Development of Selective Catalytic Reduction for Low-speed Marine Diesel Engines

- Super-clean Marine Diesel R&D Project for the IMO NOx Tier III Regulations -

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1. Introduction

In response to strengthened International Maritime Organization (IMO) regulations, the “Super-clean Marine Diesel” research and development project was initiated and overseen by Japan Marine Equipment Association and promoted by the Nippon Foundation, led by the Ministry of Land, Infrastructure, Transportation and Tourism. Mitsubishi Heavy Industries, Ltd. (MHI) and Akasaka Diesels Ltd. are participants in this project, which aims to develop selective catalytic reduction (SCR) for slow-speed diesel engines. We will complete a verification test for the first step of this project using a land test rig this September. This article provides an outline of our activities to date.

2. IMO Exhaust Gas Regulations

Air pollutant reductions from international ships and vessels have been actively discussed on the IMO stage since Norway first proposed discussions at the IMO 26th Marine Environment Protection Committee (MEPC26) meeting. A new protocol was adopted at the MARPOL73/78 session of the Conference of Parties in 1997, and its Appendix VI has been in effect since May 2005.

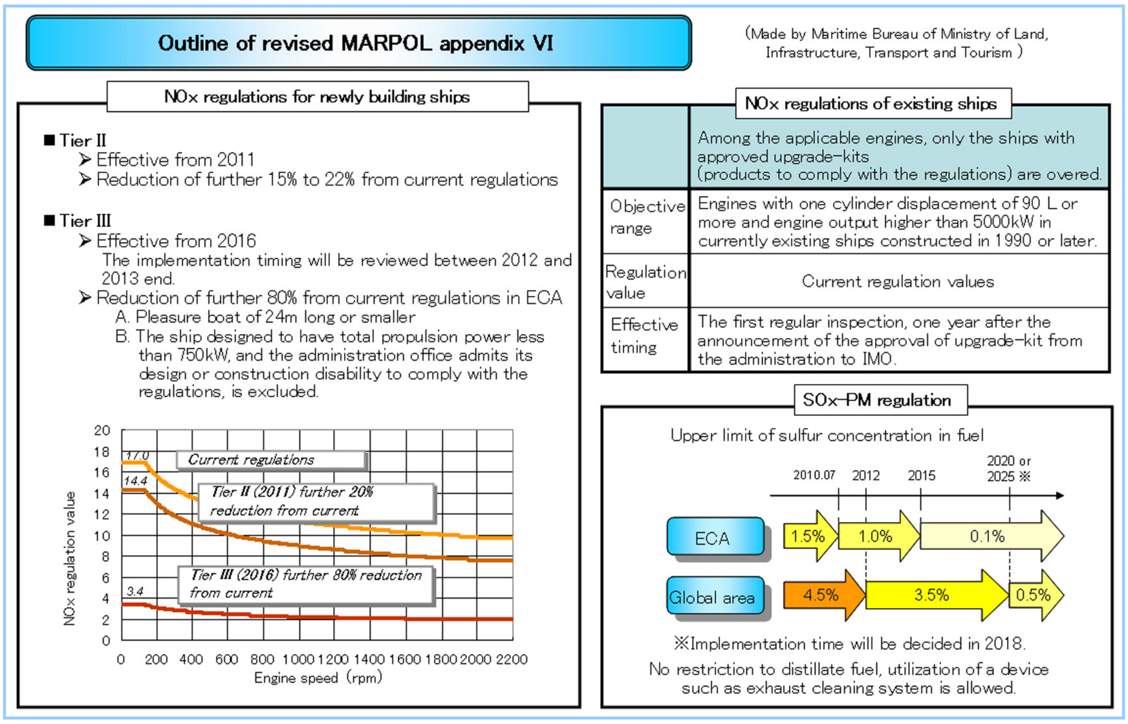

Figure 1 Exhaust gas regulations of the IMO

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As shown in **Figure 1**, the Appendix VI Revision, which requires more stringent regulations, was approved by the MEPC57 in 2008 and is effective from July 2010. The emission regulations include nitrogen oxide (NOx), sulfur oxide (SOx) and particulate matter (PM) exhausted from main diesel engines. SOx and PM will be implemented by sulfur content regulation for fuel.

NOx is mainly generated by combustion in the engine. It can be reduced to some extent by improving the combustion itself. However, in the IMO discussions, the introduction of an SCR system, which is already utilized in land facilities, has been considered, rather than consideration of smaller step-by-step improvements. In the Tier III NOx regulations of the Emission Control Area (ECA), which are expected to be in effect in 2016, NOx emission must be drastically reduced by 80% relative to the current Tier I regulations.

3. Outline of the Research and Development of Super-clean Marine Diesel Engines

In Europe, many SCR have been installed in midium-speed diesel engine ships due to political incentives in Sweden and other countries. Investigations have also been performed to install SCR systems in low-speed diesel engine ships.

Figure 2 shows an exhaust gas cleaning system using SCR. **Figure 3** shows the same type of honeycomb catalyst that was used in the present tests.

The most critical problem when installing an SCR system in a ship is the deterioration of the catalyst caused by the sulfur content in the fuel. The reducing agent ammonia reacts with the sulfur content in fuel at ambient temperatures below 300°C to produce ammonium hydrogen sulfate (NH_4HSO_4); this compound deposits on the catalyst surface and inhibits its performance. In Europe, the majority of engines that have adopted SCR systems have exhaust temperatures of 300°C or more and therefore do not suffer from this problem. However, low-speed diesel engines operate with exhaust temperatures below 300°C, and newer low-speed engines with remarkable performance levels have exhaust temperatures below 250°C. The lower exhaust temperature decreases the amount of heat rejection, increasing the engine efficiency and decreasing fuel consumption and carbon dioxide (CO_2) emissions. Consequently, the purpose of this project is to develop an SCR system compliant with the Tier III NOx regulations without impairing the high performance obtained with low exhaust temperatures.

Land plant SCR systems are used in favorable environments with low-sulfur-content fuel and high-temperature conditions to attain high SCR performance with no catalyst deterioration. In some cases, SCR systems have been installed in low-speed diesel engine ships, but they are located upstream of the turbocharger, where the exhaust temperature is high. In these cases, a bypass is implemented so that the SCR is only used under high-load stable voyage conditions to avoid the possibility of significant ship operating problems at low speeds or unstable loads. However, NOx emissions also need to be reduced for coastal voyages and for midium- to low-speed voyages in seas that are close to land. An SCR system with stable NOx reduction performance at low temperatures downstream of the turbocharger is required.

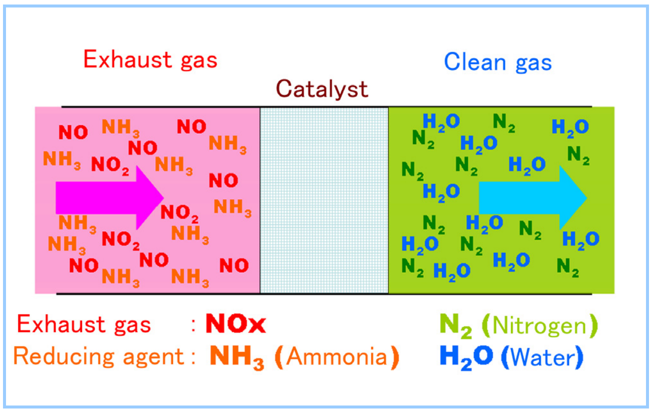

Figure 2 Exhaust gas purification with an SCR system

Courtesy of Sakai Chemical Industry Co., Ltd.

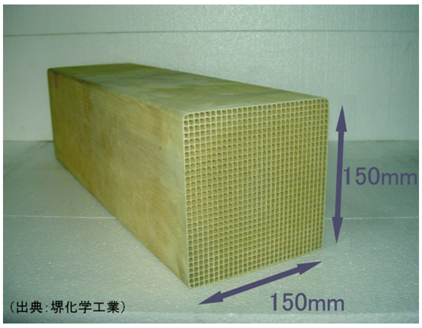

Figure 3 SCR honeycomb catalyst

4. Characteristics of an SCR with Low-temperature Exhaust Gas and Aqueous ammonia Injection for Low-speed Engines

One of the largest domestic test rigs for low-speed diesel engine Mitsubishi–Akasaka 3UEC37LA (1 103 kW, 188 rpm), owned by Tokyo University of Marine Science and Technology, was selected as our test rig. **Figures 4** and **5** show the denitration tests with full-flow exhaust gas at 100% load that were mainly conducted in fiscal year 2008. The exhaust temperature was adjusted by diluting the air, and NOx was measured at the SCR inlet and outlet to monitor the NOx removal efficiency. The fuel used for the test was marine diesel oil (MDO) fuel, which has sulfur content of 0.7%, reasonably obtainable and close to the planned 0.5%. The reducing agent was 25% aqueous ammonia, for which ample low-temperature denitration results are available. Aqueous ammonia provides a simple chemical reaction. The engine was operated for approximately 100 hours for each case, noting that the engine could only be operated during the daytime due to facility restrictions.

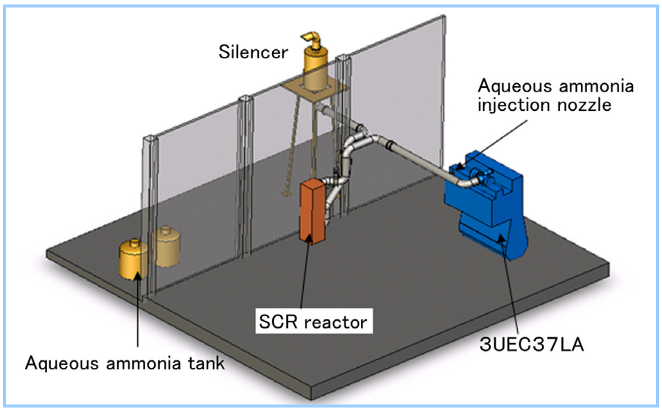

Figure 4 Test rig used in fiscal year 2008

Figure 5 Test rig photo from fiscal year 2008

In fiscal year 2009, the test rig was converted so that it had four small-flow branch lines of diesel engine exhaust gas, as shown in **Figures 6** and **7**, allowing four test results at a time and increasing the number of test cases. The same reducing agent was used, but the MDO fuel had a sulfur content of 0.07%. The exhaust gas conducted into the SCR system could be cooled with diluted air and heated with an electric heater, and the performance degradation caused by the exhaust gas temperature and catalyst deterioration was examined. Regeneration of the deteriorated catalyst was attempted by making use of elevated exhaust gas temperatures using the electric heater.

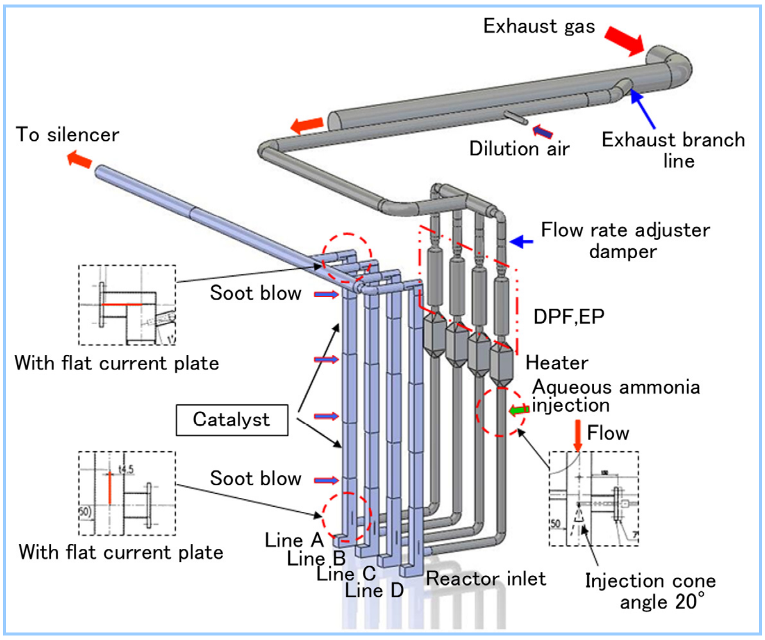

Figure 6 Test rig used in fiscal year 2009

Figure 7 Four line reactors

The exhaust gas measurements during the engine tests consisted of continuous monitoring of the CO, CO_2, and O_2 in addition to the NOx and ammonia to detect any leaks, and PM measurements to determine the effect of dust. The amount of dust stuck to the catalyst surface was rather high. The effects of a soot blower, diesel particulate filter (DPF), and electrostatic precipitator (EP) were verified.

An outdoor tank of aqueous ammonia was installed next to the test room, and facilities such as an absorption tank were used to treat the vapor. With these additions, the aqueous ammonia did not cause any problems due to leaks for the entire test period spanning approximately two years. Safety must be carefully evaluated before installing an aqueous ammonia supply in a ship. Our study demonstrated that few safety issues should arise if sufficient equipment is used.

5. SCR Verification Tests with the Engine at Tokyo University of Marine Science and Technology

In the fiscal year 2008 test, the denitration performance of the catalyst gradually decreased with operating time. The possibility of an uneven concentration of catalyst in the exhaust gas was considered because of the unexpectedly low denitration rate from the initial stages of the test and the analysis results of the catalyst. The exhaust gas flow was simulated, and the flow speed distribution control was tested with porous plates to ensure uniform distribution of the reducing agent on the catalyst surface in exhaust gas. With these countermeasures, the initial denitration rate was improved to some extent.

However, the flow control could not stop the degradation of catalyst performance caused by the sulfur content in the fuel. Class “A” heavy fuel with low sulfur content was used to verify this effect. Although the IMO Tier III NOx regulations do not refer to fuel limitations, the type of fuel will be limited within the ECA. SOx and PM regulations in ECA, which come into effect in 2015, state that the sulfur content in fuel must be 0.1% or less. If both regulations are considered, it is likely that fuel containing less than 0.1% sulfur will be used with an SCR system. Therefore, we decided to test MDO fuel with a sulfur content of 0.07% in fiscal year 2009. The test results showed a drastic improvement in the performance degrading speed, in contrast to our predictions, and the relationship with the sulfur content of the fuel was verified. **Figure 8** shows the difference in denitration performance according to fuel sulfur content.

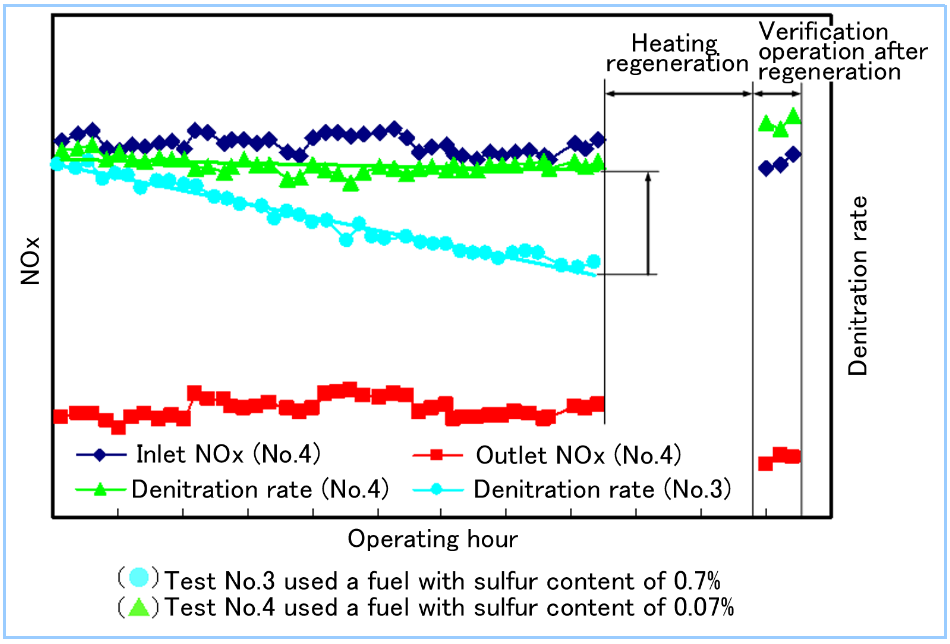

Figure 8 Denitration performance with fuel sulfur content

In fiscal year 2009, the denitration performance was examined for different temperatures. The tests also considered the catalyst regeneration effect due to heating and dust removal in the exhaust gas to reduce the amount of dust stuck to the catalyst. The optimum denitration conditions were considered.

With the use of 0.07% sulfur content fuel, the catalyst performance was improved, and the degrading trend of the catalyst denitration performance was not significant. As a result, the effect of changing conditions was small. The parallel test operation allowed more accurate comparisons of the test results and a better assessment of the denitration performance. A significant degradation of the denitration performance was not apparent after 100 hours of operation at an exhaust gas temperature of 250°C, making the possibility of denitration with an SCR system more realistic. Also, degraded catalyst was revitalized almost to the level of new catalyst performance by heating to a temperature of approximately 350°C. This heating regeneration can be done any time it is required, even while denitrating. **Figure 9** shows the heating regeneration test results. Evaluation of the catalyst durability of multiple regenerations has not yet been verified, and further tests are required.

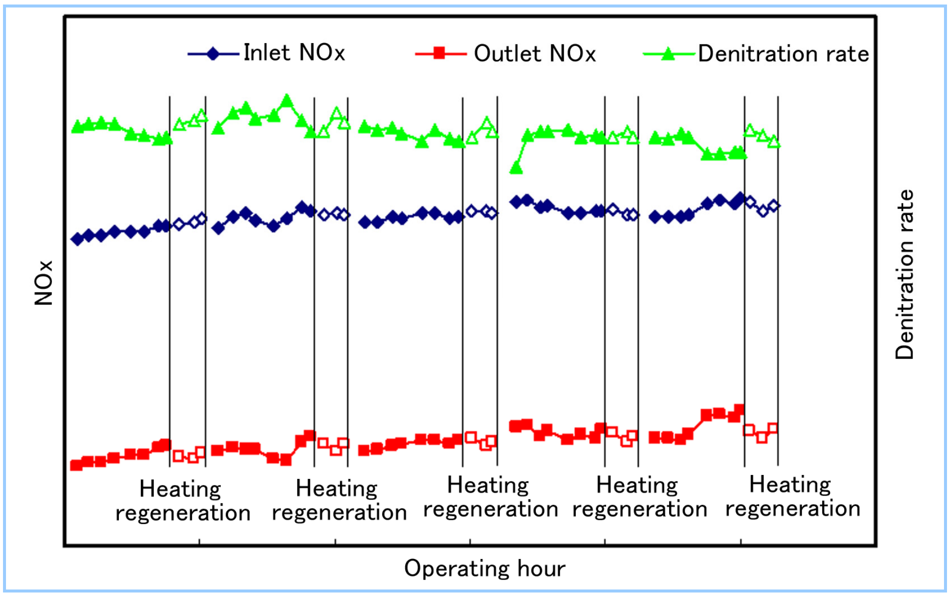

Figure 9 Test results after heating regeneration

6. Conclusion

The exhaust gas denitrating tests carried out in fiscal years 2008 and 2009 at Tokyo University of Marine Science and Technology were initially aimed at achieving a denitration rate of 80% using MDO fuel with 0.5% sulfur content. However, this target was changed to consider fuel with a sulfur content of less than 0.1%. At the start of this research, denitration at exhaust temperatures of 250°C was not possible, and the implementation of the test itself was thought to be significant. However, using fuel with a sulfur content of less than 0.1% enabled stable denitration performance at low exhaust temperatures.

This research and development project will now proceed to the second step, which consists of installing an SCR system in a ship with a low-speed diesel engine downstream of the turbocharger. Further investigation is needed to develop the regeneration method and ensure the durability of the system. The knowledge attained in this study will be utilized for future practical use.

This research and development project was overseen by Japan Marine Equipment Association and promoted by the Nippon Foundation. The participants were MHI and Akasaka Diesels, Ltd. The supply and analysis of the catalyst was assisted by Sakai Chemical Industry Co., Ltd. and the test engine was provided by Tokyo University of Marine Science and Technology for a long period of time. We would like to express our gratitude to these organizations and to the people who made this study possible.