HERCULES-2 Project

Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine

Deliverable: **8.6**

Results from test with engine-integrated SCR on two-stroke diesel engine

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1 Executive Summary

An engine-integrated high-pressure SCR system has been developed, installed and tested on MAN Energy Solutions’ two-stroke R&D engine in Copenhagen. The exhaust gas receiver has been replaced with a new and larger receiver with catalyst elements located inside the receiver, see Figure 1.

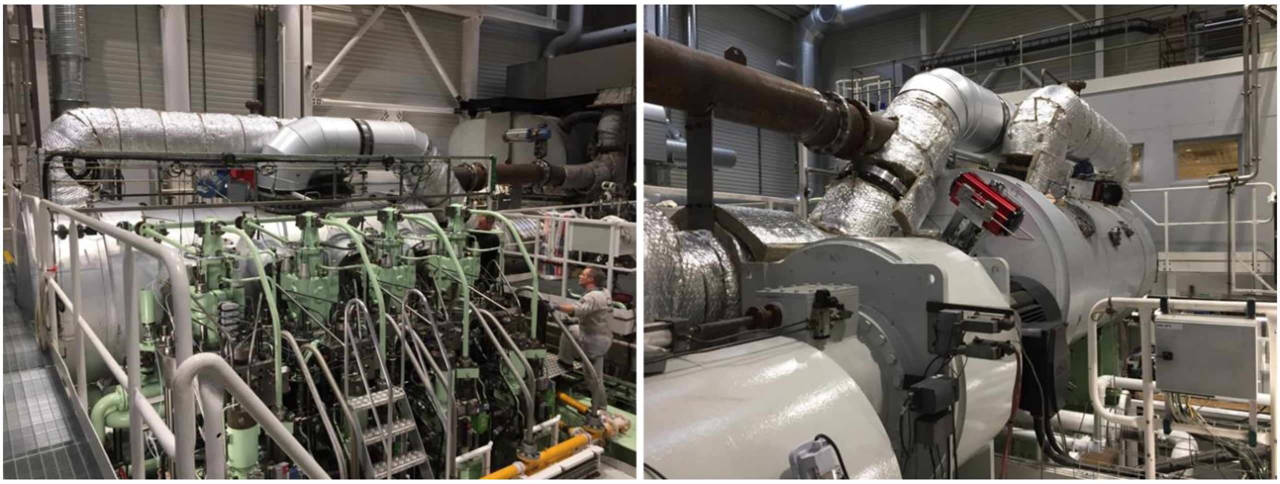

Figure 1 Integrated SCR receiver installed on 4-cylinder two-stroke R&D test engine in Copenhagen

The integrated SCR system was tested at 100% load, 75% load, 50% load and 25% load. More than 80% NO_x reduction was obtained at all four load points. These results show that a marine two-stroke engine can be made IMO Tier III NO_X compliant by installing an engine-integrated SCR system.

The integration of an SCR system into the engine with no additional engine room footprint constitutes a bold development effort. The objective was to use a real-sized engine to identify both the potential, the challenges and the problems of such a design solution at an early stage. The results show a large overall DeNOx potential of the downsized installation and also help pinpoint areas where further development will be needed if such a system should be made into a product.

2 Introduction

The use of selective catalytic reduction (SCR) systems for two-stroke diesel engines has proven to be Tier III compliant with regard to NOx emissions according to the IMO criteria. Marine SCR applications are still being developed and investigated in order to support a higher degree of freedom with regard to fuel flexibility and to ensure manageable installation requirements for the shipyards. Today's SCR systems for two-stroke diesel engines are installed as large standalone units, taking up a considerable amount of space in the engine room. The objective of task 8.1 within WP 8 of Hercules 2 has been to realise a design that reduces the space and footprint occupied by the SCR system as much as possible by integrating it directly into the engine.

The design consideration and the final design have been described in Deliverable 8.2. The installation of the system is reported in Deliverable 8.5. The focus of the present deliverable is to document the prototype test results of the new integrated SCR installed on the 4T50ME-X two-stroke diesel R&D engine in Copenhagen.

3 Objectives

The overall objectives of Hercules II WP8.1: "Engine-integrated high-pressure SCR for two-stroke marine diesel engines" are the following:

- Investigation of the high-pressure SCR process; injection, mixing, decomposition and flow distribution with the aim of making the SCR components compact, while still maintaining the same high performance as the best technology available of today.
- Designing an engine-integrated high-pressure SCR with unaffected engine footprint and only slightly affected gallery arrangement around the engine.
- Testing of compact high-pressure SCR component performance on the 4T50ME-X R&D engine.

This deliverable covers the last objective, documenting the results from the test with the full size engine-integrated SCR installed on the two-stroke R&D diesel engine in Copenhagen.

4 Test results

A new engine-integrated design for high-pressure SCR has been developed and tested. This section describes the test results.

The SCR is located inside the exhaust gas receiver and is fully integrated with the engine, see Figure 2. The receiver has two operating modes: 1) Tier II mode, where the exhaust gas goes straight to the turbocharger and 2) Tier III mode, where the exhaust gas is led through the reactor inside the receiver. The red arrows in Figure 2 show the flow direction in Tier III mode. The engine is equipped with MAN Energy Solutions' standard high-pressure SCR control system called ERCS. This system enables the SCR system to adjust the urea dosing rate automatically.

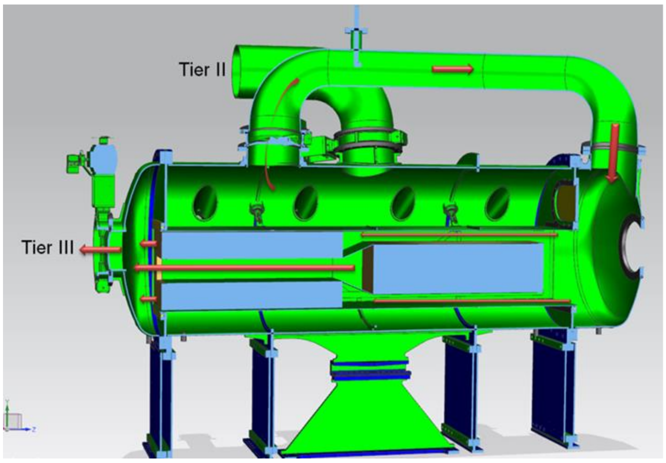

Figure 2 New receiver for the integrated SCR

Figure 3 Installation on 4T50ME-X R&D engine

Figure 3 shows the installation on the R&D engine. The red valve is the Tier III valve. The photo was taken during the period of insulation of the pipes.

4.1 Commissioning of the 4T50ME-X R&D engine (Tier II mode)

The engine was first commissioned in Tier II mode in order to evaluate how the receiver would affect engine performance, in particular with regard to pressure pulsations and resonances. As expected, no changes were seen, neither during engine start-up nor during engine performance at steady operation.

4.2 Test plan

In order to evaluate the performance of the integrated SCR system, a urea dosing sweep were performed for each load point: 25, 50, 75 and 100%. In an urea dosing sweep, the reducing agent is varied (amount of urea), and the corresponding NOx level and ammonia slip in the exhaust gas is measured. Ideally, all urea is used for DeNOx, and no ammonia slip is measured. The number of catalyst elements installed was chosen on the 4T50ME-X R&D engine to be on the borderline of what is necessary for Tier III compliance. This decision was made in order to be able to clearly identify any problems with inhomogeneity of the urea distribution in the receiver and the mass rate distribution through the SCR. This would otherwise be masked easily if more catalytic elements would have been installed. Hence, the SCR system was specified with a target of 70% DeNOx level and with ammonia slip to start at around 80% DeNOx.

The test plan was to first test the SCR system with low-sulphur fuel. Secondly, to commission the ERCS control system, so the SCR system could run in Auto. And finally to test the SCR system with heavy fuel oil. The test plan is show in table 1.

Table 1 Test plan

Low-sulphur fuel								
Engine load	**Target DeNOx**							
25%	0 %	25 %	50 %	75 %	80 %	90 %	100 %	110 %
50%	0 %	25 %	50 %	75 %	80 %	90 %	100 %	110 %
75%	0 %	25 %	50 %	75 %	80 %	90 %	100 %	110 %
100%	0 %	25 %	50 %	75 %	80 %	90 %	100 %	110 %
Auto mode								
Engine load	**Target DeNOx**							
25%					80%			
50%					80%			
75%					80%			
100%					80%			
Heavy fuel oil								
Engine load	**Target DeNOx**							
25%	0 %	25 %	50 %	75 %			100 %	
50%	0 %	25 %	50 %	75 %			100 %	
75%	0 %	25 %	50 %	75 %			100 %	
100%	0 %	25 %	50 %	75 %			100 %	

For each measurement point:

- Urea is dosed in order to obtain the target DeNOx level
- Performance data is collected
- Standard emission is measured (O_2, NO, NO_2, CO_2, CO and THC)
- Ammonia slip is measured

4.3 SCR tests with low-sulphur fuel

This section shows the results from the tests using low-sulphur fuel. The results of the urea dosing sweeps, performed at 25, 50, 75 and 100% load, are shown in Figures 4-7. Obtained NOx conversion (%) is plotted as a function of the urea dosing ratio for the target DeNOx level (%). The solid line is the ideal line where all added urea is used for NOx conversion.

The measured NH3 slip was corrected because the actual prototype design had some small leakages where exhaust gas could bypass the catalytic elements. The source of these leakages is known and discussed in Section 5. The relative bypass amount was calibrated at each load by assuming that the ammonia slip should be zero at the lowest urea dosing ratio of around 25%. At this point, the NOx conversion obtained is seen to be very close to the 1:1 line corresponding to complete DeNOx of the reducing agent (urea). Both measured and corrected values for ammonia slip are shown in Figures 4-7

25% load test results

The results of the urea dosing sweep, performed at 25 % load, are shown in Figure 4.

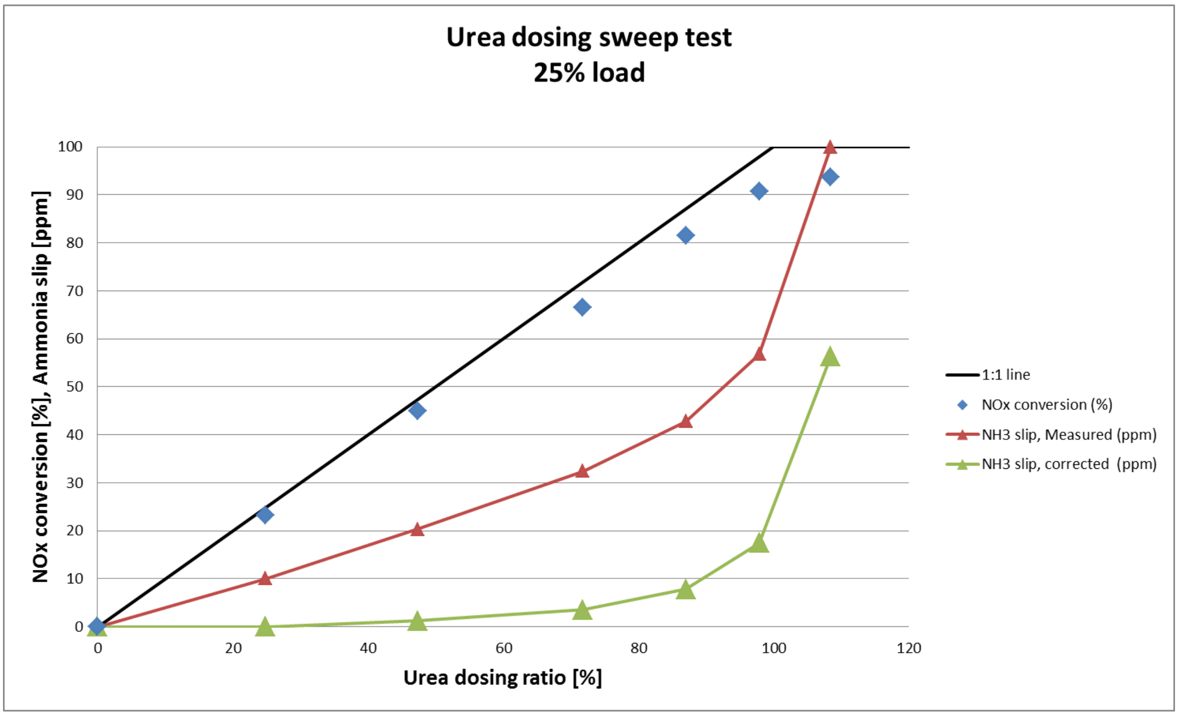

Figure 4 Urea dosing sweep at 25% engine load, low-sulphur fuel. NH3 slip shown as measured and corrected

The results show that a high DeNOx performance is obtained at 25% load. Over 90% DeNOx can be obtained with the system. A small corrected ammonia slip is seen to start around the 75% urea dosing ratio point. At the 85% urea dosing point ratio, the ammonia slip is still within the acceptable limit for the low-sulphur system and an 81% NO_x reduction was obtained.

50% load test results

Figure 5 shows the results of the urea dosing sweep, performed at 50% load.

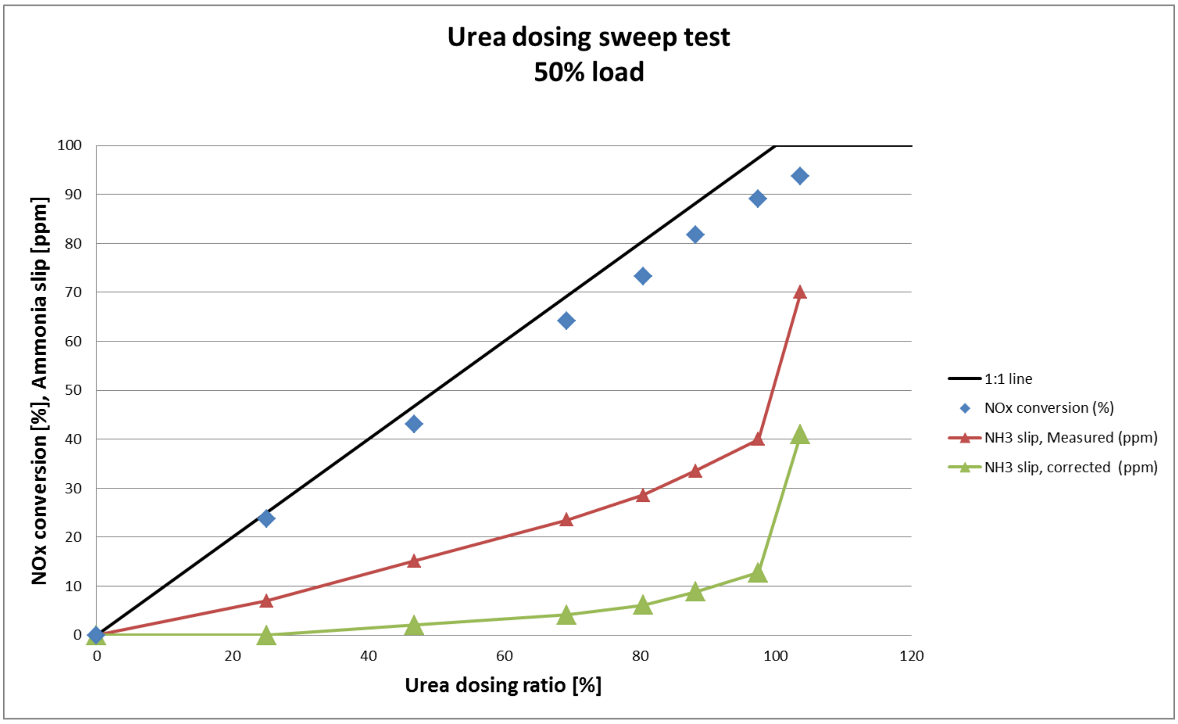

Figure 5 Urea dosing sweep at 50% engine load, low-sulphur fuel. NH_3 slip shown as measured and corrected

The results show that a high DeNOx performance is obtained at 50% load. 89% DeNOx can be obtained with the system without overdosing with urea. A small corrected ammonia slip is seen to start around the 50% urea dosing ratio point. At the 85% urea dosing ratio point, the ammonia slip is still within the acceptable limit for the low-sulphur system and 82% NOx reduction is obtained.

75% load test results

Figure 6 shows the results of the urea dosing sweep, performed at 75% load.

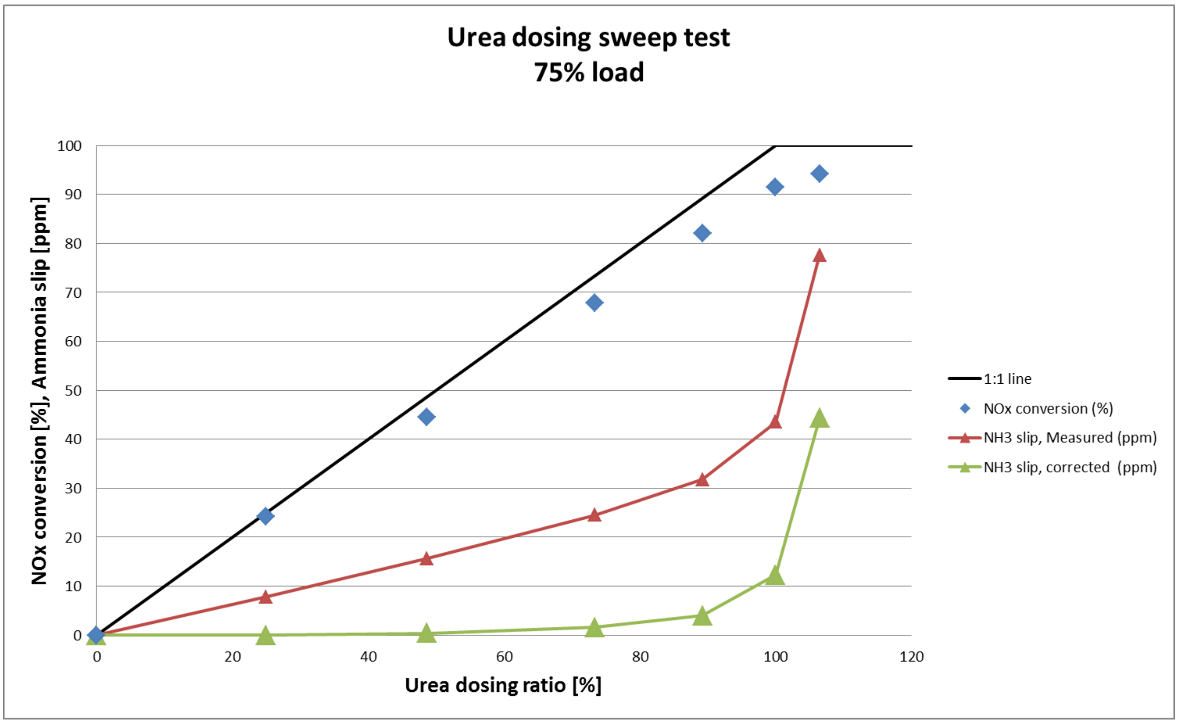

Figure 6 Urea dosing sweep at 75% engine load, low-sulphur fuel. NH3 slip shown as measured and corrected

The results show that a high DeNOx performance is obtained at 75% load. 92% DeNOx can be obtained with the system without overdosing with urea. A small corrected ammonia slip is seen to start around the 90% urea dosing ratio point. At the 90% urea dosing ratio point the ammonia slip is still within acceptable limit for the low-sulphur system, and an 82% NOx reduction is obtained.

100% load test results

Figure 7 shows the results of the urea dosing sweep performed at 100% load.

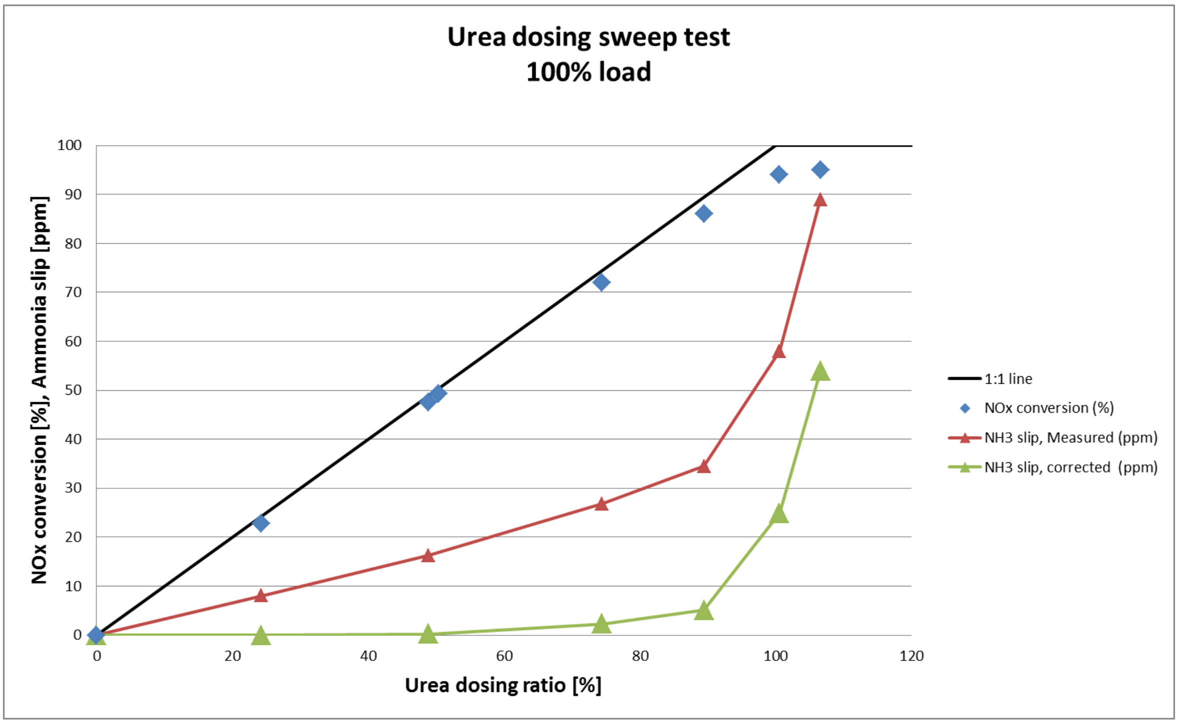

Figure 7 Urea dosing sweep at 100% engine load, low-sulphur fuel. NH3 slip shown as measured and corrected

The results show that a high DeNOx performance is obtained at 100% load. 86% DeNOx was obtained with the system at the 90% urea dosing ratio point. The corrected ammonia slip is well within the acceptable limit for the low-sulphur system.

Mass balance

The mass balance for the 100% load tests is close to ideal, as all urea is used for DeNOx up to the 90% urea dosing ratio point. It shows that very good evaporation of urea occurs, and that the flow distribution over the catalyst is sufficient. The mass balance for the other load points, 25%, 50% and 75% loads, is less good, as it starts to deviate at the 50% urea dosing ratio point. However also for these load points, the obtained DeNOx and limited ammonia slip show that the evaporation, the mixing and the flow distribution are sufficient for the system. The test results are summarised in Table 2.

Table 2 Obtained NOx conversion, with low-sulphur fuel oil

Load	Obtained DeNOx with acceptable mass balance	Obtained DeNOx, with acceptable corrected ammonia slip
25%	90% DeNOx	81% DeNOx
50%	89% DeNOx	82% DeNOx
75%	92% DeNOx	82% DeNOx
100%	95% DeNOx	86% DeNOx

These tests demonstrate that the engine with the integrated SCR system can reach Tier III DeNOx performance.

4.4 Test in Auto-mode

While the tests reported in Section 4.3 were conducted by setting the urea dosing manually and then measuring the engine emissions, in a second step, the SCR control system was commissioned with a target of 70% DeNOx level and then tested without any further manual intervention. The test program contained both steady running at selected operating points and transient scenarios.

Steady operation in selected operating points

For each of the four load points (25%, 50%, 75% and 100% load) performance measurements were performed with and without urea dosing in order to validate the settings and compare the data with the results obtained under the dosing sweep test, see Figures 8-11.

Better NOx reduction and less ammonia slip are obtained at 25% load. For 50%, 75% and 100% load, the results are almost identical, showing that the DeNOx levels obtained during the first tests are reproducible.

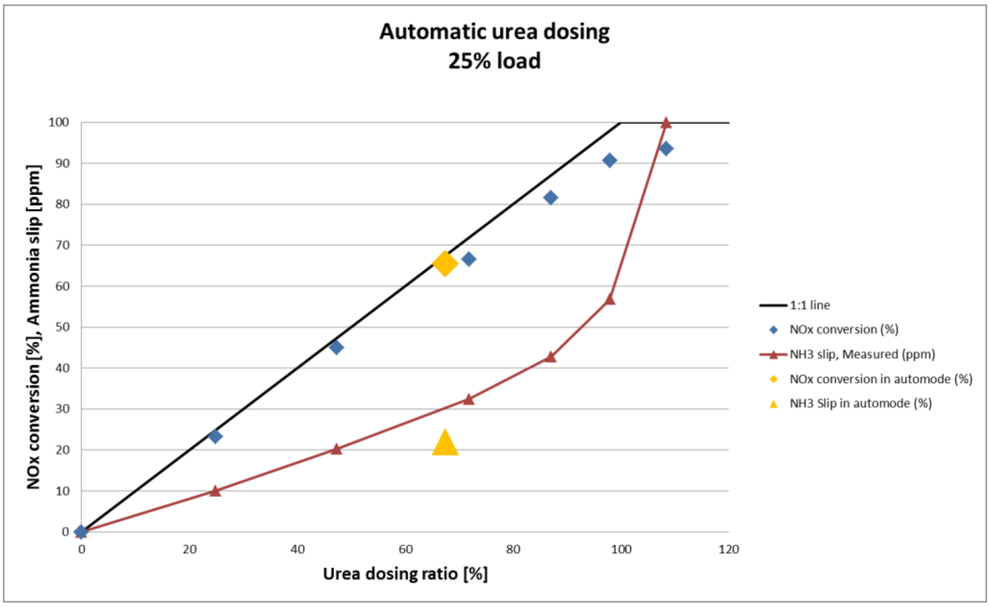

Figure 8 Automatic urea dosing results at 25% load, including urea sweep tests for reference

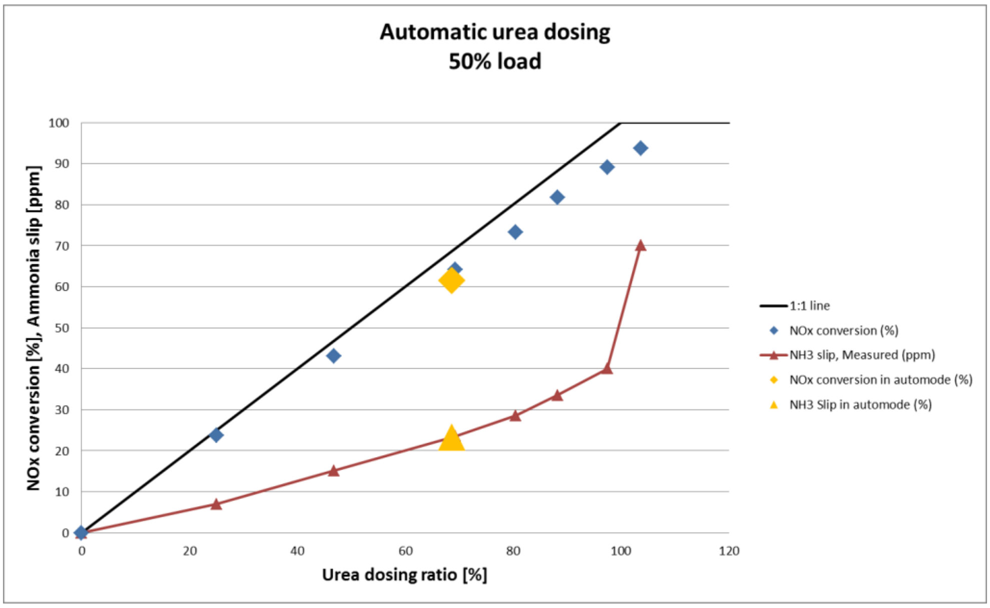

Figure 9 Automatic urea dosing results at 50% load, including urea sweep tests for reference

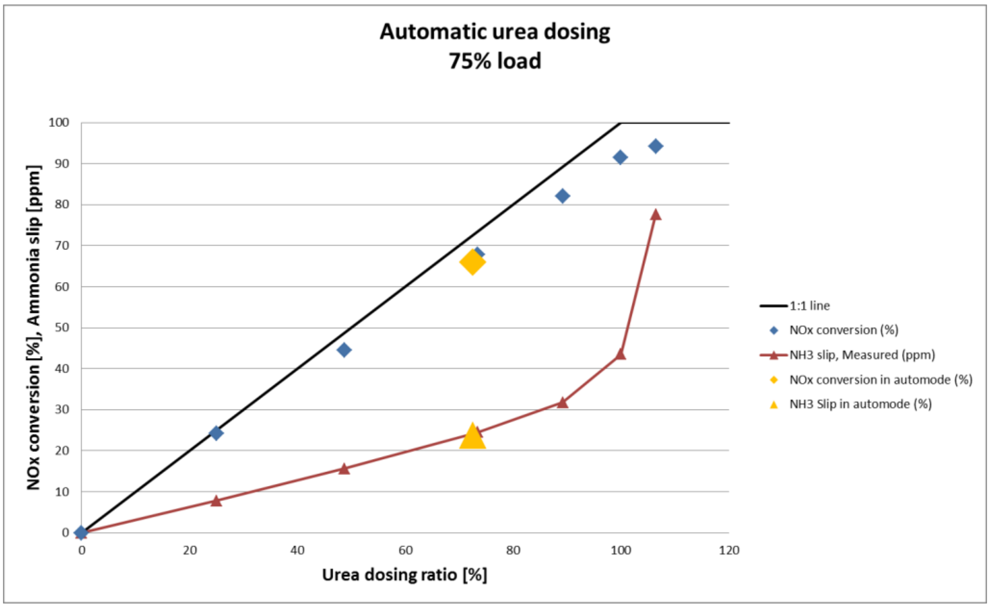

Figure 10 Automatic urea dosing results at 75% load, including urea sweep tests for reference

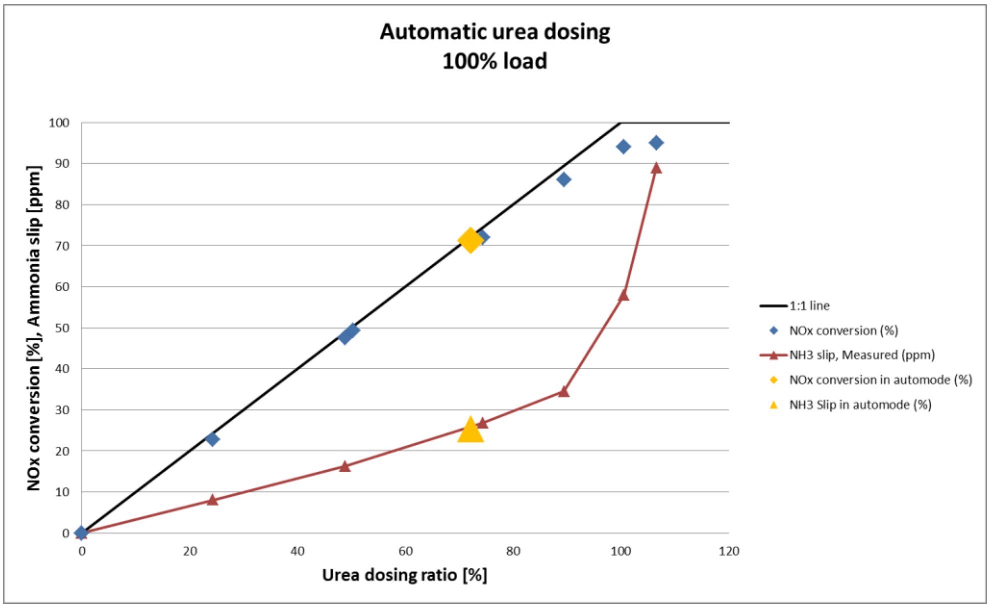

Figure 11 Automatic urea dosing results at 100% load, including urea sweep tests for reference

Transient operation

Figure 12 shows the results for the entire day running in auto-mode. The urea dosing is given as a percentage of the maximum urea pump capacity. Normal load changes from 25% to 100% are performed during hours 1.5 to 4. Fast transient conditions are tested during hours 4.5 to 5.

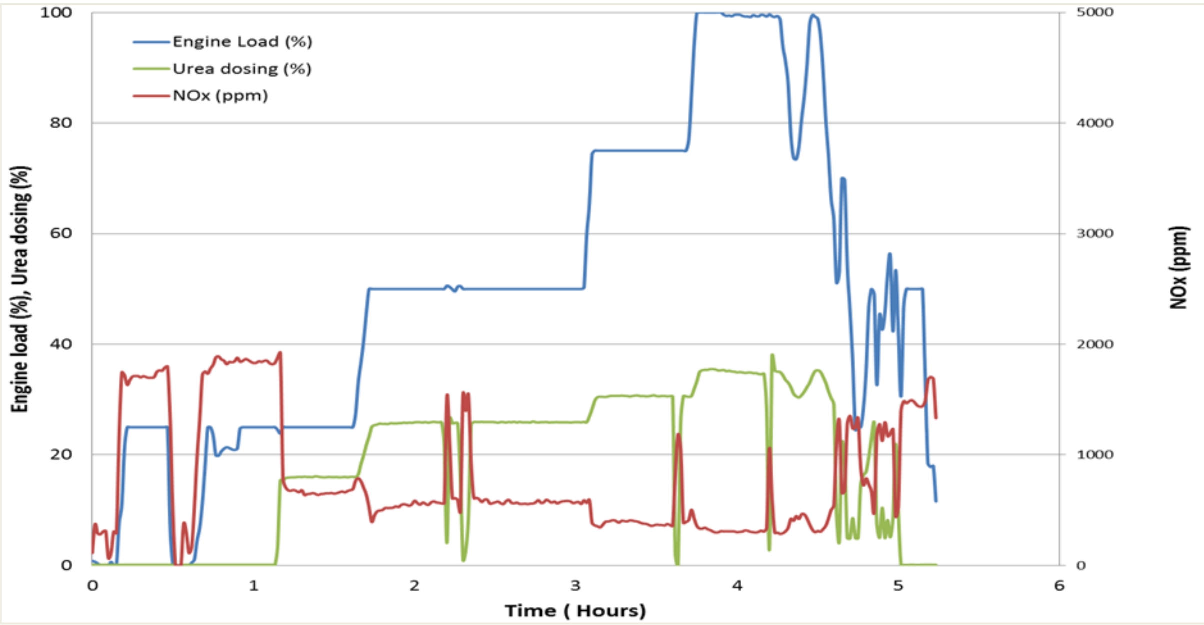

Figure 12 Running in auto-mode, low-sulphur fuel oil

The system performs as expected:

- Urea dosing is automatically increased, and the NOx measured in ppm, is kept at the expected level after the load change. No extra ammonia slip is observed.
- When a rapid load change is detected, the reactor bypass valve is temporarily opened to ensure unrestricted engine acceleration, and urea dosing is reduced to minimum dosing in order to avoid ammonia overdosing. For example, this was observed during load change from 75 to 100%.
- When rapid transient conditions are detected, urea dosing is temporarily reduced to minimum dosing in order to avoid ammonia overdosing. This is observed during the fast transient test.

5 Mechanical challenges

A number of practical difficulties were experienced during the manufacturing and installation of the integrated SCR system on the 4T50ME-X test engine. The practical solutions caused the actual design to be leaking during operation after a few operating hours. It was estimated that around 2.5% of the exhaust gas was bypassing the catalytic elements, see Section 4.3. Furthermore, the actual design appeared to lack sufficient stability and durability overall. In particular, the used catalytic material showed insufficient durability. The experience gathered will be very important for the next stages of the development process.

6 Conclusions

An engine-integrated high-pressure SCR system has been developed, installed and tested on MAN Energy Solutions' two-stroke R&D engine in Copenhagen. The receiver was replaced with a new and larger receiver with the catalyst elements located inside the receiver. This new design has reduced the size of the SCR system significantly, that is more than 90% compared to traditional high-pressure SCR systems.

The engine was re-commissioned with the new receiver in Tier II mode. No significant changes were seen in engine performance. However, a higher pressure drop over the total system was observed due to changes in the exhaust pipe arrangement.

Tests were performed at 100% load, 75% load, 50% load and 25% load. A dosing sweep was performed for each load point, in order to evaluate the DeNOx performance as a function of reducing agent (urea).

Table 3 Obtained NOx conversion, with low-sulphur fuel oil

Load	**Obtained DeNOx, with acceptable corrected ammonia slip**
25%	81% DeNOx
50%	82% DeNOx
75%	82% DeNOx
100%	86% DeNOx

These results verified the concept and showed that the engine-integrated SCR system can be IMO NOx Tier III compliant.

Important lessons were learned regarding manufacturing and installation of the catalytic elements in the exhaust gas receiver.

The initial prototype test results validate the engine-integrated high-pressure SCR design from an overall perspective and prove the concept. However, further work remains in order to solve mechanical challenges and improve access for maintenance.

7 References

Deliverable 8.2: Design of engine-integrated SCR on two-stroke diesel engine.
Deliverable 8.5: Engine-integrated SCR on a two-stroke diesel engine.