Test Results of Marine SCR System for Large Diesel Engines during Long Term Service test

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The International Maritime Organization (IMO) has decided to implement a tighter limit for nitrogen oxide (NOx) emissions from ships operating in emission control areas (ECA) from 2016. Hitachi Zosen Corporation has developed a marine SCR system to denitrify exhaust gas of large two-stroke diesel engines in order to comply with the IMO regulation. Nippon Kaiji Kyokai issued a certificate attesting that certifies a large two-stroke diesel engine Hitachi-MAN B&W 6S46MC-C7 fitted with the SCR system achieved the NOx emission level required by the IMO regulation. The system was installed on a new-built vessel, and verification tests were carried out for a long period.

In this paper, we will present a summary of the marine SCR system, and report on sea trial results of the marine SCR system installed on the new-built vessel, as well as those of a similar SCR system installed on a multi-cylinder test diesel engine in order to solve technical issues encountered during long-term service test.

1. Introduction

In recent years, with growing interest in the preservation of the global environment, international efforts are under way to reduce air pollutant materials emitted from marine diesel engines. The IMO adopted the amendment to the MARPOL Annex VI and the NOx Technical Code in 2008, which requires greater reduction of NOx emissions. In accordance with this, the NOx emission regulation by the IMO has been strengthened stepwise as shown in Figure 1.

![Figure 1: NOx emission limits in accordance with IMO regulation](image)

Tier II regulation has been applied to ships constructed in and after 2011. The reduction ratio of NOx emission is 15-22% from Tier I, which was applied in and from 2000. Although Tier III is applied only in designated emission controlled areas (ECAs) in and from 2016, its reduction ratio is 80% from Tier I. The NOx emission limits for Tier I and Tier II respectively were achieved by minor changes such as optimization of atomizers or engine tuning. However, Tier III requires 80% NOx reduction, and this drastic reduction cannot be achieved only by such conventional techniques.

One of the techniques anticipated to contribute to meeting Tier III reduction is Selective Catalytic Reduction (SCR), which has been used successfully in stationary plant facilities and trucks. The authors, who have many years’ experience and knowledge obtained through catalytic denitrification for stationary plant facilities, started developing a marine SCR system in
collaboration with MAN Diesel & Turbo SE. Baba et al. have reported that a large two-stroke engine fitted with the SCR system achieved the NOx emission level for Tier III regulation in this development1), 2), 3).

This paper reports on sea trial results of the marine SCR system installed on a newly-built vessel and test results for a similar system installed in a multi-cylinder test diesel engine fitted on a test bed in order to solve technical issues experienced through long-term service tests on board.

2. Summary of the marine SCR system

The developed marine SCR system is composed of a vaporizer and an SCR reactor installed at the upstream side of a turbocharger (T/C) as shown in Figure 2.

Exhaust gas from the exhaust receiver is led to the vaporizer, where reducing agent is injected and vaporized. The gas mixed with the reducing agent enters the SCR reactor. The denitration reaction takes place, when the exhaust gas passes through the catalyst. The processed exhaust gas is led to the T/C, drives the turbine and is exhausted through the flue to the outside.

In general, the activation temperature of the denitration catalyst is 300 °C or more, and the exhaust gas temperature at the turbine inlet of marine two-stroke diesel engines is approximately 300 °C or more. Additionally, since the exhaust gas at the upstream side of the turbine is pressurized, this is expected to improve the catalyst activity. Thus, this system, which utilizes the high temperature and pressurized exhaust gas at turbine inlet, has the following advantages:

a) The high temperature in the SCR system is maintained above that of catalytic activity without any additional heating system;

b) Downsized catalyst volume and SCR system components due to the catalytic activity are improved under high pressure conditions

This system employs three butterfly valves (RSV, RTV, RBV; Figure 2). These valves are controlled to improve the response of scavenging air to engine load change. This system is equipped with a cylinder bypass valve (CBV), which reduces the amount of air going through the cylinders, to increase the exhaust gas temperature, because the exhaust gas temperature may otherwise be lower than that required for catalytic activity even at the turbine inlet when operating at low load.

The catalyst of the SCR system is shown in Figure 3. This catalyst is of Ti-V-based components impregnated into sheets of substrate and corrugated to form a honeycomb as shown in Figure 3. The SCR reactor can be downsized, as this catalyst is light and thin and has a large surface area per volume.
3. Shop test and sea trial results of the marine diesel engine installed to the new ship

3.1 Engine performance in the shop test

Prior to testing the developed marine SCR system onboard, the marine diesel engine (6S46MC-C7) equipped with the SCR system was built on a test bed at Hitachi Zosen Corporation simulating the intended layout of the engine room of the new-built ship as shown in Figure 4.

Confirmation tests on engine performance and denitration properties were conducted on the test bed. As a reference, the engine properties are shown in Table 1.

Denitration performance during SCR system operation is shown in Figure 5. The NOx regulation to be applied to the engine is Tier I of IMO. It can be seen that the NOx emission from the engine itself was 14.6g/kWh in weighted average of the E3 cycle values, which is lower than the Tier I limit. The NOx emission in the E3 cycle during SCR operation was 2.9g/kWh, which is low enough for the 3.4g/kWh limit for Tier III. It was also confirmed that the NOx emission values were below 3.4g/kWh at each engine load. In recognition of the fact that the SCR system showed the capability to reduce the NOx emission below the Tier III limit, a certificate was issued by Nippon Kaiji Kyokai (ClassNK) as shown in Figure 6.

Table 1: Property of the 6S46MC-C7 engine

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cylinders</td>
<td>6</td>
</tr>
<tr>
<td>Bore</td>
<td>460 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>1,932 mm</td>
</tr>
<tr>
<td>Output/Speed</td>
<td>6,780 kW × 111 rpm</td>
</tr>
</tbody>
</table>

Figure 4: Large two-stroke marine diesel engine 6S46MC-C7 equipped with SCR system
3.2 Sea trial

3.2.1 Layout of the SCR system in the engine room of the ship

An onboard service test was conducted to solve the practical problems regarding denitrification performance, maneuverability and maintenance in the ocean. Properties of the ship that the SCR system was installed in are shown in Table 2. The engine and the SCR system were arranged in the engine room as shown in Figure 7. It can be seen that enough space had been reserved taking into account easy maintenance of the engine and the SCR system.

<table>
<thead>
<tr>
<th>Name</th>
<th>Property of the ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Santa Vista</td>
</tr>
<tr>
<td>Type</td>
<td>General Cargo, 38000DWT</td>
</tr>
<tr>
<td>Operator</td>
<td>JX Shipping Co., Ltd</td>
</tr>
<tr>
<td>Builder</td>
<td>Naikai Zosen Corporation</td>
</tr>
<tr>
<td>Ship delivery</td>
<td>31 October 2011</td>
</tr>
<tr>
<td>Main engine</td>
<td>1×Hitachi-MAN B&amp;W 6S46MC-C7 (6,780 kW×111 rpm)</td>
</tr>
</tbody>
</table>
3.2.2 Engine performance and denitration performance on the sea trial

a) Engine performance

Engine performance is shown in Figure 8 for both conditions, one where the SCR system was in operation and the other where it was not operated (SCR-bypass operation). Since the SCR components were positioned at the inlet of the turbine in this system, the pressure loss was higher than with a system where the exhaust gas is led directly to the turbine (SCR-bypass operation). The influence of the compromised T/C efficiency on the engine performance, therefore, had been of concern. However, the engine performance was not very different between the SCR operation condition and the SCR-bypass operation condition, as shown in Figure 8. In addition, the exhaust gas temperature at the cylinder outlet was kept at around 300 °C, at which the catalytic denitration reaction is possible, by CBV, even at low load during SCR operation.

It can be seen that the exhaust gas temperature at T/C inlet during SCR operation was slightly higher than that during SCR bypass operation, whereas the engine performance, including scavenging pressure, T/C speed and cylinder outlet exhaust gas temperature was almost the same. This is thought to be explained by the decrease in exhaust gas flow caused by duct resistance in the SCR path.

Figure 8  Engine performance measured in the sea trial
b) Denitration performance

Figure 9 shows denitration performance during SCR operation with automatic control aiming at 80% denitration rate during the sea trial. It can be seen that the 80% denitration ratio was achieved for the range of engine loads: 25%, 50%, 75% and 100%. The E3 cycle value of NOx emission was 3.1 g/kWh, which is lower than the Tier III limit.

4. Challenges found through the onboard service test and solutions derived on a multi-cylinder test engine on a test bed

On the ship equipped with the SCR system, a long-term service test was conducted to ascertain reliability of the system and any change in the catalyst performance over time. The SCR system operated for 1896 hours at the denitration setting value for Tier III. In addition, when tested at 30% and at other denitration setting values, it also gave good results, i.e. that denitration was achieved in accordance with the set values and that no deterioration was seen in the catalyst activity.

However, the long-term service test revealed challenges that could not be anticipated from the shop tests. The next chapter describes these challenges and their solution derived through tests on a multi-cylinder test engine on a test bed. As a reference, properties of the test engine 4S50ME-T9 are shown in Table 3.

<table>
<thead>
<tr>
<th>Hitachi-MAN B&amp;W 4S50ME-T9</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Bore</td>
<td>500 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>2,214 mm</td>
</tr>
<tr>
<td>Output/ Speed</td>
<td>7,120 kW × 117 rpm</td>
</tr>
</tbody>
</table>

Although the 4S50ME-T9 differs from the 6S46MC-C7 in the number of cylinders and bore/stroke, the output and exhaust gas flow rate of both are similar. A similar SCR system was installed on the test engine in the same way as on the ship, i.e., with a horizontal vaporizer and a vertical reactor. The 4S50ME-T9 engine equipped with the SCR is shown in Figure 10.
4.1 Corrosion of SCR components

To confirm the mechanical robustness of the SCR system in the engine room, the ship was sailed with the SCR-bypass in operation during the first period of the service test. When the SCR system was inspected at the port after the first sailing, corrosion and deposits were found inside the vaporizer and reactor and on top of the catalyst blocks as shown in Figure 11.

This is thought to have been caused by leakage of exhaust gas from seating parts of the butterfly valves into the SCR system during the SCR-bypass operation. Since the sulfur content in the fuel oil was 3.15wt% when the corrosion occurred, it is thought that the exhaust gas contained a considerable amount of sulfur oxide (SOx). In addition, since the inside of the SCR system becomes cold during the SCR-bypass operation, it is thought that the dew point of sulfuric acid made corrosion more likely.

To solve this problem, the following countermeasures were proposed.

a) Change the material to be acid resistant,

b) Improve the sealing of the butterfly valves or

c) Prevent exhaust gas from leaking into the system.

In this paper, countermeasure c), which was applied to the ship, is reported. To prevent exhaust gas from leaking, air from the air injection nozzle, which is used for reducing agent injection, was fed to the SCR system to purge away the remaining exhaust gas. The result of this method is shown in Figure 12. RTV and RSV were closed to change the SCR operation to SCR-bypass operation at 12:07 to start the exhaust gas leakage test. It is thought that the SCR system was filled with exhaust gas, because NOx concentration was high before starting the test. By feeding the air to the system afterwards, the NOx concentration was decreased. It seems that the exhaust gas was purged away and prevented from leaking inside. The appearance of the reactor inlet after applying this method is shown in Figure 13. No corrosion or deposits, as illustrated in Figure 11, were found. At inspections of the SCR system at port after every sailing, no significant corrosion has been found since then.
4.2 Increasing pressure loss in the exhaust gas economizer (EGE)

In the onboard service test, when operating the SCR system at the denitration ratio for Tier III, the pressure loss in the EGE, which is installed at the outlet of the turbine, increased rapidly as shown in Figure 14. Inspection at a port showed deposits on the water tubes and interior walls of the EGE, as shown in Figure 15.

It was inferred that the increase in pressure loss was caused by the clogging of gas flow passages in the EGE. This phenomenon was thought to have been caused by leaking NH₃, which is a remaining part of NH₃ after the denitration reaction, while operating the SCR system, because no significant deposits were found after the SCR-bypass operation. In addition, chemical analysis showed that the deposits consisted mainly of carbon, which is thought to be from soot, but a lot of ammonia bisulfate (NH₄HSO₄) was also found in the deposits. NH₄HSO₄ is formed in the reaction between H₂O, SO₃ and NH₃. These materials are present in exhaust gas during SCR operation. To suppress deposits in the EGE, the following methods were considered as countermeasures:

a) Decreasing the incoming materials (soot, H₂O, SO₃ and NH₃) or
b) Thermal removal of the deposits
Considering method a), the amount of soot depends on combustion conditions and fuel properties, and the SO\(_3\) concentration depends on the sulfur content in the fuel. These depends on the ship's operator. The way to solve the problem of such deposits within the SCR system is, therefore, to decrease NH\(_3\) leakage. Method b) relies on a property of NH\(_4\)HSO\(_4\), which is that it decomposes at temperatures above 300 °C. As a method for heating deposits, heated exhaust gas was utilized in our study.

This paper reports on the effect of decreasing NH\(_3\) leakage concentration on the EGE deposits. Instead of the EGE used in the onboard service test, a small EGE (equipment of EGE) shown in Figure 16 was used in our test on test bed. The equipment of EGE was installed in a passage of exhaust gas diverging downstream of the turbine outlet of the test engine 4S50ME-T9.

![Figure 16](image)

**Figure 16** Equipment of exhaust gas economizer (EGE) on

The increasing rate of pressure loss in the equipment of EGE for various concentrations of NH\(_3\) leakage is shown in Figure 17. In this test, fuel containing 2.4% sulfur was used, and concentrations of NH\(_3\) leakage were tested in three conditions, i.e. 80, 10 and 5ppm. The SO\(_3\) concentration for the test condition of 5 ppm of NH\(_3\) leakage was lower than for those of the other test conditions, because the testing apparatus was changed.

![Figure 17](image)

**Figure 17** Increasing ratio of pressure loss in the equipment of EGE with various NH\(_3\) leakage

In the first test, in order to accelerate the deposits in the equipment of EGE, the 80 ppm of NH\(_3\) leakage condition was tested. As anticipated, the pressure loss in the equipment of EGE increased as sharply as that in the EGE in the service test. The appearance of the deposit is shown in Figure18.

Next, in order to see the effect of decreasing NH\(_3\) leakage concentration, the 10 ppm of NH\(_3\) leakage condition was tested. As shown in Figure 17, the increase in the rate of pressure loss was suppressed significantly. However, because the rate of increase was around 10% per 10 h, the pressure loss could double in 100 h (approximately 4 days).

The next test was to lower the NH\(_3\) concentration much more. NH\(_3\) leakage was decreased to 5 ppm, and the increasing ratio of pressure loss in the equipment of EGE was suppressed to 44% compared with that in the 10 ppm NH\(_3\) leakage condition. The appearance of the deposits in the 5 ppm NH\(_3\) leakage condition is shown in Figure19. The deposits were steady and thin.
Results confirmed that the rate of increase of the pressure loss in the equipment of EGE, and that deposits were suppressed by decreasing the concentration of NH₃ leakage. In addition, the concentration of the NH₃ leakage can be decreased by optimizing the catalytic volume. The authors have found the optimal catalytic volume to keep the EGE operating safely by using information from the above test results and experience with stationary plant facilities. In the future, it is hoped to carry out a service test onboard ship, in a condition in which catalytic volume is optimized.

5. Conclusion

The authors acquired the technical knowledge to design the marine SCR system and deal with resulting technical issues, from the onboard service tests and from tests on the test engine 4S50ME-T9 on a test bed. Since development for this equipment configuration of the SCR system has been nearly completed the authors will move on to organizing design and manufacture for mass production.

Development for long-term operation will be continued, and a compact SCR system with an integrated vaporizer and reactor will be considered to enhance the superiority of this system compared with other systems located downstream of turbine(s).
References

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3) T. Fujibayashi, S. Baba, H. Tanaka:
   Development of Marine SCR System for Large Two-Stroke Diesel Engines Complying with IMO NOx Tier III, 27th CIMAC World Congress 2013, Paper No. 29 (2013).