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Development of an aftertreatment system for an ammonia-fueled engine

Exhaust Gas Aftertreatment Solutions & CCS

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ABSTRACT

Marine engines using ammonia as carbon-free fuel are being developed to reduce greenhouse gas (GHG) emission. An SCR (selective catalytic reduction) system may be applied to the engine in order to reduce both NOx emission and unburned NH3 slip in the exhaust gas. Accordingly, the SCR system for the ammonia-fueled engine may be continuously operated in- and outside NOx Emission Control Areas. Furthermore, the SCR system should be compatible with both diesel and ammonia fuels powering the DF (dual-fuel) marine engine.

This paper is describing the development of the NOx SCR system for ammonia-fueled two-stroke and four-stroke engines from HD Hyundai Heavy Industries. A high-pressure SCR is applied to two-stroke ammonia engines, while a low-pressure SCR is applied to four-stroke ammonia engines, considering the required exhaust temperature for operating SCR systems. Catalyst types and specifications may be decided depending on the emission compositions of NOx and NH3 in the exhaust gas. Traditional SCR catalysts can simultaneously reduce NH3 and NOx when NH3 slip is lower than the NOx level. On the other hand, when NH3 slip is similar or higher than the NOx level, ammonia oxidation catalysts may be added downstream the SCR catalysts to remove remained NH3 slip. Reducing agent may be adjusted considering unburned NH3 slip levels, hence a reducing agent dosing and control system is required for responding to varying emission compositions depending on each engine load, operation conditions and circumstances.

HD Hyundai Heavy Industries is developing SCR systems for ammonia engines alongside ammonia-fueled engine development, focusing on catalysts and relevant equipment for the development of efficient and safety SCR systems considering emission characteristics of ammonia engines.

1 INTRODUCTION

In the maritime industry, ammonia has garnered significant attention as a key alternative fuel for achieving the International Maritime Organization's (IMO) goal of net-zero emissions by 2050. This interest stems from two key characteristics: firstly, ammonia does not emit carbon dioxide during combustion, and secondly, green ammonia produced using renewable energy can achieve near-zero lifecycle carbon emissions when accounting for production, transportation, and combustion processes.

However, during the combustion process in engines using ammonia as fuel, unburned ammonia, known as ammonia slip, is emitted in the exhaust gas. Due to its highly toxic and harmful properties, this ammonia slip must be removed. Consequently, aftertreatment devices such as Selective Catalytic Reduction (SCR) systems are essential for eliminating the ammonia slip. Notably, ammonia is already utilized as a reducing agent for NOx reduction in SCR systems, making it particularly well-suited for effective use in ammonia-fueled engines.

HD Hyundai Heavy Industries Engine & Machinery (hereinafter HHI-EMD) has its own developed NoNOx SCR for marine main engines and auxiliary engines. In 2023, we began developing NoNOx SCR for ammonia dual-fuel (DF) engines simultaneously with the development of ammonia-fueled engines. Unlike in the past, when aftertreatment devices were developed based on exhaust gas information from already commercialized engines, this time, SCR development is proceeding with assumed emission scenarios, as the exhaust gas composition from ammonia-fueled engines has yet to be finalized. In particular, an ammonia oxidation catalyst has been developed to prepare for cases where NH_3 concentrations are similar to or greater than NOx in the engine exhaust gas composition. Additionally, a reducing agent injection and control system has been developed to meet IMO NOx Tier III standards, considering variations of NOx and NH_3 slip emissions. Furthermore, safety designs have been incorporated considering the characteristics and risks of NH_3 gas.

Meanwhile, nitrous oxide (N_2O) may be produced during the combustion process when using ammonia fuel. N_2O is not a toxic or harmful emission but a greenhouse gas (GHG) with a Global Warming Potential 265 times over a 100-year period compared to that of CO_2 according to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Therefore, the N_2O emission should be minimized, and This is to be achieved by engine tuning because it is challenging to treat N_2O using catalytic aftertreatment systems given the typical exhaust gas temperatures of marine engines.

This paper introduces HHI-EMD's SCR technology for ammonia main engines and HiMSEN (auxiliary) engines. It also presents SCR test results conducted in conjunction with the HiMSEN ammonia engine, as well as the current status of initial ammonia engine projects incorporating SCR technology.

2 SCR TECHNOLOGY FOR AMMONIA FUELED ENGINE

2.1 The role and purpose of SCR for ammonia dual-fuel (DF) engine

Marine ammonia fueled engines are designed as dual-fuel engines, capable of operating on both diesel and ammonia. Consequently, the Selective Catalytic Reduction (SCR) systems for these engines must be engineered to function effectively in both diesel and ammonia operating modes.

In diesel operating mode, the SCR system isn’t operated in Tier II mode and is activated in Tier III mode. Its primary function is to reduce NOx emissions in the exhaust gas from Tier II to Tier III levels, achieving approximately 75-80% NOx reduction rate.

When operating in ammonia mode, the SCR system faces a more complex challenge. It must not only reduce NOx emissions but also mitigate unburned NH_3 slip in the exhaust gas. The necessity for continuous SCR operation in ammonia mode arises from the fact that unburned NH_3 slip occurs in both Tier II and Tier III operating modes.

The operational requirements for the SCR system in different modes can be summarized as illustrated in Table 1.

Table 1. SCR operation depending on engine running mode

Engine running mode	Typical SCR	Ammonia SCR
Diesel Tier II	Stop	Stop
Diesel Tier III	Run	Run
Gas (Ammonia) Tier II	Stop	Run
Gas (Ammonia) Tier III	Stop/Run[1]	Run

[1] SCR stops when the engine complies with Tier III NOx by itself (X-DF, HiMSEN). Otherwise, SCR runs (ME-GI).

The SCR system's role in ammonia DF engines is multifaceted and mode-dependent:

- In ammonia Tier II mode, the SCR primarily functions to reduce unburned NH_3 slip.
- In ammonia Tier III mode, the SCR performs not only reducing unburned NH_3 slip but also reducing NOx emissions to meet IMO NOx Tier III standards.

This operational profile distinguishes the SCR system for ammonia DF engines from conventional typical SCR systems that only activate in Tier III mode. Consequently, the SCR for ammonia DF engines experiences significantly higher usage rates and longer operational hours. This increased utilization underscores the critical importance of ensuring high durability and stability in these systems.

The NoNOx SCR has demonstrated its product viability in the market since its business inception in 2011. As shown in Table 2, it has achieved an impressive track record of over 6,000 units ordered. This extensive field experience indicates that the NoNOx SCR system is well-prepared to meet the challenges posed by ammonia DF engines.

Table 2. NoNOx SCR reference (Jan. 2025)

Engine type	SCR type	No. of reference
2-stroke engine	HP SCR	1,078
	LP SCR	146
4-stroke engine	LP SCR	5,132
Total		6,356

2.2 SCR principle for Ammonia fueled engine

The basic design and principle of the SCR system vary depending on the composition ratio of NOx and NH_3 in the exhaust gas.

The primary reactions occurring in the SCR catalyst are:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (1)$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \quad (2)$$

The chemical reaction mechanism for NOx reduction in SCR catalysts indicates that the stoichiometric ratio of NH_3 to NOx molecules is 1:1. This stoichiometric relationship enables a direct comparison of the concentration ratio using volume ppm units, as measured by emission analyzers.

As the emission composition ratio of ammonia engines is not yet finalized, this paper distinguishes between CASE 1 and CASE 2 to explain the differences.

2.2.1 CASE 1 (NOx > NH_3 slip)

CASE 1 is currently the most likely scenario, where in ammonia mode, NOx emission in the exhaust gas satisfies Tier II level by itself, and unburned NH_3 slip is lower than the NOx level. In this case, the objectives of reducing both NOx and NH_3 slip can be achieved by conventional SCR catalysts as shown in Figure 1.

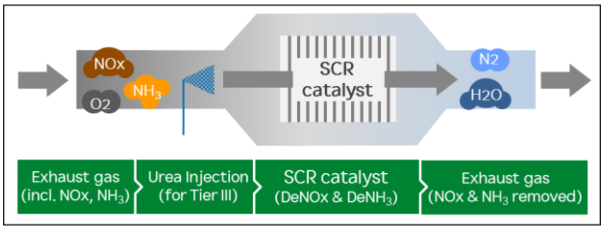

Figure 1. SCR principle in ammonia mode for CASE 1

In ammonia Tier II mode, as the exhaust gas passes through the SCR catalyst, unburned NH_3 slip reacts chemically with NOx, converting to H_2O and N_2. This SCR process requires a temperature of about 285°C or higher for SCR reaction and preventing ABS (Ammonium bi-sulfate) formation. Therefore, warming up of the SCR should be done by exhaust gas in diesel mode before changing to ammonia mode.

Since an NH_3 emission limit has not yet been established in the marine regulations, HHI-EMD has developed a target of less than 10 ppm NH_3 emissions after the SCR, considering the toxicity of NH_3.

In ammonia Tier III mode, 40% urea solution is injected as a reducing agent to meet IMO NOx Tier III standards while also reducing NH_3 slip. Since unburned NH_3 slip can act as a reducing agent, only the amount of urea solution necessary to meet Tier III standards should be injected. Precise control of the urea solution injection is crucial to prevent excess NH_3 emissions after SCR.

A feedback control system for reducing agent injection, related to NOx and/or NH_3 emission analyzer measurements, can be applied as one of the options for precise control due to variations in NOx and NH_3 slip emissions under different atmospheric and operating conditions.

2.2.2 CASE 2 (NOx ≤ NH_3 slip)

CASE 2 occurs when unburned NH3 slip emissions are similar to or greater than NOx levels. In this scenario, an Ammonia Oxidation Catalyst (AOC) is added downstream of the SCR catalyst, as the SCR catalyst alone cannot remove excess NH_3 slip as shown in Figure 2.

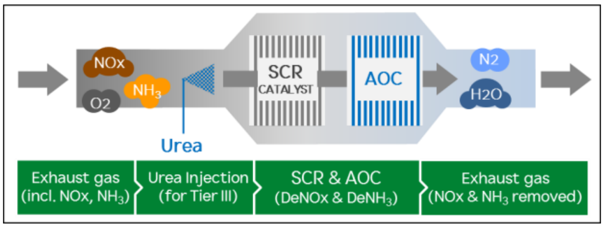

Figure 2. SCR principle in ammonia mode for CASE 2

The ammonia oxidation reactions occurring in the AOC are:

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O \quad (3)$$

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \quad (4)$$

The NH_3 removal mechanism in the AOC involves the oxidation of NH_3, which can also produce NOx. To allow the converted NOx to react with remaining NH_3, the AOC includes the reduction function of the SCR catalyst. Thus, the AOC has multiple functions, simultaneously reducing both NOx and NH_3.

When applying AOC, nitrous oxide (N_2O) is generated as a side reaction during the ammonia oxidation process. As N_2O is a greenhouse gas with a high Global Warming Potential (GWP), it is imperative to minimize this side reaction.

In ammonia Tier II mode, exhaust gas first passes through the SCR catalyst, where NOx and unburned NH_3 slip react together according to the chemical reaction mechanism of the SCR catalyst. Most of the NOx is removed, and any NH_3 exceeding the NOx level remains after passing through the SCR catalyst. The remaining NH_3 emission is then removed by the AOC catalyst placed downstream of the SCR catalyst.

Ammonia Tier III mode is similar to Tier II mode, with no need for additional reducing agent injection due to the sufficient presence of unburned NH_3 slip in the exhaust gas. However, a reducing agent injection system is still required for diesel Tier III mode operation.

2.3 SCR components for the ammonia DF engines

HHI-EMD has designed the SCR for the initial ammonia projects to cover both CASE 1 and CASE 2 scenarios. This approach was necessary due to the project timeline and manufacturing period, as the exhaust gas information and emission data for ammonia engines were not yet finalized. While the components of the ammonia SCR are similar to those of the conventional diesel engine SCR as shown in Figure 3, there are some differences in specifications of each component.

Considering the exhaust gas temperature required for SCR reactions, HP (High Pressure) SCR is applied to the main engine, while LP (Low Pressure) SCR is used for the auxiliary engine (HiMSEN) in the initial ammonia projects.

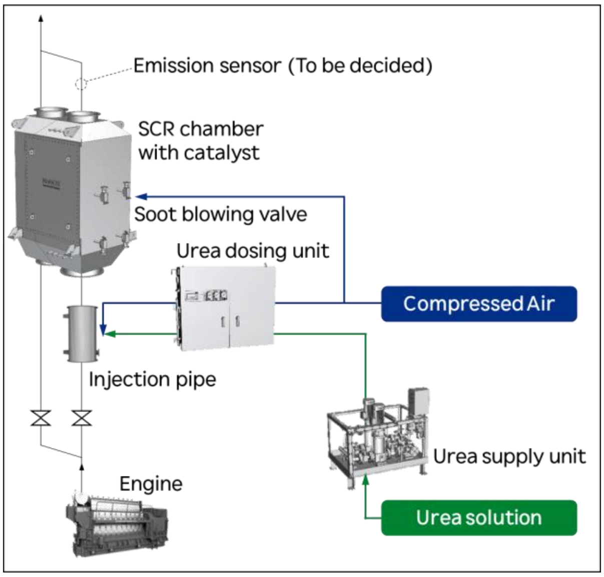

Figure 3. LP SCR system configuration for HiMSEN ammonia DF engines (Preliminary)

2.3.1 SCR chamber with catalysts

The main characteristics of SCR chamber for ammonia engines are:

- The SCR chamber includes an additional spare catalyst layer to potential addition of AOC. The SCR chamber specifications may be subject to change based on finalized engine exhaust gas emission data.
- Spiral wound gaskets with enhanced sealing capabilities are used to prevent ammonia exhaust gas leakage at flange connections.
- Caution plates are installed, advising the use of ammonia detectors to check for residual NH_3 emissions before opening the chamber manhole cover for catalyst replacement.

2.3.2 Urea dosing system

The urea dosing system consists of a urea supply unit, urea dosing unit, urea injection nozzle, and injection pipe (including mixer).

Compared to conventional typical SCR, the ammonia SCR differs in some components of the urea dosing unit and urea injection nozzle. To account for unburned NH_3 slip in the exhaust gas, urea flow control valves, flowmeters, and injection nozzles with higher turn-down ratios are employed. These changes do not affect the overall dimensions of these components.

For reference, the reducing agent currently used in the injection system for ammonia SCR is the same 40% urea solution used in conventional SCR systems. Under current classification society regulations, ammonia cannot yet be used as a reducing agent. Considering the toxicity and risks associated with ammonia, it is necessary to use the easily handled and safer 40% urea solution. However, a reducing agent supply system that directly uses ammonia is under development. This system is expected to be implemented in the future when the application of ammonia DF engines on ships matures and when safety in handling ammonia can be ensured in compliance with classification society regulations.

2.3.3 SCR control system

The SCR control system for ammonia DF engines includes the following modifications and additions to the internal control logic:

- Control functions for various operating mode changes (e.g., diesel Tier II ↔ ammonia Tier II, diesel Tier III ↔ ammonia Tier III, etc.)
- Safety controls for abnormal engine conditions such as ammonia misfiring and trip
- Integrated control for SCR warm-up in diesel mode and monitoring of required temperature satisfaction for ammonia mode operation
- Potential addition of urea dosing control with emission sensor (NOx and/or NH_3) feedback to account for variations in NOx and unburned NH_3 slip under different atmospheric and engine operating conditions

2.3.4 Emission sensors (NOx and/or NH_3)

Currently, NOx or NH_3 emission sensors are optional rather than mandatory. These sensors can be used to monitor emissions before / after the SCR or to adjust a reducing agent consumption as mentioned in Section 2.2.1.

For NOx emission sensors, zirconia type which is widely used in the market, is limited in application for ammonia engines due to potential errors of NOx measurement caused by NH_3 interference. IR or UV type sensors are expected to be applicable.

NH_3 emission sensors are currently scarce in the market, but IR or UV types are anticipated for future applications for ammonia engines.

3 PERFORMANCE & VERIFICATION

3.1 SCR test facility with HiMSEN ammonia DF engine

In 2024, HHI-EMD established and conducted tests on a full-scale SCR test facility in conjunction with a HiMSEN ammonia DF engine (6H22CDF-LA) within their engine test center.

These tests were instrumental in verifying the SCR system's performance when integrated with the HiMSEN ammonia DF engine.

3.2 SCR performance test results

In ammonia mode, engine emissions upstream of the SCR system exhibited NOx levels below IMO Tier II standards, while NH_3 slip was lower than the NOx emissions. This scenario corresponds to CASE 1 described in Section 2.2.1, suggesting that an Ammonia Oxidation Catalyst (AOC) is not required. As illustrated in Figure 5, the SCR system effectively reduced NH_3 emissions to nearly 0 ppm.

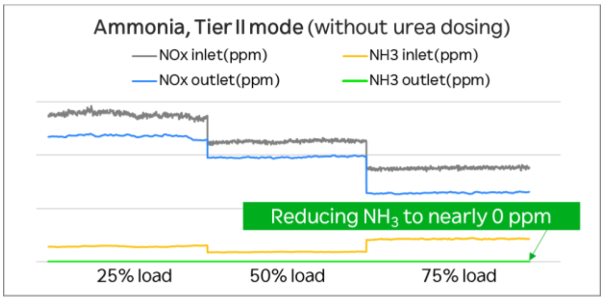

Figure 5. SCR performance test result with 6H22CDF-LA

To prepare for Case 2 scenarios, additional tests were conducted to simulate excessive NH_3 slip conditions by injecting extra urea solution, thereby verifying AOC performance as shown in Figure 6. The test results showed the following differences with and without AOC.

- SCR catalyst only (without AOC):

When the NH_3 slip to NOx ratio upstream of the SCR was below 1, NH_3 emissions downstream of the SCR were near to 0 ppm or below 10 ppm. However, as this ratio exceeded 1, a sharp increase in NH_3 emissions was observed. To ensure catalyst lifetime and continuously stable SCR operation, it is recommended that the NH_3 to NOx ratio upstream of the SCR be kept at 0.8 or lower.

- With both SCR and AOC catalysts:

The integration of the AOC catalyst demonstrated improved NH_3 reduction performance. Even when the NH_3 slip to NOx ratio surpassed 1, NH_3 emissions downstream of the SCR remained below 10 ppm, up to the designed capacity of the AOC catalyst.

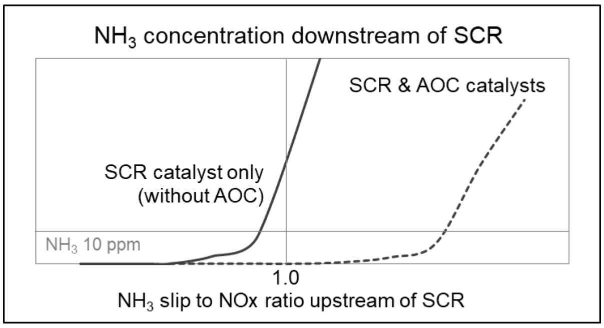

Figure 6. SCR test result with and without AOC

These results align with the predicted performance based on the intended design of both the SCR and AOC catalysts.

In conclusion, as mentioned in Section 2.2.1, considering the actual emissions from marine ammonia engines, it is anticipated that SCR systems will be designed based on Case 1 criteria, without the need for AOC. However, AOC technology retains potential for future applications in fields where extreme minimization of NH_3 emissions becomes necessary.

4 CONCLUSION

This paper introduces the principles, technology, components, and performance verification results of HHI-EMD's NoNOx SCR system for ammonia DF engines. HHI-EMD developed the SCR system concurrently with both main (2-stroke) and auxiliary (4-stroke) DF engines.

For the ammonia DF auxiliary engine (HiMSEN), the world's first Type Approval Test (TAT) for an auxiliary ammonia DF engine was conducted in October 2024, with results as described in Section 3.1.

Regarding ammonia DF main engines, the following milestones are scheduled:

- WinGD, 6X52DF-A with HP SCR: Factory Acceptance Test (FAT) according to scheme A procedure is planned for the second quarter of 2025.
- MAN-ES, 6G60ME-C10.5-LGIA with HP SCR: FAT is scheduled for the second quarter of 2026.

Notably, HHI-EMD prepared SCR design to described potential scenarios such as CASE 1 and CASE 2 for the initial ammonia DF engines. This approach was taken in the absence of finalized exhaust gas information, emission data, and relevant maritime regulations.

As ammonia DF engines mature, the SCR design will be gradually optimized to reflect the evolving understanding and requirements of these systems. Future work will focus on further optimization and real-world performance evaluation of these systems across various operational conditions, not only on testbeds but also onboard vessels.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

HHI-EMD: HD Hyundai Heavy Industries Engine & Machinery

DF: Dual Fuel

IMO: International Maritime Organization

GHG: Greenhouse Gas

GWP: Global Warming Potential

IPCC: Intergovernmental Panel on Climate Change

IPCC AR5: IPCC Fifth Assessment Report

SCR: Selective Catalytic Reduction

Typical SCR: SCR for conventional engines (NOT ammonia DF engines)

Ammonia SCR: SCR for ammonia DF engines

HP SCR: High pressure SCR

LP SCR: Low pressure SCR

AOC: Ammonia Oxidation Catalyst

ABS: Ammonium bi-sulfate

IR: Infrared Rays

UV: Ultraviolet Rays

TAT: Type Approval Test

FAT: Factory Acceptance Test