteristics through the construction of an LP EGR-DOC-DPF system to satisfy IMO Tier III criteria and to reduce air pollutants of 500 ps high-speed diesel engines that are used in domestic coastal fishing vessels.

2. Experimental device and method

2.1 Schematic of the experiment

To evaluate the reduction of air pollutants released by high-speed diesel engines when LP EGR-DOC-DPF is applied, the experiment was conducted by configuring an experimental device, as depicted in **Figure 1**. We selected the DD6CE model, a 500 ps Tier II diesel engine of D, a domestic small engine manufacturer for this experiment. The LP EGR-DOC-DPF system was mounted on the engine and configured to enable load testing by connecting the engine shaft and the dynamometer. **Figure 2** shows the mounting diagram of the target diesel engine and LP EGR-DOC-DPF.

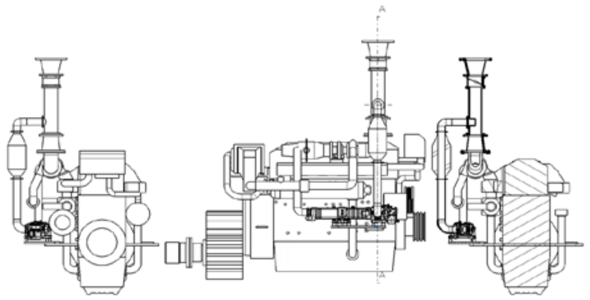

Figure 1: The composition of the experimental device

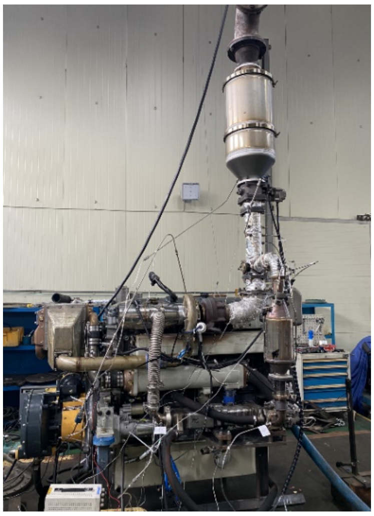

Figure 2: LP EGR-DOC-DPF system engine installation

2.2 Experimental apparatus

Tables 1 to **4** list the main specifications of the 500 ps high-speed diesel engine, dynamometer, exhaust gas analyzer, and smoke detector, respectively. To calculate the emissions according to the IMO NO_X technical legal standards, the exhaust gas component, fuel consumption, air supply temperature, air supply pressure, atmospheric pressure, temperature, and humidity were measured using calibrated equipment.

Table 1: Major specifications of high-speed diesel engines

Category	Specification
Engine Model	DD6CE
Displacement	12,742 cc
Bore / Stroke	130 mm / 160 mm
Injection type	Electronic Unit Injection
Cylinder No. / Type	6 / in line
Stroke	4 Stroke
Type	Turbocharged / Intercooled
Rated Power	500ps (368 kW) / @2 000 rpm
Maximum Torque	271 kgf·m @1 200 rpm

Table 2: Specifications of dynamometer

Category	Specification
Maker / Model	GO-Power / DT-3000
Maximum Power	1 500 bhp / 1 120 kW
Maximum Torque	4 745 N·m
Maximum Speed	5 000 rpm
Brake Type	Water Brake

Table 3: Specifications of exhaust gas analyzer

Category		Specification
Maker		HORIBA
Model		MEXA-9100EGR
Measure-ment, method & scope	CO	NDIR / 1~3 000 μ mol/mol
	CO_2	NDIR / 0.01~20 %
	THC	HFID / 1~50 000 μ mol/mol
	O_2	PMD / 0~25 %
	NO_X	CLD / 0~5 000 μ mol/mol

Table 4: Specifications of opacity meter

Category	Specification
Maker	QROTECH
Model	OPA-102
Principle	Light extinction method
Light source	Green LED (565 nm)
Detector	Photo diode
Range	0.0 ~ 100.0 %
Accuracy	Less than 1 %

2.3 Experimental methods and conditions

To test the efficiency of the system in reducing NO_X and air pollutants, an experiment was conducted in accordance with Chapter 5. of IMO MARPOL 73/78 NO_X Technical Code 2008 'PROCEDURES FOR NO_X EMISSION MEASUREMENTS ON A TEST BED'[13]. Type E3, which is the test cycle of the engine driving the propeller, was adopted, and the details of the type E3 test and the test conditions of the DD6CE engine are listed in **Tables 5** and **6**. Additionally, a carbon comparison method was used to measure the exhaust gas flow rate.

Table 5: E3 Test cycle for 'Constant Speed Main Propulsion' application

Speed	63%	80%	91%	100%
Output	25%	50%	75%	100%
Weighing factor	0.2	0.5	0.15	0.15

Table 6: Engine power and speed of DD6CE for test condition

Category	Unit	25%	50%	75%	100%
Power	kW	92	184	276	368
Speed	rpm	1 260	1 600	1 820	2 000

Table 7: Operating conditions of LP EGR-DOC-DPF by case

Category	LP EGR	DOC-DPF
Case 1	OFF	OFF
Case 2	ON	OFF
Case 3	ON	ON

As shown in **Table 7**, the main parameters and exhaust gas components of the engine required for calculating NO_X emissions were measured in three cases: before and after LP EGR installation and after DOC-DPF installation. After the experiment, the final NO_X emissions were calculated by referring to the IMO NO_X Technical Code with the measured value. The smoke values were compared with the average of the values measured three or more times after power stabilization for each load.

Table 8: Result of fuel analysis

Test Item	Unit	Result	Method
Density at 15℃	kg/m3	821.3	ISO 3675:1998
Viscosity at 40℃	mm2/s	2.489	ISO 3104:1994
Sulfur	mass %	< 0.03	ISO 8754:2003
Carbon	mass %	84.93	ASTM D 5291-16
Hydrogen	mass %	13.94	ASTM D 5291-16
Oxygen	mass %	1.13	Calculation
Nitrogen	mass %	0.00	ASTM D 5762-18a

Table 8 shows the results of the component analysis of diesel used in the test, which are reflected in the calculation of NO_X emissions after the experiment.

3. Experimental results and study

3.1 Engine parameter and exhaust gas measurement results

Tables 9-11 show the engine parameters and exhaust gas measurements before the LP EGR operation (Case 1), after the operation (Case 2), and after the DOC-DPF operation (Case 3).

Table 9: Engine parameters and exhaust gas measurement values before the LP EGR operation (Case 1)

Category	Unit	Load (%)			
		25	50	75	100
Charge air temperature	℃	33.20	33.20	33.20	33.20
Charge air Pressure	MPa	0.042	0.118	0.188	0.200
T/C Inlet temperature	℃	14.10	14.10	14.00	13.80
CO	ppm	79	70	40	76
CO_2	vol%	6.32	6.21	6.87	8.21
NO_X	ppm	1 114	816	686	1 276
O_2	vol%	11.89	12.09	11.29	9.49
HC	ppmC	65	55	49	41
Fuel Consumption	kg/h	21.00	39.90	61.80	79.20

Table 10: Engine parameters and exhaust gas measurement values

Category	Unit	Load (%)			
		25	50	75	100
Charge air temperature	℃	20.00	31.00	46.30	55.70
Charge air Pressure	MPa	0.032	0.085	0.147	0.167
T/C Inlet temperature	℃	24.40	22.60	22.80	21.00
CO	ppm	821	1 362	1 003	1 061
CO_2	vol%	9.35	8.88	9.22	9.83
NO_X	ppm	155	212	217	369
O_2	vol%	7.09	7.88	7.39	6.35
HC	ppmC	59	37	23	21
Fuel Consumption	kg/h	21.80	40.50	62.50	79.50

Table 11: Engine parameters and exhaust gas measurement values

Category	Unit	Load (%)			
		25	50	75	100
Charge air temperature	℃	41.8	47.1	57.7	64.5
Charge air Pressure	MPa	0.131	0.181	0.243	0.264
T/C Inlet temperature	℃	19.90	20.30	20.00	17.50
CO	ppm	91	86	85	91
CO_2	vol%	9.93	10.32	10.14	9.15
NO_X	ppm	224	224	244	354
O_2	vol%	6.28	5.72	6.16	5.10
HC	ppmC	3	3	3	4
Fuel Consumption	kg/h	22.20	41.40	63.00	79.80

Figures 3-6 depict the variations in the emission values of NOx, CO, oxygen (O_2), and HC, respectively, based on the measured values.

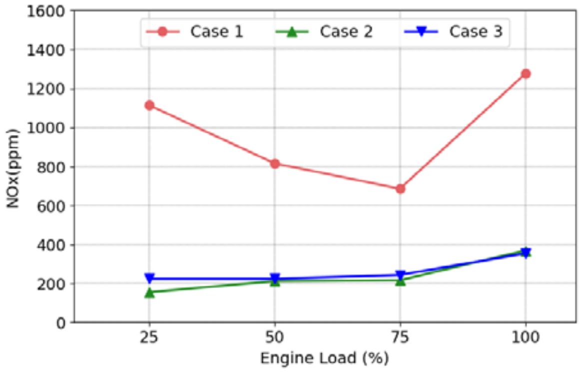

Figure 3: NOx change at the engine load

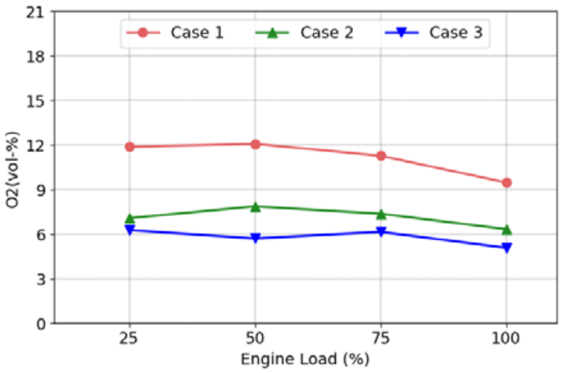

Figure 4: O_2 change at the engine load

As depicted in **Figure 3**, it was confirmed that NOx emissions were reduced by up to 86% when compared to the measures obtained before application while operating the LP EGR. Thereafter, when the DOC-DPF was additionally operated, the NOx emission concentrations were partially increased at 25%, 50%, and 75% loads. The EGR rates of Cases 2 and 3 were the same, and the fuel consumption increased from a minimum of 0.30% to a maximum of 3.81% at the measured value of Case 3 compared to Case 2. Therefore, when the DOC-DPF is additionally applied to the EGR, it can be inferred as a result of a partial increase in the NOx emission concentration owing to an increase in the fuel consumption caused by an increase in engine back pressure.

As depicted in **Figure 4**, the concentration of O_2 decreased by up to 40% when compared to that before the LP EGR operation(Case 1). This observation was due to the exhaust gas being partially substituted with air after combustion, so it was burned at a lower oxygen concentration than the new supply air. Furthermore, the O_2 concentrations partially decreased after applying the DOC-DPF (Case 3). Because DOC converts NO into NO_2, and DPF oxidizes smoke using the converted NO_2, it can be inferred that O_2 is further reduced via consumption by this oxidation catalyst reaction.

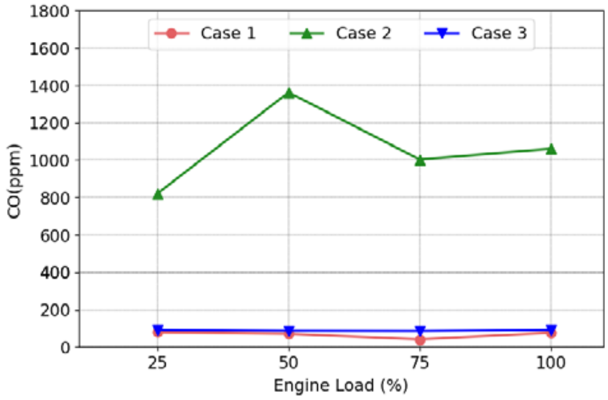

Figure 5: CO change at the engine load

Figure 5 shows the change in CO concentration by case. When operating the LP EGR (Case 2), CO increased up to 25.1 times compared to that before the LP EGR operation (Case 1). It was found that CO rapidly increased owing to incomplete combustion in the combustion process with a decrease in oxygen concentration in the air supply and a low combustion temperature when applying the EGR. Subsequently, during the DOC-DPF operation, CO reacted with the catalysts in the DOC-DPF and converted to CO_2, and decreased by up to 94% compared to that after the LP EGR operation (Case 2), when CO increased rapidly.

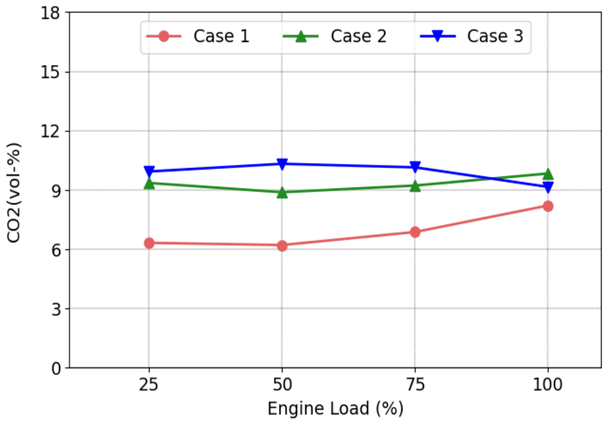

Figure 6: CO_2 change at the engine load

Figure 6 shows the change in CO_2 by case. Compared to previous LP EGR application (Case 1), CO_2 increased by at least 19.7% and up to 47.9% after the LP EGR application (Case 2). It is analyzed as an increase in the concentration due to the recirculation of exhaust gas, and CO_2 has a higher heat capacity than NO_2, further resulting in a lower temperature increase rate during combustion, which affects the reduction of NOx emissions. Subsequently, when applying the DOC-DPF (Case 3), CO_2 increased by at least 6.2% and up to 16.2% at 25%, 50%, and 75% loads, respectively. It is inferred that the concentration increased as CO reacted with the DOC-DPF catalyst and it was further converted into CO_2. However, at 100% load, the concentration of CO_2 in Case 3 was approximately 6.9% lower than that in Case 2. It is referred that the catalyst-oxidation reaction of the exhaust gas flow rate and DOC-DPF increased at 100% load was not performed sufficiently.

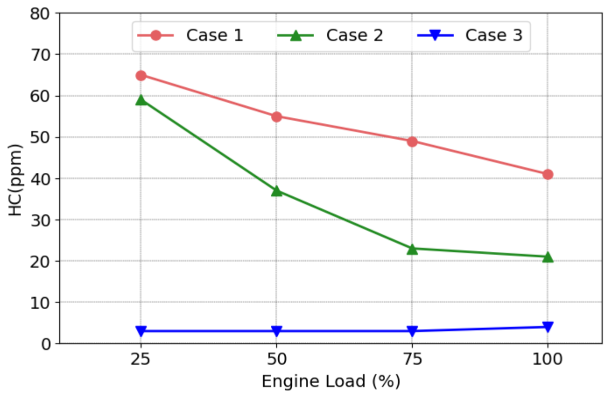

Figure 7: HC change at the engine load

The HC in **Figure 7** decreased by up to 54% during the LP EGR operation owing to the action of the DPF inside the LP EGR system. Subsequently, when using the rear DOC-DPF, the HC decreased by up to 95% compared to its release before the system was applied.

3.2 Comparison of fuel consumption

Table 12 compares the results of the fuel consumption in the three cases before and after the LP EGR operation and after the DOC-DPF application.

Table 12: Measurement of fuel consumption

Category	Unit	Load (%)			
		25	50	75	100
Case 1	kg/h	21.00	39.90	61.80	79.20
Case 2		21.80	40.50	62.50	79.50
Case 3		22.20	41.40	63.00	79.80

According to the LP EGR application (Case2), fuel consumption increased by 0.4 to 3.8 percent compared to that before the application (Case 1). In addition, fuel consumption increased by 0.8 – 5.7% compared to the stage before application (Case 1) when the LP EGR-DOC-DPF was operated (Case 3). In particular, the fuel consumption rate was the highest in the 25% section. This was due to the increase in the incomplete combustion as a result of low oxygen concentrations when LP EGR was applied; therefore, greater fuel consumption was required to generate the same output. Under the condition that the same EGR rate was applied to the LP EGR, a partial increase in fuel consumption was judged to be a result of an increase in the back pressure due to the additional application of the rear-stage reduction device.

3.3 Comparison of NO_X emissions

Table 13 lists the final NO_X emissions calculated for each case according to the IMO NO_X technical code calculation method.

After the LP EGR operation (Case 2), NO_X emissions were reduced by approximately 75.9%, from 7.56 g/kWh to 1.82 g/kWh, which meets the Tier III baseline of 2.0 g/kWh or less. During the DOC-DPF operation(Case 3), NOx was emitted at 1.83 g/kWh, an increase of 0.01 g/kWh compared to Case 2, which was attributed to the increase in back pressure and fuel consumption from the application of the DOC-DPF.

Table 13: NO_X emissions by case

Category	Unit	Load (%)				Total NO_X
		25	50	75	100	
Case 1	g/kWh	11.17	7.91	6.21	9.27	7.56
Case 2		1.13	1.57	1.60	2.46	1.82
Case 3		1.60	1.43	1.61	2.45	1.83

3.4 Comparison of smoke emission values

Table 14 lists the values of smoke concentrations(%) measured using a light-transmitting smoke meter before and after the LP EGR was applied and when the DOC-DPF was operated.

Table 14: Smoke measurement result

Category	LP EGR	DOC-DPF	Unit	Load (%)			
				25	50	75	100
Case 1	OFF	OFF	%	5.0	4.5	2.7	3.0
Case 2	ON	OFF		42.2	55.8	31.4	18.0
Case 3	ON	ON		0.1	0.0	0.1	1.0

After combustion, the exhaust gas was re-injected into the combustion chamber, resulting in incomplete combustion in the combustion chamber, and the concentration of smoke increased by up to 12.4 times after operation compared to before the EGR operation. Subsequently, the measured value of 1% or less of the smoke concentration was confirmed when the DOC-DPF was operated, and the effect of reducing smoke through the use of DOC-DPF was confirmed.

4. Conclusion

In this study, LP EGR and DOC-DPF were applied to reduce the NOx and air pollutants(HC, CO, and smoke) in a 500 ps high-speed diesel engine for small ships, and the emission characteristics of the engine parameters and exhaust gas were studied. The following conclusions were drawn from this study:

1) LP EGR can be applied to high-speed diesel engine for small ships using diesel, and NO_X emissions can be reduced by approximately 75.9%, from 7.56 g/kWh to 1.82 g/kWh, when operating LP EGR within the range of no loss of output.
2) When LP EGR was applied, the oxygen concentration was reduced by exhaust recirculation, which increased CO by up to 25.1 times and smoke by up to 12.4 times.
3) To reduce HC, CO, and fumes that are released from the application of EGR, it is possible to reduce NO_X emissions to 1.83 g/kWh and less than 1% per annum during the simultaneous operation of the LP EGR and DOC-DPF installed at the end of the exhaust pipe. In addition, up to 95% of HC and 94% of CO were processed.
4) Fuel consumption increased by up to 5.7% after the application of LP EGR and DOC-DPF, which partially increased the NOx emissions. This was presumed to be either a decrease in intake fluidity or an increase in fuel consumption because of back-pressure effects.

Air pollutant reduction was analyzed using a 500 ps high-speed diesel engine by performing NOx and smoke reduction experiments with the LP EGR-DOC-DPF system.

Satisfaction with the IMO Tier III criteria and high reduction performance of CO, HC, and smoke were confirmed when applying the LP EGR-DOC-DPF. However, additional studies examining the adjustment of the EGR rate and engine injection time are needed for greater fuel consumption at a certain load and an increase in smoke from incomplete combustion. In addition, further studies are needed on the tendency of CO_2 reduction identified at 100% engine load through the catalytic reaction of the DOC-DPF and confirmation of additional engine parameters.

Therefore, it is expected that integrated processing technology will be secured to reduce the air pollutant emissions of diesel engines for small domestic ships by upgrading the LP EGR and DOC-DPF through future research to efficiently reduce the NOx and optimize engine power variations.

Author Contributions

Writing-Original Draft Preparation, M. K. Kang; Writing-Review & Editing, M. K. Kang and S. U. Park; Supervision, K. Y. Min and J. D. Choi; Project Administration, J. D. Choi.

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