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Methane slip reduction technology of an LNG-fueled engine by catalyst and engine modification

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

Methane slip emissions, which contribute to GHG emissions, have become an issue for LNG-fueled vessels, which can reduce CO2 emissions compared with fuel oil-fueled vessels. To reduce methane slip, a consortium comprising Hitachi Zosen Corporation, Yanmar Power Technology Co., Ltd., and Mitsui O.S.K. Lines, Ltd. is engaged in a methane slip reduction project under the Green Innovation Fund Project "Development of Methane Slip Reduction Technology from LNG Fueled Vessels by Catalyst and Engine Modification" [LK1] run by the New Energy and Industrial Technology Development Organization (NEDO). In this project, efforts were made to reduce methane slip by combining engine improvements using EGR (exhaust gas recirculation) and the installation of a methane oxidation catalysts for aftertreatment. As a result, a methane slip reduction rate of 93.8% was achieved, and a certificate of methane slip reduction rate was obtained from ClassNK. Starting in fiscal year 2024, this system has been installed on actual ships for demonstration tests. This contribution reports on the results of methane slip reduction by combining engine modification and methane oxidation catalysts, as well as the outcomes of the actual ship demonstration tests.

1 INTRODUCTION

In response to growing awareness of global warming, IMO adopted an initial strategy on GHG (greenhouse gas) reduction at the IMO 72nd Meeting of the Marine Environment Protection Committee (MEPC72) in April 2018. At the meeting, the IMO initial strategy for the reduction of greenhouse gas (GHG) emissions from ships was agreed upon with the aim of achieving zero GHG emissions as early as possible in this century. This GHG reduction strategy is to be reviewed every five years, and at MEPC80 in July 2023, reflecting the latest intentions of each country and company, it was decided to bring forward by 50 years the year for achieving the GHG net zero[1].

To address this background, technologies are being developed to utilize alternative fuels such as hydrogen[2], methanol[3-4], and ammonia[5-6] with the aim of reducing GHG emissions from marine engines. On the other hand, Liquified Natural Gas (LNG) is mainly composed of methane (CH_4), which has a lower carbon intensity than diesel fuel oil, enabling a reduction in CO_2 emissions per unit of fuel consumption. Gas engines fueled by LNG are already in practical use[7] and are expected to contribute to achieving carbon neutrality in a stepped manner, either as a bridge solution until the aforementioned alternative fuels become widely available or until the use of synthetic CH_4 produced with CO_2 captured from the atmosphere, etc. is realized.

Marine engines are required to operate safely and reliably, and diesel engines, with their long-term track record, are highly reliable. Therefore, dual-fuel (DF) engines, which combine the environmental performance of LNG-fueled gas engines with the reliability of diesel engines[8], have been requested from the market and are becoming increasingly popular. On the other hand, reducing CH_4 slip (unburned CH_4 emissions), which affects GHG emissions, is a challenge[9].

This paper describes the Yanmar group's efforts to reduce CH_4 slip from LNG-fueled DF engines for marine application. Yanmar is participating in the project titled “Development of Methane Slip Reduction Technology from LNG Fueled Vessels through Catalyst and Engine Improvement” under the Green Innovation Fund Project by the New Energy and Industrial Technology Development Organization (NEDO). In this project, a consortium of Kanadevia Corporation (Kabadevia), Yanmar Power Technology (YPT), and Mitsui O.S.K. Lines (MOL) is developing CH_4 slip reduction technology[10]. Figure 1 shows the consortium structure for this project. The plan is to combine engine modifications to reduce CH_4 slip with a CH_4 oxidation catalyst as aftertreatment device to minimize the total CH_4 slip and resulting GHG from LNG-fueled marine DF engines.

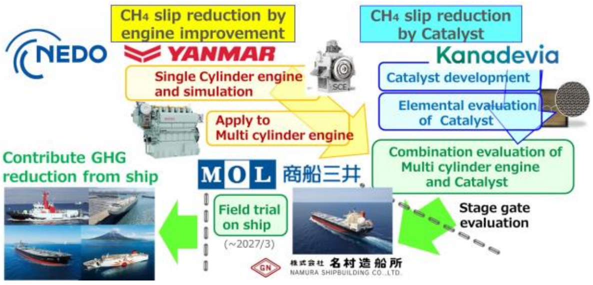

Figure 1. Structure of consortium for this project in New Energy and Industrial Technology Development Organization (NEDO) Green Innovation Project.

Moderate lean combustion concept and exhaust gas recirculation (EGR) technologies were applied in the engine modification. As a first step in this research project, combustion experiments using a single cylinder engine was performed to study the effects of moderate lean combustion and EGR on unburned THC emissions from an LNG-fueled engine. Next, the layout of the CH_4 oxidation catalyst in a multicylinder engine was also studied by one-dimensional (1D) engine cycle simulation. Based on the plan determined by these elemental studies, the EGR and CH_4 oxidation catalysts were evaluated in onshore bench tests using a multicylinder engine to confirm their effectiveness in reducing CH_4 slip in real scale. In addition, new engine control technology was implemented to introduce EGR on the multicylinder engine for stable operation. The system has been installed on a real vessel since the fall of 2024 and is being evaluated under actual operational conditions onboard. This paper also introduces the evaluation method for CH_4 emission measurement used in the ship trial test.

2 METHANE SLIP REDUCTION BY CATALYST AND ENGINE MODIFICATION

Figure 2 shows the concept of CH_4 slip reduction from the engine outlet by engine modification. Conventional LNG-fueled DF engines are operated in the ultra lean range with an excess air ratio of 2.0 or higher to reduce NO_X emissions below regulation limit and to achieve the highest thermal efficiency. In the ultra lean condition, CH_4 slip tends to increase as the combustion temperature decreases due to the high excess air ratio. In this study, a moderate lean combustion concept is applied, in which the excess air ratio is slightly reduced compared to conventional ultra lean condition. This aims to reduce CH_4 slip from the engine outlet by increasing combustion temperature resulting from decreasing the excess air ratio. In addition to this, generally decreasing the excess air ratio increases the exhaust gas temperature of engine, which can be synergistic with the performance of CH_4 oxidation catalyst.

There are concerns that a decrease in excess air ratio will result in increased NO_X emission and occurrence of knocking at high load, to which EGR technology is applied. EGR increases the heat capacity of the working gas, thereby preventing an excessive increase in combustion temperature due to a lower excess air ratio and reduces the NO_X emission at the engine outlet by decreasing the oxygen concentration of the mixture as well. Furthermore, an increase in the ratio of CO_2, an inert gas, in the mixture by EGR is expected to suppress the knocking[11]. In addition, re-burning unburned components in the recirculated exhaust gas can be expected to further reduce the amount of CH_4 slip, and optimizing the balance between EGR and excess air ratio can prevent deterioration in thermal efficiency[12].

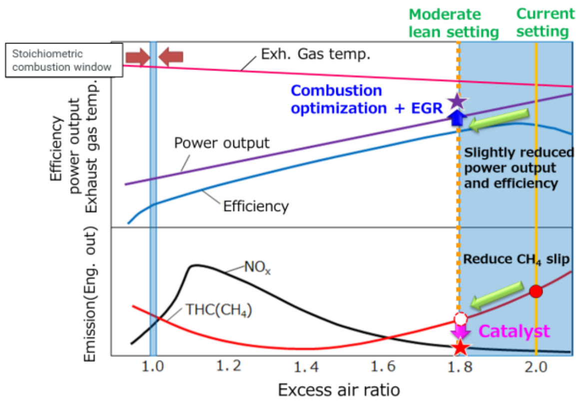

Figure 2. Conceptual diagram of CH_4 slip reduction by engine modification.

For further GHG reduction, the use of a CH_4 oxidation catalyst is promising. Although it is possible to reduce CH_4 slip sufficiently using only a CH_4 oxidation catalyst without the engine modifications described above, there are many challenges, because a large amount of precious metal is required and there is a risk of melting down due to catalyst overheating caused by high concentrations of CH_4 flowing over the catalyst. Therefore, in this project, the concept of combining a CH_4 oxidation catalyst after reducing CH_4 slip in the engine as much as possible was adopted.

3 EFFECT OF EGR AND MODERATE LEAN COMBUSTION ON UNBURNED METHANE EMISSION AND ENGINE PERFORMANCE

First, combustion experiments were conducted using a single cylinder engine to study the effects of EGR and moderate lean combustion on CH_4 slip from an LNG-fueled engine and on engine performance.

3.1 Experimental setup

Table 1 and Figure 3 show the main specifications of the tested engine and the overview of the experimental apparatus, respectively. The tested engine was a spark-ignition gas engine (single cylinder) which has a bore of 155 mm.

Table 1. Main specifications of tested single cylinder engine.

Item	Value
Number of cylinder(s)	1
Bore [mm]	155
Stroke [mm]	180
Displacement [L]	3.4
Number of valves	4
Intake system	External boosting
Fuel	LNG (City gas 13A)

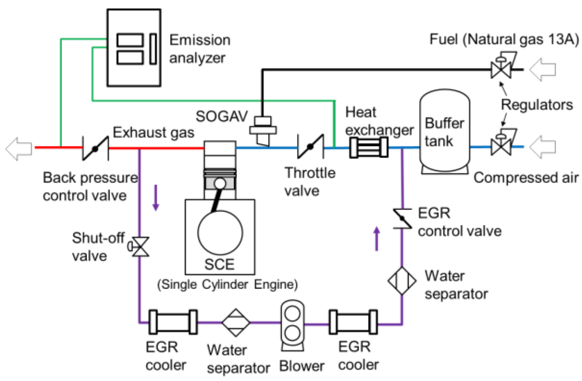

Figure 3. Experimental setup for EGR testing with single cylinder engine.

The supplied air was boosted by a compressor driven by an external power source, and then reduced to a desired pressure by a regulator and throttle valve before being supplied to the engine. Exhaust back pressure was controlled by a throttle valve to simulate the condition of a turbocharged multicylinder engine. The fuel, natural gas, was fed into the intake port by a gas admission valve installed in the intake manifold to form a fuel-air premixture. The EGR system was constructed by taking a portion of the exhaust gas, cooling it with a cooler, removing water with a mist separator, boosting the pressure with a blower, and returning it into the air supply path. A cooler and a mist separator were also installed after the EGR compressor. The EGR rate was controlled by the blower speed and throttle valve and measured by emission analyzer using following equation.

EGR rate = $(CO_{2\_EGR} - CO_{2\_ambient}) / CO_{2\_exhaust}$

Where CO_{2_EGR} is the volumetric fraction of CO_2 in the EGR gas, and $CO_{2\_ambient}$, $CO_{2\_exhaust}$ are those in the ambient air and exhaust gas, respectively. CH_4 slip reduction was evaluated by measuring THC in the exhaust gas since most of the components in THC emission is considered to be CH_4 in this experiment.

3.2 Results and discussion

First, in order to understand the effect of EGR on combustion characteristics of LNG-fueled gas engine, experiments were conducted in which the EGR rate was varied under the conditions of constant spark timing and manifold air pressure. The experimental conditions are listed in Table 2.

Table 2. Experimental conditions (EGR rate variation).

Item	Value
Engine speed [min-1]	1500
BMEP [MPa]	1.46
Spark timing [°aTDC]	Constant
Intake manifold pressure [kPa]	Constant
EGR rate [%]	0,10, 20, 25

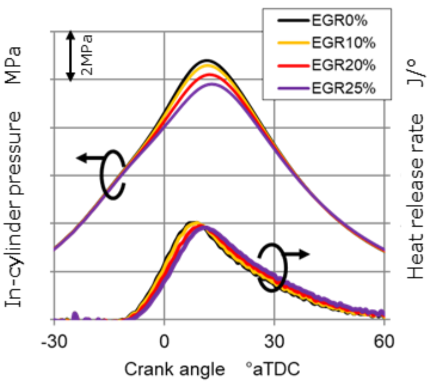

Figure 4. Effect of EGR on in-cylinder pressure and heat release rate under constant manifold pressure.

Figure 4 shows the effect of EGR rate on in-cylinder pressure and heat release rate, showing that as EGR rate increases, the heat release rate becomes slower and the peak of in-cylinder pressure decreases. Figure 5 shows the effect of EGR rate on emission characteristics in relative percentage. It is shown that the THC and NO_X emissions are reduced as the EGR rate increases. As mentioned earlier, the decrease in NO_X is owing to the lower oxygen concentration and combustion temperature due to the increased heat capacity of the working gas, and the decrease in THC is attributed to the re-burning of unburned components in the recirculated exhaust gas.

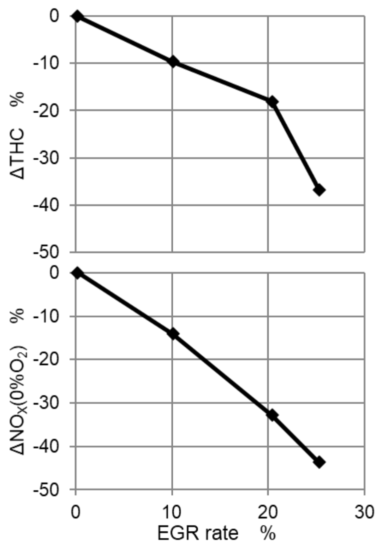

Figure 5. Effect of EGR on emission characteristics under constant manifold pressure.

Next, to optimize the EGR rate and excess air ratio, experiments were conducted in which the excess air ratio was changed by changing the manifold air pressure under conditions where EGR was applied. Table 3 lists experimental conditions. Figure 6 shows the results with the trade-off between NO_X and THC, indicating that optimising the excess air ratio while increasing the EGR rate improves the trade-off between NO_X and THC emissions.

Table 3. Experimental conditions (Excess air ratio variation).

Item	Value
Engine speed [min-1]	1500
BMEP [MPa]	1.46
Spark timing [°aTDC]	Constant
Intake pressure [kPa]	Adjusted
EGR rate [%]	0, 10, 15, 20, 25

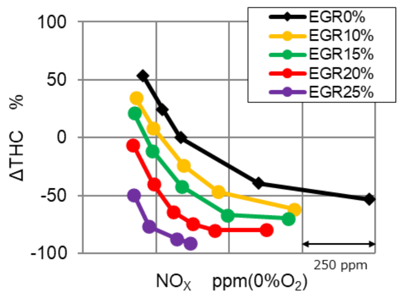

Figure 6. Effect of EGR on the trade-off between NO_X and THC.

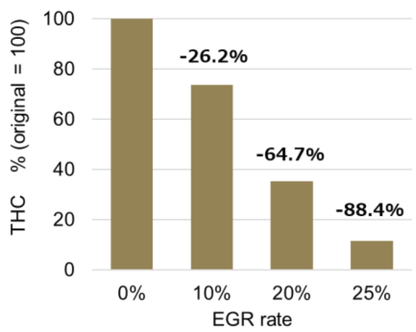

Figure 7. THC emission reduction rate by applying EGR and optimised excess air ratio.

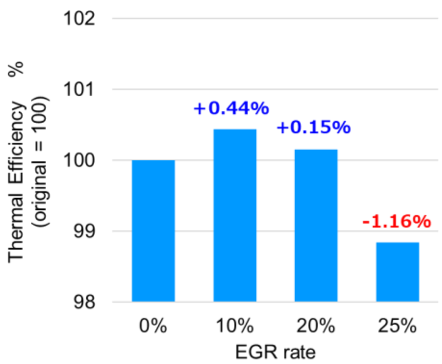

Figure 8. Change in thermal efficiency by applying EGR and optimised excess air ratio.

Figures 7 and 8 show the THC emission reduction rate and change in thermal efficiency, as a result of these optimizations, respectively. NO_X emissions for those results were kept as same level or even lower than that of original condition. Note that these results were obtained after adjusting (optimising) the spark timing as well. Figure 7 shows that at an EGR rate of 20-25%, adjusting operating parameters such as excess air ratio and spark timing has the potential to reduce CH_4 slip by about 70% compared to the base condition. Focusing on the thermal efficiency in Figure 8, the results up to 20% EGR rate show rather improved efficiency compared to the original condition. This could be attributed to the increase in combustion efficiency thanks to the reduction of unburned THC that is directly connected to improvement in combustion efficiency.

4 METHANE OXIDATION CATALYST AND ITS LAYOUT

Due to its stable structure, CH_4 is the most difficult components of all hydrocarbons to oxidize over catalysts. In addition, the available catalysts are limited to precious metals such as Pt and Pd, and a large amount of those precious metals are required to obtain sufficient performance at practical exhaust gas temperatures at turbocharger outlet of medium-speed engines. On the other hand, when the exhaust gas temperature exceeds 500°C, CH_4 oxidation with less precious metal or even non-precious metal catalysts is possible[13]. Therefore, previous studies have reported catalyst layouts upstream of turbochargers with high exhaust gas temperatures [14-15]. This chapter describes the study on installation layout of the CH_4 oxidation catalyst and the results of elemental tests of catalyst.

4.1 Layout of methane oxidation catalyst

In general, the exhaust gas temperature of a turbocharged engine decreases as it passes through the turbocharger, which may affect the performance of the CH_4 oxidation catalyst.

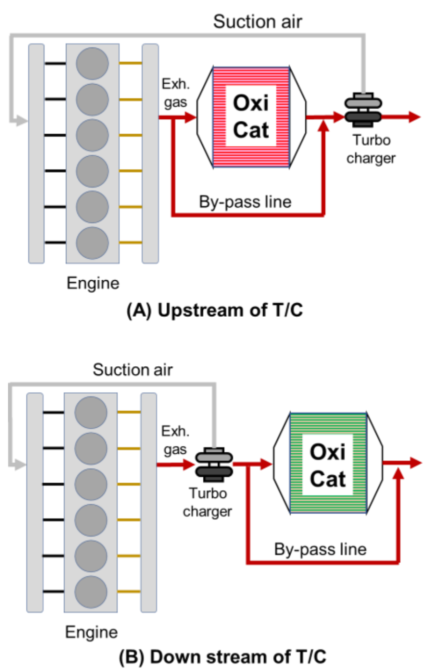

Figure 9. Layout image of CH_4 oxidation catalyst installed upstream and downstream of the turbocharger (T/C).

Figure 9 shows an image of the layout of a CH_4 oxidation catalyst installed upstream and downstream of the turbocharger. As shown in Figure 9-(A), a higher CH_4 reduction rate can be expected by installing a CH_4 oxidation catalyst upstream of the turbocharger, which has a higher exhaust gas temperature, while the volume of the exhaust system will increase, which may affect the transient performance of the turbocharger. Figure 10 shows an image of a CH_4 oxidation catalyst installed upstream of the turbocharger.

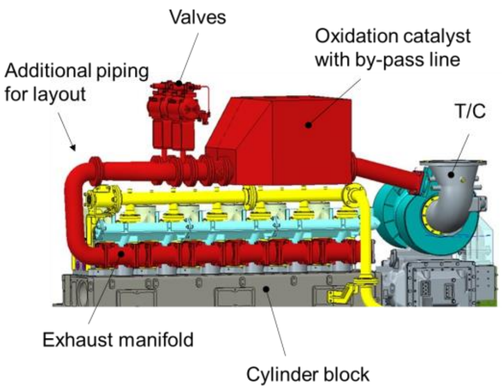

Figure 10. An image of a CH_4 oxidation catalyst installed upstream of the turbocharger.

On the other hand, the installation of a CH_4 oxidation catalyst downstream of the turbocharger, shown in Figure 9-(B), is not expected to affect the transient characteristics of the turbocharger and engine, but the CH_4 reduction rate under relatively lower exhaust gas temperature can be a challenging issue.

4.2 Modeling and transient simulation

A one-dimensional (1D) engine cycle simulation model was developed to study the effect of installing a CH_4 oxidation catalyst upstream of the turbocharger on the transient characteristics of turbocharger and engine. Figure 11 shows an overview of the 1D cycle simulation model for analysis of transient behaviour of the target engine with CH_4 oxidation catalyst installed upstream of the turbocharger. Firstly, based on the model of the 6-cylinder engine and turbocharger targeted in this project, calibration was performed using load input test data to reproduce the speed governor function of the actual engine. A transient simulation model was then constructed by adding a model of the CH_4 oxidation catalyst and related piping to simulate the condition in which the CH_4 oxidation catalyst is installed upstream of the turbocharger. The volume of the CH_4 oxidation catalyst was determined by preliminary elemental tests, and the additional piping length due to the installation of the CH_4 oxidation catalyst was calculated from the results of a 3D-CAD layout study.

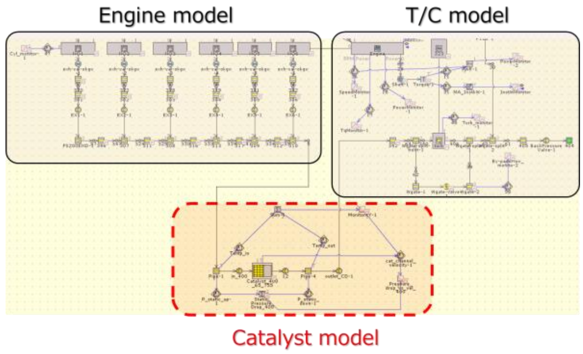

Figure 11. 1D cycle simulation model for analysis of transient behaviour of the target engine with CH_4 oxidation catalyst installed upstream of the turbocharger.

4.3 Calculation results and discussion

Figure 12 shows an example of the calculation results. In the model without CH_4 oxidation catalyst (original), engine speed temporarily dropped due to load input, but recovered to the target speed by the speed control function. On the other hand, the model with the addition of the CH_4 oxidation catalyst and related piping resulted in a gradual decrease in engine speed, finally leading to an engine stall.

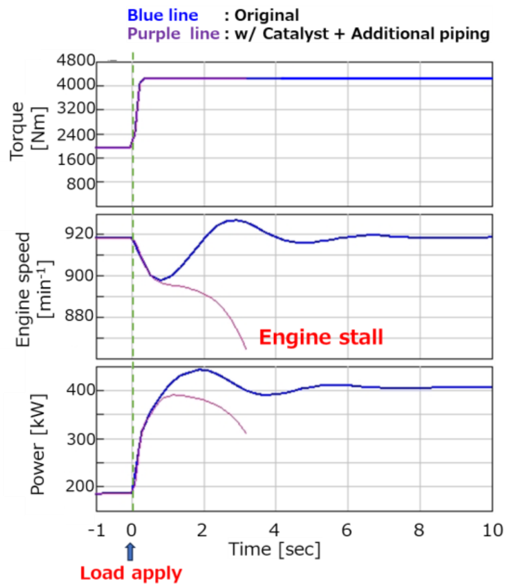

Figure 12. An example of the result of transient simulation by developed 1D simulation model.

The increase in volume of the exhaust pipe from the engine outlet to the turbocharger affects the acceleration rate of the turbocharger speed after load input, which is considered to have caused an excessive reduction in the excess air ratio of combustion, resulting in the engine stall. Although some minor improvement can be possible by optimizing the speed control function, it is difficult to install an oxidation catalyst upstream of the turbocharger because of the inevitable longer settling time and the response delay due to the heat capacity of the catalyst that must be taken into account in actual application.

4.4 Performance of methane oxidation catalyst installed downstream of the turbocharger

The image of layout for installing the CH_4 oxidation catalyst downstream of the turbocharger in this project is shown in Figure 13. When the catalytic converter is installed after the turbocharger, as it might be located far from the engine (for example up to 22 meters in this project), the temperature drops of the exhaust gas when it reaches the catalyst can be an issue.

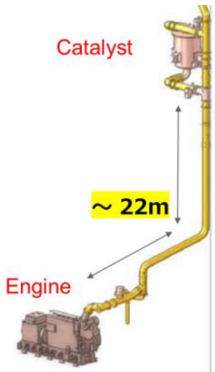

Figure 13. The image of layout for installing the CH_4 oxidation catalyst downstream of the turbocharger in this project.

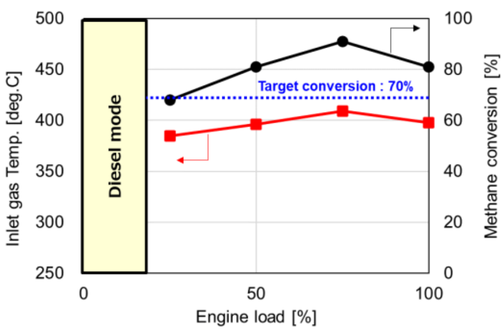

Figure 14. The estimated catalyst inlet gas temperature and measured catalyst performance for the catalyst layout of downstream of the turbocharger.

We attempted to solve this problem by optimizing the catalyst capacity and other factors. Figure 14 shows the estimated catalyst inlet gas temperature considering heat loss from piping and measured catalyst performance for the catalyst layout of downstream of the turbocharger based on the element tests. Even after taking into account the effect of the temperature drop, the CH_4 slip reduction rate was expected to be generally above 70%, which means that the target performance can be achieved.

5 ONSHORE MULTICYLINDER ENGINE TESTING WITH EGR SYSTEM AND METHANE OXIDATION CATALYST

Based on the results of the previous chapters, an LNG-fueled multicylinder DF engine (6EY22ALDF) was retrofitted with an EGR system and a CH_4 oxidation catalyst for real-scale onshore testing.

5.1 Experimental set up and testing conditions

Table 4 shows the specifications of the tested DF engine for this project. A system diagram of the EGR and CH_4 oxidation catalyst system (manufactured by Kanadevia) installed in this engine is shown in Figure 15. A low-pressure EGR system was employed; exhaust gas from the engine at the outlet of the turbocharger is diverted and extracted, cooled by an EGR cooler, and then pressurized by a blower before being mixed with the intake air at the inlet of the compressor. One butterfly valve each was installed at the inlet and outlet of the system to control the EGR flow rate. The engine operating conditions were adjusted to the optimum EGR rate and excess air ratio at each load point to maximize the reduction effect of CH_4 slip at the engine outlet. In addition, a CH_4 oxidation catalyst was installed to reduce the total CH_4 slip at the system outlet. The CH_4 oxidation catalyst was installed downstream of the turbocharger based on the results of the study in Chapter 4, and the system had a bypass line considering the diesel mode. The piping layout from the engine simulated the actual ship trial. Figure 16 and Figure 17 show a diagram of the CH_4 oxidation catalyst layout for the onshore bench testing and a photograph of the actual layout, respectively.

Table 4. Main specifications of tested engine.

Item	Value
Engine type	6EY22ALDF
Application	Marine auxiliary
Rated power output [kW_{elec}]	800
Rated engine speed [min^{-1}]	900
Number of cylinders	6
Bore [mm]	220
Stroke [mm]	320

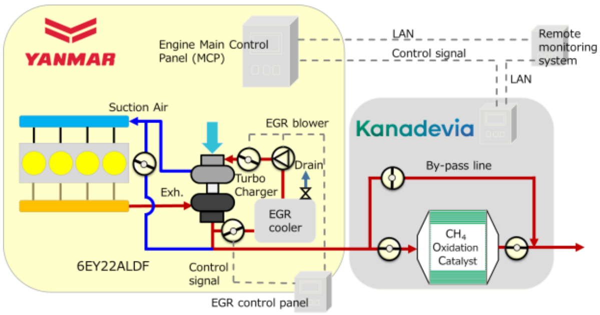

Figure 15. System diagram for multicylinder engine testing at onshore test bench.

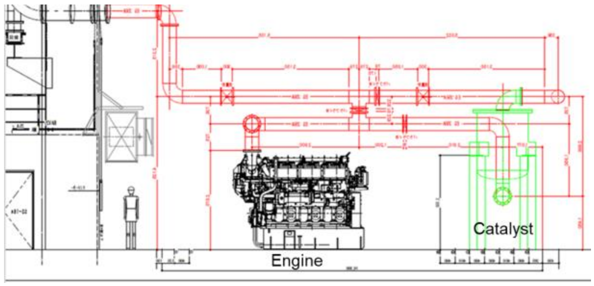

Figure 16. Layout of CH_4 oxidation catalyst at onshore bench testing.

Figure 17. Picture of the actual layout of CH_4 oxidation catalyst.

5.2 Real-time combustion control by using cylinder pressure sensor for optimized EGR control

In natural gas premixed combustion, the formation of premixture is an important process for the stable engine speed and good transient behavior of the engine. In general, conventional EGR control such as used in automotive engines employs model-based control, in which the EGR volume is controlled to achieve the target NO_X emission based on the relationship equation between oxygen concentration and NO_X emission inputted in advance. In this control system, an estimated value of the oxygen concentration in the combustion chamber is used based on the EGR flow rate calculated from the characteristics of the mechanical opening area of the EGR valve and the intake air flow rate. However, this control system becomes open-loop control when feedback is not applied by measuring NO_X concentration with a sensor, in which case it is less robust to variable factors such as environmental conditions, operating conditions, and cylinder-to-cylinder variations that are sometimes unique to marine applications. To ensure this robustness, it is important to determine how much variation to take into account in the aforementioned “relationship equation between oxygen concentration and NO_X emissions input in advance,” and how to improve the accuracy of the correction control to compensate for this variation. However, such control system becomes more complicated, and the efforts required for calibration testing increase. Such control is essentially combustion control, but in general, automobile engines do not have cylinder pressure sensors, so this indirect control seems to be adopted. On the other hand, Yanmar’s EY-type DF engines are equipped with cylinder pressure sensors and a controller that automatically analyzes combustion characteristic values as standard equipment, making it possible to detect abnormalities in real time if NO_X or engine performance is affected due to significant effects on combustion caused by various variable factors. Therefore, as shown in Figure 18, that information is fed back to the EGR valve opening control unit so that the EGR valve opening can be appropriately corrected on site in real time. In addition, the information of misfiring obtained by the cylinder pressure sensor is also effective for the safety function of the CH_4 oxidation catalyst, so the information of misfiring is shared with the catalyst control panel.

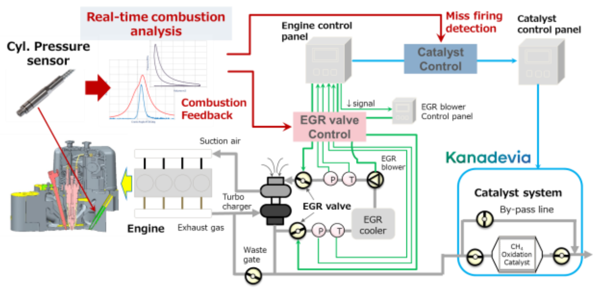

Figure 18. System diagram of EGR control with real-time combustion feedback control system.

5.3 Results and discussion

5.3.1 Effect of EGR rate on combustion and emission characteristics of multicylinder engine

Figure 19 and Figure 20 show the effect of EGR rate on CH_4 slip and NO_X emission, respectively, with 50% load factor as representative. Each emission rate represents a percentage of the original emissions. Under constant manifold air pressure conditions, as EGR rate increased, CH_4 and NO_X emission rates decreased, with CH_4 and NO_X reduced by about 40% and 60%, respectively, at an EGR rate of 25%. These results reproduced well the single cylinder engine test results shown in Chapter 3. Next, to optimize the EGR rate and excess air ratio, experiments were conducted with varying the manifold air pressure under the conditions of with EGR. The excess air ratio was reduced by reducing the manifold air pressure, and the combustion temperature was slightly increased under these EGR conditions. By allowing NO_X emission to increase to the same level as the original conditions, the CH_4 emission at the engine outlet are further reduced by more than 60%.

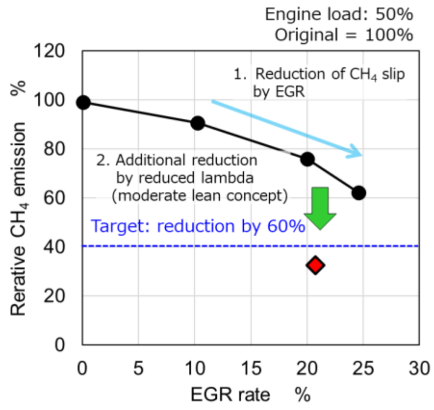

Figure 19. Effect of EGR rate on reduction of CH_4 slip.

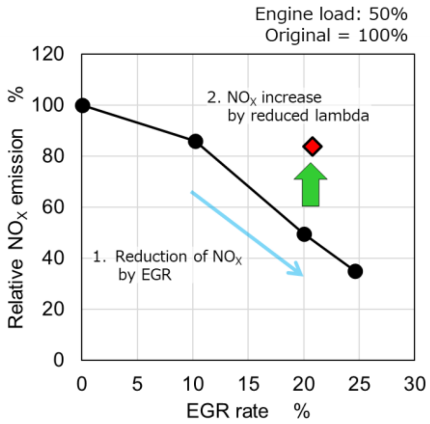

Figure 20. Effect of EGR rate on NO_X emission.

5.3.2 Total methane slip reduction by engine modification and methane oxidation catalyst

Figure 21 shows the reduction of CH_4 emissions by engine modification at each load. Below 75% load, which is the practical load range for marine auxiliary engines, the emission ratio of CH_4 was reduced to less than 40% compared to original engine. Figure 22 shows the change in fuel consumption rate in the results of Figure 21. The optimized EGR rate and excess air ratio resulted in a rather better fuel consumption rate in the practical range of marine auxiliary engines than without EGR. Figure 23 shows the overall CH_4 emission ratio after passing through the CH_4 oxidation catalyst. Exhaust gases with reduced CH_4 concentration by the engine modification further pass through a CH_4 oxidation catalyst to reduce CH_4 slip at the system outlet. Total CH_4 slip reduction as a system reached 97 to 99%. The CH_4 slip reduction rate before and after the CH_4 oxidation catalyst was 93.8% at 100% load, and the results were verified by NK's on-site inspection.

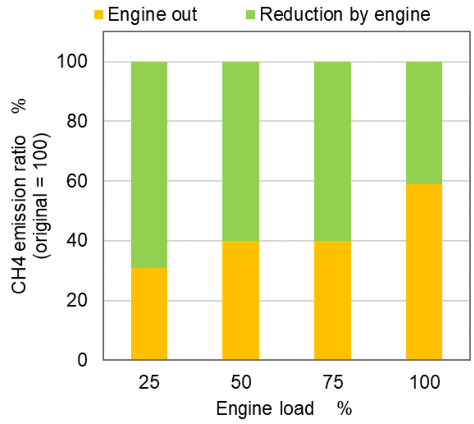

Figure 21. CH_4 slip reduction by engine modification with LP-cooled EGR and its control system at various engine load conditions.

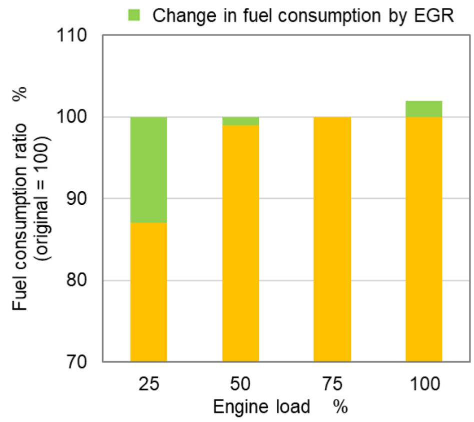

Figure 22. Change in fuel consumption rate at various engine load conditions.

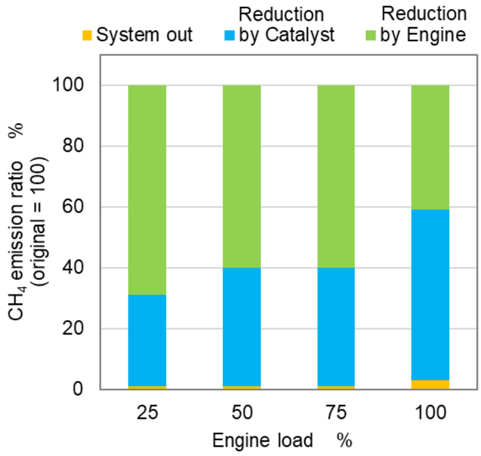

Figure 23. Total CH_4 slip reduction by engine modification with LP-cooled EGR and CH_4 oxidation catalyst at various engine load conditions.

Figure 24 shows the emission ratio of GHG in the results of Figure 23. The synergistic effect of the high CH_4 slip reduction rate (engine modification plus CH_4 oxidation catalyst) at the system outlet and the improved fuel efficiency in the practical load range resulted in a GHG emission reduction from 16% at 100% load to 61% at 25% load.

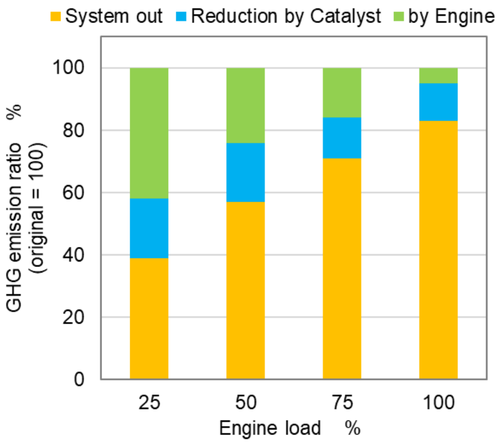

Figure 24. Reduction in GHG emission by engine modification and CH_4 oxidation catalyst at various engine load conditions.

6 MEASUREMENT METHOD OF METHANE SLIP REDUCTION FOR SEA TRIAL TESTING

This project plans to install the system (engine modification plus CH_4 oxidation catalyst) on an actual vessel and evaluate the CH_4 slip reduction rate. However, it is difficult to measure the exhaust gas flow rate with the carbon balance method used in onshore bench tests in an actual shipboard test. Therefore, measurement equipment that has been verified for accuracy in onshore tests was used to measure the exhaust gas flow rate in the actual shipboard tests. In the actual shipboard test, the exhaust gas flow rate was measured by pitot tube differential pressure method, and the CH_4 concentration in the exhaust gas was measured by IR analysis method. Figure 25 and Figure 26 show an accuracy comparison of exhaust gas flow rate and CH_4 concentration, respectively. Though all the measurement methods have errors compared to the onshore test, it is confirmed that the measurement results have linearity and can evaluate the results as well as the onshore test by using correction coefficients. The plan of this project is to begin actual vessel trials in the fall of 2024 on an LNG-fueled vessel operated by MOL. Figure 27 shows photo of a coal carrier vessel REIMEI, scheduled for actual ship demonstration in this project.

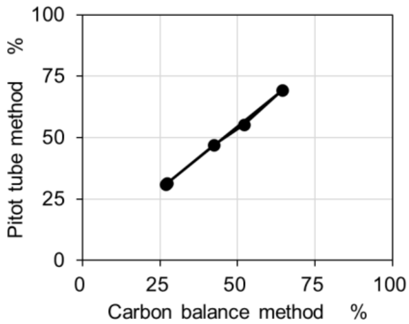

Figure 25. Comparison of carbon balance and pitot tube methods for exhaust gas flow rate measurement.

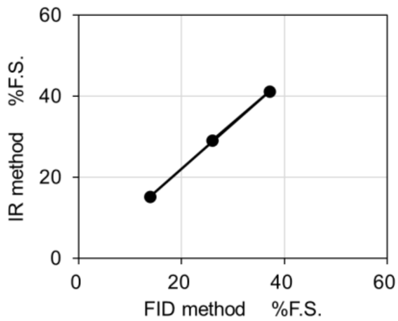

Figure 26. Comparison of FID and IR analysis methods for CH_4 concentration measurement.

Figure 27. Photo of a coal carrier vessel REIMEI, scheduled for actual ship demonstration in this project.

7 CONCLUSIONS

In this study, a combination of engine modification and CH_4 oxidation catalyst was investigated to maximize the reduction of CH_4 slip from LNG-fueled marine DF engines. The results obtained in this study can be summarized as follows:

(1) Single cylinder engine tests have shown that the combination of moderate lean combustion and EGR is effective in reducing CH_4 slip while keeping NO_X emission same or even lower level than that of original value.

(2) The layout of the CH_4 oxidation catalyst was studied by 1D cycle simulation, and the installation downstream of the turbocharger was selected, considering the results of elemental tests of the catalyst performance.

(3) Real-time combustion feedback control using cylinder pressure sensors was developed and applied for EGR control.

(4) The application of EGR to a 6EY22ALDF engine during onshore testing reduced CH_4 slip by approximately 60% at the engine outlet.

(5) The CH_4 oxidation catalyst reduced CH_4 emissions by greater than 93% by passing through the catalyst.

(6) The optimized EGR rate and excess air ratio resulted in a rather better fuel consumption rate in the practical range of marine auxiliary engines than without EGR.

(7) The synergistic effect of CH_4 slip reduction at the system outlet (engine modification + CH_4 oxidation catalyst) and improved fuel efficiency in the practical load range reduced GHG emissions from 16% at 100% load to 61% at 25% load.

(8) To enable the evaluation of CH_4 slip reduction in actual shipboard tests, we verified the accuracy of the onboard measurement equipment. As a result, it was confirmed that the evaluation is feasible.

8 ACKNOWLEDGEMENT

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