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The Latest Technologies of NOx Emission Control for UE Engines

4 - Emission Reduction Technologies - What's in Store for the Future

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ABSTRACT

UE diesel engines feature high economic efficiency, high reliability, and environment-friendliness. High economic performance of the UE diesel engine can give solutions to save ship owners operating costs and achieve long-term safe operation. UE diesel engines have been developed and improved for more than half a century, adapted more strict environmental regulations and market needs. IMO NOx Tier III regulation which provides the reduction of the NOx emission by approximately 76% compared to the Tier II regulation within ECA (Emission Control Area) have been applied to ships keel laid on or after 1 January 2016. To comply with IMO Tier III regulation, we have developed exhaust emission reduction technology the Low Pressure Selective Catalytic Reduction (LP-SCR) and the Low Pressure Exhaust Gas Recirculation (LP-EGR) because of its drastic NOx reduction possibility. LP-SCR is an after-treatment technology which react exhaust gas after turbocharger. Those systems treat low pressure exhaust gas downstream of turbocharger, are so called low pressure system. By treat the exhaust gas after the turbocharger, it can be separated from the engine operation. However, engine exhaust gas temperatures are low, optimization of engine tuning is necessary to efficiently perform SCR operation. Also, regarding the catalyst important for SCR, we have determined our optimum amount through durability tests and built our SCR system. Then, we have supplied SCR for commercial engine with optimization of engine tuning and confirmed that it satisfies NOx Tier III regulation. LP-EGR is a technology which NOx emission is reduced by changing combustion condition inside an engine, by means of recirculating a part of low pressure exhaust gas emitted from an engine turbocharger outlet to a turbocharger intake after scrubbed by EGR scrubber. In EGR scrubber, wash water is used to clean exhaust gas then re-use after treatment for saving water. Water treatment means removal of soot from wash water and prevention of an increase in specific gravity due to neutralization. As a result of soot removal and specific gravity control, residual water is separated from washing water. Residual water needs to be processed as industrial waste in compliance with regulations. In this way, not only complying with NOx regulation, but also the treatment of washing water is necessary. In order to adapt to the regulations, we had applied integrated on-engine LP-EGR system into a commercial engine 6UEC45LSE-Eco-B2 aiming for on-board endurance test based on experience with the test engine. As a result of its test, we confirmed its NOx emission level was complied with IMO Tier III regulation in witness whereof the ClassNK and the increase of fuel oil consumption was less than approximately 1%. Furthermore, we had installed the system into a 34,000DWT Bulk Carrier and conducted a long-term durability confirmation during the commercial voyages. Result of on-board verification, we could confirm reliability of the LP-EGR system. We fed back the result of on-board verification and improved LP-EGR system for UE engine as simple solution. For example, simplification of water treatment system and optimization of residue and waste water handling. We introduce these latest concept and technologies.

1 INTRODUCTION

Regulations for preventing air pollution from ships are being further tightened up. As for the regulations on low speed marine diesel engines of the International Maritime Organization (IMO), the International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted at IMO for the purpose of the prevention of pollution of the marine environment by ships. MARPOL Annex VI entered 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 II regulations are applied to ships keel laid on or after 1 January 2011. Tier III regulations, which provide for a reduction of NOx emissions by approximately 76% compared to Tier II regulations. Tier III regulation was already valid within North American ECA (Emission Control Area), being applied to ships keel laid on or after 1 January 2016. In addition Baltic Sea and the North Sea ECA are going to apply to ships keel laid on or after 1 January 2021. As for the sulfur content in fuel, there are also two regulations. Since 2015, sulfur content in fuel has to be below 0.1% in ECAs, while, in the global area, it will have to be restricted below 0.5% after 2020. It is necessary not only to satisfy the NOx regulation but also to conform to rules that may be modified year by year. Figure 1 shows regulations map. To comply with the IMO Tier III regulations, Japan Engine Corporation (J-ENG) has developed Low Pressure Exhaust Gas Recirculation (LP-EGR) technology and Low Pressure Selective Catalyst Reduction (LP-SCR) technology as exhaust emission reduction technologies because of their drastic NOx reduction possibility for J-ENG's "UE-Engine" (2-stroke marine diesel engine). This paper especially introduces the LP-EGR's latest concept and technologies.

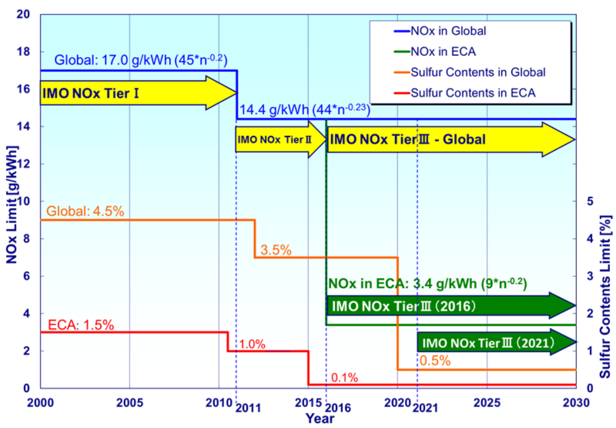

Figure 1. Emission regulations of IMO

2 NOX REDUCTION TECHNOLOGIES

2.1 OUTLINE OF LP-EGR SYSTEM

EGR technology has been adapted to many types of small and medium internal-combustion engines. In an engine equipped with EGR, a part of the exhaust gas is induced into the scavenging air or air intake, after that these gases are led to the combustion chamber. During the 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 is suppressed, as a result, the amount of thermal NOx emissions decreases. Figure 2 shows the principle of the EGR system.

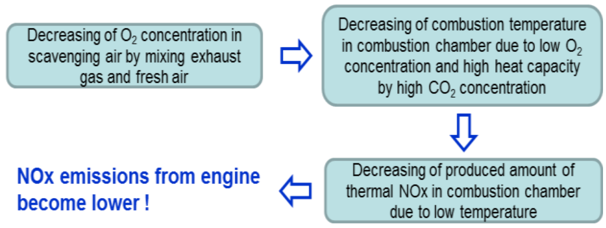

Figure 2. Principle of the EGR system

Generally EGR system is divided into two categories, Low Pressure loop EGR (LP-EGR) and High Pressure loop EGR (HP-EGR). Among the two categories, we developed LP-EGR for UE-Engine [1] [2]. This system was developed by our test engine, and verified through an on-board test. In the on-board verification test, the EGR operation was carried out for 860 hours and fully verified the performance and reliability. This paper introduces the results and developments to the latest engine. First, we will explain LP-EGR. LP-EGR system handles low pressure exhaust gas discharged from the turbocharger. Therefore, this method is generally called LP (Low-Pressure). Figure 3 shows outline of the LP-EGR system. A part of the exhaust gas is branched from the main flow downstream of a turbocharger turbine. After branched, those gases are washed and cleaned by scrubber, then led to the intake of the turbocharger, mixing evenly with fresh air.

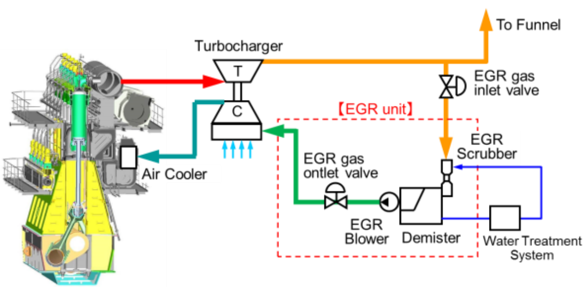

Figure 3. Outline of LP-EGR

In this system, the exhaust gas scrubbing system is a core technology. That is because, the usual marine diesel engines use MDO, MGO and so on in ECA, however the exhaust gas contains much soot and SOx. In addition, a large amount of gas is exhausted from marine diesel engines. If this exhaust gas is led into the engine without cleaning, we can easily imagine that a fatal failure will occur to the engine. Therefore, we have developed a new wet scrubber with high performance of soot and SOx removal by utilizing the technology of an Inert Gas Scrubber (IGS) system. This scrubber cleans gases using water, and the water is cleaned by the Water Treatment System (WTS) and re-used.

2.2 Water Treatment System

After cleaning by scrubber, EGR gas and water (scrubbing water) are separated in demister. Then, WTS collects scrubbing water. Continuing re-use of scrubbing water, it becomes black color by soot and its pH is decreased by sulfur, and the temperature increases by hot gas. To re-use scrubbing water, WTS needs to have soot removing and pH control, and cooling functions at least. The WTS consists of a centrifuge, pumps, tanks, a heat exchanger, valves and sensors as shown in Figure 4 (This WTS is a conventional type with overboard discharge function). Centrifuge can assuredly separate off soot from scrubbing water as shown in Figure 5. The after-treatment water (center of Figure 5) is clean and has transparency. Meanwhile, the residue is concentrated soot and oil; therefore it cannot be overboard. The residue must be landed and treated as industrial waste disposal.

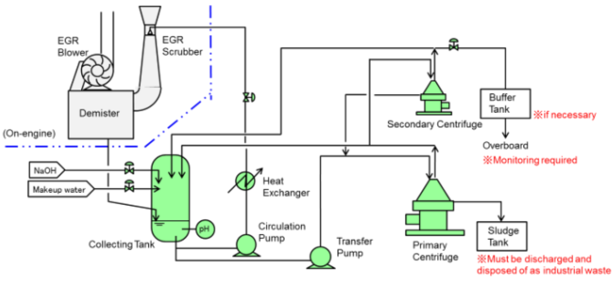

Figure 4. Outline of WTS

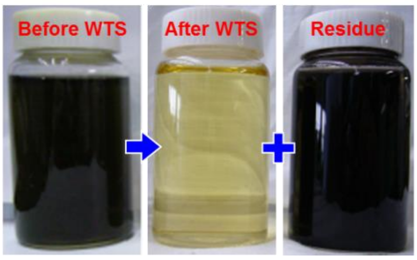

Figure 5. Before and after WTS

In addition, since the scrubbing water becomes an acidic liquid due to the sulfur content of fuel, it is necessary to control the pH by using alkali. Usually NaOH is used for neutralization. When neutralization is carried out, a salt (Na_2SO_4) is produced in scrubbing water. This salt increases the density of scrubbing water. Increasing the density may cause an increase in pump power and a decrease in centrifugal separation performance. Therefore, in addition to control pH, it is necessary to control density by discharging scrubbing water and replenishing fresh water. By using WTS with these functions, the EGR system can continue operation.

3 ON-BOARD VERIFICATION RESULT

3.1 LP-EGR Design for On-Board verification

We confirmed already that the LP-EGR had enough ability to comply with the IMO NOx Tier III regulations and minimize the FOC penalty substantially using 4UE-X3, a full scale test engine, then as the next step we decided to perform onboard verification tests. The target vessel was a 34,000DWT Bulk Carrier named “DREAM ISLAND”, built by The Hakodate Dock Co., Ltd, owned by; Shikishima Kisen K.K., and operated by NYK Bulk & Projects Carriers Ltd.

3.2 Entire system

The target engine was a 6UEC45LSE-Eco-B2 having a relatively small size bore; therefore it was assumed to be 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. Figure 6 shows EGR engine.

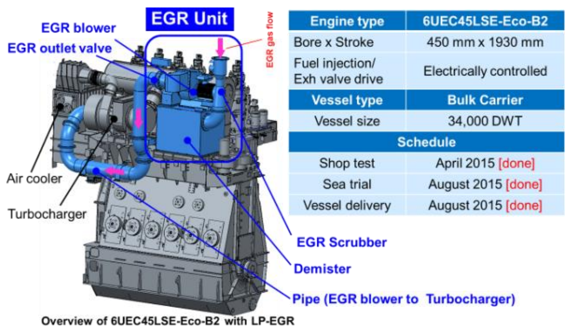

Figure 6. 6UEC45LSE-Eco-B2 with LP-EGR

3.3 Test result of the shop test

We manufactured all equipment for the LP-EGR of engine, conducted the shop test for confirmation of performance and control system check. Figure 7 shows an overview of the engine at work shop. The WTS is simplified and temporary facility for only the shop test since it is not necessary regular component for confirming NOx reduction performance.

In the control system check, the operation check with the EGR ON / OFF, the EGR rate control test with load up / down, and the EGR system shut down test were carried out. Regarding the EGR rate control test, it was confirmed that the EGR system controlled the optimum amount of EGR gas according to the engine load (see Figure 8). And regarding the emergency stop test, it was confirmed that after the EGR system emergency shut down, the engine continues to operate steadily (see Figure 9). In all the tests, we confirmed that the intended operation was carried out as planned. We also confirmed that satisfied Tier III limits.

Figure 7. Overview of the shop test

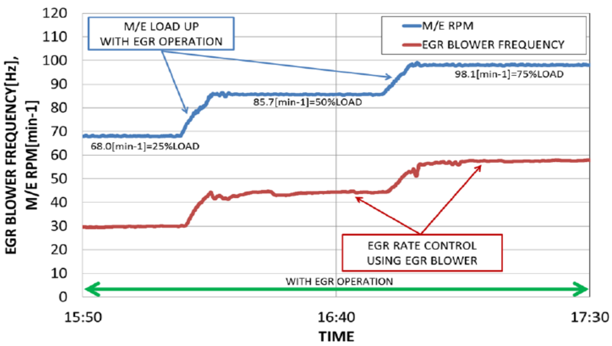

Figure 8. EGR system control test

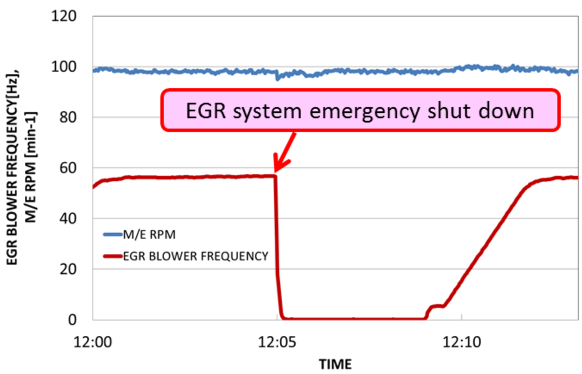

Figure 9. EGR system shut down test

3.4 Test result of the sea trial

After confirming the good performances in the shop test, we conducted the sea trial. Figure 10 shows an overview of the installed LP-EGR system including the WTS, despite relatively small size of the vessel, all system components are managed to arrange inside the engine room thanks to compactness.

In the sea trial, we tried to confirm control system check again. In addition, crash astern test, harbor test with EGR were demonstrated. In the crash astern test (see Figure 11), it was set to operate EGR even in astern. When crash operation was ordered, EGR system shifted to the standby mode, and the O_2 concentration of scavenging air was increased. After the engine speed was decreased to the set value, astern operation started normally. And we confirmed that EGR re-started automatically. The stoppage time was equivalent to that of without EGR.

Figure 10. Overview of the installed LP-EGR

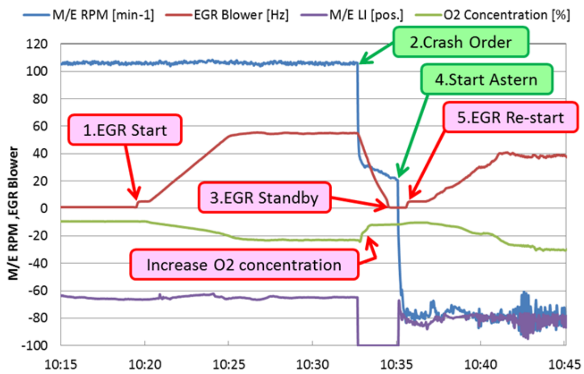

Figure 11. EGR crash astern test

3.5 Long term On-Board Verification

After the vessel delivery, we continued to monitor long-term onboard verification tests approximately for 860 hours. Some operating parameters were optimized and the long-term reliability of the EGR system and EGR dynamic performance during rough sea condition were verified. Details are as follows.

3.5.1 Long-term reliability

Long-term continuous operation was achieved without issuing alarm. Even before the stop, it was stable as a system, and it was evaluated that the system can operate without problems even for more hours. And it was confirmed that stable operation can also be performed for the main engine even in long-term operation as shown in Figure 12.

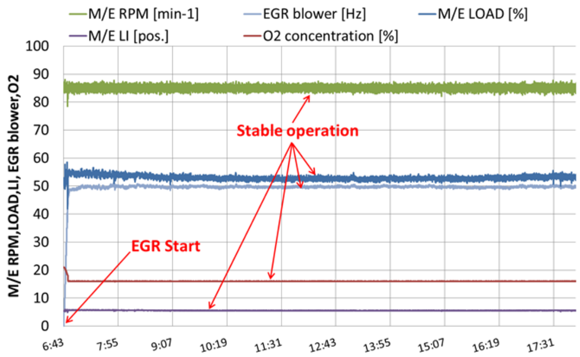

Figure 12. Stable operation

3.5.2 Dynamic performance

Under rough sea conditions, we confirmed that the EGR system operated following the load (speed) fluctuation of the engine and it was possible to operate without problems as shown in Figure 13.

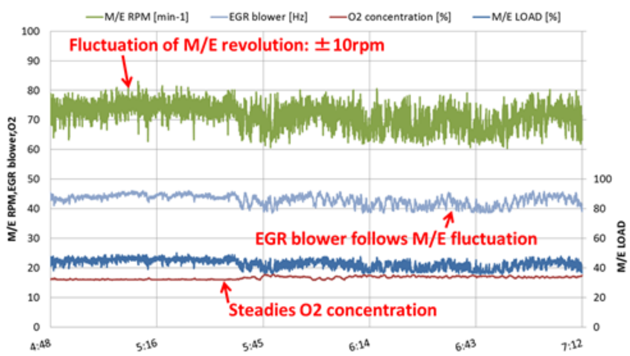

Figure 13. Dynamic performance

3.5.3 Reliability confirmation of engine parts

During the long term on-board verification, we confirmed not only the EGR system but also the reliability of the engine parts such as the combustion components. For cylinder liners and piston rings which were often observed in normal operation for confirm engine condition, we confirmed them to evaluate the effect of EGR operation on the combustion chamber. As a result, those parts were in good condition (see Figure 14 to 16). Furthermore, we confirmed that the sliding surface of the liner was in good condition without signs of corrosion (see Figure 17).

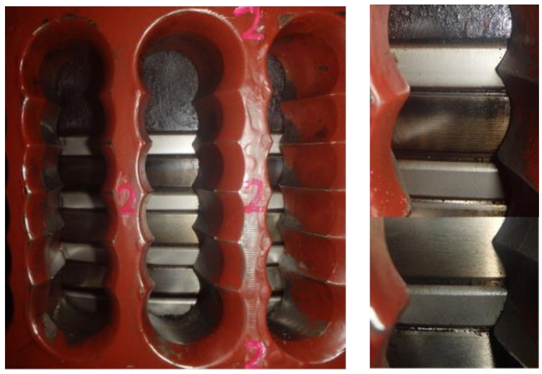

Figure 14. Inspection result of piston rings

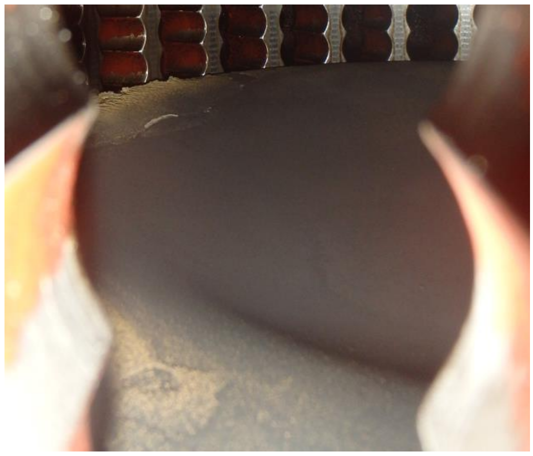

Figure 15. Inspection result of piston

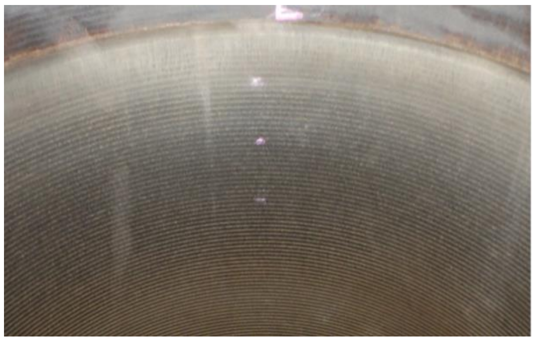

Figure 16. Inspection result of cylinder liner

Figure 17. Sliding surface of the liner

In case of LP-EGR system, the EGR gas is induced to the compressor of the turbocharger, therefore the ambient condition is different from the normal Tier II engine. EGR gas contains a small amount of soot after cleaned by scrubber and a small mist after captured by demister. There is a concern that corrosion or erosion will occur. Therefore, long-term reliability verification test by on-board and resistance test of compressor wheel material at laboratory were also carried out.

We have investigated applying a titanium alloy to compressor wheel, which material has a specific strength equivalent to that of aluminum alloy used for compressor wheel and high corrosion resistance. Firstly, we verified corrosion resistance and erosion resistance in the laboratory. The corrosion test was conducted for about 1000 hours in the immersion test simulating the EGR operating atmosphere when ECA compatible fuel is used. After the test, it was confirmed that corrosion did not occur protecting by a stable passive coating. In the erosion test, an acceleration test equivalent to 8500 hours of the EGR operation was carried out with simulating the EGR system (see Figure 18). The state of the surface after the test was very good as the machined surface traces were confirmed (see Figure 19). As a result, it was found that by applying the titanium alloy, it has corrosion resistance and erosion resistance even under EGR operation environment.

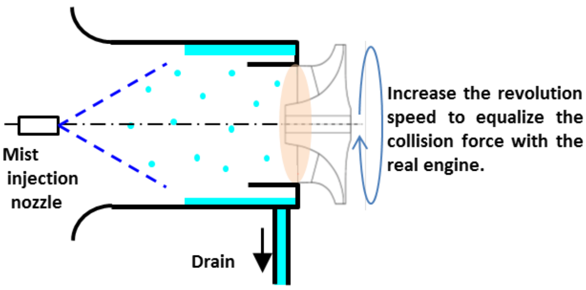

Figure 18. Method of erosion test

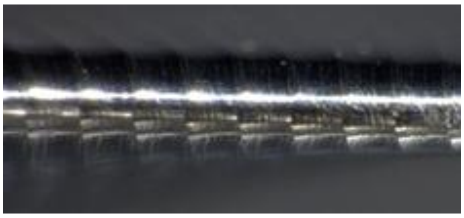

Figure 19. Result of erosion test
(surface of compressor)

After the laboratory test, the titanium alloy wheel was applied to the actual on-board engine and the long-term reliability verification was carried out. Verification operation for 200 hours was carried out, visual check and cutting inspection were carried out. In visual check of the compressor wheel, it was confirmed that slight soot contained in the EGR gas and salt derived from the scrubber water mist were slightly deposited, but it was in a good condition (see Figure 20 and 21). Also, there was no problem with the dynamic balancing. As a result of cutting inspection, it was finally confirmed that it had corrosion resistance and erosion resistance (see Figure 22). From the results as above, it was proved that reliability is secured by adopting titanium alloy for compressor wheel of LP-EGR system.

Figure 20. Compressor wheel after operation

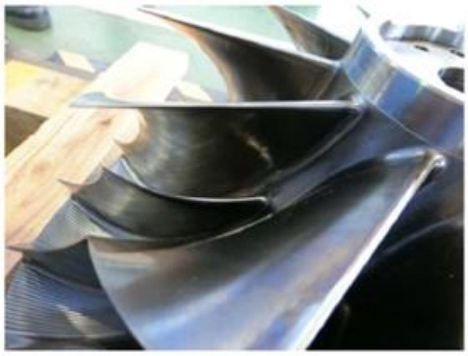

Figure 21. Compressor wheel after cleaning

Figure 22. Cutting surface of compressor

3.5.4 Reliability of LP-EGR system

In addition to the main parts of the engine, the LP-EGR system was inspected at the vessel's 1st dock. Inspection results are shown in below. (EGR operation time 860 hours)

EGR Gas Inlet Valve (EGIV)

The EGR gas inlet valve is also affected by the high temperature exhaust gas from the engine in addition to the EGR operation. We checked the valve after it was removed from the piping. Body had soot adhesion but it was in good condition, and also in the valve seat was in a good condition without noticeable scratch. (see Figure 23)

EGR scrubber

Venturi part of EGR scrubber cools and cleans the high-temperature exhaust gas. Therefore it may be affected by the influence of heat and corrosion by scrubbing water. Since stainless steel is used, there are no cracks and no corrosion on the welded part which proved that it was in sound condition (see Figure 24). And it could be applied with the selected material.

Demister

The demister is a device for separating the EGR gas and scrubbing water from venturi. And it has mist separator that made of stainless steel. It was in a good condition without clogging or corrosion of the separator. (see Figure 25)

EGR Blower

Since the EGR blower has a rotating part, not only the impeller part but also the bearing part was confirmed. There was no abnormality in both, and it was in a good condition. (see Figure 26)

EGR Gas Outlet Valve (EGOV)

This valve uses rubber type seat to completely separate the EGR system and the engine when EGR is not used. We checked the valve after it was removed from the piping. Visual inspection and hardness of the sheet surface were carried out, and it was confirmed that it was in good condition. (see Figure 27)

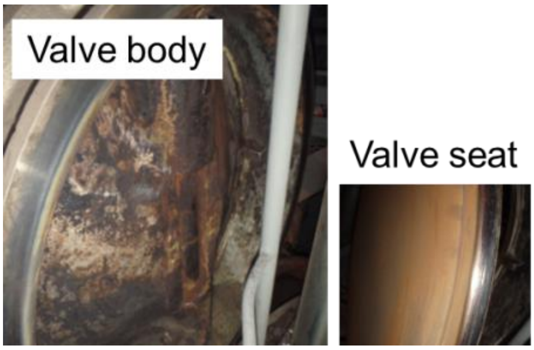

Figure 23. Inspection of EGIV

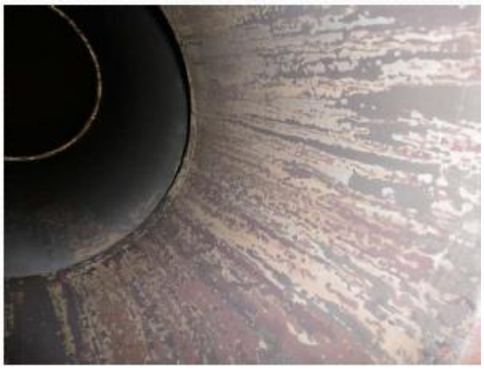

Figure 24. Inspection of venturi duct

Figure 25. Inspection of separator

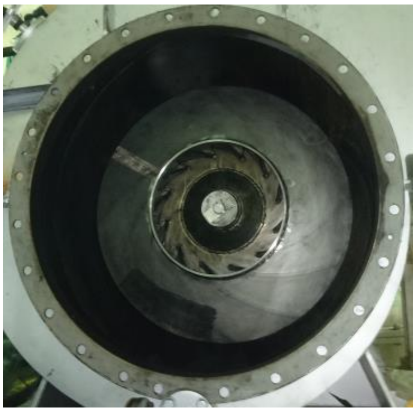

Figure 26. Inspection of EGR Blower impeller

Figure 27. Inspection of EGOV

4 FEEDBACK TO LATEST ENGINE

Using the results of LP-EGR system development and long-term reliability verification, we began to deploy to other engine models. During deployment design, we were conscious of not only the mounting property of the LP-EGR system in the engine, but also the improvement the flexibility of arrangement related equipment that will be placed inside the vessel. As our target engine, we chose UEC50LSJ-EGR engine which is our latest engine. The UEC50LSJ-EGR engine is an engine that is compatible with both SOx and NOx regulations, and has water injection system to reduce fuel for MGO mono-fuel.

4.1 Equipment

4.1.1 Compact EGR unit

First, we examined the compactification of the EGR unit mounted on the engine. The EGR unit (demister) was large because it has allowance for the amount of EGR gas that can through. We carried out optimization using verification results and established design method. The internal structure of demister was optimized by flow analysis as shown in Figure 28. As a result, we achieved compactness than before.

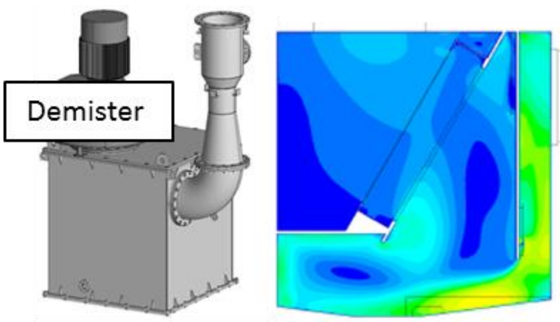

Figure 28. Internal flow analysis of demister

4.1.2 Minimize EGR gas outlet pipe

Since the EGR unit was compact, it has become easier to arrange it on the engine. And piping connecting the EGR unit to the turbocharger could be made as short as possible and it became possible to place it on the engine as shown in Figure 29.

4.1.3 Minimize WTS

Until now WTS was restricted to be installed under the demister. By arrangement a tank (SCWR) and a pump on the engine, the constraint was solved.

As mentioned in the previous chapter, WTS has several functions. Among them, the specific density control function needs to discharge scrubbing water out of the EGR system. For example, when discharging outside the vessel, it is necessary to satisfy the rule of Bleed-off water of EGR determined by MEPC 73. According to regulations, Bleed-off water is measured with an oil content sensor and it is necessary to satisfy that it is below 15 ppm. In addition, there are areas where it is impossible to bleed off depending on regional regulations, and when operating in that area it cannot be discharged outside the vessel, therefore it must be stored on the vessel. It is easy to think that this non-dischargeable area will be expanded in the future. Therefore, we decided to remove discharge system and to promote environmentally friendly concepts.

<u>Zero Bleed-off concept</u>

In the case of zero bleed-off, density control wastewater of scrubbing water discharged from the EGR system and residue after separated by the centrifuge are stored in the vessel's tank and all will discharge ashore is needed. Instead of discharge it to ashore, tank, pump and a piping system of the bleed-off water system become unnecessary. In addition, maintenance and management of emission monitoring sensors for Bleed-off water become unnecessary, and operation costs can be reduced. In addition, the WTS can be used only for cleaning the washing water solely for continuing the EGR operation. (see Figure 30)

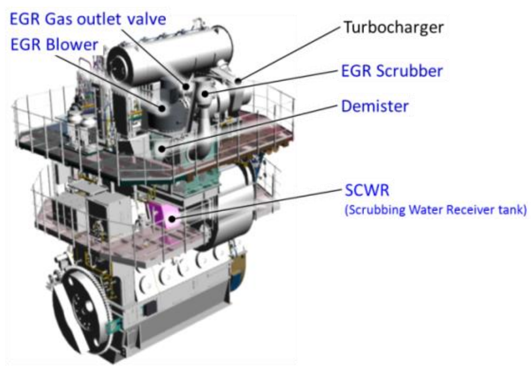

Figure 29. Outline of UEC50LSJ-EGR

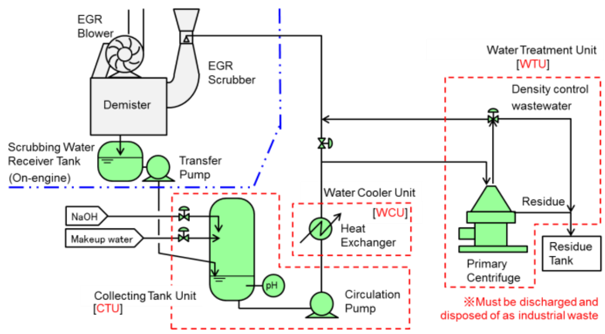

Figure 30. Outline of Zero bleed-off type WTS

Minimize wastewater and residue

Since it does not discharge to the outside of the vessel, it is necessary to reduce the generation amount of both. We plan it will be possible to reduce by implementing the following.

Density control wastewater is required to suppress the increase in density caused by neutralizing the sulfur content in the exhaust gas. Therefore, when the sulfur content of the fuel oil being used decreases, the amount of discharged water inevitably decreases. Since the increase in density is proportional to the sulfur concentration, if 0.1%S fuel is changed to 0.01%S fuel, the amount of density control wastewater can be reduced to 1/10.

On the other hand, the Residue discharged from the centrifuge depends on the amount of soot contained in the exhaust gas. Water-soluble sulfur changes depending on the concentration of sulfur in fuel, but since it is water-soluble, sulfate in exhaust gas does not affect the amount of residue. According to our previous test results, there is no difference in the amount of soot between MDO and HFO (see Figure 31). If light oil such as MGO is predominant in the future, we believe that it is possible to reduce residue, therefore we will continue to measure the amount of soot of various fuels.

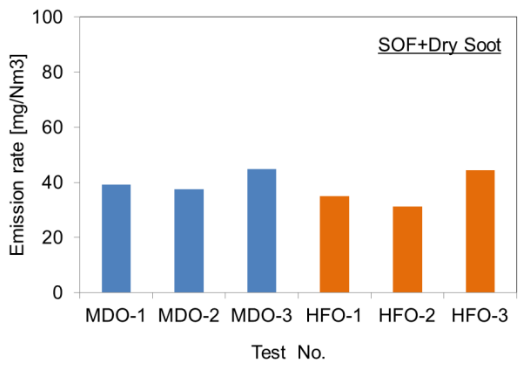

Figure 31. Soot measurement result

When the engine load is constant, the amount of insoluble matter such as soot entering the EGR system is assumed to be constant. Therefore, the amount entering the EGR system decreases when the engine load decreases. In the case of a centrifuge, when separating soot etc. from the scrubbing water used in the EGR scrubber, the amount of separated soot can be stored mechanically. Also, it is not stored in the space until it is filled up, but when it is stored up to a certain place, the scrubbing water and the soot in the inside of the centrifuge are discharged together, and it becomes a liquid type residue. When the engine load is high, soot accumulates quickly, and when the load is low, it accumulates slowly. Therefore, we thought that the timing of discharging the residue from the centrifuge was carried out with the engine load and timer. There is also a plan to control the discharge time while detecting the separation performance of the centrifugal separator with a sensor. However, it is considered necessary to maintain the sensor and it may be impossible to discharge when the sensor malfunctions. Therefore, it is considered that controlling by engine load and timer can minimize operation cost. When controlled by engine load and timer, amount of residue can be estimated. We also estimated the Density control wastewater when 0.1%S fuel is used, but since the residue also contained scrubbing water, the amount of density control wastewater is about 1/7 of residue. If the amount of residue can be increased slightly, there is a possibility that piping for discharging as density control wastewater apart from residue may be unnecessary. Residue amount is optimized through exhaust load test with engine load and timer.

5 FIRST 5UEC50LSJ-EGR

The first 5UEC50LSJ-EGR engine has a compact LP-EGR and water injection system applying stratified water injection technology, which had been developed in the past engine and this technology had been proved [3]. This engine was built at J-ENG factory in December 2018 (see Figure 32). This engine was developed under a support of The Nippon Foundation subsidy program. As for LP-EGR unit is installed on engine exhaust side (see Figure 33). And as for WTS, zero bleed-off water specification is adopted, installed on the side of the engine. (see Figure 34). Improvement on EGR control could not be described, but procedure of EGR operation starting become easier. After pushing the Tier III button, the engine switches to the EGR control mode in a few minutes, and the water treatment device is stated automatically (see Figure 35). Thus, it is very easy because it is only a one button operation.

Figure 32. First 5UEC50LSJ-EGR

Figure 33. LP-EGR unit

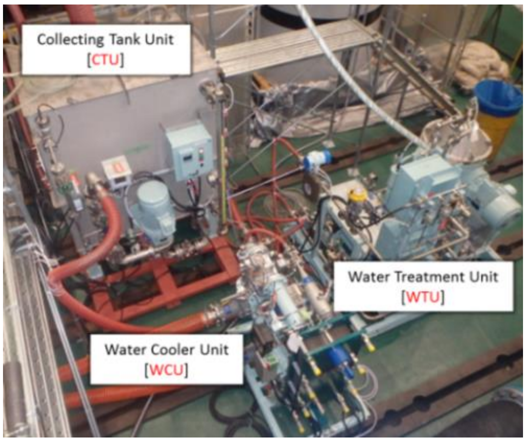

Figure 34. Zero bleed-off type WTS

Figure 35. EGR start selector

As for the verification test, in addition to the test of only LP-EGR which has been carried out before, we will verify the combination of water injection system and LP-EGR and optimize the parameters of each system by this engine.

First, the relationship test between the EGR rate and the NOx reduction rate was carried out. The results are as follows.

It is confirmed that the NOx reduction rate is equivalent to that of the LP-EGR engine without stratified water injection when the actual measurement result of the UEC50LSJ-EGR engine is plotted with the EGR rate on the horizontal axis and the NOx reduction ratio on the vertical axis (see Figure 36).

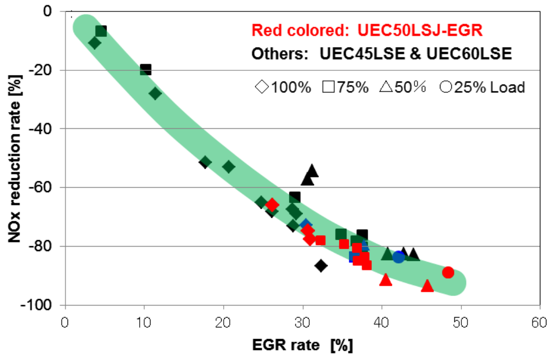

Figure 36. Result of NOx reduction rate

In an EGR operation that the O_2 concentration of scavenging air decreases, controlling smoke emission is a future task. Generally, water injection is said to contribute to the reduction of smoke emission. Since the UEC50LSJ-EGR engine is equipped with a water injection system, it is possible to improve discharge of smoke. By increasing the number of verification test cases, it is necessary to continue to evaluate the engine's total performance regarding NOx, smoke, fuel oil consumption and reliability.

6 CONCLUSIONS

J-ENG developed a unique LP-EGR system that has sufficient performance for complying with IMO's NOx Tier III regulations. And in long-term on-board verification, the reliability of LP-EGR equipment was proved. Using the reliability verification result and the established design method, we designed the compact EGR system for latest engine. As for the water treatment equipment system, it was possible to make it simple and compact without discharging to sea. In addition to the above results, we developed the latest engine with water injection system, and built in December 2018. The combination of EGR and water injection has a great potential. We will continue the verification test with this engine.

LP-EGR has completed the application design for all the latest engines of UEC45LSE-Eco-B2, UEC 50LSH-Eco-C2, UEC50LSJ, and UEC60LSE-Eco-A2. In addition, our order book is already piling up, and these engines will start commercial operation after 2020. This will prove performance and reliability, the advantages of LP-EGR for other systems, etc.

7 ABBREVIATIONS

HFO: Heavy Fuel Oil
MDO: Marine Diesel Oil
MGO: Marine Gas Oil
NOx: Nitrogen Oxides
SOx: Sulfur Oxides

8 ACKNOWLEDGEMENTS

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