Marine Advanced Retrofit System

Deliverable 2 – System Design

for:

New Technology Research and Development Program

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Table of Abbreviations

DOC – Diesel oxidation catalyst

DPF – Diesel particulate filter

SCR – Selective catalytic reduction

NH3 – Ammonia

PM – Particulate matter

NMHC - non-methane hydrocarbon

HC – Hydrocarbon

CO – Carbon monoxide

NOx – Nitrogen oxides

DCU – Dosing control unit

DEF – Diesel exhaust fluid

Greek Letters

γ -- Flow uniformity index

Abstract / Executive Summary

This report describes the second deliverable of the Marine Advanced Retrofit System (MARS) project funded by the Texas Commission on Environmental Quality (TCEQ). According to the initial project plan, in the first phase - second task of this development, a marine aftertreatment system has been designed, simulations are being performed and system performance is under investigation.

Most importantly, the selection of the proper catalysts, diesel particulate filter (DPF) and selective catalytic reduction (SCR), for this aftertreatment system has been completed and integrated into the system design.

A compact aftertreatment system has been designed, taking into account expected space limitation on most vessels. This system will be further subjected to full calibration in an engine dyno.

Introduction / Background

The goal of this project is to develop a diesel emission reduction aftertreatment retrofit system that includes both, a SCR and a 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 (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 nitrogen oxides (NO_x) and particulate matter (PM) by 75% and 90%, respectively; i.e. it would reduce the emissions on US-EPA Tier 0 and 2 (current regulation) engines down to Tier 2 and Tier 4 engine levels respectively.

This stand-alone retrofit system will not only be 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 aftertreatment technology before the start of its production and distribution, anticipated to take place in 2012.

Project Objectives/Technical Approach

Phase 1 includes the identification of 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, amongst others. Also, in Phase 1, advanced engineering models and simulation tools such as CFD and 1-D 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 diesel soot filter.

In Phase 3, a prototype SCR-DPF aftertreatment system will be installed on the vessel and the conversion efficiency measured. Testing will be completed according to accepted industry standards.

Tasks

Phase 1: Task 2 - System design

2.1. Catalyst selection using engine baseline measurements from vessel

2.2. Urea delivery system: tank, hoses, supply and urea return lines

2.3. Layout of wiring harness

2.4. CAD layout using of the entire aftertreatment system

2.5. CFD Modeling and analysis

Phase 1: Task 2.1 - Catalyst selection using engine baseline measurements from vessel

The main target for the catalyst components of this aftertreatment system- diesel oxidation catalyst (DOC), DPF and SCR- is to reduce the emission species, notably unburned hydrocarbons (HC), CO, PM, and NO_x.

DOC, DPF, and SCR catalysts were chosen according to the engine power rating of 600 hp and measured engine data (see Deliverable Report 1 – Baseline measurements). This measurement is particularly important for proper selection of the catalysts' substrate size and the coating technologies (Table 1). Consideration of cost and performance indicates it is best to use standard Cordierite substrates for these catalysts. To keep the catalyst backpressure (hence, later on, the aftertreatment system fuel penalty) low, standard cell density and wall thickness combinations are being considered

Use of a passive particulate filter regeneration strategy for the DPF, also known as 'NO_2-assisted regeneration' of soot, in this system necessitates the presence of platinum in the DPF and DOC catalyst coating. Platinum coating allows formation of NO_2 in the DOC and accelerated reactions between NO_2 and soot/PM in the DPF. Platinum loading (grams of platinum per cubic feet of the substrate volume) is adjusted so to assure formation of 'sufficient' NO_2 for this 'passive' oxidation process of diesel soot. Also, typically a presence of a separate DOC immediately upstream of the DPF is needed to assure sufficient NO_2 formation.

Fitting the engine baseline emission measurement of NO_x, a SCR catalyst has been also chosen. This catalyst is expected to deliver the NO_x reduction conversion efficiency targeted for this system.

Table 1. Catalyst Selection: dimensions and data

Parameter	DOC	DPF	SCR
Volume (liter)	13	30	37
SV (1/h)	148.000	63.500	58.000
Pressure drop (mbar)	25	123	72

Phase 1: Task 2.2 - Urea delivery system design: Tank, hoses, supply and return lines:

As part of the preparation for the upcoming Phase 3, which will also include the installation of the urea tank and delivery system in the vessel engine room, the available space on the existing test vessel for the installation is measured. The observation on the test vessel in the Port of Houston shows that, for the purpose of the upcoming in-field demonstration, there are 3 potential space options available for installing the urea tank. This space consideration, particularly for the urea tank, is shown in figure 1. The preferred space on this vessel appears to be on the left and on the right of the engine room.

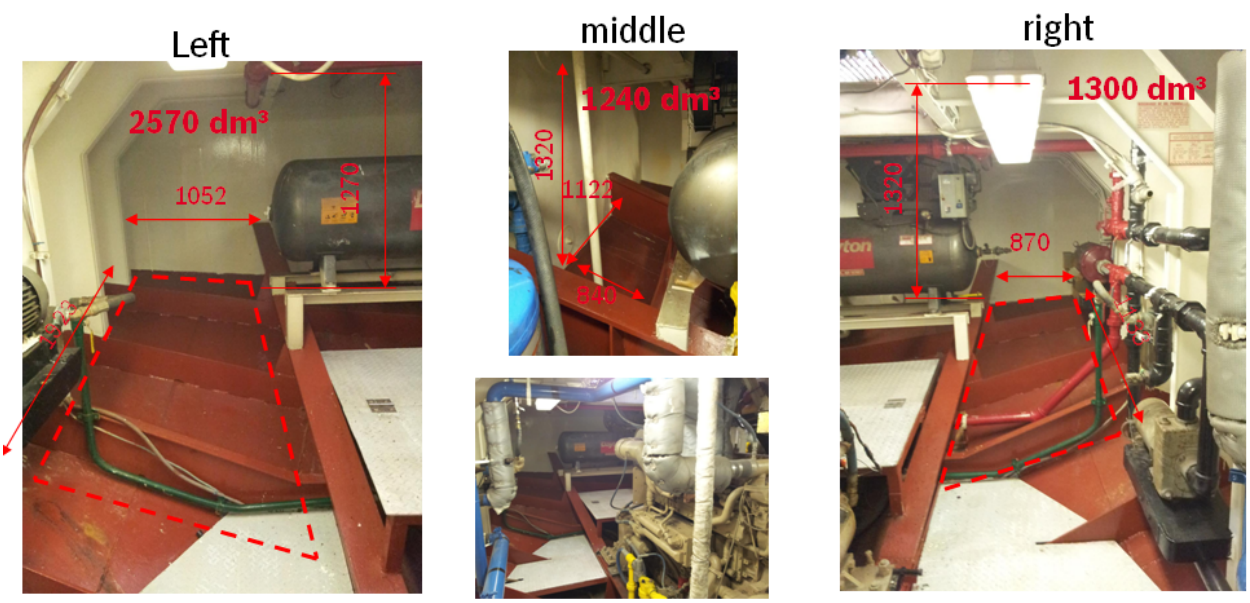

Figure 1. Potential spots in the vessel for installing the urea tank in the engine room

A Bosch urea supply system is integrated into this design. Figure 2 shows a schematic overview of the urea delivery system and the considered 'pumping head' of 2 meters. This supply module has one suction line from and one return line to the tank. The urea dosing module is supplied by the pressure line. Supply module and dosing valve are controlled by the dosing control unit (DCU) and as well the urea level and temperature in the tank. The tank design will also include a heating element to incorporate urea anti-freeze protection.

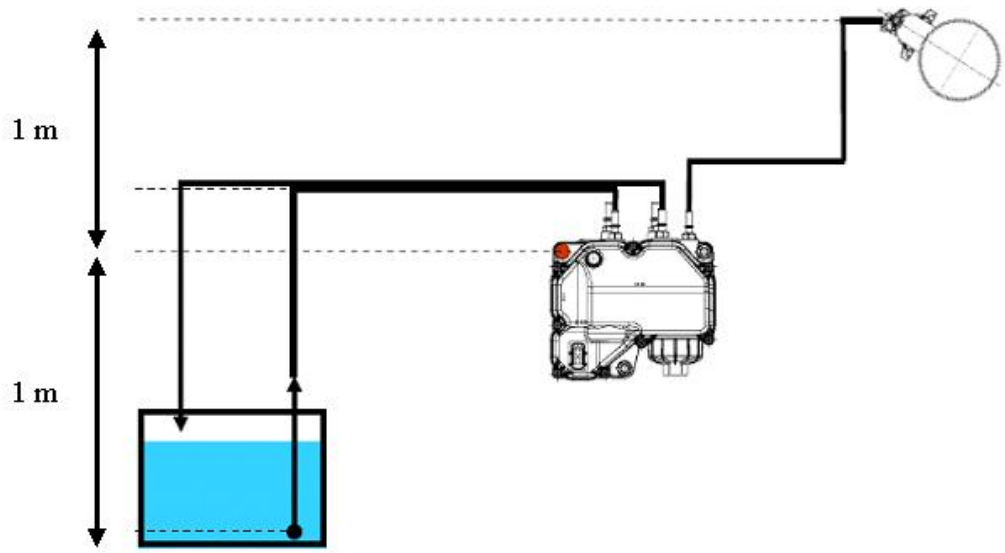

Figure 2. Schematic of the DEF [urea] system

Phase 1: Task 2.3 - Layout of wiring harness

Figure 3 displays a diagram of the overall system, including the electronic control unit, the catalysts, the urea tank and the urea delivery lines. The electronic control unit is the heart of the exhaust gas aftertreatment system; it is the 'command and control' center.

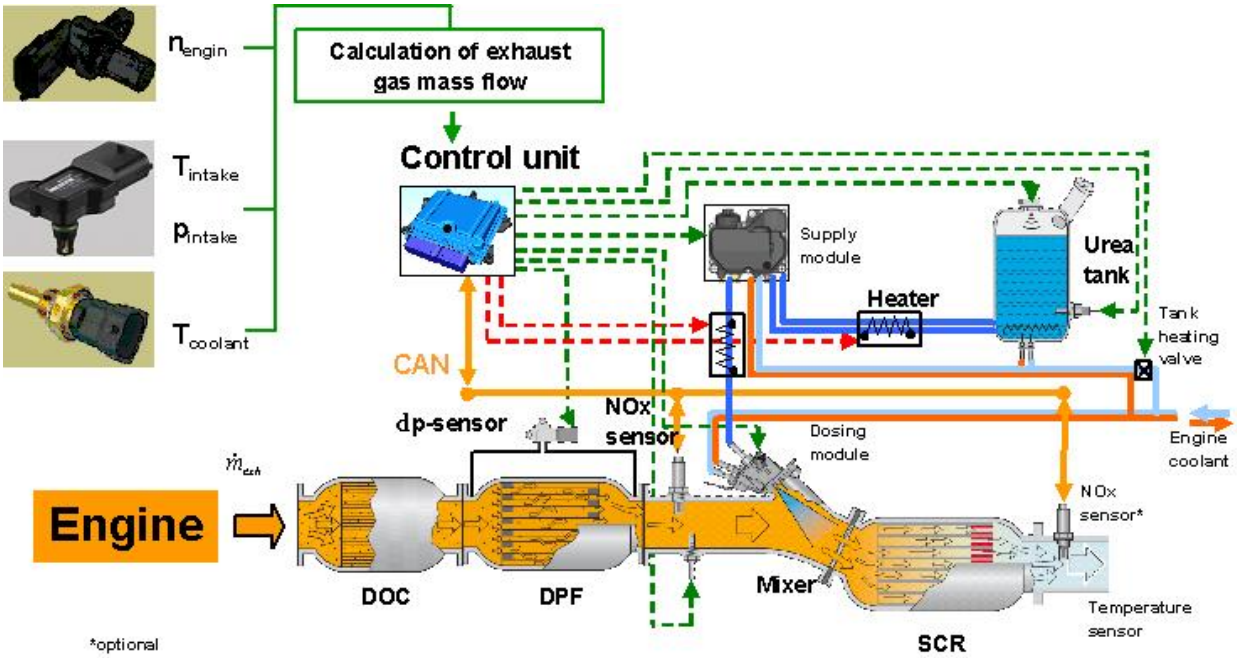

Figure 3. System overview including the control unit and the wiring

Many older engines still operating in marine vessels do not have an engine controller; this deprives an aftertreatment system certain information on engine functions, such as the engine exhaust mass flow rate needed for proper calibration and operation of the urea dosing strategy for the SCR catalyst. Therefore, to allow this system to calculate the engine exhaust mass flow rate, modified software will be integrated to read the engine speed sensor, boost pressure and temperature sensor; this information is then used by the controller software to calculate the engine mass flow rate.

The controller must be connected to and receive information from all the sensors and actuators in the aftertreatment system. Therefore, the wiring harness is modified for connecting to the controller unit so to send signals from temperature sensors (green lines) to the controller.

Preliminary information from marine supervisory organization Germanischer Lloyd (German Lloyd), an expert organization in mitigation of risks and assurance of technical compliance in marine platforms, indicates that a bypass exhaust pipe may need to be included in the aftertreatment system. In rare cases of component or system failure, or in an emergency (e.g. potential failures of the DPF regeneration or lack of urea in the urea tank), this bypass pipe can be used by the vessel operator to mitigate and control an otherwise risky operation of the aftertreatment system. However, this is only a temporary mean; the system must be checked and/or repaired by a qualified technician in the first available opportunity.

The controller unit software has been modified to interpret sensor signals (and other information sources in the system) and decide if it should prompt the vessel operator to consider a secondary measure, i.e. switching the exhaust system to pass through the bypass pipe, instead of through the main aftertreatment system.

The length of the wiring is designed to be flexible enough to accommodate engines in various vessel engine rooms, since the applicable distances could vary in length from one vessel to another.

Phase 1: Task 2.4 - Aftertreatment System Design Layout

Error! Reference source not found.~~Figure 4~~ illustrates the available installation space on the test vessel in Houston. This picture shows the upper deck of the engine room; the engine is on the ground floor (seen through the grid) and the exhaust pipe nearly vertically passes through the upper deck. This upper deck is being considered a favourable location for installing the aftertreatment system as it allows proximity to the engine itself for fast catalyst light-off considerations.

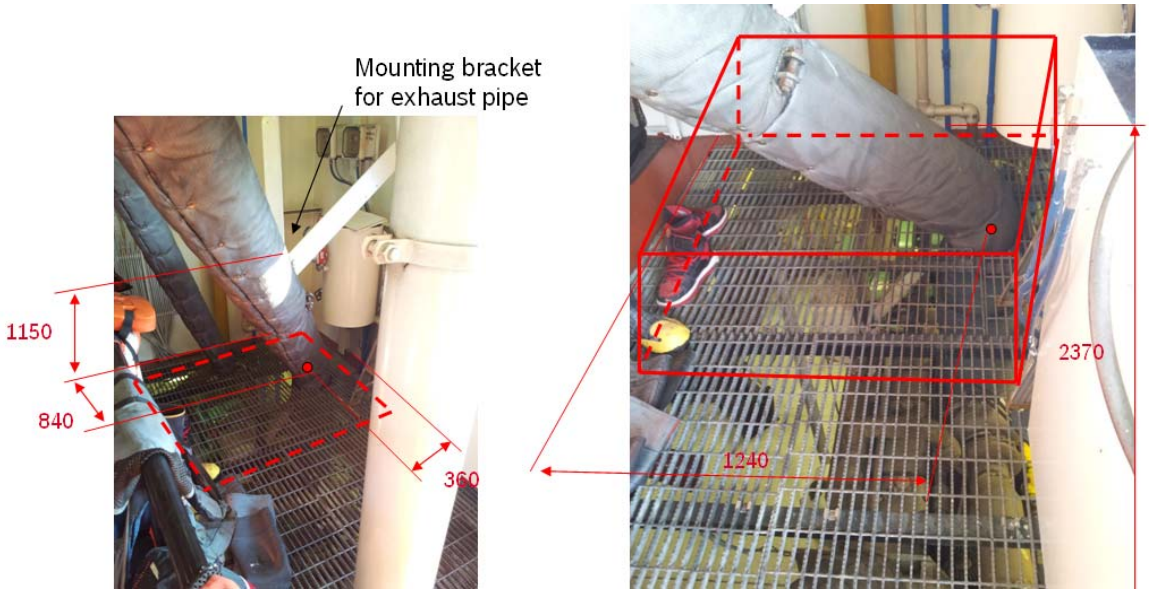

Figure 4. Installation space for Aftertreatment system on the vessel

The aftertreatment design is exposed in figures 5, 6 and 7. Following the approach taken for designing many off-road emission aftertreatment retrofit systems, the packaging design allows a compact aftertreatment system to fit in most vessels. This packaging design also allows a relatively fast and simple removal for a catalyst, in the event of its failure or a need to service or exchange a component or to clean a DPF during the scheduled DPF ash cleaning service intervals.

Error! Reference source not found.~~Figure 5~~ displays the package and its internal components. The steel frame is built so to allow each substrate or component a well-defined, compartmentalized mounting position. The frame may be disassembled into an 'upper' half, that includes the SCR and the urea dosing system, and a 'lower' half, encompassing the DOC-DPF assembly only. This flexibility provides two distinct benefits, amongst others: it allows ease in shipping, handling and installations of the system, and also flexibility in fitting the system and its components in a variety of vessel platforms. Furthermore, some platforms may only require just a PM reduction or only a NOx reduction sub-system; this design approach accommodates such platforms via installing merely the proper DOC-DPF 'or' the SCR sub-system.

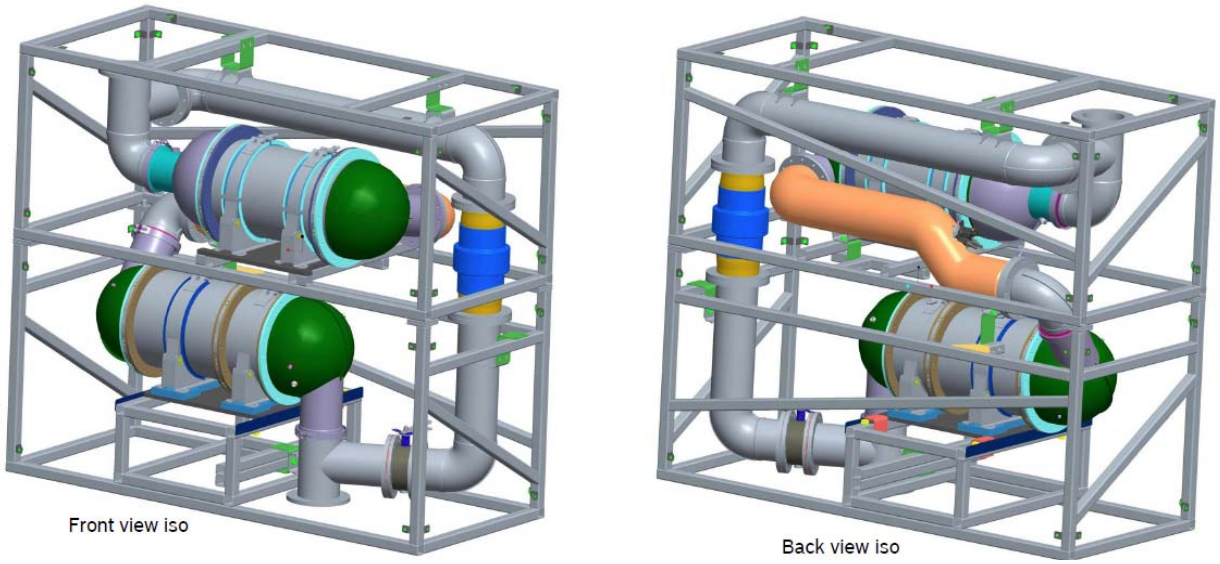

Figure 5. Design assembly seen via back-iso and front-iso views

Error! Reference source not found.~~Figure 6~~ shows the relevant aftertreatment components. The interface to the engine is the flange on the bottom of the exhaust system. The flow enters the system and passes the DOC/DPF unit. After that, it follows the mixing pipe (illustrated in orange), where the dosing valve is mounted. Before the exhaust gas leaves the system, the last component that it flows through is the SCR unit.

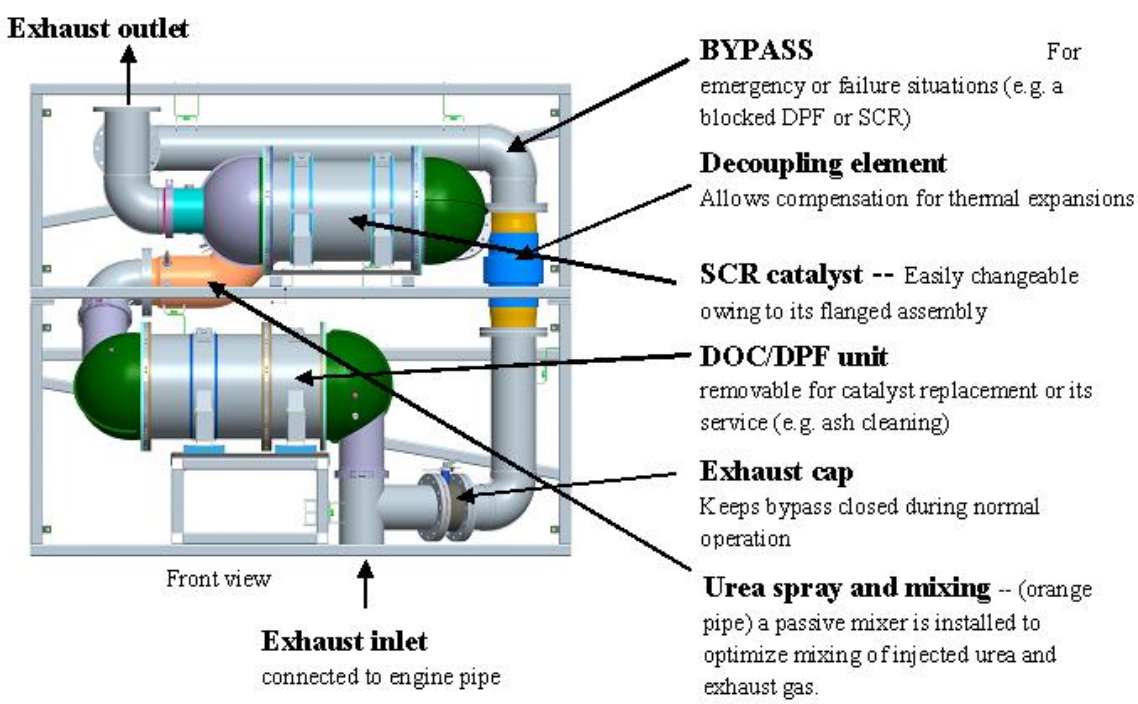

Figure 6. Description of components' lay-out in the current design

A Bosch monitoring system controls the exhaust system status with special focus on the bypass valve status. According to the German Lloyd standards, a bypass is required in case of an emergency; examples include filter clogging or urea deposits that can cause an engine failure or shut off. In this case, the bypass can be opened manually by the operator and allow the vessel operation to continue.

The exhaust gas heat induces modest expansions in the pipes and metal components. Some of the engines are equipped with a decoupling element attached to the turbo that absorbs these expansions. For engines not equipped with this decoupling piece, Bosch exhaust system will provide the needed a component (not shown in Figure 6.) The expansion in the bypass pipe is accommodated by a decoupling element, as well illustrated in Figure 6. Figure 7 shows the complete assembled aftertreatment system.

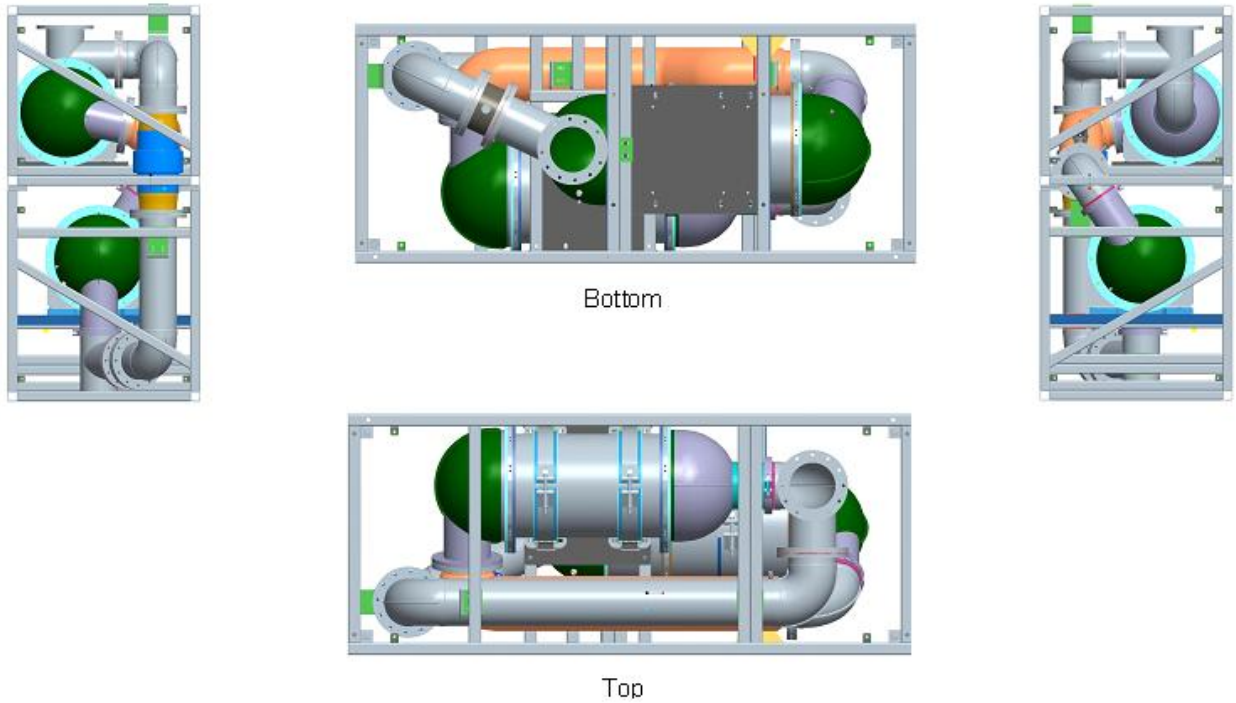

Figure 7. Various views of the aftertreatment system assembly: Back, bottom, top, side views

Phase 1: Task 2.5. - 3-D CFD and 1-D Emissions Modeling and Analysis:

It is common practice to use computational means in order to predict component and system performance in various operating conditions. There are two modeling tools for this: one-dimensional (1-D) models, commonly used for predicting temperature and reactions light-off behavior in catalysts, and Computational Fluid Dynamics (CFD), a well-accepted practice in designing aftertreatment systems and in predicting their performance. Both 1-D and CFD are adequate tools for predicting component or system functions subjected to extreme conditions, like low temperature or high soot loading operations, amongst others.

CFD Simulation

In this design approach, CFD was used to predict flow distribution in DOC and DPF, and the urea spray droplet distribution, transport and evaporation in exhaust gas and its conversion to gaseous ammonia (NH_3) and isocyanic acid (HNCO) upstream of the SCR catalyst. Particular attention has been paid to achieving optimal flow uniformity at the entrance of the DOC, DPF and SCR; this in order to achieve rapid thermal and chemical light-off, acceptable CO and HC oxidation and adequate NO-to-NO_2 conversion in the DOC and achieve acceptable flow uniformity at the entrance of the SCR catalyst and DPF substrates.

Error! Reference source not found.~~Table 2~~ illustrates the boundary conditions used for the CFD Simulation. Two operation points were considered: OP1 and OP2. OP1 resembles a high flow rate and a high temperature exhaust flow in the aftertreatment system equivalent of a full load operation of the vessel engine. OP2 represents a low flow and low temperature case indicating a half load state.

Table 2. Boundary conditions for CFD analysis

Operation Point	Inlet Condition: Mass Flow (kg/h)	Inlet Condition: Temperature (C)	Outlet Condition: Static Pressure (bars)
OP1	2500	400	1
OP2	400	280	1

Error! Reference source not found.~~Figure 8~~ displays the flow uniformity (γ) in the DOC substrate inlet. A theoretical ideal value of $\gamma = 1.0$ represents an equal distribution of exhaust flow amongst all channels of the catalyst substrate. In practice, a value of $\gamma \geq 0.9$ is needed for a catalyst optimal performance.

The 90-degree bend upstream of the DOC results in an increased flow velocity at the outside radius of the inlet cone. However, the DOC uniformity values for OP1 and OP2 are near to 0.93 and 0.99, respectively.

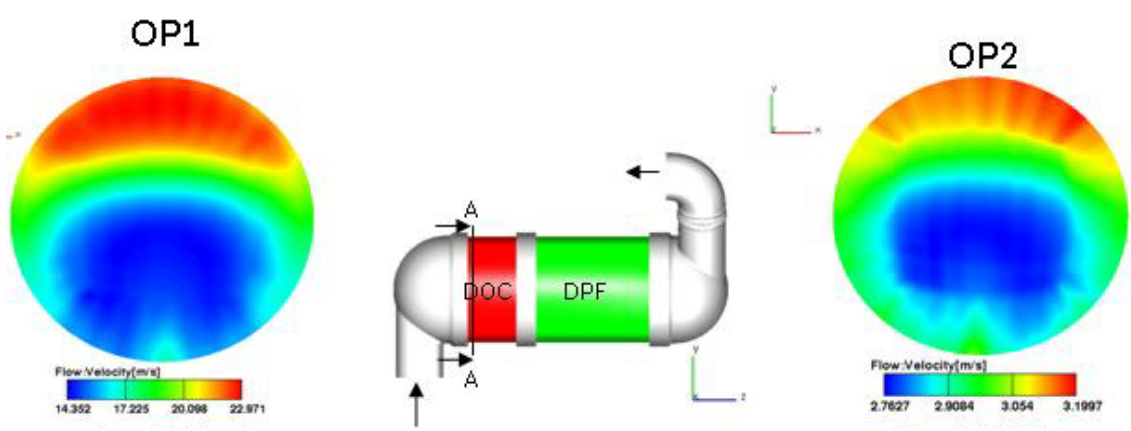

Figure 8. Velocity uniformity at the DOC inlet

Error! Reference source not found.~~Figure 9~~ displays the flow uniformity index (γ) at the DPF entrance, which has the value of 1. Here, γ is improved as the flow moves from the DOC to the DPF inlet. This is due to the effect of the DOC honeycomb structure on the flow, which essentially acts as a flow straightener by removing flow streamline curvatures.

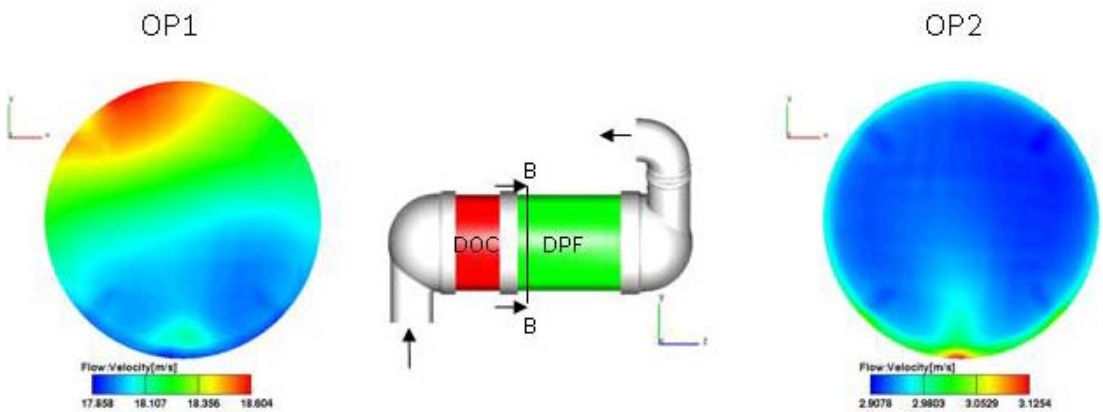

Figure 9. Flow uniformity at the DPF entrance

This improvement enhances passive regeneration behaviour inside the DPF by providing proper distribution of flow and, hence, NO_2, inside the DPF channels.

Error! Reference source not found.~~Figure 10~~ depicts the SCR catalyst and the piping upstream of the SCR (that includes the mixing pipe and the urea dosing injector used for injecting urea spray inside the exhaust gas and its decomposition into ammonia.

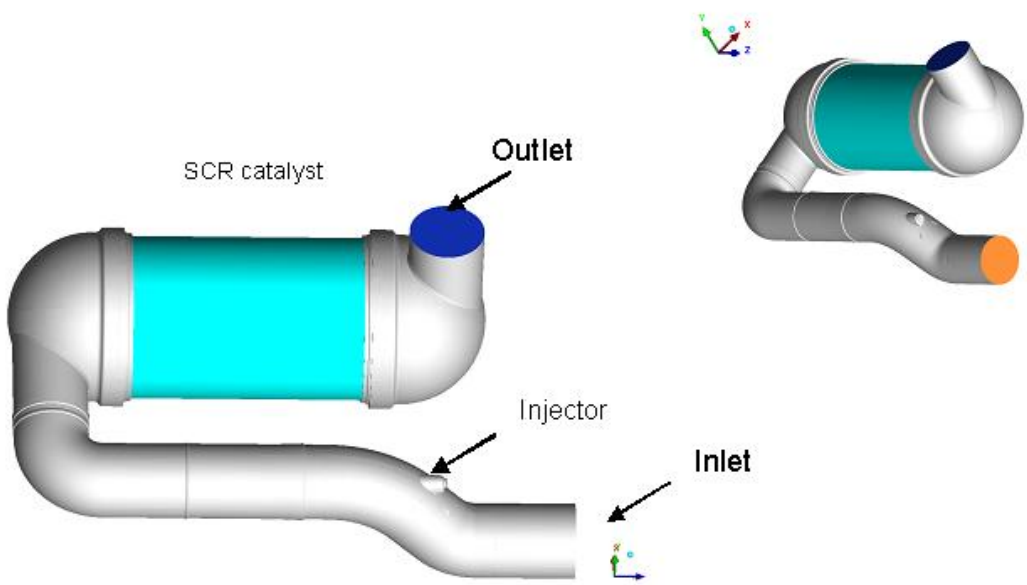

Figure 10. SCR System used in the CFD simulation

Error! Reference source not found.~~Figure 11~~ shows the CFD simulation of flow streamlines upstream of the SCR catalyst. The bends in the mixing pipe produce eddy structures in the inlet cone at the SCR catalyst inlet.

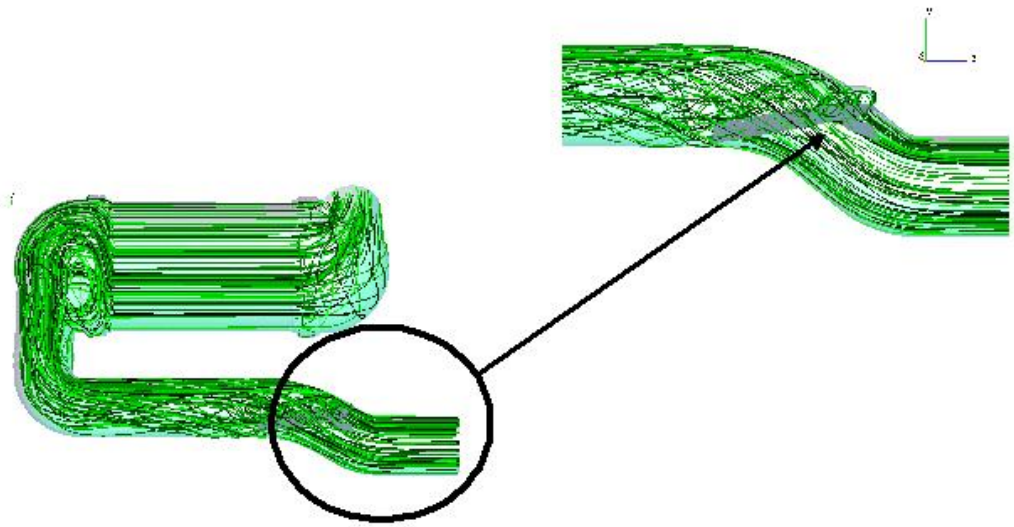

Figure 11. Flow streamlines in the mixing pipe upstream of the SCR catalyst

However, analysis of flow uniformity index (γ) show that this effect is minimal, as the SCR inlet flow uniformity indices for both OP1 and OP2 have nearly ideal values of 0.98 and 0.99, respectively.

The agents that reduce NO_x in the SCR catalyst include unevaporated urea droplets and gaseous isocyanic acid (HNCO) and are mixed with the exhaust gas upstream of the SCR catalyst. A proper distribution of the reducing agents is necessary to achieve acceptable levels of NO_x reduction. Simulation results indicate γ-values of the reducing agents of 0.94 and 0.91 for OP1 and OP2, respectively, and are displayed in Figure 12.

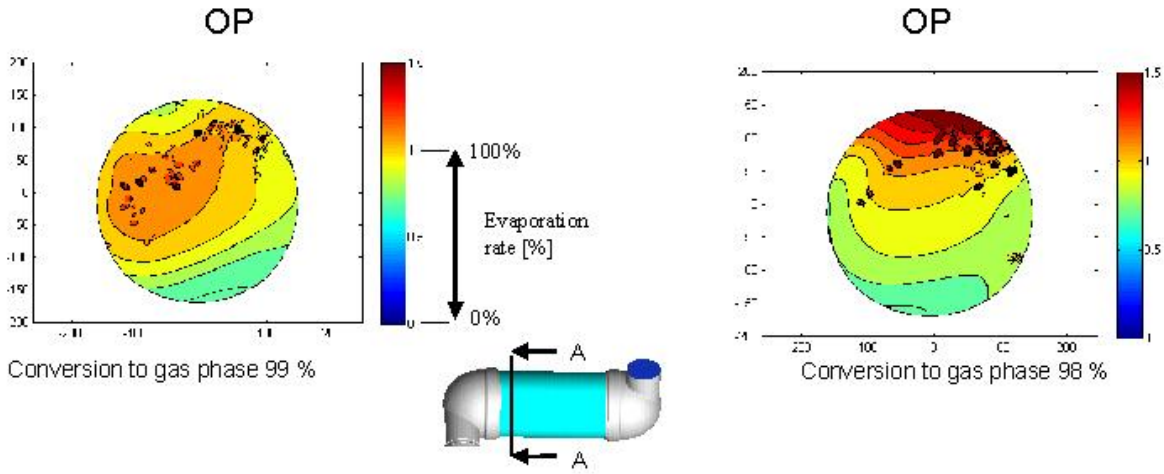

Figure 12. Ammonia distribution in front of SCR catalyst

During engine operation modes resembling OP1 and OP2, injected urea droplets nearly totally evaporate (by 99%, 98%). The dots in the figure illustrate the remaining unevaporated droplets, accounting for only 1-2% of the injected liquid urea.

During the upcoming dyno testing of this aftertreatment system, it will be tested if solid urea deposit will form in the exhaust pipe downstream of the urea injection point. If required, the current mixing pipe used here will be replaced with one including a mixer, which could substantially remove the likelihood of formation of urea deposit. This is to be further investigated in the coming phases.

Simulation of Temperature Using 1-D Model:

Aftertreatment components typically perform best when they reach and surpass their so-called light-off temperature. Light-off temperature itself is best achieved when the catalyst is positioned as close to the engine-out location as possible (most commonly called 'closed-couple' installation.) This proximity is especially important in retrofit systems since, typically, an exhaust pipe needs to be situated between the engine-out location and the entrance of the first catalyst (typically a Diesel oxidation catalyst). Also, urea dosing is expected to be released in the exhaust gas when the exhaust temperature reaches 200°C; NO_2-assisted oxidation of soot in the DPF at about 250°C, as shown in **Error! Reference source not found.**~~Figure 13~~. In brief, the closer the aftertreatment system entrance to the engine-out location is, the better the temperature light off and emission reduction performance.

Error! Reference source not found.~~Figure 13~~ displays simulation of light-off temperature in the aftertreatment system using the engine duty cycles, as observed in the baseline emission measurement performed previously on the vessel. The simulation indicates that the DOC has a rapid light-off and closely follows the exhaust gas temperature, reaching the 200° C target temperature in about 500 seconds after the engine starts. NO_2-assiasted soot oxidation in the DPF is well established after nearly 1900 seconds, when the DPF reaches the target 250° C. At the end, the SCR catalyst achieves a temperature of 200° C, needed for urea dosing, at about 2000 seconds. These modeling observations will be fully investigated and scrutinized during the upcoming dynamometer testing of this aftertreatment system.

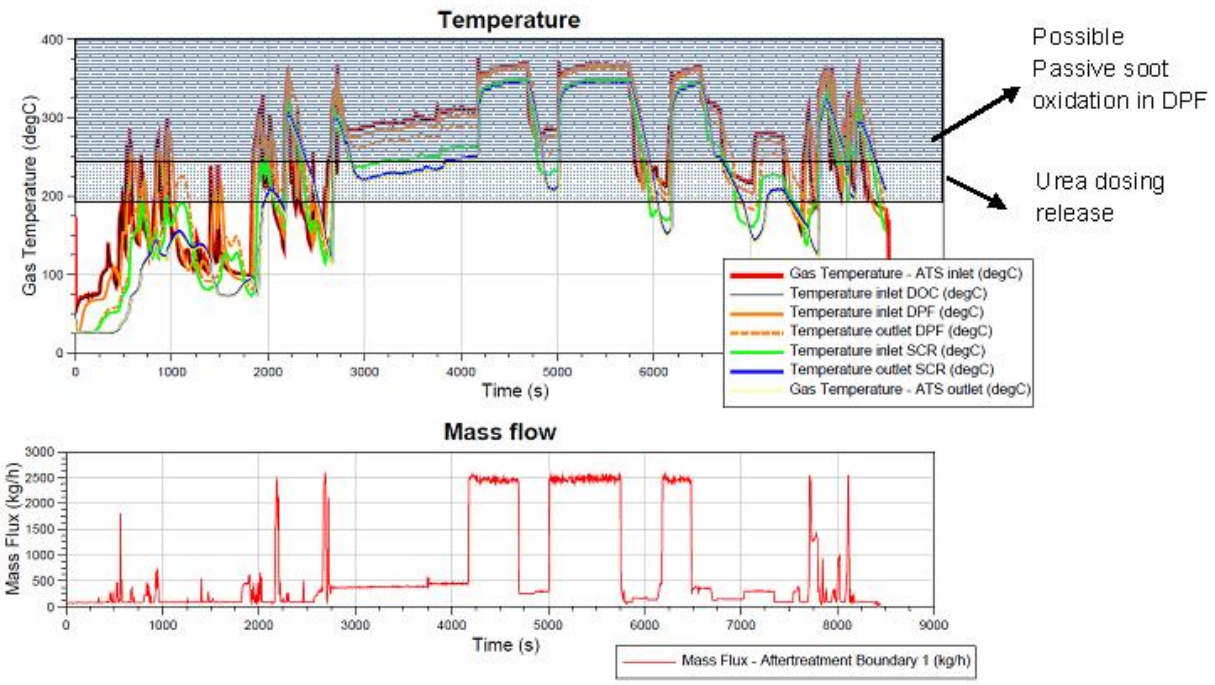

Figure 13. Simulated Temperature profile over EGT-System

Discussion/Observations

Objectives vs. Results

For Phase 1, Task 2 all the proposed objectives were achieved. The aftertreatment system was designed based on the requirements, e.g. space limitations, box solution and robustness. The results of CFD simulation confirmed the initial assumptions.

No urea deposits were identified. SCR performance will reach more than the proposed 75% conversion rate.

Theoretical NO_x/PM ratio for CRT and temperatures is high enough for good regeneration results.

Critical issues

Urea deposits

Contrary to expectations, the CFD analysis indicated that no urea mixer is needed. A detailed investigation during the upcoming dyno testing will clarify the need.

Technical and commercial viability of the proposed approach

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

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/TASK	DESCRIPTION	WEEKS
PHASE II	Dynamometer Testing	6-28
Task 1	System Installation and Baseline Measurements	6-13
1.1	Procure all components of aftertreatment system including DPF, DOC, SCR catalyst, SCR supply module, SCR dosing module, SCR control unit, sensors and exhaust pipes.	8-16

1.2	Engine selection and purchase. Purchase marine engine with identical marine emissions rating. Similar displacement and exhaust flow rate.	6-8
1.3	Install engine (without aftertreatment) on engine test bed. Instrument engine for test bed measurements and emissions measurement (PM, NO_x, CO, HC)	9-12
1.4	Baseline raw emissions measurement without aftertreatment. Comparison with baseline marine vessel data.	12-13
Deliverable 1	Baseline raw emissions on test bed and comparison of raw emissions between test bed and actual marine vessel.	13
Task 2	Final Design Changes, Measurement of Emissions Reduction	16-28
2.1	Install aftertreatment system.	16-18
2.2	Final design changes to system and emissions measurement with aftertreatment. Several iterations of the design are anticipated to determine final mixer location and design, mixer location, dosing location and orientation. Durability study to determine deposits. Catalyst characterization and calibration of software. Determine proper NO/NO_2 ratio. Change out catalyst design to optimize emissions reduction. Measurement and optimize for minimum ammonia slip.	18-28
Deliverable 2	Final system design for marine vessel. Measurement of emissions reduction.	28
MILESTONE II	End of PHASE II: Report and Review of Deliverables 1, 2	28
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 to this point.

Summary/Conclusions

After completing the baseline emission testing on the vessel and the data analysis, the aftertreatment system for marine application was designed. Components have been procured. Flow and temperature response of the system analysis with CAD design, CFD and 1-D simulation was completed. Urea (DEF) injection system, including the urea tank, was allocated and the control system, wiring and most hardware was prepared. An engine was procured and dyno testing of this aftertreatment is to start soon.

It is anticipated that, consistent with the initial target, the proposed aftertreatment system will be able to provide the NO_x and PM emission reduction by 75% and PM 95%, respectively.