Modern Environmental Science and Engineering (ISSN 2333-2581)
April 2017, Volume 3, No. 4, pp. 215-223
Doi: 10.15341/mese(2333-2581)/04.03.2017/001
Academic Star Publishing Company, 2017
www.academicstar.us

The Leading-edge and Unique Technology, Mitsubishi Low Pressure EGR

Takashi Ueda, Kazuhisa Ito, and Naohiro Hiraoka

Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd., Nagasaki city, Nagasaki, Japan

Abstract: To comply with IMO NOx Tier III regulations, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd. has developed a new and unique exhaust emission reduction technology “Low Pressure Exhaust Gas Recirculation (LP-EGR) system”.

We Mitsubishi have applied integrated on-engine LP-EGR system into a commercial engine 6UEC45LSE-Eco-B2. As a result of its shop test, we confirmed its NOx emission amount was complied with IMO Tier III regulations in witness whereof the ClassNK and the increase of fuel oil consumption was less than approximately 1%.

Thereafter, we have installed the system into a 34,000DWT Bulk Carrier and now being conducting a long-term durability confirmation during commercial voyages. The installation of the LP-EGR system adapted IMO NOx Tier III into a vessel is the world’s first effort for marine low speed two-stroke diesel engine. Furthermore, since Mitsubishi LP-EGR system utilizes exhaust gas after turbocharger as the EGR gas, it is easy to install any type of engines. Therefore, LP-EGR is the best solution for IMO NOx Tier III.

Key words: marine diesel engine, LP-EGR, IMO NOx Tier III

1. Introduction

Regulations for preventing air pollution from ships are being further tightened up as shown in Fig. 1. As for the regulations on marine diesel engines of the International Maritime Organization (IMO), the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI [1] was adopted at IMO for the purpose of the prevention of pollution of the marine environment by ships. MARPOL Annex VIentered into force on 19 May 2005, then the amendment of the Annex VI was adopted at the MEPC58 (58th Marine Environment Protection Committee) held in October 2008 and entered into force on 1 July 2010. Tier III regulations, which provide for a reduction of NOx emissions by approximately 76% compared to Tier II regulations within a NOx ECA (Emission Control Area) shown in Fig. 2, are applied to ships keel-laid on or after 1 January 2016. As for the sulfur content in fuel, there are also two regulations. After 2015, sulfur content in fuel has to be below 0.1% in SOx ECAs, while, in the global area, it will have to be restricted below 0.5% in near future.

For Mitsubishi’s “UE-Engine”, several candidate technologies have been developed [2]. This paper introduces our approach to NOx reduction using unique Low Pressure Exhaust Gas Recirculation (LP-EGR) technology [3, 4].

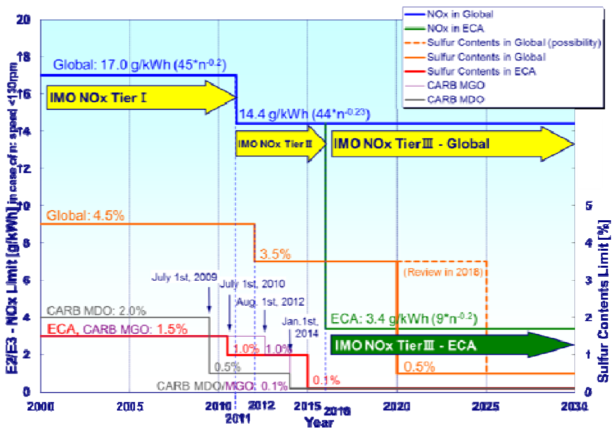

Fig. 1 Emission regulations of IMO and CARB.

Corresponding author: Takashi Ueda, research areas: combustion, diesel engine, exhausts gas cleaning system. E-mail: takashi4_ueda@mhi.co.jp.

Fig. 2 The map of NOx ECA.

2. NOx Reduction Technologies

To comply with the IMO NOx Tier III regulations, measures should be fundamentally different from those for Tier II. Among several technologies, EGR and Selective Catalytic Reduction (SCR) themselves comply with the Tier III limits, therefore we have decided to develop both of these technologies.

After-treatment technology, SCR is one of the most effective solutions for the Tier III, as it can reduce NOx emissions drastically and basically has no increase in CO_2 emissions. SCR is a well-known technology using especially in power-generating plants.

We developed Low Pressure SCR (LP-SCR) for low speed two-stroke marine diesel engines which installed the SCR reactor after the turbocharger, did bench tests in the laboratory and full-scale on-board tests using an 88BC, with a main engine output of 11.9 MW (6UEC60LSII). We confirmed that the NOx reduction rate of our LP-SCR system was a stable 80% at all loads [5].

As an alternative countermeasure for the Tier III, EGR is now under hot development by engine licensers and licensees because of its many merits. Hereinafter we describe the EGR technology.

3. EGR Technology

3.1 Principle of EGR Technology

Recently, EGR technology has been adapted to many types of small and medium internal-combustion engines, which are used in cars, locomotives, generators and so on. In an engine equipped with EGR, a part of the exhaust gas is introduced into the scavenging air or air intake, after that these gases are led to the combustion chamber. At the time of combustion, the low O_2 concentration gas makes the combustion reaction slow and high CO_2 concentration gas makes high heat capacity, then the peak temperature of the local flame surface drops; as a result, the amount of thermal NOx emissions decreases. Fig. 3 shows the principle of the EGR system.

3.2 EGR Technology for Marine Diesel Engine

In the case that the EGR technology is adapted to marine diesel engines, the system is divided into two categories, as shown in Fig. 4: Low Pressure loop EGR (LP-EGR) and High Pressure loop EGR (HP-EGR) [6].

In the case of the LP-EGR, a part of the exhaust gas is branched out after the turbocharger turbine and returned to the turbocharger intake. On the other hand, in the case of the HP-EGR, the exhaust gas is branched out before the turbocharger turbine and returned to the scavenging air trunk, which is downstream of the turbocharger compressor.

The characteristics of these EGR technologies depend on simply these EGR gas features, so they have both merits and demerits. For example, an advantage of the LP-EGR is that a return line of the EGR gas is simple structure because of its low pressure and low temperature. In addition, the EGR blower power, which needs to draw in the EGR gas to the turbocharger intake, is smaller than the HP-EGR because turbocharger suction pressure is utilized.

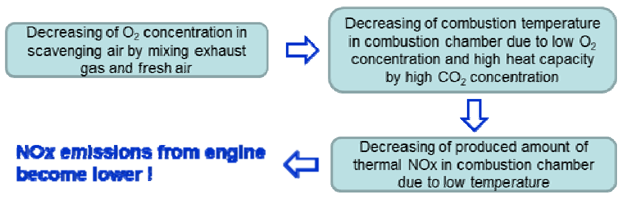

Fig. 3 Principle of EGR system.

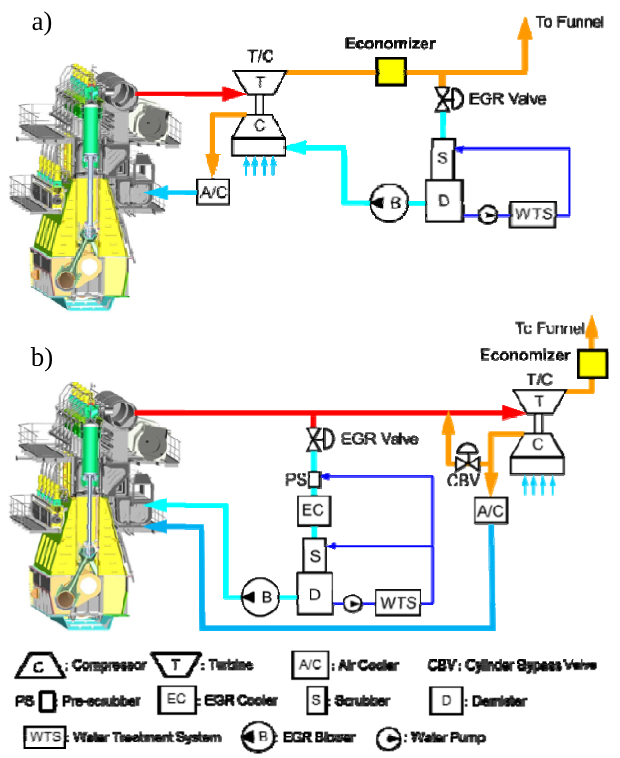

Fig. 4 (a) LP-EGR, (b) HP-EGR.

However, due to the low pressure, the volume of the EGR gas is big and therefore equipment for the LP-EGR system tends to become larger than for the HP-EGR. A merit of the HP-EGR is its compact size, but the system has demerits: a scrubber for cleaning the EGR gas is a complicated structure because of the high pressure and high temperature and the EGR blower power is bigger than for the LP-EGR because of joining EGR gas into scavenging air with rising the pressure.

From the above viewpoint, we have made the decision to develop the LP-EGR system because of its simplicity and superior operability including operating cost.

4. LP-EGR Development

4.1 LP-EGR System Design (1st Generation)

The LP-EGR system was tested in our NC33 single-cylinder test engine and 4UE-X3 full-scale test engine (based on 4UEC60LSE-Eco type engine), and its design concepts were as follows.

Since exhaust gas is dirty, for the EGR system, a scrubber which cleans the exhaust gas is a key component because its performance will affect the durability of the engine. Therefore, we developed a new wet scrubber with high removal performance of soot and SOx by utilizing the technology of an Inert Gas Scrubber (IGS) system. This type of scrubber consists of two parts in series: the first is a venturi and the following is a scrubber tower, both parts clean gases using water. The venturi is mainly responsible for removing soot, whereas the scrubber tower works to remove SOx in the exhaust gas. Fig. 5 shows the tested IGS type scrubber and we confirmed the SOx reduction rate of more than 98%, which was the design target.

4.2 Test Results of on-engine LP-EGR System Using 4UE-X3 (2nd Generation)

The performance of the IGS type wet scrubber was excellent but the size of equipment was very big; therefore we conducted many tests and improvements aiming to downsize the scrubber. Finally the scrubber could be mounted to an engine, as shown in Fig. 6.

The EGR scrubber was applied a venturi scrubber solely because of its simple structure and good performance. The venturi scrubber is popular technology in land-use and can realize both atomization

Fig. 5 IGS type wet scrubber (Photo taken during construction).

Fig. 6 Adaption of the LP-EGR to the 4UE-X3, Demister (left), Venturi (right).

of scrubbing water and mixing atomized scrubbing water into the EGR gas by only increasing flow velocity with a narrow throat. As a result, high performance of SOx and soot removal from the EGR gas can be realized despite its simple structure.

The demister is also a key component for the LP-EGR system. It is responsible for removing almost all scrubber droplets and mists from scrubbed EGR gas in order to prevent erosion and corrosion of the turbocharger compressor wheel derived from carried over mists. The demister element has extremely high removal performance of droplets and mists, therefore it can be realized the design which is enough to be installed on the engine.

This is a big advantage, because the demerit of the LP-EGR is its size for the low pressure as mentioned before, it was common opinion that could not be downsized. Since we conquered this most difficult problem, our development progress was accelerated rapidly toward to practical use.

The test results of on-engine LP-EGR system are shown in following sections.

4.2.1 Scrubber Performance

Scrubber test results are shown in Figs. 7 and 8. It can be understood that this scrubber can remove over 80% of soot and over 95% of SOx. It should be noted that the SOx removal rate is calculated with measured SO_2 values. SOx removal rate seems not to achieve the design target, but the SOx value is only a few ppm; therefore this scrubber can be considered to have enough performance essentially.

4.2.2 Water Treatment System (WTS) Performance

EGR scrubber is a wet scrubber, therefore a WTS is needed to keep scrubbing water clean. The WTS consists of a centrifuge, pumps, tanks, a heat exchanger, valves and sensors. The most important equipment centrifuge was confirmed that it can assuredly separate off sludge from scrubbing water as shown in Fig. 9. The after-treatment water shown in the center of Fig. 9 is very clean and has high transparency; therefore it can be overboard as-is. Meanwhile, the sludge is concentrated soot and oil; therefore it cannot be overboard. The sludge must be taken ashore and treated as industrial waste disposal.

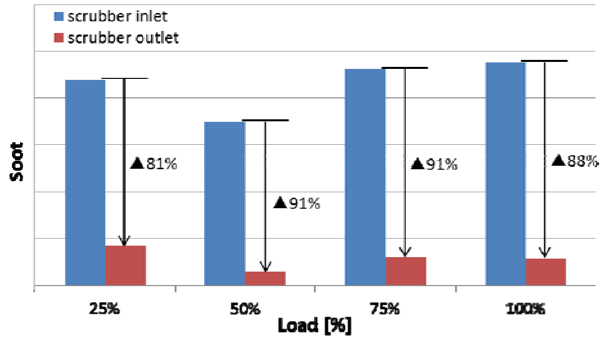

Fig. 7 Soot removal performance.

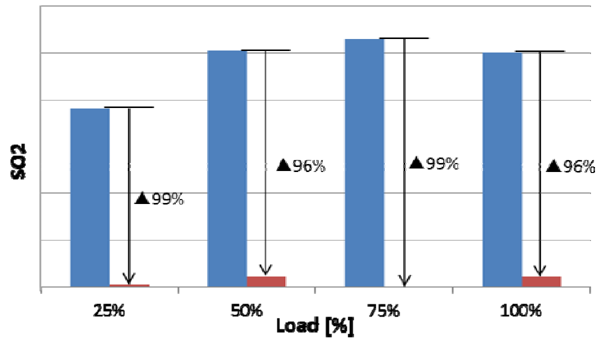

Fig. 8 SOx removal performance.

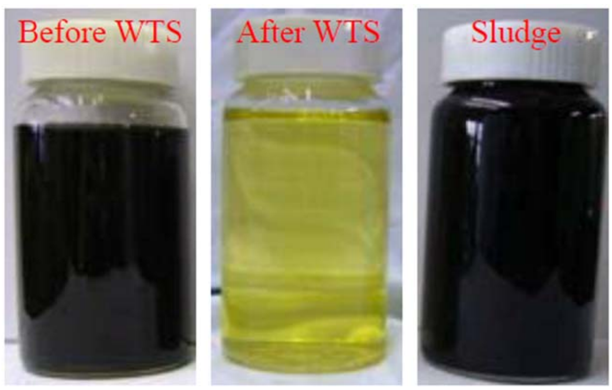

Fig. 9 WTS test results: Before water treatment (left), after water treatment (center), sludge (right)

4.2.3 Engine Performance

In the engine performance tests, we optimized the engine parameters: fuel injection timing, exhaust valve timing, fuel injection rate and so on, with the Eco system [7]. As a result, an 80% reduction in NOx was achieved at all engine loads as shown in Fig. 10.

5. On-board Verification

5.1 LP-EGR Design for On-board Verification

We confirmed that the LP-EGR had enough ability to comply with the IMO's NOx Tier III regulations using our 4UE-X3 test engine described already, then as the next step we decided to perform on-board verification tests.

The target vessel was a 34,000DWT Bulk Carrier named "DREAM ISLAND" (the owner; Shikishima Kisen K.K., the operator; NYK Bulk & Projects Carriers Ltd. and the shipyard; The Hakodate Dock Co., Ltd.).

5.1.1 Entire System

At first, the entire system of on-board LP-EGR was discussed and decided. The EGR gas branch point was downstream of the exhaust gas economizer because of superior performance of the overall system. The target engine was 6UEC45LSE-Eco-B2 which was relatively small size type; therefore it was said difficult to install the EGR unit on-engine. However, we successfully managed to arrange the LP-EGR unit on the upper side of the scavenging air trunk shown as Fig. 11. Regarding the turbocharger, we applied special coatings onto the compressor wheel against erosion and corrosion caused by mist carried over from the LP-EGR unit.

The WTS was planned to arrange both its equipment and some tanks at ship side as the design policy adhered from the system of 4UE-X3 tests.

The control system is multi-layered. The EGR control panel is responsible for head control for the entire EGR system and a communication interface to the engine control system. The EGR control panel is the master, while the EGR blower inverter and the

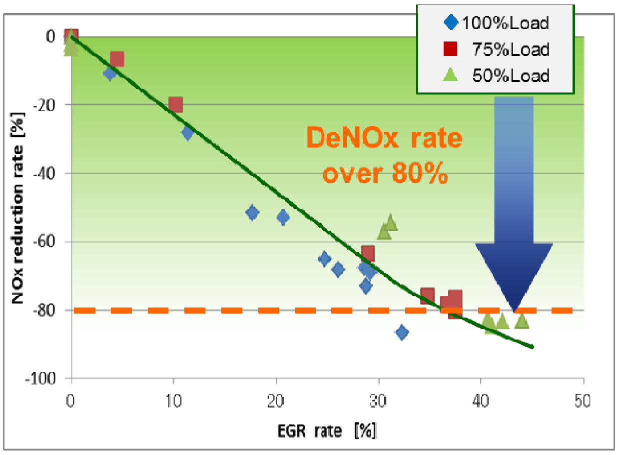

Fig. 10 NOx reduction with LP-EGR.

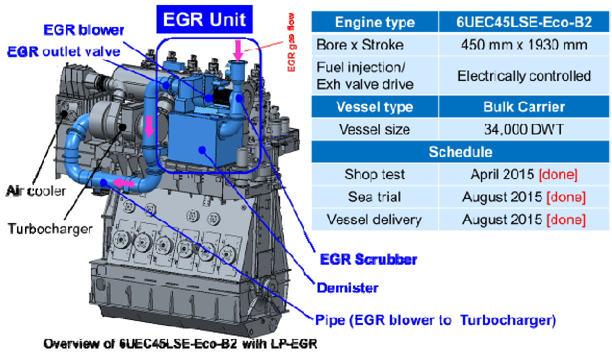

Fig. 11 Overview of 6UEC45LSE-Eco-B2 with LP-EGR.

WTS control panel are slaves. Furthermore, centrifuges and the Waste Water Monitoring Unit (WWMU) are slaves of the WTS control panel.

5.1.2 LP-EGR Unit

The LP-EGR unit consists of an EGR scrubber, demister, EGR blower, EGR outlet valve and sensors. The EGR scrubber is needed for high SOx and Particulate Matter (PM) removal performance. A venturi scrubber was applied because of its simple structure and good performance in tests with 4UE-X3.

The demister structure adheres basically to 4UE-X3 test equipment. The key component demister element and internal flow are almost same as that of 4UE-X3's, but we optimized dimensional details using CFD and realized the design which was compact enough to be installed on the engine. The EGR blower adheres to a blower for IGS not only in structure but also materials, since it is highly reliable and has a long track record.

The EGR outlet valve is of tight-shutting, butterfly type.

5.1.3 Water Treatment System

The WTS should comply with “the 2009 Guidelines for Exhaust Gas Cleaning Systems”(the 2009 Guideline) [8] at this moment. We designed specifications from past test results; consequently two centrifuges were necessary to comply with the 2009 Guideline regarding waste water quality as shown in Fig. 12. Two centrifuges were named “primary” and “secondary”: the primary centrifuge is responsible for roughly cleaning scrubbing water and the secondary centrifuge is responsible for cleaning waste water after the primary centrifuge enough to overboard.

The WWMU is working for monitoring waste water qualities such as pH, turbidity and PAHs.

In this on-board verification project, the WTS equipment were arranged separately, not as a unit, because of arrangement difficulty inside restricted engine room space. As a result of this policy, there was no need to enlarge the engine room.

5.2 Test Results of the Shop Test

We conducted the shop test for confirmation of performance and system check. The shop test was held at Kobe Diesel Co., Ltd., which is our licensee. Fig. 13 shows an overview of the shop test. The WTS is simplified and temporary facility for only the shop test since it is not necessary regular component for confirming NOx reduction performance.

At first, we confirmed that the control system was working properly as designed, such as mode changes, following capability, 110% load operation and safety.

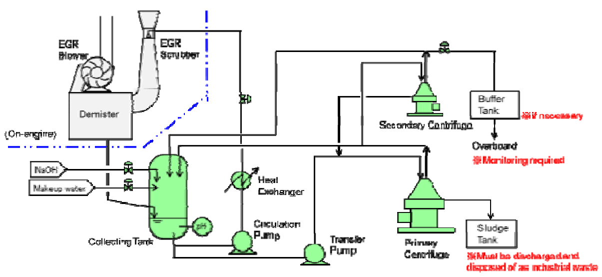

Fig. 12 Outline of water treatment system.

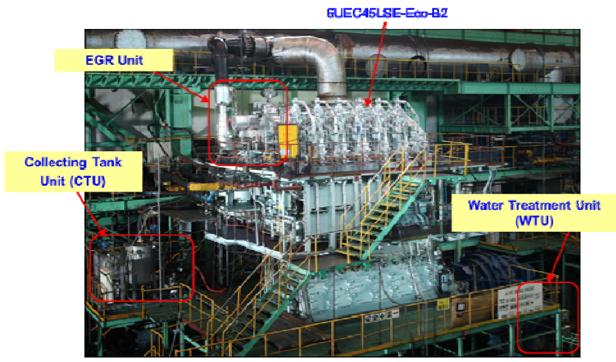

Fig. 13 Overview of the shop test.

Figs. 14 and15 show results of the shop test. Fig. 14 shows NOx reduction performance versus EGR rate, compared with past test results from 4UE-X3. Boxed marks by red line are shown the results of 6UEC45LSE-Eco-B2, which performed the same as in past tests. We optimized the EGR rate for each load, between 30 to over 40%, realized fuel oil consumption (FOC) penalty within approximately 1% as shown in Fig. 15.

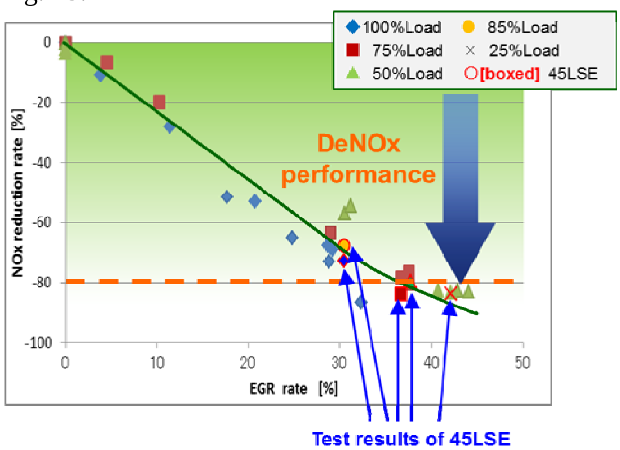

Fig. 14 Shop test results of NOx reduction.

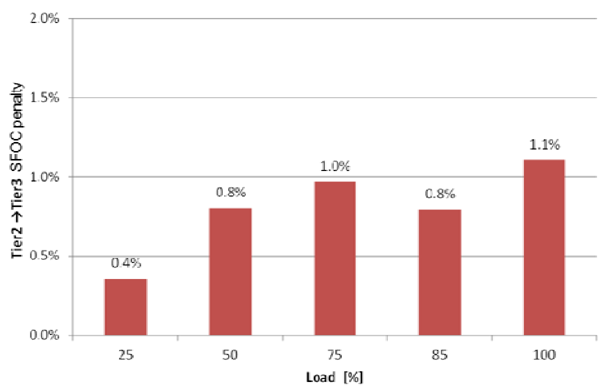

Fig. 15 Shop test results of FOC penalty.

And in this condition, we confirmed that our LP-EGR system complied with the IMO NOx Tier III regulations in witness whereof ClassNK and its NOx emission amount was 3.2 g/kWh in the E3 mode, and which was sufficient performance against the regulatory value of 3.4 g/kWh.

5.3 Test Results of the Sea Trial

After we confirmed good performances in the shop test, we conducted the sea trial at the Hakodate Dock. Fig. 16 shows an overview of the installed LP-EGR system including the WTS, despite relatively small size of the vessel, all EGR components managed to arrange inside the engine room because of its compact size.

Figs. 17 and 18 show test results of the sea trial. We confirmed that performances of NOx reduction and FOC penalty were almost the same as the shop test. Because of the restricted the sea trial schedule, the NOx reduction was confirmed by using MDO, and FOC penalty was confirmed by using HFO at NR.

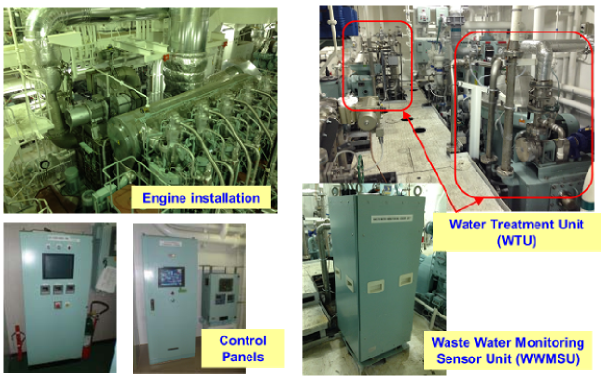

Fig. 16 Overview of the installed LP-EGR system.

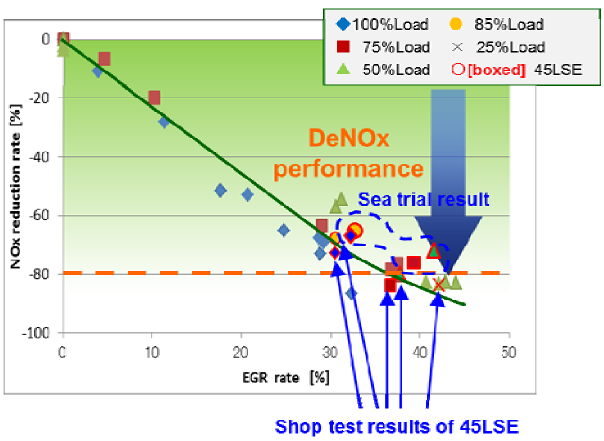

Fig. 17 Test results of NOx reduction.

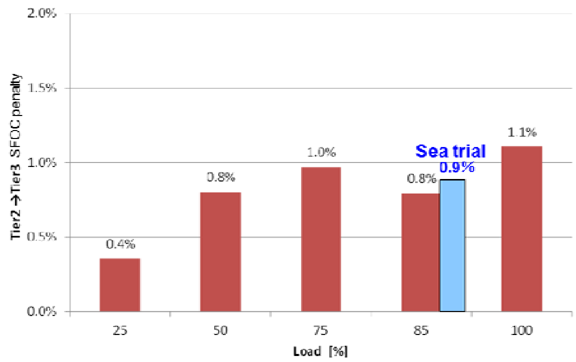

Fig. 18 Test results of FOC penalty.

And further, the SOx reduction performance of the compact sized LP-EGR unit with HFO is shown in Fig. 19. We confirmed that sufficient performance was as designed.

Furthermore, we also confirmed that the WTS was working properly with attendance of ClassNK surveyor.

Consequently, our LP-EGR system was objectively verified to have adequate performance and reliability as designed.

5.4 Long term On-Board Verification

After the vessel delivery, we continue to conduct on-board verification tests. To date, we have optimized some operating parameters and confirmed the durability of EGR components and experienced over 400 hours EGR operation. Results of inspection check are shown in Figs. 20-23, these are considered to be in good condition.

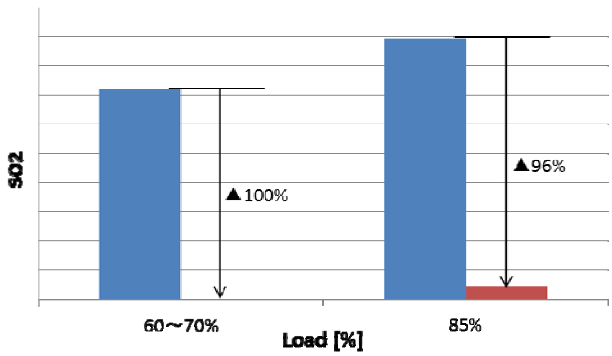

Fig. 19 SOx reduction performance of EGR unit.

Fig. 20 Piston ring.

Fig. 21 Cylinder liner.

Fig. 22 Turbocharger compressor wheel.

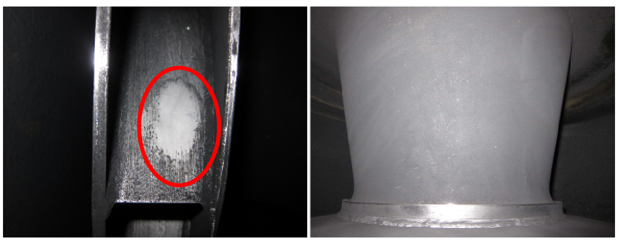

Fig. 23 EGR blower (circle: easy to wipe off the soot).

6. Future Perspective

Now we are executing further optimizing the entire EGR system and confirming its long-term durability. By using the achieved results and acquired knowledge, we will brush-up our whole LP-EGR system with the aim of impending business.

And furthermore, we plan to adopt our unique and superior technology of the LP-EGR system into not only UE engines but also other licensed engines owing to its simplicity and easiness to combine.

7. Conclusions

Mitsubishi developed a unique LP-EGR system that has sufficient performance for complying with IMO's NOx Tier III regulations. We achieve and come to the below conclusions.

(1) Mitsubishi's LP-EGR system has many merits which are simple system, simple operation, small CAPEX and small OPEX.

(2) We confirmed that above merits were realized by using an actual engine and vessel adopted the LP-EGR system on-board.

(3) Mitsubishi's LP-EGR system will be applied into not only UE engines but also other licensed engines in the near future because of its simplicity and easiness to combine.

Therefore, LP-EGR is the best solution for IMO NOx Tier III.

Because of global demand for low emission and high efficiency simultaneously, Mitsubishi continues to further develop and spread widely technologies, in an effort to contribute to global environmental conservation.

Acknowledgements

This Low Pressure EGR system was developed under the ClassNK's "Joint R&D for Industry Program" scheme.

Abbreviations

CAPEX: CAPital EXpenditure

CARB: California Air Resources Board
CFD: Computational Fluid Dynamics
ETM: Exhaust gas cleaning system Technical Manual
HFO: Heavy Fuel Oil
MDO: Marine Diesel Oil
NOx: Nitrogen Oxides
NR: Normal Rating
OMM: Onboard Monitoring Manual
OPEX: OPerating EXpense
PAH: Polycyclic Aromatic Hydrocarbon
SOx: Sulfur Oxides

References

[1] Revised MARPOL Annex VI, Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code 2008, International Maritime Organization, London, 2009.

[2] A. Miyanagi, K. Watanabe and J. Yanagi, Exhaust emission control of Mitsubishi UE diesel engine, in: *26th CIMAC World Congress Bergen*, 2010, paper No. 299.

[3] T. Ueda, K. Ito, J. Yanagi and N. Hiraoka, Development of exhaust gas recirculation system for exhaust gas emission control of Mitsubishi UE diesel engine, in: *Proc. of ISME Harbin*, PID: 129, 2014.

[4] N. Hiraoka, T. Ueda, T. Nakagawa and K. Ito, Development of low pressure exhaust gas recirculation system for Mitsubishi UE diesel engine, in: *28th CIMAC World Congress Helsinki*, 2016, paper No. 142.

[5] N. Hiraoka and K. Imanaka, Exhaust emission control of Mitsubishi UE diesel engine, in: *27th CIMAC World Congress Shanghai*, 2013, paper No. 418.

[6] J. Kaltoft and M. Preem, Development of integrated EGR system for two-stroke diesel engine, in: *27th CIMAC World Congress Shanghai*, 2013, paper No. 219.

[7] M. Sugihara, K. Edo and T. Tanida, Creating a whole range of benefits with the Mitsubishi UEC eco-engine, in: *25th CIMAC World Congress Vienna*, 2007, paper No. 75.

[8] MEPC. 184 (59), Guidelines for exhaust gas cleaning systems, 2009.