Marine Advanced Retrofit System

Task 4 - Final System Design for Marine Vessel and Measurement of Emissions Reduction

for:

New Technology Research and Development Program

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Submitted by:

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Abstract/Executive Summary

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

According to the initial project plan, after the first task of this development, in the second part an engine in combination with a specially developed and designed marine after treatment system had been built up on engine test bench.

The main focus in this report is the installation of the after treatment system on the test bench, the final design change, and the emission measurements. It includes the urea deposit study and calibration of the selective catalytic reduction (SCR) system. On the other hand, the investigations with a single and a double diesel particulate filter (DPF) system are discussed. Finally, the key objectives of 75% NO_x and 95% particulate matter (PM) conversion are demonstrated.

Introduction/Background

The goal of this project is to develop a diesel emission reduction after treatment retrofit system that includes both, a SCR and a DPF for diesel-powered harbor crafts. This SCR-DPF after treatment retrofit system is particularly important for vessels operating within the US-EPA National Ambient Air Quality Standards and the 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 US-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 emitting 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: around $25,000 installed cost for engines up to 500 kilowatt (kW) or 680 horsepower (hp), which is significantly lower than current retrofit and repower options. It is planned to verify this after treatment technology before the start of its production and distribution, anticipated to take place in 2013.

Project Objectives/Technical Approach

Phase 1 includes 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 after treatment 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, amongst others. Also, in Phase 1, advanced engineering models and simulation tools such as CFD and one-dimension models are used to achieve appropriate system design.

Phase 2 will include developmental testing and analysis, performed in an engine dynamometer lab where the following regulated emissions will be measured: NO_x, PM, total hydrocarbons (THC), non-methane hydrocarbon (NMHC), carbon monoxide (CO), and carbon dioxide (CO_2). The exhaust gas temperature will be measured before the particulate filter to ensure a proper passive regeneration temperature profile; maintaining with this the proper operation of the DPF.

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

Tasks

Phase 2: Task 2 - Final Design Changes, Measurement of Emissions Reduction installation

From the Grant Activities (Scope of Work):

> *"Task 4: Final Design Changes and Laboratory Emissions Measurements*
>
> *2.4. Task Statement: The PERFORMING PARTY will install and test the aftertreatment retrofit on the laboratory test bed engine, adjusting and refining the design as appropriate.*
>
> *2.4.1. The PERFORMING PARTY will install the aftertreatment system on the laboratory test engine.*
>
> *2.4.2. The PERFORMING PARTY will measure the emissions impact due to the installed aftertreatment system and make final design changes to the system to improve performance. Several iterations of the design are anticipated to determine final mixer location and design, dosing location, and orientation. Design refinements and testing will include:*
>
> - *a durability study to determine the extent of urea deposits caused by crystallization of the urea at low temperatures;*
> - *SCR catalyst characterization including urea storage capacity, NOx conversion efficiency with respect to temperature in order to satisfy the catalyst model that is calibrated within the software;*
> - *calibration of the dosing strategy, hydraulic functions and diagnostics;*
> - *determination of the proper NO/ NO_2 ratio*
> - *modifications to the catalyst design to optimize emissions reductions; and*
> - *measurement and optimization of minimum ammonia slip*
>
> *2.4.3. Schedule: The PERFORMING PARTY shall complete this task within 8 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.4.4. 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 evidence, including pictures, of the installation of the aftertreatment system on the laboratory test engine, the final aftertreatment system design, and results of the final laboratory emissions testing."*

The work for Task 4 may be summarized in two basic subtasks:

1. Install after treatment system on test bench
2. Final design changes to system and emissions measurement with after treatment.

Phase 2: Task 2.1 – Install after treatment system on test bench

The initial after treatment system with one diesel oxidation catalyst (DOC)/DPF and SCR was installed after the conducted baseline testing. Illustrated in Figure 1, the frame construction can be seen. The inlet respectively the interface to the engine is shown in the right picture.

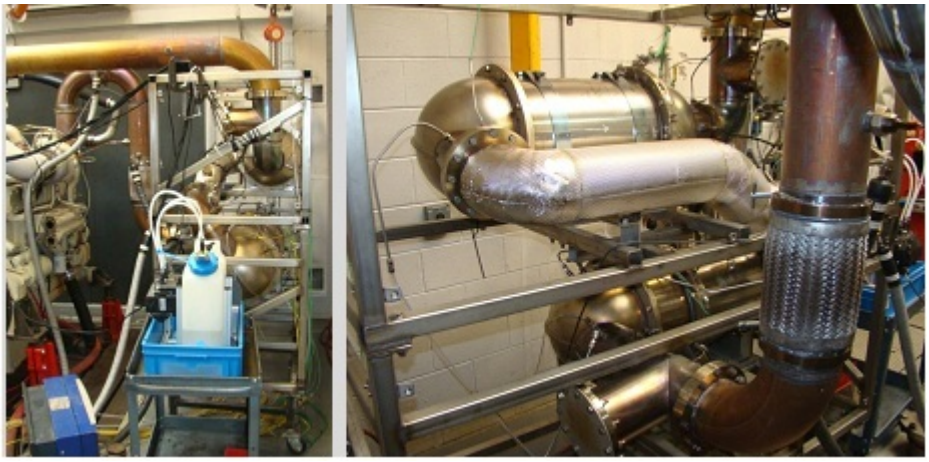

Figure 1. After treatment system on the test bench in initial configuration

The entire after treatment system was equipped with several sensors to monitor the system behavior. One of these sensors can be seen in Figure 2. It is a temperature and pressure sensor for the SCR downstream.

Figure 2. Thermocouples and sensors for SCR catalyst

Phase 2: Task 2.2 – Final design changes to system and emission measurement with after treatment

Initial system backpressure:

Before the investigation of the catalyst and emission testing was started, the verification of the system backpressure was done at several points on the propeller curve. Most important is the rated point at 600 hp with 2350 kilograms (kg)/hour (h) massflow. This point could not be achieved because of exceeding the maximum allowable turbo charger temperature of 730°Celsius due to the system backpressure. The following Figure 3 illustrates the backpressure values for propeller curve up to 2000 kg/hr massflow.

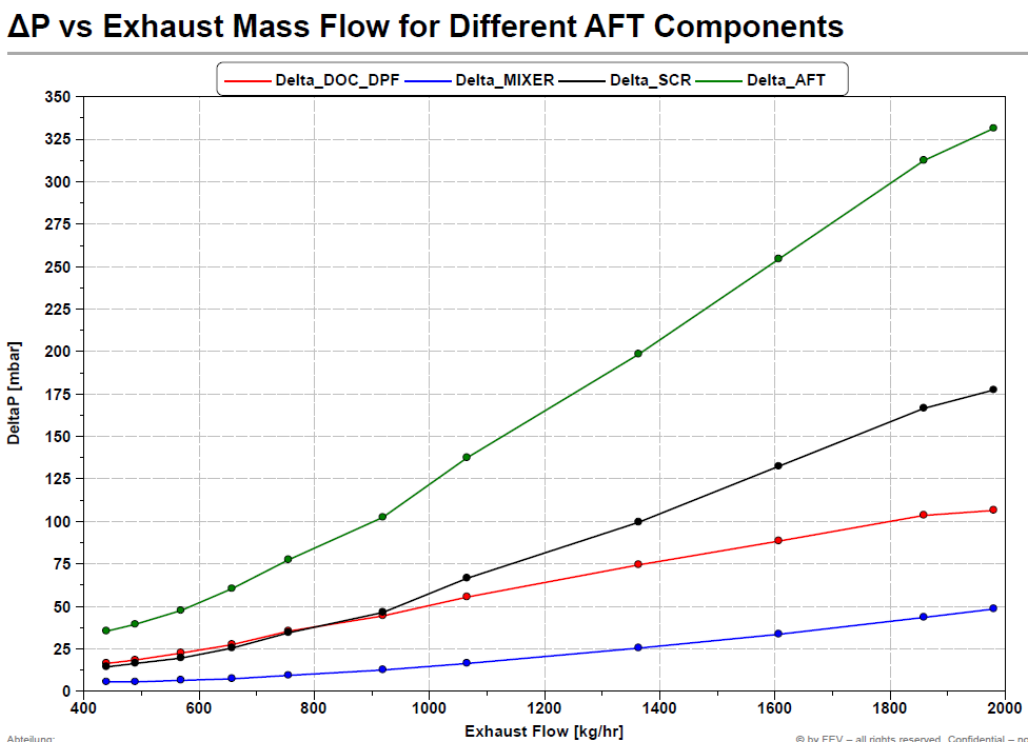

Figure 3. Back pressure consideration for initial configuration

Modification of aftertreatment system with two DPFs:

In order to minimize the system backpressure and to improve the engine out emissions, a different SCR substrate was used.

Additionally, a second DPF was also installed, which can be seen in Figure 4. Before the modification of the DOC/DPF inlet and outlet was done a CFD simulation was conducted to verify the uniformity of the flow in front of the DOC. The results were in a good range and the calculated backpressure as well. The mixing pipe and dosing position were not modified. Only the inlet and outlet box of the DOC/DPF system had been changed to separate and combine the exhaust flow (Figure 5). The fabrication process of the two boxes is shown in Figure 4.

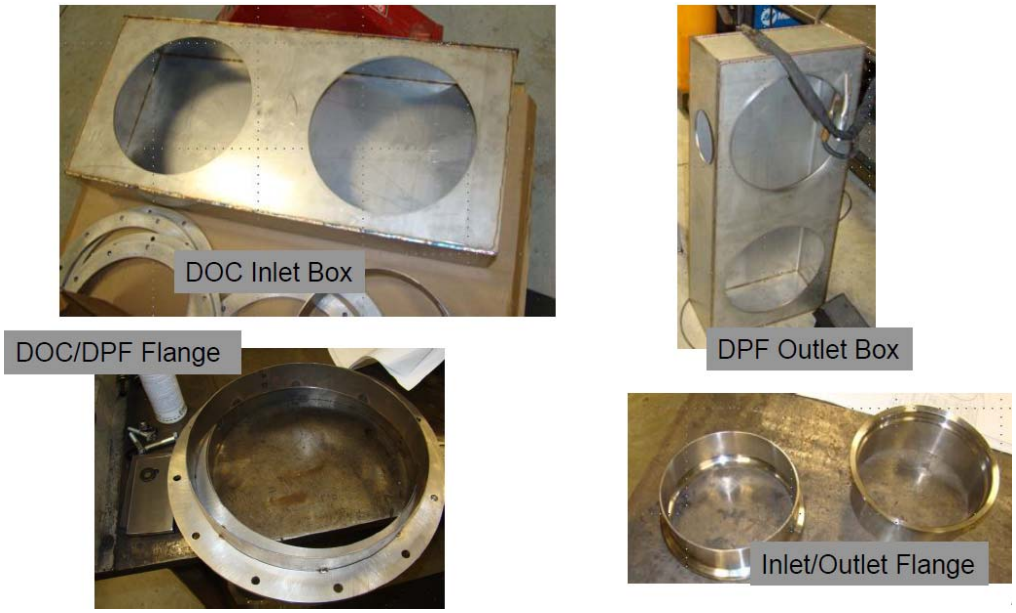

Figure 4. Fabrication of inlet and outlet box for DOC/DPF system

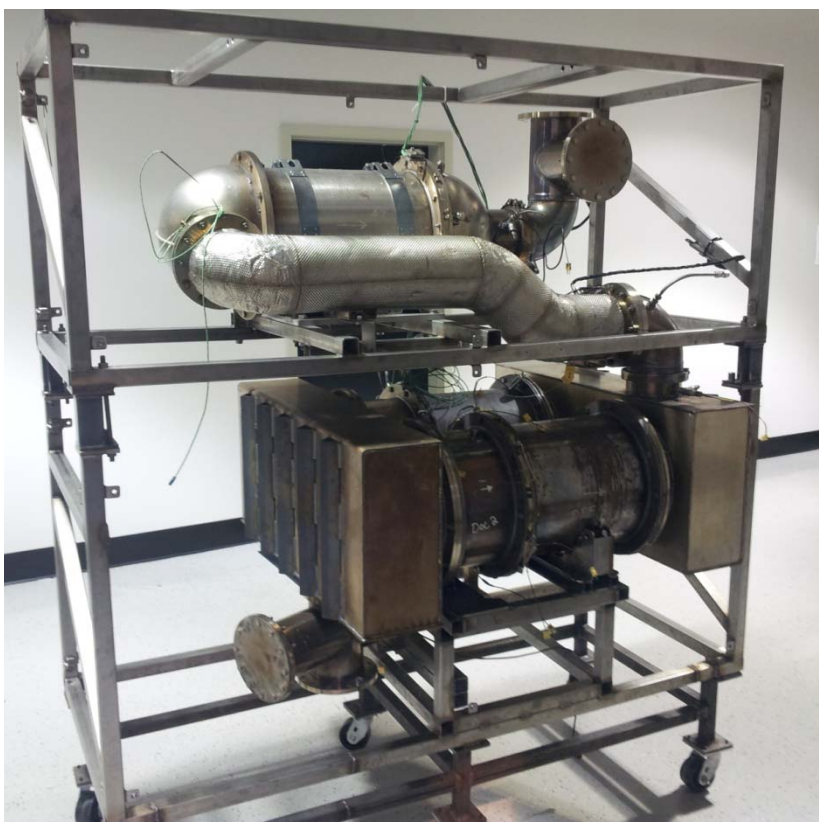

Figure 5. Entire after treatment system after modification

In addition the inlet and outlet boxes are enforced by metal sheets to prevent vibration of the incoming exhaust gas. The entire exhaust system including the frame can be seen in Figure 5. In this figure the bypass is not installed, but will be installed for the tests on the vessel in phase 3.

Backpressure verification

The backpressure was verified again by using the modified system configuration with two DOC/DPFs and one SCR system. In Figure 6 the pressure drop over every component and total backpressure is presented. The total system backpressure is reduced to 235 millabars (mbar), which ensures that the turbo charger temperature stays below the limit. Current value is around 700°Celsius whereas the critical temperature is around 730°Celsius. The points 1 to 5 represent the four certification points according to the E3 cycle and the idle operation (point 5).

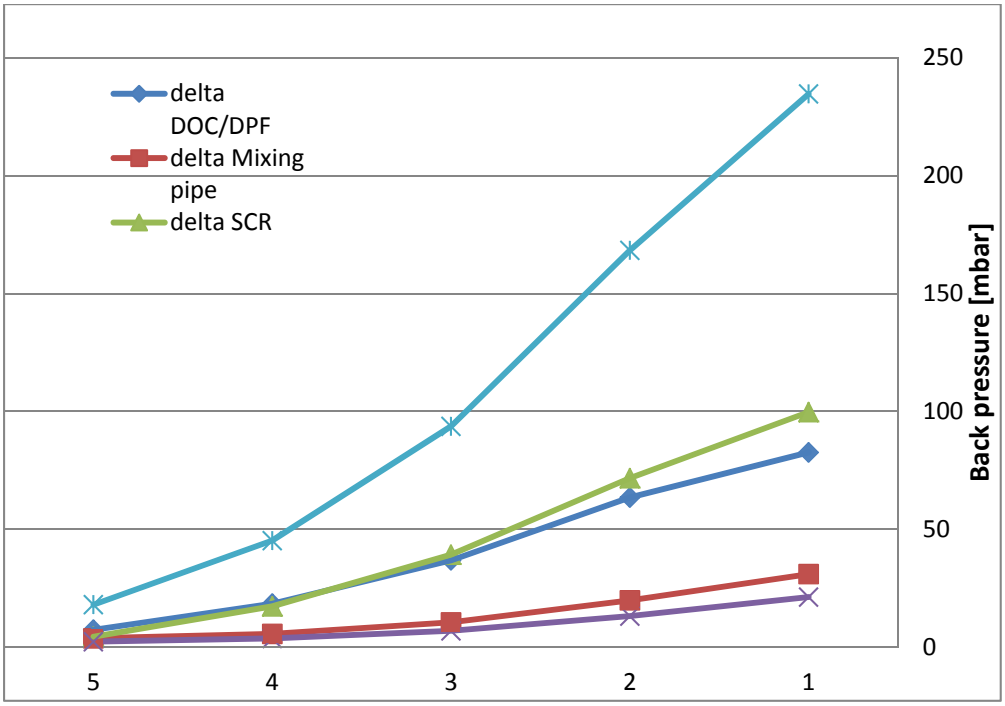

Figure 6. Back pressure consideration after modification of aftertreatment-system

DPF system during tug boat cycle

Figure 7 demonstrates that no active regeneration is necessary for this particularly engine. The accumulated soot is regenerated during full load operation when using the NO_2 based regeneration effect. This can be seen in terms of the backpressure, which was stable over 100 hours of running the transient tug boat cycle. It was also investigated that the flow in front of the DOC was equally distributed, which is also essential for an efficient NO to NO_2 conversion using a passive regenerated system.

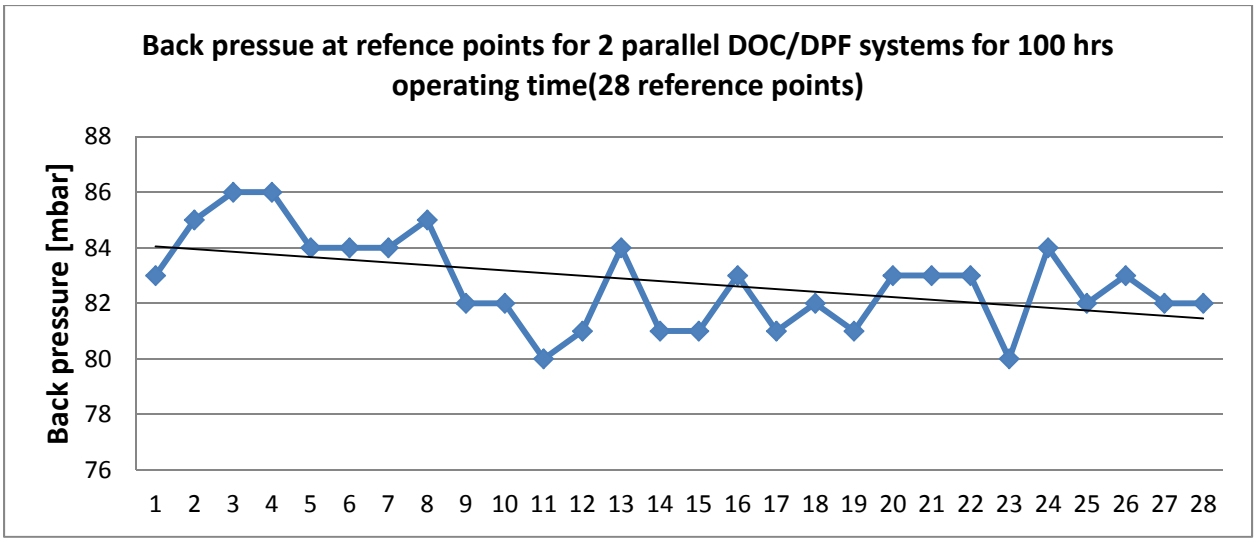

Figure 7. Back pressure of parallel DOC/DPF system for 100 hours operating time

Mixing pipe and dosing position

After several iterations of testing, the final mixing pipe design and dosing location were determined. Due to the long mixing pipe length and insulation, no mixer is needed and no deposits are identified because the dosing release temperature was set to 220°Celisus. The orientation of the urea dosing unit can be seen in the Figure 8, which has the same vertical axis as the inlet elbow pipe in front of the mixing pipe.

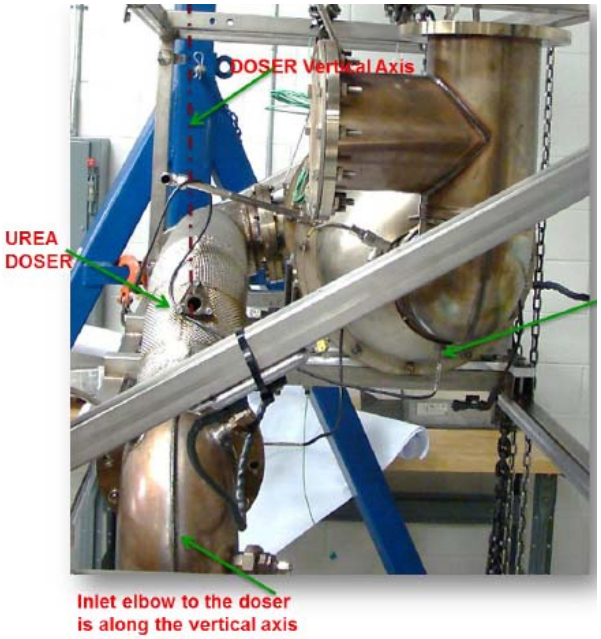

Figure 8. Mixing pipe and dosing position

SCR system calibration and E3 and tug boat cycle

The E3 test cycle according to ISO 8178 is the relevant cycle for the certification of the engine and the after treatment system. The following Table 1 provides the comparison of the conducted E3 tests during

the data collection for the engine baseline without the aftertreatment system, engine out with aftertreatment system and tailpipe data with a calibrated aftertreatment system. Appropriate conversion rates can be seen for NO_x (~86 %), PM, CO and HC. Based on the current EPA regulation this system is able to reach the Tier 4 final values, which are defined as NO_x 1.8 grams per kilowatt-hour (g/kWh) and PM 0.04 g/kWh.

Tested Criteria	Engine out baseline data (g/kWh)	Engine out data with aftertreatment system (g/kWh)	Tailpipe data with aftertreatment system (g/kWh)	Percent Reduction
NO_x	9.00	8.70	1.20	**86.7%**
PM	0.20	0.44	0.00	**100.0%**
CO	1.75	4.89	0.01	**99.2%**
THC	0.36	0.15	0.01	**96.5%**
Measured Fuel	218.10	213.90	213.90	**NA**

Table 1. E3 test results for engine baseline and with after treatment system

Furthermore the transient tug boat cycle was also investigated, which was collected in Houston harbor during the first measurement phase 1 to determine the baseline emission on the vessel. The magenta curve represents the NO_x conversion rate over the cycle, see Figure 9. Also the engine out NO_x (NOx_EO) in black and tailpipe NO_x (NOx_TP) in gray are displayed. The cumulated NO_x engine out and tailpipe illustrates the overall NO_x reduction ratio for this tug boat cycle.

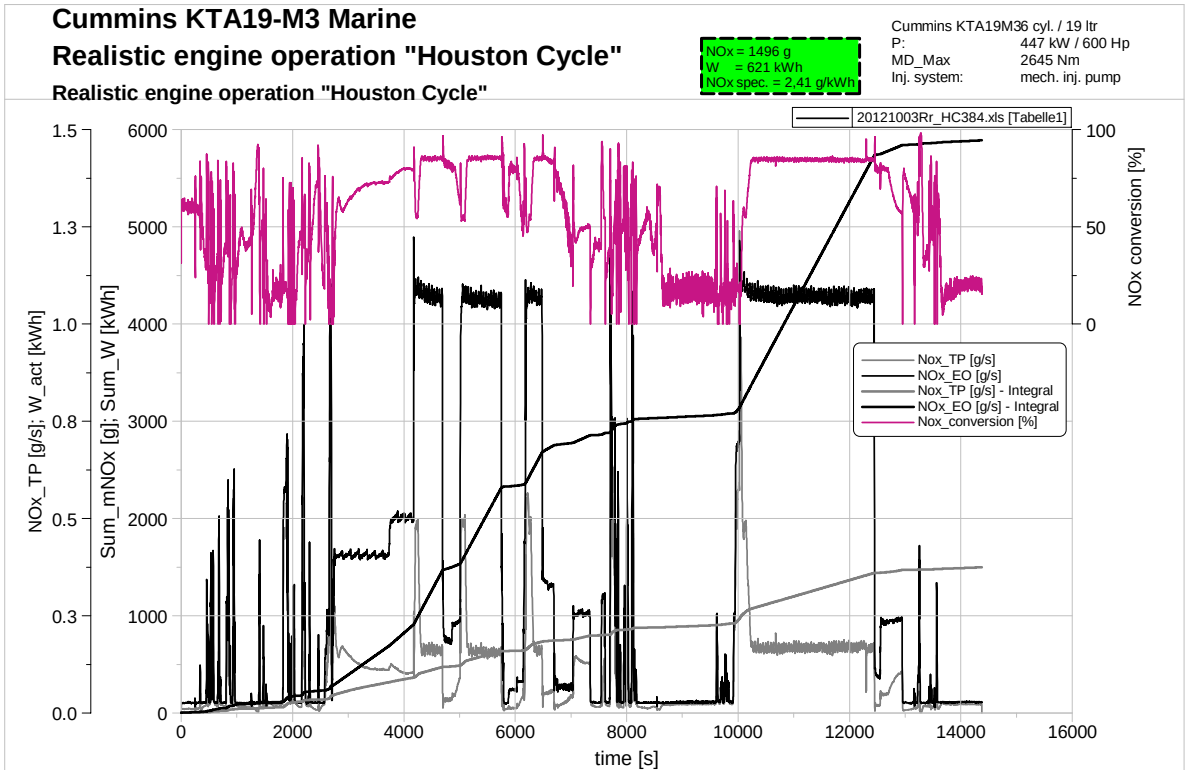

Figure 9. NO_x conversion, NO_x engine out and tailpipe over tug boat cycle

All relevant temperature values, which were monitored, are illustrated in Figure 10. In respect to the temperature distribution of the entire after treatment system, the temperatures from turbine inlet to temperature tailpipe are shown. It can be seen that the critical turbo charger temperature will not be reached anymore. Only moderate temperatures for the catalysts are detected within the first 2500 seconds, which also has an influence on the NO_x conversion.

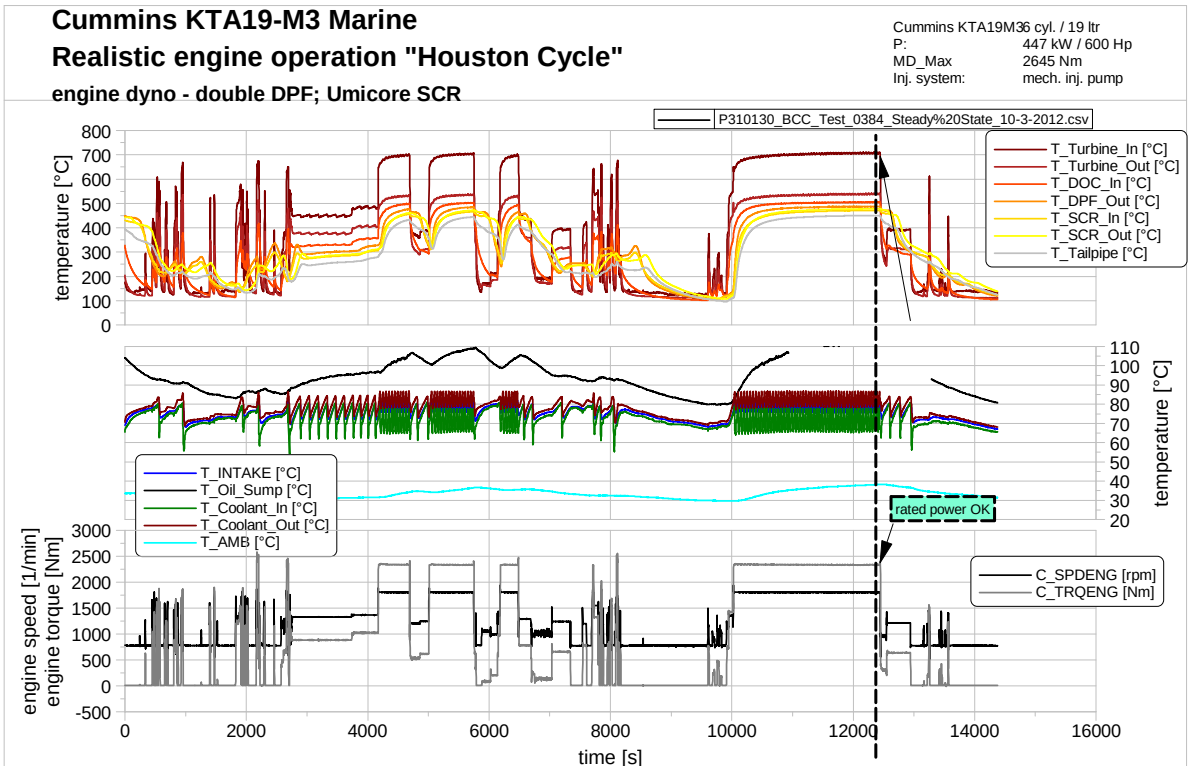

Figure 10. Relevant temperatures for engine and after treatment system over tug boat cycle

The goal of the urea dosing strategy was to avoid NH_3 slip after the SCR catalyst. This can be seen in the next Figure 11 with NH_3 values around 1 part per million (ppm).

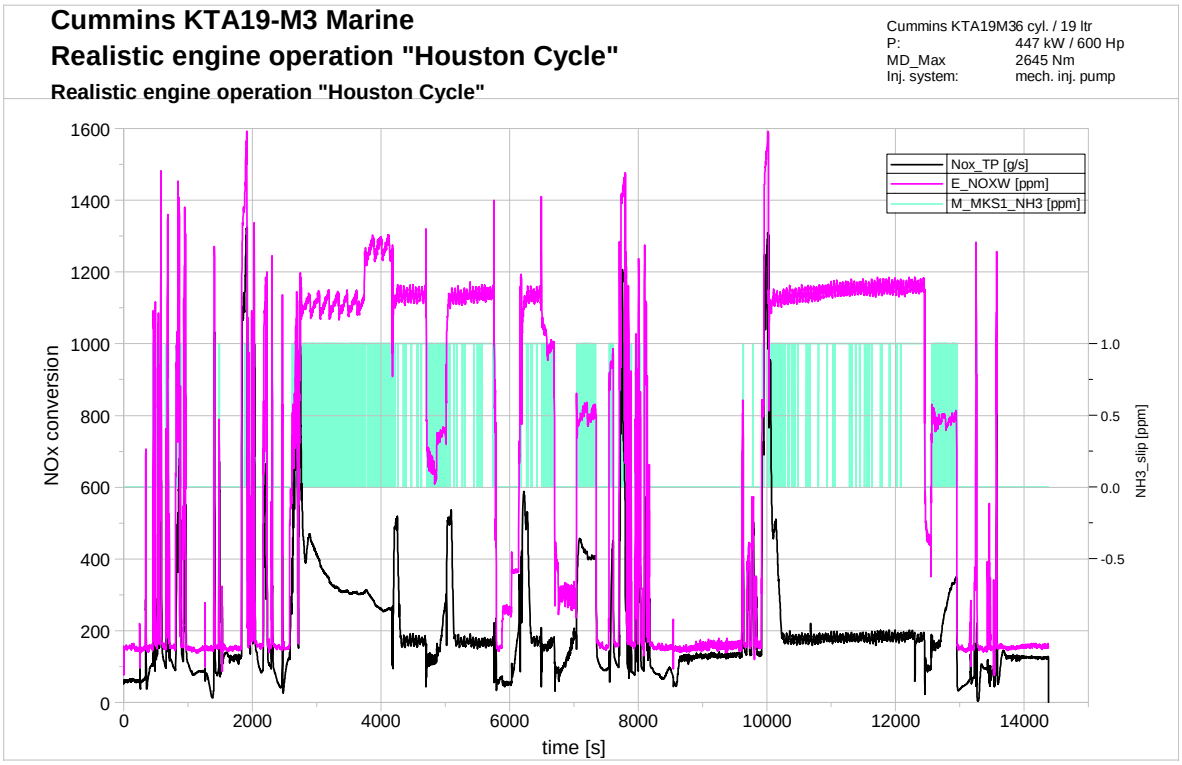

Figure 11. NOx engine out, NOx tailpipe, and NH3 slip

Discussion/Observations

Objectives vs. Results

The weighted NO_x value running the E3 test cycle is about 1.2 g/kWh, which can be improved by using a larger dosing module to increase the urea quantity. Furthermore, lower load points in the engine map can also be calibrated using higher urea rates. In case of running the tug boat cycle and in respect to the previous mentioned point the NO_x conversion rate was about 70%.

Filter loading and passive filter regeneration on the test bench was also successful within that time period by using two parallel particulate filters. Further long term investigation concerning the filter regeneration is useful with different applications and load profiles. Based on the conducted testing it is hard to predict how long the passive filter regeneration will perform.

Critical issues

Further long term investigation of passive regeneration using two parallel filters should be done before starting with the verification process.

Technical and commercial viability of the proposed approach

To date, no risks in achieving the initially-proposed commercial objectives of this development are seen. Technical barriers have not been identified.

Scope for future work

The following table is a summary of the remaining tasks and phases to be pursued and reported in the upcoming steps:

PHASE III	**Emissions Reduction on Marine Vessel**	**28-36**
Task 1	**Measurement of Actual Emissions Reduction on Marine Vessel**	**28-36**
1.1	Ship and install system on marine vessel.	28-31
1.2	Install PEMS equipment for emissions measurement. Minimum of two days testing with emissions during normal operation including raw and engine out emissions. Final calibration changes to the software.	31-33
1.3	Final analysis of data and report writing	33-36
Deliverable 1	*Verification of emissions reduction on vessel including a comparison of simultaneous raw and engine out emissions.*	*36*
MILESTONE III	**End of PHASE III: Report and Review of Deliverables 1**	**36**

Intellectual Properties/Publications/Presentations

None.

Summary/Conclusions

The installation of the marine engine including the developed after treatment system on the test bench has been accomplished. Baseline testing was conducted with a complete engine map, marine certification points, and a typical tug boat driving cycle. Furthermore a design change to reduce the system backpressure was completed. The calibration of the SCR system has also been finalized. The system will meet the EPA Tier 4 final limits for 2015 and demonstrate passive filter regeneration within the given tug boat driving cycle.

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