Marine Advanced Retrofit System

Task 5 - Verification Of Emissions Reduction On Vessel Including A Comparison Of Simultaneous Raw And Engine Out Emissions

for:

New Technology Research and Development Program

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Submitted by:

Robert Bosch LLC

Principal Investigators:
Christoph Doehring
Eberhard Gruber
Johannes Raeder

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Abstract/Executive Summary

This report describes the fifth and last deliverable of the Marine Advanced Retrofit System (MARS) project funded by TCEQ.

According to the initial project plan, the developed and designed marine aftertreatment system has been shipped and installed on a tugboat.

The main focus in this report is the installation of the aftertreatment system on a tugboat, the installation of the portable emission measurement devices, and the final calibration of the urea dosing system to meet the key objectives of 75% nitrogen oxides (NO_x) and 95% particulate matter (PM) conversion. The final data analysis including load profiles, exhaust temperatures, and conversion rates also will be discussed.

Introduction/Background

The goal of this project is to develop a diesel emission reduction aftertreatment retrofit system that includes both a selective catalytic reduction (SCR) system and a diesel particulate filter (DPF) for diesel-powered harbor crafts. This SCR-DPF aftertreatment retrofit system is particularly important for vessels operating within the United States Environmental Protection Agency (EPA) National Ambient Air Quality Standards and non-attainment areas such as those within the State of Texas, including within the Port of Houston. The proposed retrofit system has the potential to reduce NO_x and PM by 75% and 90%, respectively; i.e. it would reduce the emissions on EPA Tier 0 down to Tier 2 or Tier 2 (current regulation) engines to Tier 4 engine levels.

This stand-alone retrofit system will not be only applicable to newer, electronically controlled engines, but also to older, mechanically governed ones (i.e. Tier 1 and earlier). This is significant, since these older and higher pollutant engines may still have considerable remaining useful lifetime and their replacement is neither desirable nor cost-effective. This retrofit system would provide a cost-effective solution of approximately $25,000 installed cost for engines up to 500 kilowatts (kW) or 680 horsepower (hp), which is significantly lower than current retrofit and repower options. It is planned to verify this aftertreatment technology before the start of its production and distribution.

Project Objectives / Technical Approach

Phase 1 included identifying a harbor vessel (for which the SCR-DPF system is to be designed), followed by measuring its engine baseline emissions. These measurements are needed for the proper design of the aftertreatment system: selection of the catalysts, computational fluid dynamics (CFD) analysis of the component and system performance, and for selecting an engine for dynamometer testing in later phases. Also, in Phase 1, advanced engineering models and simulation tools such as CFD and one dimensional models were used to achieve appropriate system design.

Phase 2 included developmental testing and analysis, performed in an engine dynamometer lab where the following regulated emissions were measured: NO_x, PM, total hydrocarbons (THC), non-methane hydrocarbon (NMHC), carbon monoxide (CO), and carbon dioxide (CO_2). The exhaust gas temperature was measured before the particulate filter to ensure a proper passive regeneration temperature profile similar to the operation of the particulate filter on the tugboat.

In Phase 3, a prototype SCR-DPF aftertreatment system was installed on the vessel and in situ measurement of the conversion efficiency was made. Testing was completed according to the acceptable industry standards.

Tasks

Phase 3: Task 1 - Measurement of Actual Emissions Reduction on Marine Vessel

From the Grant Activities (Scope of Work):

> *"Task 5: Field Emissions Measurements on Marine Vessel*
>
> *2.5. Task Statement: The PERFORMING PARTY will install the aftertreatment system on the test marine vessel and test the retrofit's emissions impact using PEMS equipment.*
>
> *2.5.1. The PERFORMING PARTY will ship the aftertreatment system to and install the aftertreatment system on the test marine vessel selected in Task 1.*
>
> *2.5.2. The PERFORMING PARTY will install the PEMS equipment on the test marine vessel and complete emissions measurements with the aftertreatment system installed. A minimum of two days of testing will occur during normal vessel operation. Data collection will include raw and engine out emissions. The PERFORMING PARTY may make final calibration changes to the software as part of this testing.*
>
> *2.5.3. Schedule: The PERFORMING PARTY shall complete this task within 16 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.5.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include but is not limited to emissions test results from the test vessel including a comparison to the baseline test results and laboratory test results."*

The work for Task 5 may be summarized in three basic subtasks:

1) Ship and install system on marine vessel
2) Install portable emissions measurement equipment for emissions measurement including testing during normal operation
3) Final analysis of data

Phase 3: Task 1.1 - Ship and install system on marine vessel

Before the installation of the system, the available space in the upper engine compartment was inspected along with the feasibility of lifting the aftertreatment system into the boat. Figure 1 shows the roof top on the upper deck allowing the lifting of the frame including the aftertreatment system. Figure 2 shows the available installation space in the tugboat.

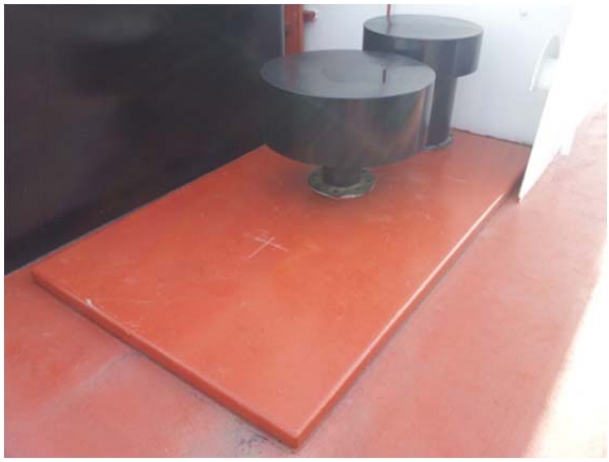

Figure 1. Roof top on the upper deck allowing the lifting of the frame including the aftertreatment system

Figure 2. Selected installation space in engine compartment

After removing the insulation, exhaust pipes, and the handrails in the upper engine compartment the aftertreatment system was delivered to the shipyard (Figure 3). The frame was lifted onto the vessel through the roof top by a crane, as seen in Figure 4.

Figure 3. Delivered aftertreatment system at the shipyard

Figure 4. Aftertreatment system being lifted on the tugboat

Figure 5 illustrates the inside of the upper engine compartment where the system is mounted. The grid in the bottom was re-enforced to hold the entire weight of the system. Dampers were used at the bottom brackets to minimize the vibration coming from the engine.

Figure 5. Aftertreatment system located in the engine compartment

The aftertreatment system was connected to the turbo charger flange in the engine compartment (Figure 6) and to the muffler (Figure 7). Decoupling elements are used on each pipe to avoid vibration resulting from the engine.

Figure 6. Aftertreatment system with installed outlet pipe

Figure 7. Aftertreatment system with installed inlet pipe after turbo charger

The urea tank is located close to the aftertreatment system in the upper engine compartment (see Figure 8). This rig also includes the external cooling system for the dosing module, enough space for the electronic measurement devices, and the aftertreatment controller.

Figure 8. Urea tank rig with supply module and external cooling system

Older marine diesel engines normally do not have engine controllers. Therefore, no information is available from the engine to the exhaust controller. For this reason retrofit sensors, i.e. speed sensor, boost pressure, and temperature sensors are installed to the engine for monitoring and sending the relevant information to the controller for the dosing strategy.

The entire installation time of the aftertreatment system including urea tank and wiring harness was 4 working days with four technicians to minimize long vessel down time.

Phase 3: Task 1.2 - Install portable emission measurement equipment for emissions measurement including testing during normal operation.

Two portable emission measurement (PEMS) devices are installed to evaluate the particulates and gaseous emissions (Figure 9). The sampling lines for both devices are located upstream and downstream of the aftertreatment system (Figure 10), but only one location can be measured at the same time. The measurement locations are switched from time to time between engine out (EO) and aftertreatment out (AO).

Figure 9. Gaseous and particulate measurement devices

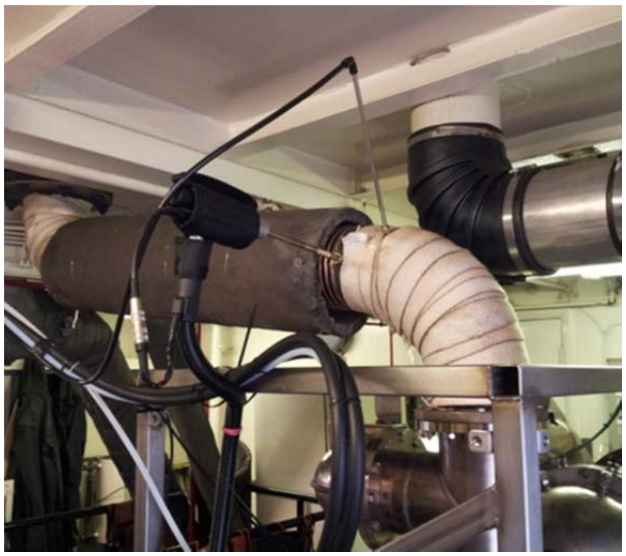

Figure 10. PEMS sampling lines

A typical tugboat cycle was used to verify the functionality of the measurement devices, which can be seen in the following Figure 11. The tugboat was moving an empty barge and had only a transient operation at the beginning and at the end. The rest of the run was steady stationary.

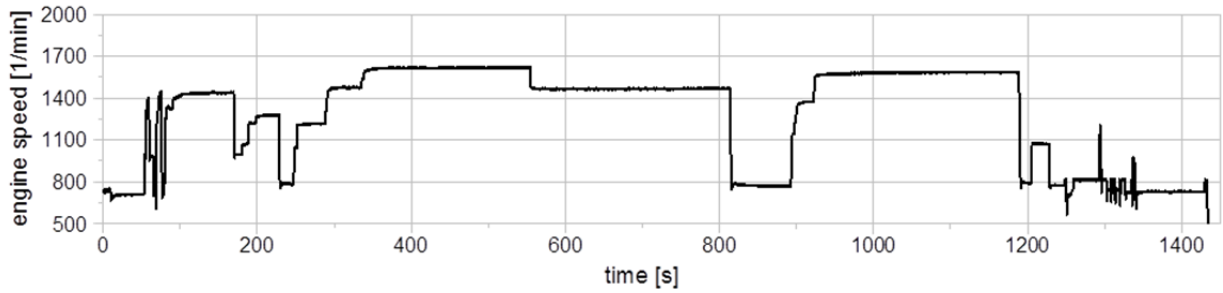

Figure 11. Tugboat cycle during PEMS installation and verification

In Figure 12, the data collection of the emission values w/o the aftertreatment system can be seen. The MRU device measures nitrogen oxide (NO), nitrogen dioxide (NO_2), CO, and THC in parts per million (ppm) while oxygen (O_2) and CO_2 are measured in percent and not shown here. The MAHA device measures the particulates (black) in milligrams per cubic meter (mg/m³), which is illustrated in the upper right label.

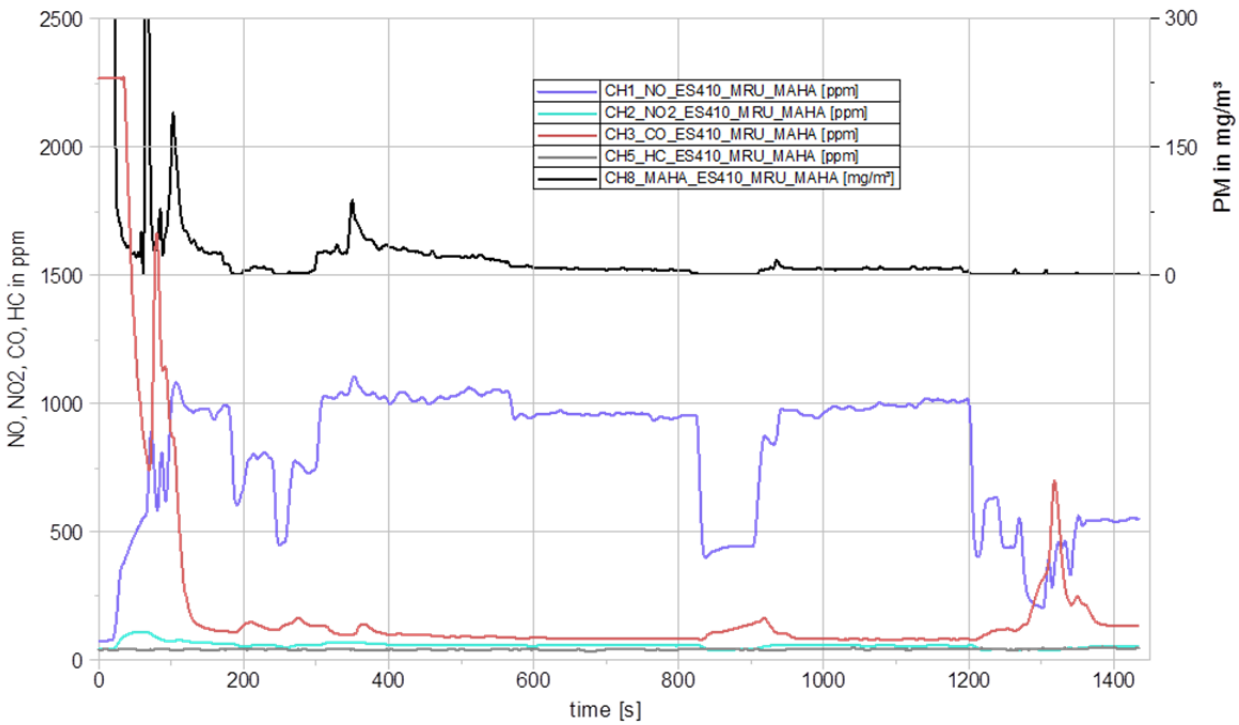

Figure 12. Engine out emissions w/o aftertreatment system

Phase 3: Task 1.3 - Final analysis of data

This chapter is dedicated to the modification of the SCR calibration and the data analysis, which shows the comparison of engine out and tailpipe emissions with the developed aftertreatment system on the tugboat.

Calibration changes

One of the first test runs is illustrated in the following figures using the aftertreatment system. Figure 13 shows the driving cycle in engine speed, which gives an overview of high and low engine operation.

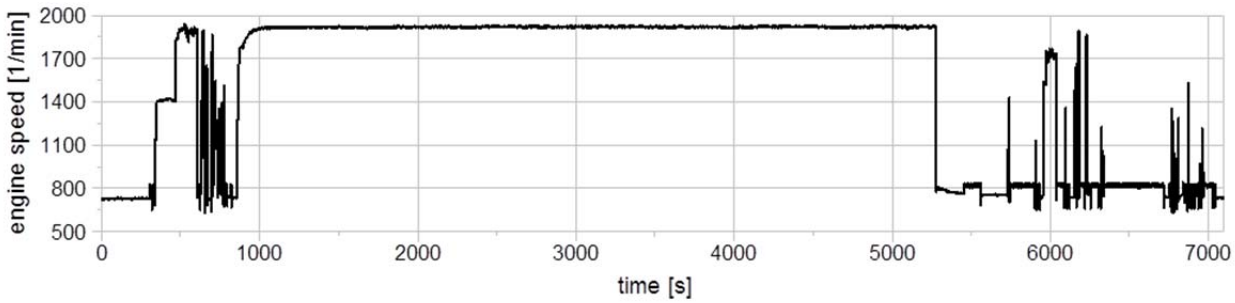

Figure 13. Tugboat cycle for modification of dosing calibration

All relevant exhaust emission values are shown in Figure 14, most importantly the NO_x values, measured by two NO_x sensors (upstream and downstream of the SCR) and by the MRU, which measures the NO and NO_2. The MRU is located at tailpipe (EO) and demonstrates a good correlation between the measured NO_2 + NO and the installed NO_x sensor, as seen in Figure 14. No soot emissions are measured after the DPF.

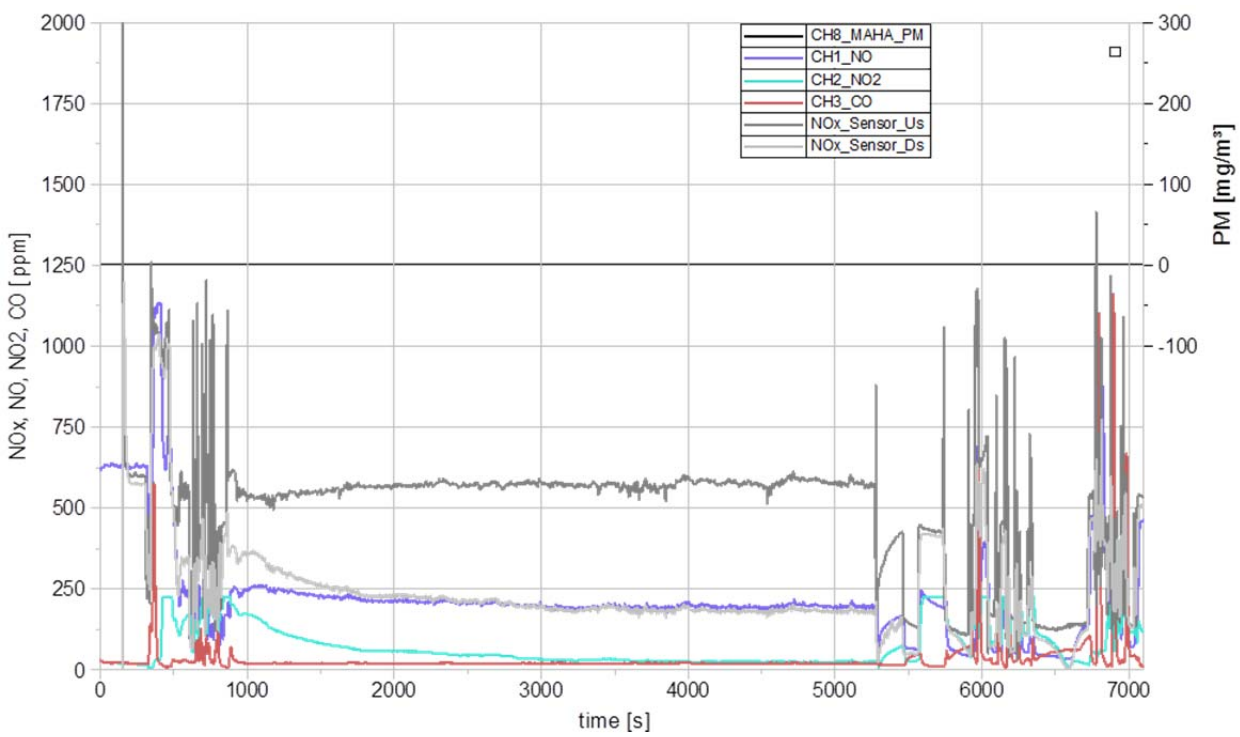

Figure 14. Tailpipe emissions w/ aftertreatment system for calibration

Within the first tests, running the rated point with the calibrated urea dosing system, it could be seen that the NO_x conversion rate was around 65%, instead of the targeted 85% seen after the test bench activities. The reason is that a Tier 1 engine was used on test bench (see Deliverable Report 4), and a Tier 2 engine

is used on the tugboat. Due to the different exhaust temperature levels, the calibration matrix has to be modified during the first test runs on the tugboat to reach the targeted NO_x conversion of greater than 75%.

Verification of emissions reduction

The following tests are conducted with the improved urea dosing calibration.

Every bunker job is different, which means that the driving profiles can diversify with every run. Because of that the tugboat cycle is displayed to see a coherency between the profile and the emissions.

Another important comment is that running the ISO 8178 E3 certification test on a tugboat is not feasible due to the non-reproducible driving conditions. The only indication for evaluating the emissions is the full load point, especially when the tugboat is pushing the barge. According to the total emissions, the full load point has the largest contribution.

Figure 15 illustrates the selected driving cycle to discuss the system behaviour and emissions reduction below. This profile has manuvering parts (at 0-1000 seconds and 2250-2600 seconds), half load parts (at 1200- 2300 seconds), and the full load operation points (at 3500-6950 seconds).

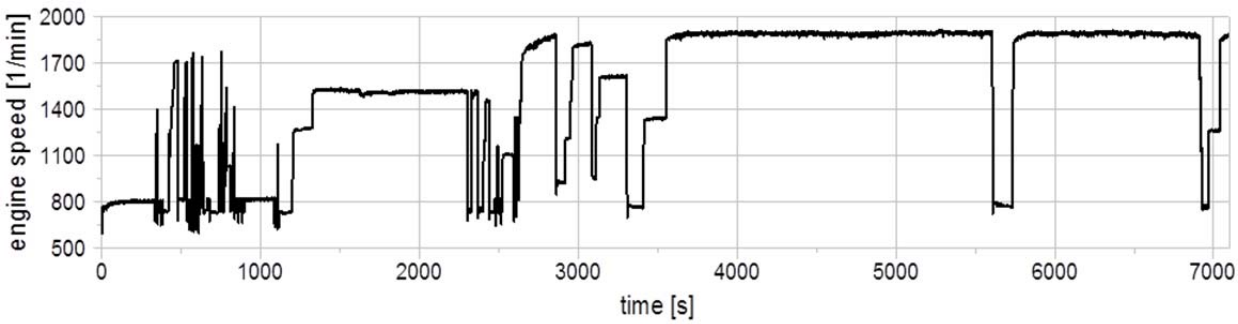

Figure 15. Tugboat cycle for the verification of emissions reduction

The exhaust temperatures are shown in Figure 16 and demonstrate temperature from engine out up to SCR downstream. It can be seen that only after the manoeuvring part the SCR temperature (red and orange) has reached the steady state condition of greater than 210 degrees Celsius for the urea dosing release. The rest of the driving profile (after 1300 seconds) indicates an optimal temperature of the SCR catalyst for good performances. The DPF outlet temperature can be described with the SCR upstream temperature and indicates a good temperature range as well for the passive filter regeneration.

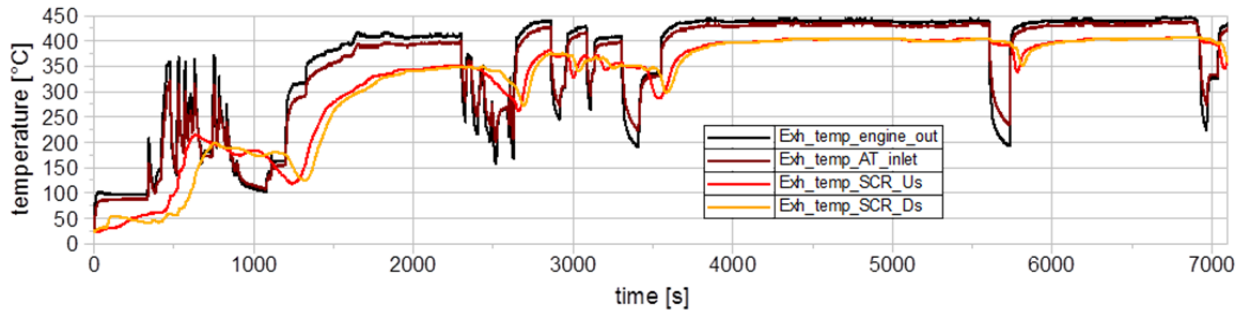

Figure 16. Exhaust temperature distribution of aftertreatment

In order to consider the emissions of the aftertreatment system, the PEMS location was shifted to the tailpipe, seen in Figure 17. The only exception is the MAHA device, which is still measuring the engine out particulates. Since no particulates are present after the DPF, further testing is not necessary, which was discussed in the chapter before and also seen in Figure 14.

In Figure 17, the high soot peaks at engine out sampling position mostly occur during manoeuvring and especially after the cold start of the engine. All these particulates are trapped in the DPF and are continuously generated within the temperature range of 250 and 450 degrees Celsius.

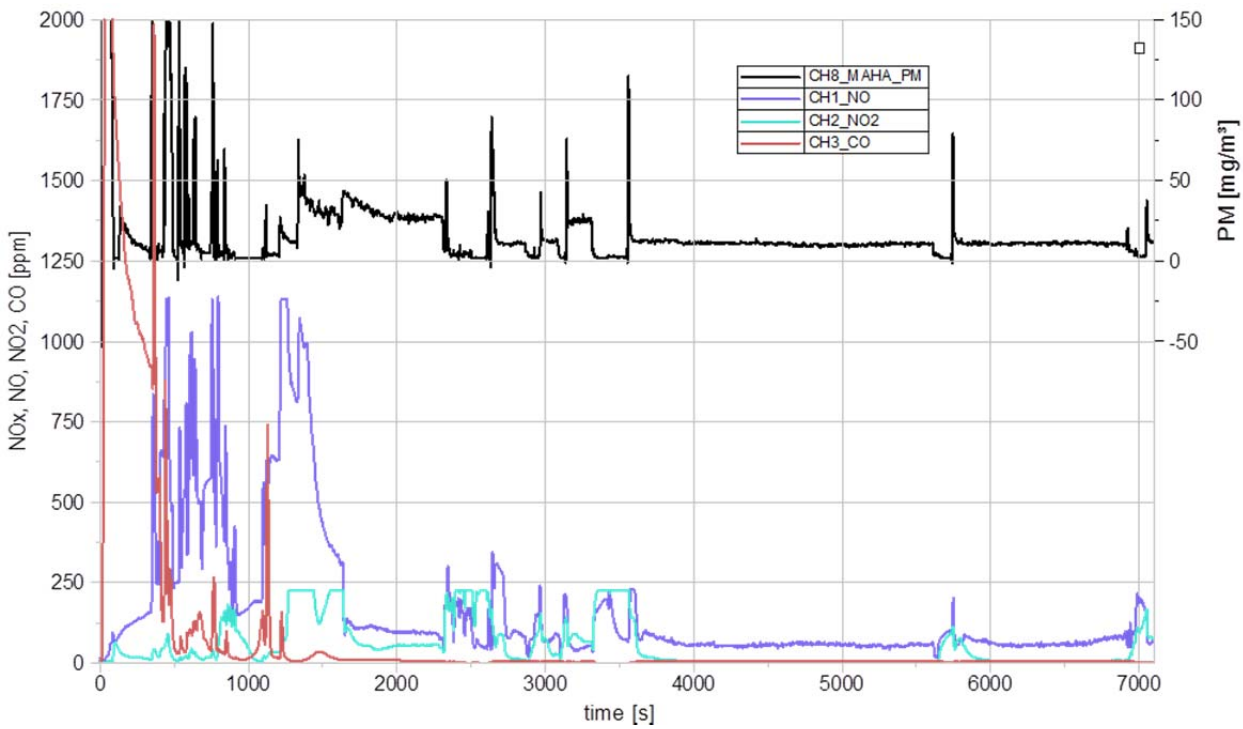

Figure 17. Tailpipe emissions w/ aftertreatment system for data verification

The measured gaseous emissions at the tailpipe also have high values in the beginning of the tugboat cycle. The main reasons for the high values are the cold engine condition and the slow warm up of the aftertreatment system to reach the light off temperature of the catalytic converter. Shortly after 1300

seconds the NO values drop off rapidly as a result of the urea dosing injection. The NO_x conversion values ($NO+NO_2$) at the steady state full load are in the range of 60-70 ppm.

To evaluate the urea dosing strategy over the tugboat profile, Figure 18 illustrates the NO_x values for SCR upstream and downstream. Additionally, the NO_x conversion rate is shown (blue), which indicates the low values after manoeuvring (at 0 - 1500 seconds) and high NO_x conversion rate up to 92% at full load operation point. The total NO_x reduction over the entire tugboat profile is approximately 80%.

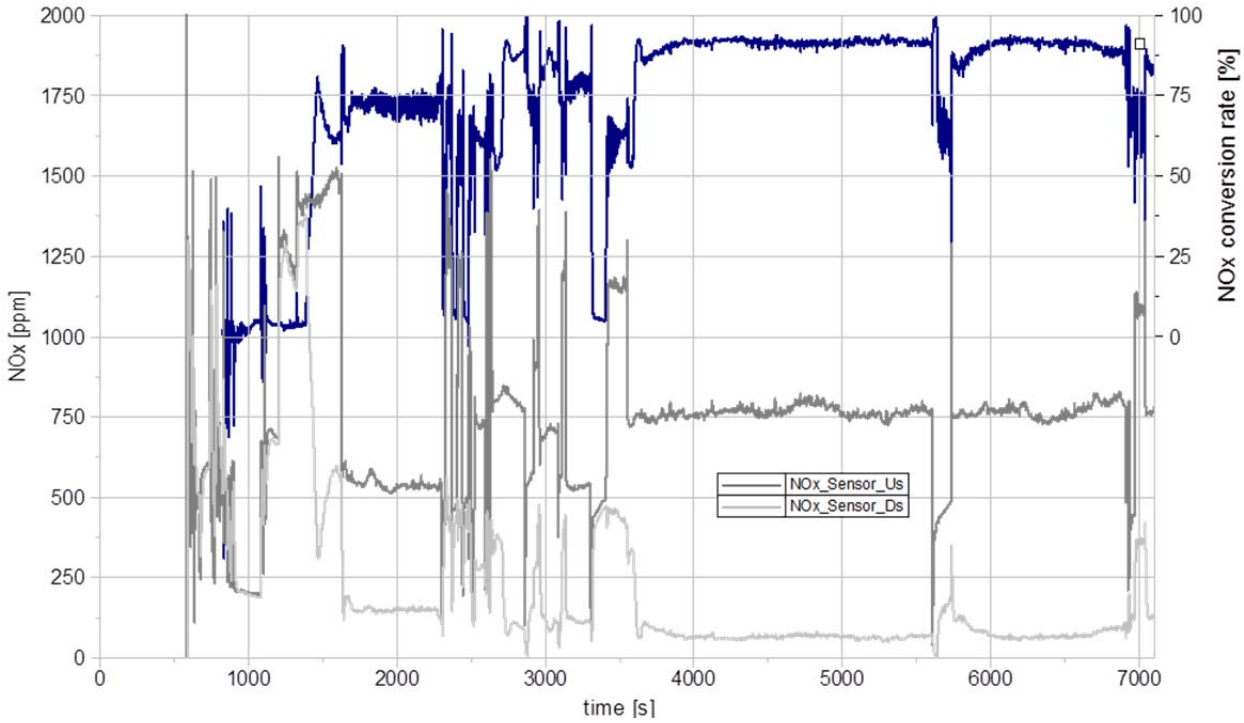

Figure 18. NO_x conversion rate over tugboat profile

Discussion/Observations

Objectives vs. Results

The estimated installation time for the entire aftertreatment system and measurement equipment was six working days. The job was actually completed within four days. It can be assumed that the installation time can be reduced by one to two days if the system has a production status and if the technicians are familiar with the aftertreatment system installation.

For a standard production, a urea tank with larger capacity of about 200 gallons is already available and can be installed within the same time frame like the demonstrated tank.

The specific NO_x value for the Tier 2 tugboat engine at full load operation is around 7.1 grams per kilowatt-hour (g/kWhr) and with the aftertreatment system the calculated value is 0.6 g/kWhr. Compared to the Tier 1 test bench engine with approximately 9.8 g/kWhr NO_x raw and 1.7 g/kWhr with the aftertreatment system, the tugboat engine has a lower NO_x level. However, for both engines the Tier 4 final targets could be achieved with the developed aftertreatment system.

Critical issues

Further investigation of passive regeneration using two parallel filters is needed to verify the long term operation of the catalytic performance of the diesel oxidation catalyst (DOC) and DPF for marine applications.

Technical and commercial viability of the proposed approach

This retrofit aftertreatment system reduces emissions of Tier 1, Tier 2, and Tier 3 engines allowing them to meet the Tier 4 levels.

At present tugboats are equipped with Tier 2 engines to meet the current regulation. If further emission enforcements are planned, the developed retrofit system can be used for a cost effective emission upgrade to Tier 3 or Tier 4 levels.

Scope for future work

Subsequent planned work that will not be part of the TCEQ project funding includes:

1) Marketing activities are planned to advertise the retrofit emission system.
2) Durability tests to demonstrate the limits of passive regeneration, and if necessary, implementation of an active regenerated particulate filter.
3) Improvement of the diagnosis system including implementation of a display on the vessel to alert the operator about the current state of the aftertreatment system (e.g. urea tank level, particulate filter differential pressure, etc.).

Intellectual Properties/Publications/Presentations

None.

Summary/Conclusions

The installation of a marine aftertreatment system including the portable emission measurement devices on a tugboat has been accomplished. The testing was conducted with several tugboat driving cycles. The calibration of the SCR system has also been finalized. The aftertreatment system is able to meet the EPA Tier 4 final limits for 2015/16 and demonstrate proper passive filter regeneration within the given tugboat driving cycle.

Contact Information

For further information about this project please contact:

Anna Kleber
Bosch
(248) 876-1680
Anna.Kleber@us.bosch.com