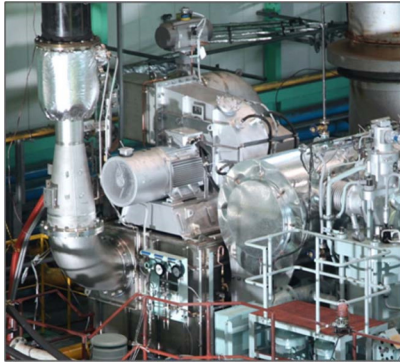


The World's First Onboard Verification Test of UE Engine with Low Pressure EGR complied with IMO's NOx Tier III Regulations



NAOHIRO HIRAOKA*1

AKIHIRO MIYANAGI*2

KENTARO KURODA*3

KAZUHISA ITO*4

TAKAHIRO NAKAGAWA*5

TAKASHI UEDA*6

The Mitsubishi Low Pressure EGR (LP-EGR) system developed by Mitsubishi Heavy Industries Marine Machinery & Engine CO., LTD. (MHI-MME) is a system that recirculates a part of the low pressure exhaust gas emitted from an engine turbocharger outlet to a turbocharger intake after being scrubbed with the EGR scrubber. We applied the integrated on-engine LP-EGR system into a 6UEC45LSE-Eco-B2 engine and verified that the system complies with the IMO NOx Tier III regulations. Furthermore, the verification of long-term reliability and durability is being conducted by the sea trial and actual commercial voyage with the system installed into a 34,000 DWT bulk carrier. This is the world's first LP-EGR system complied with the IMO NOx Tier III regulations installed into an actual ship.

1. Introduction

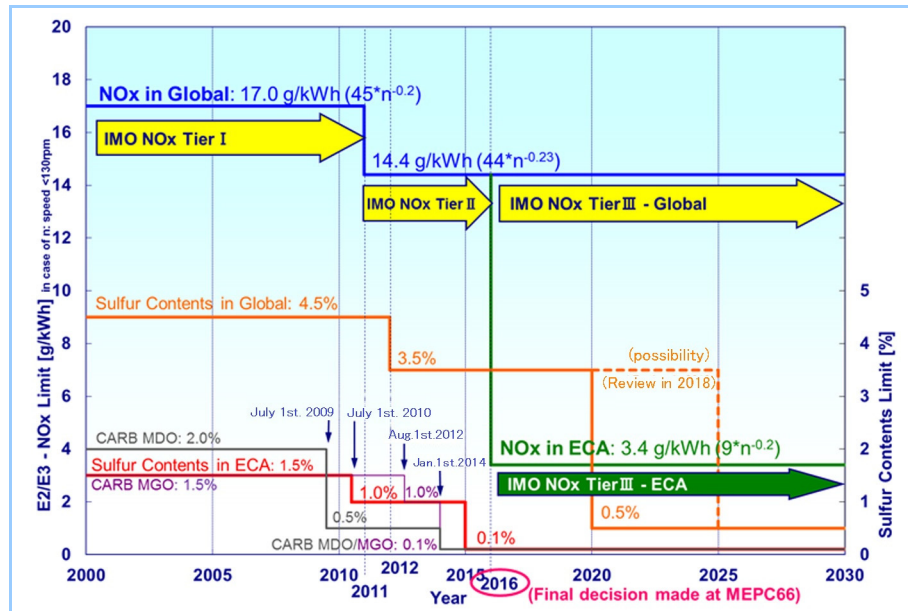


Figure 1 Emission regulations of IMO and CARB^(Note6)

The IMO^(Note 1) regulations concerning pollutants emitted from ships are being further tightened up year by year. In July 2010, the amendments of MARPOL 73/78^(Note 2) Annex VI enter into force. In particular, the implementation of NOx Tier III regulations^(Note 3) was finally decided as shown in **Figure 1** at the MEPC 66^(Note 4) under the leadership of Japan and through twists and turns such as a counterproposal from Russia. The IMO NOx Tier III regulations require newly built ships with keel-laying on or after January 1, 2016, to reduce NECA^(Note 5) by approximately 76%

*1 Engineering Manager, Technology Integration & Project MEET Development Department, Engineering & Products, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*2 Deputy General Manager, Marine Engine Division, Engineering & Products, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*3 Engineering Manager, Marine Engine Division, Engineering & Products, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*4 Senior Deputy Manager, Marine Engine Division, Engineering & Products, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*5 Deputy Manager, Marine Engine Division, Engineering & Products, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*6 Marine Engine Division, Engineering & Products, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

compared to the Tier II regulatory value. To countermeasure of these stringent regulations, MHI-MME has continued to develop various NOx reduction technologies. This paper presents the development of the Low Pressure (LP-) EGR (Exhaust Gas Recirculation) system, which is highly advantageous and very unique among the NOx reduction technologies developed by MHI-MME.

Note 1: International Maritime Organization

Note 2: Protocol of 1978 related to International Convention for the Prevention of Pollution from Ships, 1973

Note 3: Third round of regulations on emissions of nitrogen oxide (NOx).

Tier II was the second round of regulations.

Note 4: 66th Marine Environment Protection Committee

Note 5: NOx Emission Control Area

Note 6: California Air Resources Board

2. NOx reduction technology

Figure 2 and Table 1 show general NOx reduction technologies. Among many NOx reduction technologies, we dealt with the Tier II regulations via in-engine modifications, e.g., fuel injection timing retard, optimization of the fuel injection valve hole arrangement, design improvements to the scavenging and exhaust system, etc. However, under the Tier III regulations, in-engine modifications are not sufficient for the major reduction in NOx emissions that is required, therefore two technologies were selected as shown in Table 1. One method is SCR (Selective Catalytic Reduction), which is an exhaust gas after-treatment technology, and the other is EGR, which changes the combustion conditions in the engine to reduce NOx.

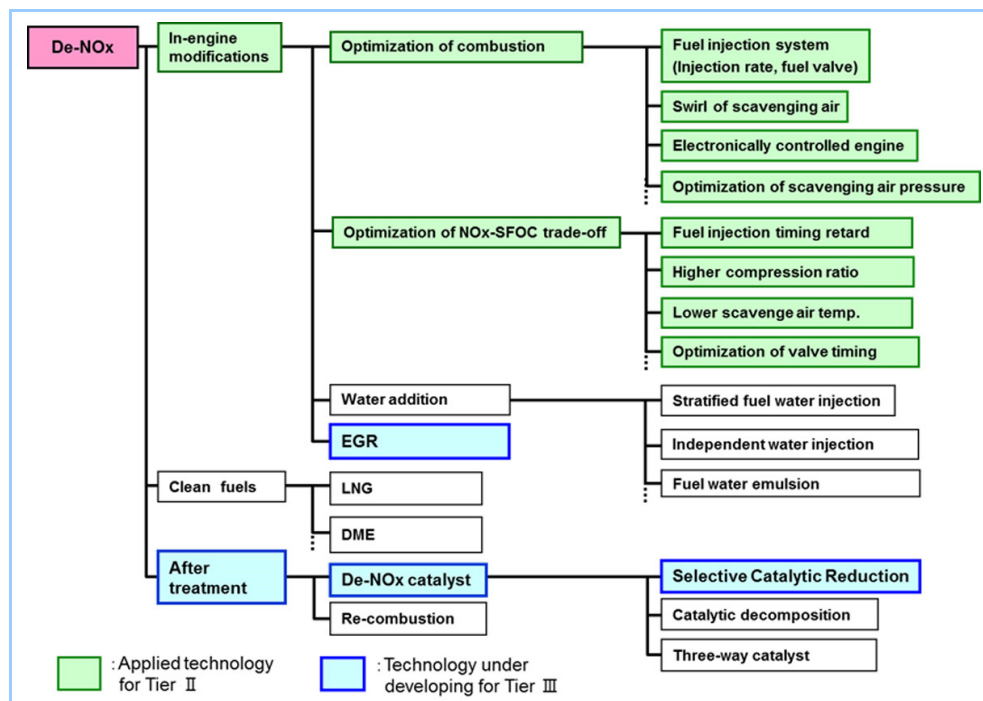


Figure 2 NOx reduction technology map

Table 1 Comparison of NOx reduction technologies

Item	NOx reduction rate (ratio to Tier I)	Decrease of fuel efficiency	Technology	Initial cost	Running cost
Optimization of engine specifications (mechanical)	-20%	+2 to +3%	Conventional technology	Low	Low
Electronic control engine	-20%	0 to +1%	Conventional technology	Mid	Low
Water injection	Water emulsion fuel: -50%	+2 to +3%	Developed	Mid	Mid
	Independent water injection: -80%	+7 to +10%	Developed	Mid	Mid
	Stratified fuel water injection: -80% (For restriction of fuel pump capacity, etc., the actual reduction rate will be at the -40% level.)	Approximately +10%	Developed	Mid	Mid
EGR	-80%	+1 to 3%	Under development (onboard test underway)	High	Mid
SCR	-90% to -80%	0 to +2%	Developed	High	High

3. LP-EGR system

3.1 Overview of EGR system

Recently, the EGR technology has been adopted to small and mid-sized land-use engines. Engines equipped with the EGR system can suppress the temperature increase of combustion gas and thermal NO_x formation reactions by recirculating a part of the exhaust gas from the engine to intake air to reduce the oxygen concentration in the combustion chamber and increase the ratio of inert gases, such as carbon dioxide, etc., contained in the exhaust gas, and the heat capacity.

3.2 EGR technology for marine diesel engines

The EGR systems applied to marine engines are classified into two types, LP-EGR and High Pressure EGR (HP-EGR) by the branch point of exhaust gas as shown in **Figure 3**.

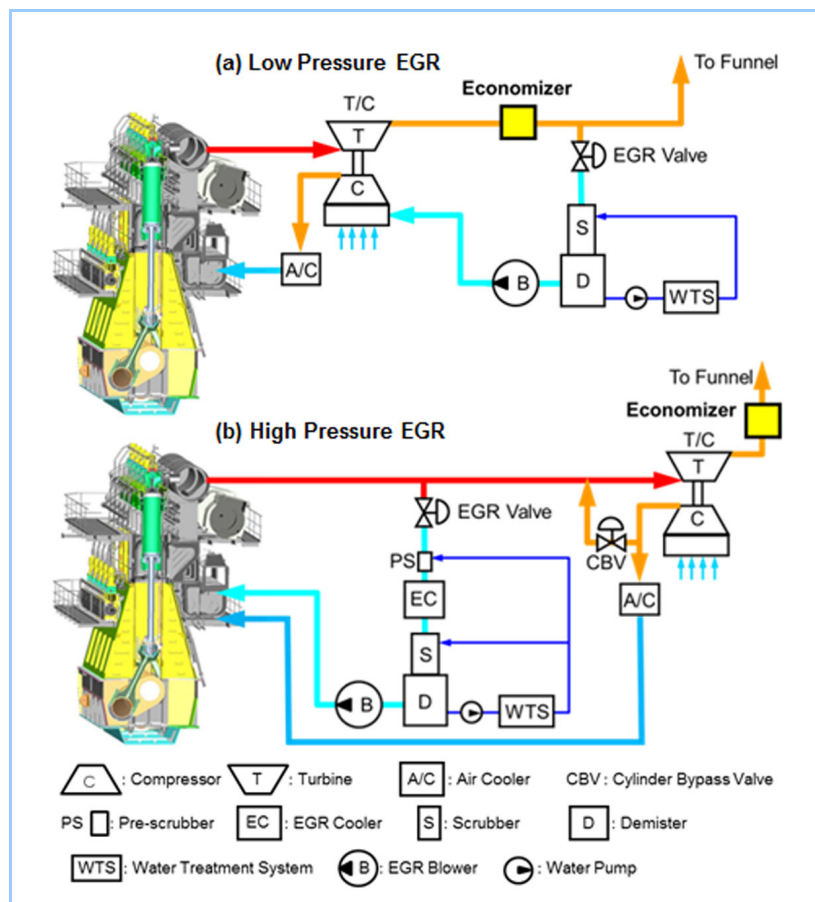


Figure 3 System configuration of LP-EGR and HP-EGR

In an LP-EGR system, exhaust gas is branched at the downstream side of the turbocharger turbine and recirculated to the intake side of the turbocharger. In an HP-EGR system, on the other hand, exhaust gas is branched at the upstream side of the turbocharger turbine and returned to the scavenging trunk.

The features of these EGR systems depend on the gas characteristics at the extraction point. The advantage of the LP-EGR is that the system is a simple structure because of the comparatively low pressure and low temperature of the exhaust gas. In addition, the EGR blower power needed to draw the EGR gas into the turbocharger intake is lower than in the HP-EGR because turbocharger suction pressure is utilized. The equipment, however, tends to be larger than an HP-EGR system, because the low pressure increases the gas volume. With an HP-EGR system, the equipment is compact because the high pressure decreases the gas volume, but the scrubber for cleaning the gas has a complicated structure due to the high pressure and high temperature of the gas, and high EGR blower power is needed to elevate exhaust gas pressure to the same level of the scavenging air pressure. MHI-MME has selected and developed an LP-EGR, which is simple and has an advantage in terms of running cost.¹

3.3 Overview of LP-EGR system

An overview of the LP-EGR system is shown below.

- (1) A part of the exhaust gas is branched at the downstream side of the turbocharger or the exhaust gas economizer (heat recovery device that uses exhaust gas heat to generate steam) as EGR gas.
- (2) The branched EGR gas is led to the EGR line and the other part of the exhaust gas is discharged outboard from the funnel.
- (3) PM (particulate matter) and SOx (sulfur oxide) are removed from the EGR gas by the scrubber, which is an exhaust gas cleaning device.
- (4) The EGR gas is led into the intake side of the turbocharger by the EGR blower.
- (5) The EGR gas and fresh air are mixed and compressed in the turbocharger compressor and then led to the engine.

Marine diesel engines use fuel containing residue such as heavy fuel oil, and the exhaust gas contains much PM and SOx. In addition, the amount of exhaust gas is very large. Therefore, the scrubber that cleans the EGR gas is a very important device. For this reason, MHI-MME developed a new scrubber based on a proven land and marine scrubber. The developed scrubber uses water to clean exhaust gas. The used water after cleaning exhaust gas is treated by a water treatment device for separating PM and adjusting pH, and is then circulated and reused.

4. Development of LP-EGR using 4UE-X3 test engine

An overview of the LP-EGR system is described above. To apply the LP-EGR system to an actual low speed two-stroke diesel engine, we accumulated expertise in developments from the basic structure with NC33 single cylinder test engine and 4UE-X3 full-scale test engine.

4.1 Development of EGR unit

In initial tests using NC33 and 4UE-X3, the scrubber structure of an inert gas scrubber (IGS) system that a structure has been sufficiently proven on oil tankers was used, and the scrubber structure and the performance of the entire EGR system were tested. The IGS type scrubber has a two-stage structure as shown in **Figure 4**. The first stage venturi (flow velocity enhancing device using a throat) removes particulates and the second stage cleaning tower absorbs SOx. Because of this role sharing, the device size, in particular the cleaning tower size for decreasing the internal flow velocity, is a fatal disadvantage.

The results of the test of the LP-EGR combined with an IGS type scrubber using NC33 and 4UE-X3 were very favorable, and it was found that a sufficient level of performance for practical use was attained, notwithstanding the problem with the size described above. Therefore, MHI-MME continued various tests aiming at the establishment of a simple and compact scrubber structure. As a result, we developed an EGR unit that attains high SOx absorption performance without a cleaning tower and has a reduced size so that it can be integrated into an engine. The details of the developed EGR unit are described later.



Figure 4 IGS type scrubber
(Front) Venturi (Rear) Cleaning tower

4.2 Water treatment system

The used water after cleaning the EGR gas in the scrubber is circulated and reused because the original water is precious fresh water. MHI-MME also developed the water treatment system for the circulation and reuse of the water in cooperation with Mitsubishi Kakoki Kaisha, Ltd.

The main roles of the water treatment system are to neutralize the scrubber water that was acidified in spraying over acidic exhaust gas for pH adjustment and to separate PM caught by the scrubber water to allow the contaminated water to be used as scrubber water again. The pH adjustment was made using a pH sensor and NaOH solution (caustic soda) injection control. As a result of comprehensive evaluation of various considerations and the test results of various treatment methods such as a ceramic filter, a water treatment unit constructed from a centrifuge was adopted as the water treatment system for the LP-EGR system.

The water treatment device can separate scrubber water into very transparent treated water and concentrated PM sludge as shown in **Figure 5**. This treated water satisfies the regulatory value of the guidelines on wastewater from an exhaust gas cleaning device (EGCS guidelines) and can be discharged overboard.



Figure 5 Water treatment device test results

5. Onboard test

Based on the results of the testing using 4UE-X3 full-scale test engine, an onboard verification test is being carried out.² This test is intended for long-term operation verification supported by the “Joint R&D for Industry Program” scheme of Nippon Kaiji Kyokai (ClassNK), which is outlined below.

5.1 Development of LP-EGR system for actual ship

As a result of arrangements with related parties, a 34,000-DWT bulk carrier (vessel name: DREAM ISLAND) built by the Hakodate Dock Co., Ltd. and owned by Shikishima Kisen KK was decided as the ship to be used for this test, and the 6UEC45LSE-Eco-B2 was chosen as the main engine. This engine has a cylinder bore of 45 cm and is a hot-selling UE engine that holds an overwhelming market share among handy size bulk carriers.

The LP-EGR unit was integrated into the engine because the performance was verified using 4UE-X3 with the LP-EGR integrated into the engine while modified. Meanwhile, the installation of the water treatment device including tanks into the vessel was oriented as the basic policy. The basic configuration was decided as the EGR gas branch point was set at the outlet of the exhaust gas economizer where we think the highest performance can be attained, and EGR gas piping to the EGR unit was installed.

As illustrated in **Figure 6**, the EGR unit consisting of the EGR scrubber, the demister unit, the EGR blower and the EGR outlet valve attains on-engine mountable compactness and high performance, as the result of the optimization of the flow velocity distribution in the EGR system based on the expected EGR gas amount. The water treatment system has two separately located centrifuges; one primary centrifuge and one secondary centrifuge, and the arrangement of the device was determined so that the tanks and pumps could be installed without major modifications to the existing series vessel, as shown in **Figure 7**. The control system consists of the EGR control panel that administers the entire system as a master controller and the EGR blower inverter panel and the scrubber control panel that controls the water treatment device, as well as other control boards are assigned as slave controllers connected to the master and issue alerts to the vessel collectively with coordinated by the EGR control panel.

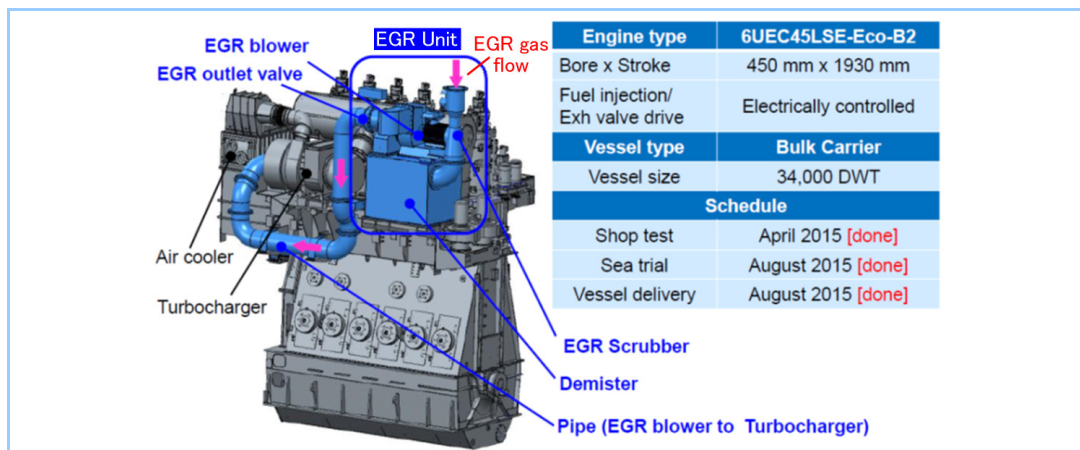


Figure 6 Summarized specifications of UEC45LSE-Eco-B2 equipped with LP-EGR

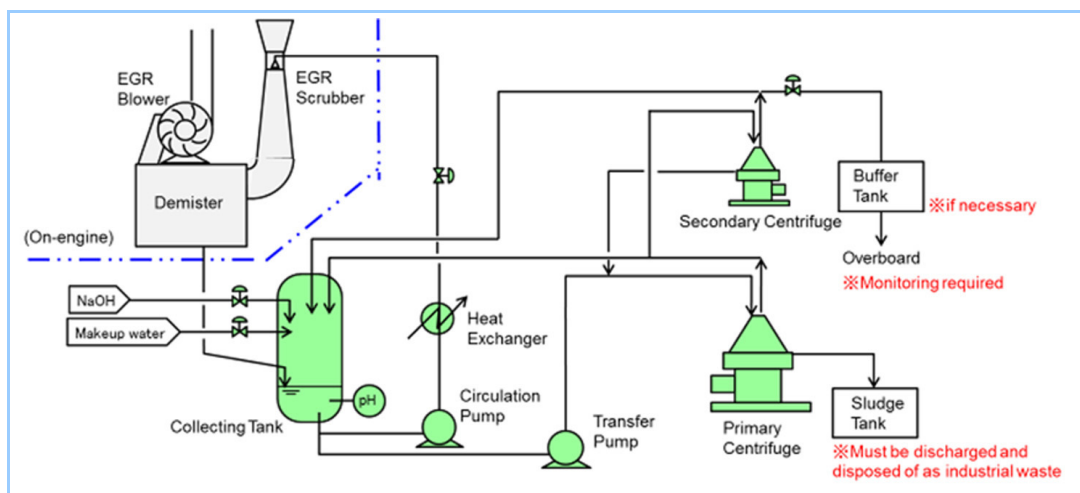


Figure 7 Water treatment system

5.2 Results of shop test

MHI-MME designed and manufactured an LP-EGR system that can be integrated into an actual 6UEC45LSE-Eco-B2 engine as described above. Then the greatest concern, the verification of compliance with the IMO NO_x Tier III regulations, was conducted at Kobe Diesel Co., Ltd., which is the manufacturer of the main engine (UE engine licensee). Because the system was to be installed into an actual ship, the verification of the safety, etc., of the entire system was conducted in the shop test unlike past test engines, and it was ensured that there was no problem with normal operation and emergency shut down for the EGR system.

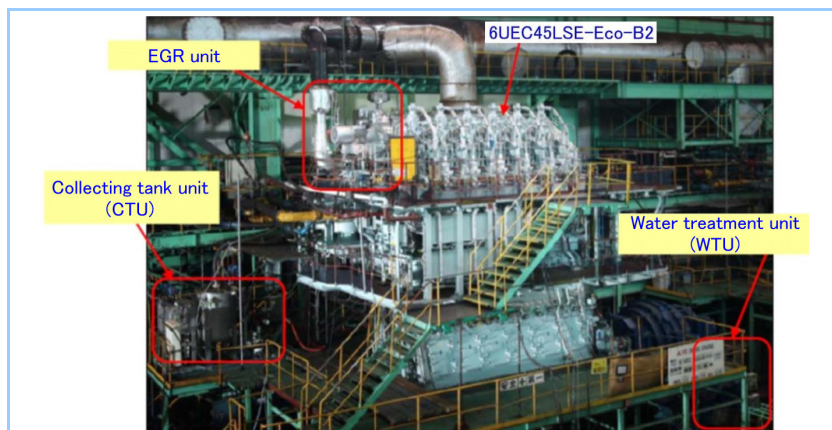


Figure 8 6UEC45LSE-Eco-B2 onshore test

Figure 8 shows the situation of the shop test conducted in April 2015, and Figure 9 and Figure 10 show the results thereof. As shown in Figure 9, the relationship between the EGR rate and the NO_x reduction rate was almost same as past test results. The NO_x emissions in the shop test were 3.2 g/kWh in E3 mode, and this value complied with the Tier III regulations; 3.4g/kWh

with a slight margin. The increase in the fuel consumption rate with the use of the LP-EGR system was within approximately 1%, and the excellent performance of the LP-EGR system in line with that obtained in past test results was reconfirmed.

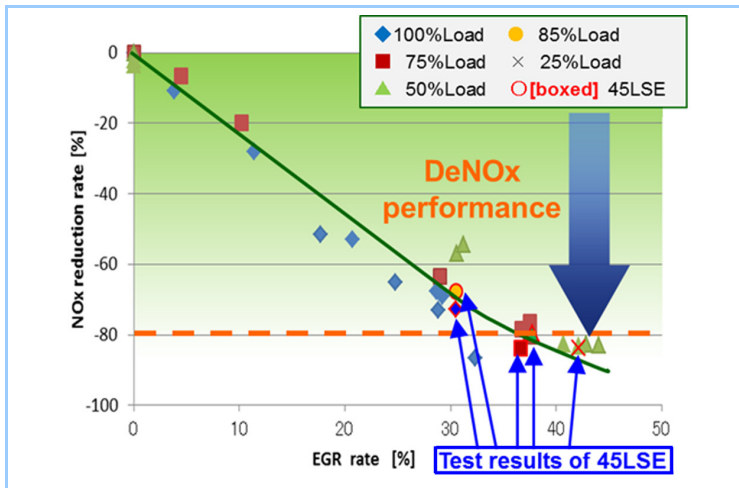


Figure 9 EGR rate and NOx reduction rate (comparison with past test results)

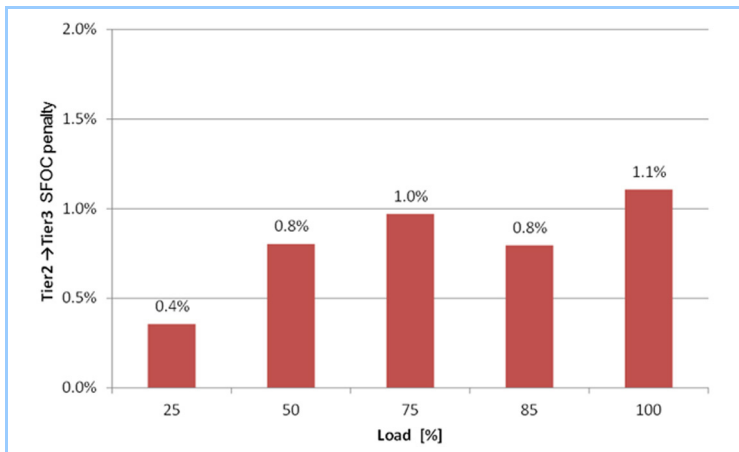


Figure 10 Decrease of fuel efficiency against load

5.3 Results of sea trial

Also in the sea trial conducted in August 2015, the LP-EGR system, NOx and main engine performance, as well as the water treatment device, were evaluated in a manner comparable to the shop test. Figure 11 shows the situation of the LP-EGR system installed into the ship.



Figure 11 LP-EGR system installed into the actual ship

As a result of two-day sea trial, it was confirmed that the main engine performance in terms of NO_x and fuel consumption was almost the same as the shop test results. In addition to manuals of the water treatment device that were appraised in advance by NK, the test procedure and the test report were appraised based on the results of the witnessed sea trial. Accordingly, it was verified that the entire LP-EGR system was in compliance with the IMO's EGCS guidelines, and the discharge approval of the flag state (Panama) was obtained.

In addition to compliance with Tier III as verified in the shop test, it was also publicly confirmed that Mitsubishi's LP-EGR system met the expected performance and features.³

6. Long-term verification test and future prospects

Since this bulk carrier went into service in August 2015, the verification test in actual voyages has been continued, and various improvements including countermeasures to the initial problems and the optimization of the operational parameters have been implemented. The action of applying the knowledge obtained in the long-term verification test in a practical environment to the further improvement of the entire LP-EGR system, which is one of the main purposes of this actual ship test, continues to be conducted.

This LP-EGR system is a very advantageous system as described above, and is a technology that can be combined widely with not only UE engines under MHI-MME's license, but also various engines under the license of other manufacturers, because the system uses low pressure exhaust gas. Thus, MHI-MME plans to spread the LP-EGR system proactively in the future. The wide diffusion of this excellent technology can suppress the effect on the global environment, even when economic activities are vigorous. MHI-MME thinks that the spread of such a technology will contribute to sustainable advancement.

7. Conclusion

MHI-MME has developed a unique LP-EGR system that complies with the IMO NO_x Tier III regulations and is advantageous in comparison with other systems due to its properties through performance verification using a test engine and an onboard test using an actual 6UEC45LSE-Eco-B2 engine conducted in the past.

We will strive for the further improvement of the system through the actual ship test that is still under way, where the evaluation of controllability and long-term reliability and the verification of practical operability such as workability in a harbor will be performed.

We would like to express our appreciation for the support we received in the development of this system, which led us to an excellent achievement, from all concerned members and parties including those mentioned above, as well as the operation management company of the bulk carrier used for the test.

References

1. Ueda, T. et al., Development of Exhaust Gas Recirculation System for Exhaust Gas Emission Control of Mitsubishi UE Diesel Engine, Proc. of ISME Harbin, (2014), PID:129
2. Hiraoka, Development of Low Pressure EGR System Complied with IMO NO_x Tier III Regulations, The 85th Meeting of The Japan Institute of Marine Engineering, Toyama (2015), S2-2
3. Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd. Press Information (August 31, 2015) <https://www.mhi-mme.com/news/0042.html>