



# HERCULES-2 Project

*Fuel Flexible, Near Zero Emissions, Adaptive Performance Marine Engine*

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Literature review regarding SCR engine integration and particulate abatement.

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# 1 Executive Summary

The ship emissions are regulated considerably via MARPOL Annex VI convention of the International Maritime Organization (IMO). These regulations aim to reduce progressively the emissions of sulphur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>).

Diesel particulates have also been subject to diesel emission regulations worldwide. In September 2014, the European Commission adopted a proposal on new requirements relating to emission limits and type-approval for non-road engines, including inland navigation vessels. The proposal includes the introduction of a new emission stage (Stage V), which includes a number of important changes. It widens the scope of regulated engines, strengthens the emission limits, and furthermore, adopts particle number emission limits for several categories. The particulate number limits can be seen as a tool to limit ultrafine particulates from diesel engines, which are known to play the largest role in affecting human health.

These new emission limits will eventually require many ships to apply efficient exhaust gas after-treatment technology. SCR is still considered the most appropriate technology to meet the tightening marine emission limits for the NO<sub>x</sub>. The aim of the present study was to explore both the compact SCR system solutions and available after-treatment methods for the removal of exhaust PM. Regarding the compact SCR system solutions, the main target was to research fresh and the latest ideas and innovations which enables SCR packing as close as possible to engine structures.

As for diesel particulate matter, it is an extremely complex mixture of organic and elemental carbon, acids, such as sulphates and nitrates, metal ashes, particle-bound water and soluble organic compounds. Numerous epidemiologic studies in recent years have consistently linked particulate matter emissions in the ambient air to negative health effects for exposed populations. One of the main findings is that the size of particles is a crucial factor behind the observed health effects.

Regarding the PM removal, the main target was to research with which kinds of exhaust gas after-treatment solutions a marine dual fuel engine could fulfil the future tightening PM emission standards in inland waterway transport in Europe, both in gas and diesel fuel use.

The first part of the study consists of literature reviews regarding close-coupled SCR systems and abatement measures for diesel particulates. In this part, the pressurized SCR concepts and layouts for medium and low-speed engines will be presented shortly. The latest information regarding the design aspects of an SCR system and operating constraints due to high-sulphur fuels will also be discussed.

This part also serves as a general technology guide for particulate emission abatement from diesel engines, including catalytic converters, particulate filters, and auxiliary systems for supporting filter regeneration. Among these techniques, diesel particulate filters with high filtration efficiency and good regeneration characteristics were considered the best option.

In the second part of the study, different supplier technologies and solutions were evaluated. Commercially available latest innovations with relation to compact exhaust after treatment systems, particularly used in off-road heavy machineries, are presented. The targets for particulate filtering system were defined and a specific inquiry was sent to potential suppliers. Based on the replies, passive diesel particulate filter systems with catalytic coating or/and an upstream diesel oxidation catalyst can be regarded as the primary choice for particulate emission control in inland navigation.

## 2 Introduction

In order to inhibit the pollution of the earth atmosphere, the emissions of transportation are regulated worldwide. There are also emission related limitations towards the ships of different sizes. The ship emissions are regulated considerably via MARPOL Annex VI convention of the International Maritime Organization (IMO). These regulations aim to progressively reduce the emissions of sulphur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>). The latest, IMO Tier III emission regulation came into force at the beginning of 2016 concerning the marine diesel engines that were installed on a ship constructed on or after 1 January 2016. (IMO 2016.)

Diesel particulates are also subject to diesel emission regulations worldwide. The first European Union wide compulsory emission limits for inland waterway vessels were introduced with Directive 97/68/EC on non-road mobile machinery, which has applied to new vessels since 2004. The currently applicable Stage IIIA standards within this framework are now under revision. (Panteia 2013: 19.) In September 2014, the European Commission proposed a new regulation on requirements relating to emission limits and type-approval for internal combustion engines for non-road mobile machinery, including inland navigation vessels. The proposal includes the introduction of a new emission stage (Stage V) which widens the scope of regulated engines, strengthens the emission limits, and furthermore, adopts particle number (PN) emission limits for several categories. (DieselNet 2015.) The particulate number limits can be seen as a tool to limit ultrafine particulates from diesel engines, which are known to play the largest role in affecting human health (Pauli 2016: 511).

The new type approval dates are expected to enter into force gradually from 2018 to 2020. After this, new emission limits will eventually require many ships to apply an efficient exhaust gas after-treatment technology. The manufacturers of off-road engines have to also take different emission technologies into use due to tightening emission regulation. The use of diesel particulate filters (DPF) or a selective catalytic reduction (SCR) catalyst coated DPF are especially mandated by the EU Stage V standard. (Nathan 2016.)

The objective of the study was to explore both the compact SCR system solutions and available after-treatment methods for the removal of exhaust PM. Regarding the compact SCR system solutions, the main target was to research fresh and the latest ideas and innovations which enables SCR packing as close as possible to engine structures. For that reason, the question regarding the effective urea mixing at short distances is also dealt with.

Regarding the PM removal, the main target was to research with which kinds of exhaust gas after-treatment solutions a marine dual fuel engine could fulfil the future tightening PM emission standards in inland waterway transport in Europe, both in gas and diesel fuel use

A literature review was first conducted concerning both close-coupled SCR systems and PM reduction systems. A number of SCR manufacturers and PM reduction system suppliers were contacted. Fresh and the latest ideas and innovations were collected by investigating commercially available compact exhaust after-treatment systems used in off-road heavy duty engines. For additional information, the different machinery manufacturers and their Finnish representatives were also contacted. Because of the information related to the topic, the results from the contacted companies remained low. Moreover, available static mixer solutions for a compact design marine-SCR were surveyed. Replies were received from several companies.

Furthermore, an inquiry was also sent to several manufacturers concerning a PM removal system for a 1 MW medium-speed marine dual fuel engine. Well-prepared proposals for particulate filtering system were received from several suppliers. Based on the replies, the general conclusions and guidelines for the selection of particulate filtering systems for inland waterway vessels were made.

### 3 Objectives

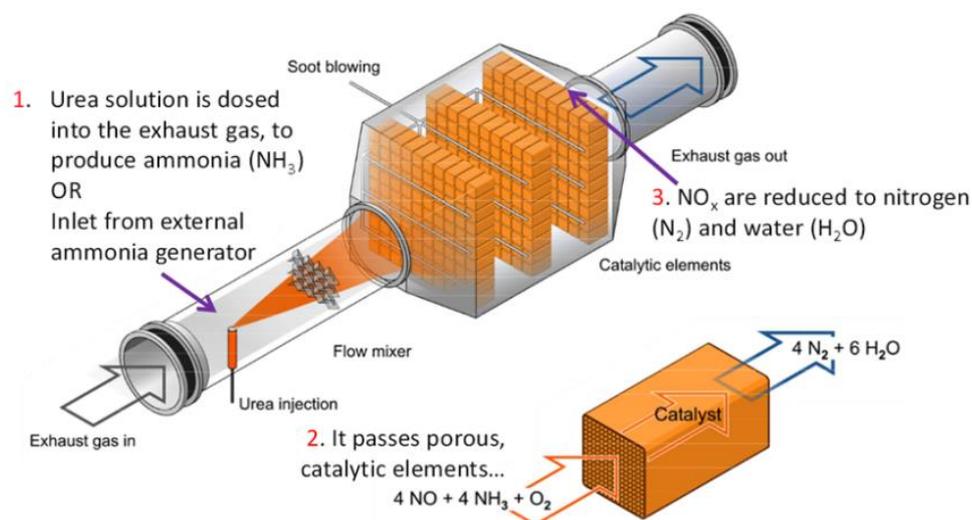
The objective of the study was to explore both the compact SCR system solutions and available after-treatment methods for the removal of exhaust PM. Regarding the compact SCR system solutions, the main target was to research fresh and the latest ideas and innovations which enables SCR packing as close as possible to engine structures. For that reason, the question regarding the effective urea mixing at short distances was also dealt with.

Regarding the PM removal, the main target was to research with which kinds of exhaust gas after-treatment solutions a marine dual fuel engine could fulfil the future tightening PM emission standards in inland waterway transport in Europe, both in gas and diesel fuel use.

## 4 Literature reviews and queries

### 4.1 Close-coupled SCR systems

Due to the tightening emission regulations, the more sophisticated methods for exhaust after treatment are needed. SCR is still considered the most appropriate technology to meet the tightening marine emission limits for the  $\text{NO}_x$ . The main principle of SCR operation is illustrated in Figure 1.



**Figure 1.** Urea-SCR operation principle (Wettstein, 2015).

#### 4.1.1 Design aspects of urea-based SCR

A urea-SCR system has to fulfill numerous criteria in order to work in a proper manner. Zheng et al. (2014) have given seven performance criteria for a successful urea SCR system design:

- Efficient catalyst usage (small size)
- High  $\text{NO}_x$  conversion efficiency
- No ammonia slip
- No urea deposits
- Low backpressure
- Compact, low cost, and low weight
- High acoustic (noise reduction) performance

Generally, the size of the SCR system and the needed active surface area of the catalyst depend on the exhaust gas temperature and mass flow. (Soikkeli et al. 2013). According to Steffe et al. (2013), the SCR catalyst volume can be reduced significantly if the higher cell density can be used.

The examination of the flow conditions at catalyst inlet is important to find solutions for the effective urea mixing and high NO<sub>x</sub> conversion at short distances. Firstly, urea and exhaust gas mixing has to occur fast. Secondly, a uniform distribution of NO<sub>x</sub> and NH<sub>3</sub> is necessary to achieve a high NO<sub>x</sub> conversion rate. (Steffe et al. 2013). Urea mixing is faster if the urea droplet size is smaller.

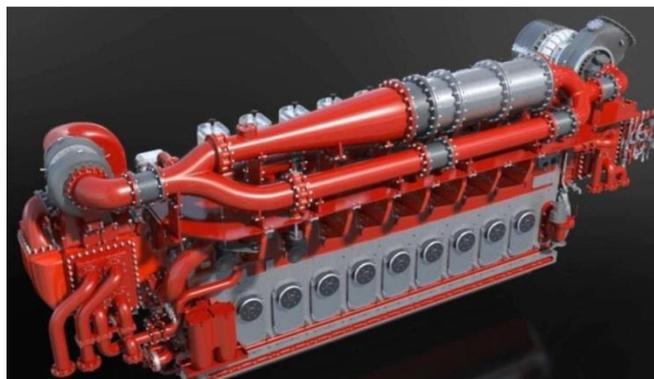
The broader temperature window is needed for the mobile SCR process with the low-temperature activity, the high temperature stability and the volumetric activity of the catalyst. Fluctuations in engine loads and high sulfur contents of the marine fuels have to be carefully taken into account when the SCR reactor is designed. Due to the diesel engine efficiency, the exhaust temperature can be low under part load conditions. Especially when the fuel sulfur level is high, designing the SCR catalyst that operates efficiently at part load is a challenge. The exhaust gas temperature window has to also be suitable for high sulphur fuels (usually 1 to 3.5% in heavy fuel oil, HFO). The lower temperature limit is typically 280–340 °C and the upper 400–450 °C when the high sulfur HFO is used. (Soikkeli et al. 2013; Johnson 2014). According to Christensen et al. (2013), the lower temperature must exceed 330 °C.

Between the abovementioned limits a sufficient reaction rate can be reached and the deactivation and fouling of the catalyst can be avoided. This is noteworthy for the long-term durable and reliable operation of the SCR system. Following the urea injection, ammonia salts and hydrocarbons may condensate on the catalyst element under the minimum exhaust gas temperature. Oxidation of the SO<sub>2</sub> to SO<sub>3</sub> can occur above the maximum temperature and the thermal aging of the catalyst may begin. (Soikkeli et al. 2013; Sun et al. 2015).

Lehtoranta et al. (2015) found that urea decomposition is more effective with heavy fuel oil (HFO) than with light fuel oil (LFO). Before urea solution enters into the SCR reactor, some isocyanic acid is hydrolyzed to ammonia. The hydrolysis of isocyanic acid is likely enhanced by the usage of HFO. Lehtoranta et al. (2015) suggest that metal oxides forming the core of exhaust gas particles, act as a catalyst enhancing the hydrolysis.

#### 4.1.2 Pressurized SCR Concepts

SCR catalyst can be located either upstream or downstream of the turbocharger turbine. The temperature and pressure levels of exhaust gas are higher before than after the charger. In a two-stage turbocharged engine, the exhaust temperatures after the low pressure turbine (LP) can decrease below 300 °C or even below 250 °C. The risk of ABS formation by SO<sub>2</sub> and NH<sub>3</sub> is obvious in this temperature range. Increased exhaust gas temperature level before the LP turbine prevents deposits to foul inside the SCR reactor. (Frobenius et al. 2013; Kröcher et al. 2014). For these reasons, the catalyst position between the LP and high pressure (HP) turbines is favorable. This concept is called inter-turbine SCR (IT-SCR), as in Figure 2.



**Figure 2.** Medium-speed CAT MaK 9M32 engine with IT-SCR system. (Frobenius et al. 2013).

Sun et al. (2015) studied the dynamic performance of four-stroke medium-speed diesel engine by Caterpillar Motoren GmbH & Co. KG Company in Kiel. The 2-stage turbocharged test engine (CAT MaK 6M32C) was equipped with an IT-SCR system. They investigated how the boost pressure build-up can be improved by controlling waste-gate (WG) and variable turbine geometry (VTG).

Figure 2 shows the designed IT-SCR system in a 9-cylinder engine version (CAT MaK 9M32) of Caterpillar.

The thermal inertia and the large volume of the SCR reactor have negative effects on the dynamic performance of the engine. (Sun et al. 2015). Moreover, Ollus et al. (2013) mention few key challenges for the IT-SCR arrangement. The first challenge is fitting of the SCR reactor on the engine. When the exhaust gas is extracted from and to the engine, the rigidness of the support and piping is another problem. Catalyst structural properties and exhaust gas flow management also cause difficulties.

Additional heat capacity is involved by the SCR reactor, which extracts enthalpy from the exhaust gas. The energy for the LP turbine is reduced and, due to the resistance of the reactor, the pressure build-up before the LP turbine is worsened. Sun et al. (2015) demonstrated that the LP turbocharger acceleration with the SCR is significantly slower than without the reactor. In consequence of this, the increase of boost pressure was also slower when the IT-SCR was used. They concluded that by using HP turbine equipped with VTG, the negative effects of SCR reactor can be potentially diminished.

Kröcher et al. (2014) investigated experimentally the effects of elevated pressure on the catalytic converter volume. At the same time, two catalyst structures, foam and conventional honeycomb, were compared under elevated pressure. According to Kröcher et al. (2014), the temperature level of 330 to 430 °C between the turbines of two-stage turbocharged engine is ideal in order to prevent the sulphur problem. Then, the pressures can be between 3 and 5 bar. If the pressure is increased, the SCR volume can be reduced significantly, but the potential for volume reduction is, however, limited. The exhaust gas volume decreases when the pressure level increases. Due to the gas diffusion, volume reduction is not proportional to the pressure increase. (Kröcher et al. 2014).

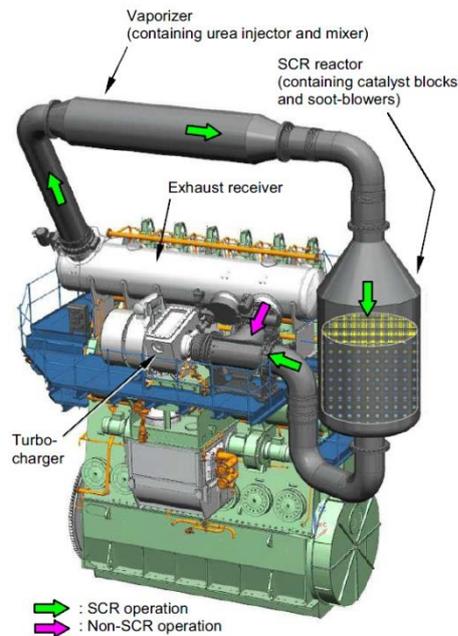
Kröcher et al. (2014) noticed that cell structures showed a high volumetric activity due to their large catalytic surface. The activity was not influenced by the pressure as much as the structure. Irregular foam structures allowed for high mass transfer. The benefit of SCR under pressure becomes much smaller, however, if the exhaust gas with a high dust loads flows through structures with smooth channels and low cell density.

MAN Diesel & Turbo and Hitachi Corporation have developed the high pressure SCR system for the two-stroke marine diesel engine, Figure 3. The 6-cylinder low-speed engine was an MAN B&W 6S46MC-C7. (Dieselnet 2016). Fujibayashi et al. (2013) reported that a NO<sub>x</sub> reduction of 80% is achievable with this engine. They also presented a conceptual model of an even more compact SCR system, Figure 4.

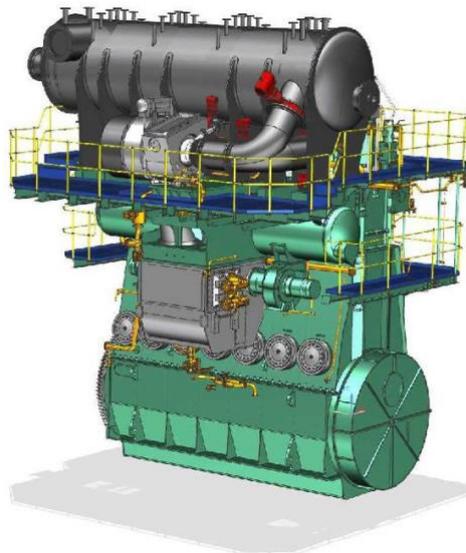
When the introduced model is compared with the concept model, Figures 3 and 4, there are notable achievements regarding the space requirements in engine rooms. In the concept model, the whole engine-SCR-system is shorter and lower than in the released model. The SCR catalyst locates straight over the engine and the piping is minimized in the concept. Fujibayashi et al. (2013) note that a more compact SCR catalyst has smaller heat capacity than a larger catalyst and as a consequence transient response may improve.

WinGD has also introduced an IMO Tier III compliant two-stroke marine diesel engine with a high pressure SCR. The first installation was seen in 2015. The 5-cylinder low-speed engine was a Wärtsilä RT-flex58T-D. The SCR reactor was manufactured by Hudong Heavy Machinery Co Ltd (HHM). (Wärtsilä Corporation, 2015)

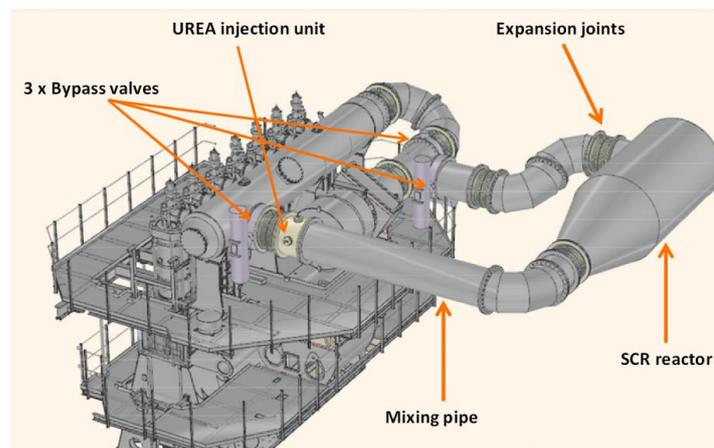
The general layout and main components of the corresponding high pressure SCR in WinGD's large two-stroke engine can be seen in Figure 5.



**Figure 3.** Introduced high pressure SCR system in a large two-stroke marine diesel engine, Hitachi-MAN B&W 6S46MC-C7 (Fujibayashi et al., 2013).



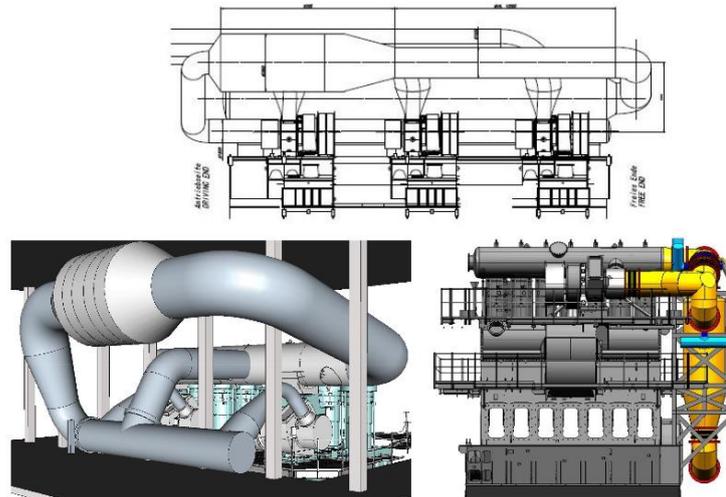
**Figure 4.** Concept for high pressure SCR system in a large two-stroke marine diesel engine. (Fujibayashi et al., 2013)



**Figure 5.** High pressure SCR in low-speed two-stroke marine diesel engine by Wärtsilä (Wettstein, 2015).

The SCR system, in Figure 5, is equipped with the bypass valves in order to conduct the exhaust gases either into the reactor or not, depending on the geographical NO<sub>x</sub> emission control areas (NECAs). (Wettstein, 2015)

Wettstain (2015) represents few examples of high pressure SCR layouts for a large two-stroke engine, Figure 6. He points out that an optimum layout need to be chosen based on the vessel specific design. The design process is a complicated development task in which the close co-operation between the ship designer, shipyard, engine designer, engine manufacturer and SCR supplier is needed. (Wettstein, 2015)



**Figure 6.** High pressure SCR layouts for a large two-stroke diesel engine (Wettstein, 2015).

Bank et al. (2013) studied the influence of increased pressure level on the SCR catalyst operation and on the chemical reactions. A single cylinder research engine was equipped with a high-pressure SCR. The engine has an external charge air supply and common rail injection system. The synthetic test bench was also used to simulate the conditions upstream a TC turbine of large diesel engines when the chemical and physical processes were investigated. The results from the synthetic test bench were compared with those detected in the real exhaust of the research engine.

Different catalyst cell densities, 100 cpsi and 200 cpsi, and materials with oxides of vanadium, wolfram and titanium were compared. During the engine test program, the conversion rates increased slightly with increasing pressure level. However, the SCR reaction was not influenced by the pressure level during the test program on a synthetic gas test bench. (Bank et al. 2013).

Despite the engine was operated with residual oils with high sulfur content (2.7 m.-%), no deposition of sulfur components were detected in the SCR catalyst. Bank et al. (2013) also concluded that independent of the SCR catalyst sample the amount of ammonia stored on the catalyst surface seemed to increase with the pressure level.

#### 4.1.3 Urea mixing length reduction

In order to reduce the required length for mixing, a number of studies have been performed considering static mixers in the pipe flow systems. The computational fluid dynamics (CFD) has been widely used in the design optimization of SCR performance, flow mixing characteristics, and urea decomposition (Zhang et al. 2006, Zheng et al. 2009, Zheng et al. 2010, Cho et al. 2014).

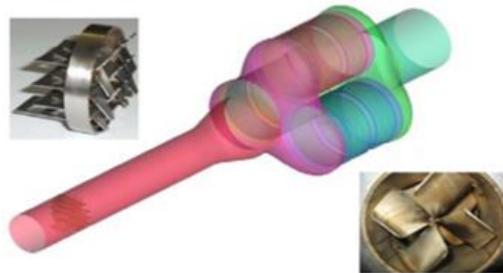
Ghanem et al. (2014) provided an extensive review of static mixers, their applications and mixing capabilities, as well as technological innovations in passive static mixers in chemical process industry, presenting guidelines for the selection of static mixers.

The effects of the shapes and locations of flow mixers on fluid mixing were investigated by Zhang et al. (2006). The results showed great improvement of flow mixing by adding a delta wing mixer. The effects of turbulent and swirling flows on flow mixing were investigated by implementing simple

flow mixers with straight or twisted blades inside the mixer. It was found that turbulent flow has a dominant effect on flow mixing index in the short distance right behind the mixer, while a greater improvement can be achieved through bulk swirling flow for a longer distance. (Zhang et al. 2006.)

In addition to serving their primary purpose of enhancing mixing between exhaust gas and spray, static mixers are effective in reducing deposits. Heat transfer via spraying onto a mixer's hot surfaces results in enhanced boiling and convective heat flux. Mixers with large surface area are promising in enhancing conjugate heat transfer despite the fact that mixers often reduce spray particle transport length. Under this principle, a grid mixer was designed and tested that demonstrated good performance and little back pressure penalty. (Zheng et al. 2010.)

Various configurations of urea SCR systems for large diesel engines were studied by Zheng et al. (2014) to address the deposit concerns. Both two-stage mixer and butterfly mixer were used to increase droplet swirling flow pattern, helping reduce the deposit formation risk, Figure 7.



**Figure 7.** Schematics of the baseline SCR system design for large marine engine. Top-left: Two-stage mixer; bottom-right: Butterfly mixer (modified: Zheng et al 2014).

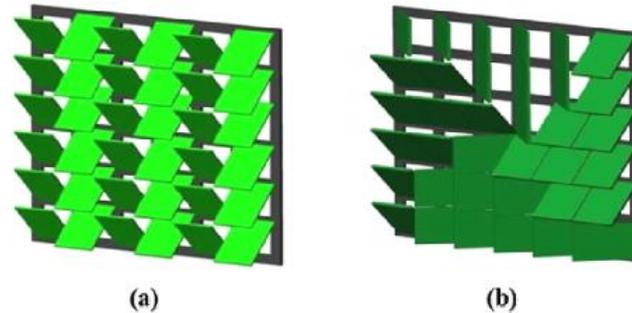
In the two-stage mixer, the first stage baffle plates use variable lengths in flow direction, hence variable distance adaptive to spray pattern, to allow enhanced spray impingements and evaporation. The second stage, composed mostly of flaps with interlocking angles, is used to enhance the mixing strength between urea vapors and exhaust gas. Butterfly mixer has been developed with leading edges that face the flow direction, thereby reducing pressure drop and avoiding flow separations. (Zheng et al. 2014)

Butterfly mixer also has large surface that facilitates atomization and evaporation of liquid droplets due to spray attachments to impingement surface. One additional characteristic for the butterfly mixer is that it can produce strong flow deflection that generates swirling turbulence diverting flow from center to periphery. (Zheng et al. 2014)

Increasing the inlet pipe diameter was found to be the most useful measure to reduce the risk of deposit formation, and to increase the amount of evaporated droplet and vapor uniformity index at the substrate inlet plane (Zheng et al. 2014).

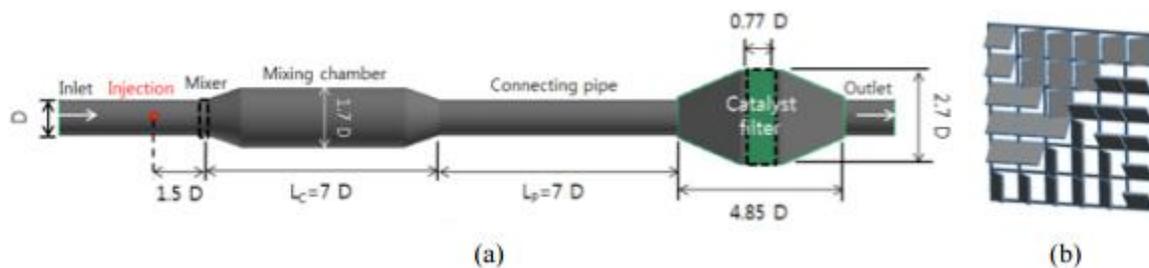
The correlation between flow mixing characteristics and pressure drop with the mixer was investigated by Park et al. (2014). Two different mixers, line-type and swirl-type, were considered, Figure 8. The presence of any type of mixer resulted in an improved flow mixing, but at the expense of additional pressure drop. The swirl-type mixer showed to be more effective than the line-type mixer with respect to the enhancement of uniformity index. The effectiveness of swirl-type mixers was considered to be initiated from the larger-scale swirl than those of line-type mixers; the line-type mixer is able to generate the vane-scale swirls whereas the duct-scale swirl is produced by the swirl mixers.

The effect of vane angles on the uniformity index and pressure drop was also investigated; these parameters were dramatically affected by the mixer geometry. In general, there was a trade-off relationship between the uniformity and the pressure drop. The swirl-type mixer with a vane angle of  $45^\circ$  was defined the most suitable model based on the results of both parameters. (Park et al. 2014)



**Figure 8.** Configuration of static mixers: a) line-type mixer, and b) swirl-type mixer (Park et al. 2014).

In order to design a compact design in a marine urea-SCR system, a numerical simulation was conducted by Choi et al. (2015). A swirl type static mixer and a mixing chamber were considered as mixing units in the system. The geometry of the SCR system and locations of each component are shown in Figure 9.



**Figure 9.** Schematic diagram: a) geometry of the SCR system, b) swirl type mixer (Choi et al. 2015).

The mixer caused flow recirculation and high level of turbulence intensity, and the chamber increased residence time of urea-water solution injected as well as the mixing performance with its wider cross sectional area. Because of those effects, reaction rates of urea decomposition were enhanced in the region. When both mixing units were combined, it showed the maximum because the recirculation zone was significantly developed.  $\text{NH}_3$  conversion was maximized in the zone due to widely distributed turbulence intensity and high value of uniformity index. (Choi et al. 2015)

The effect of the length of the chamber and connecting pipe on  $\text{NO}_x$  reduction efficiency was investigated to propose the design guidelines. It was possible to reduce 55% length of the chamber and connecting pipe without decrease of  $\text{NO}_x$  reduction efficiency. (Choi et al. 2015)

Based on the review, static mixing has been found to be effective for mixing together two (or more) fluid streams. A wide variety of different baffle and plate designs with different shapes and geometric configurations have been proposed and used in connection with static mixers. With the evidences from several studies, it has proved that

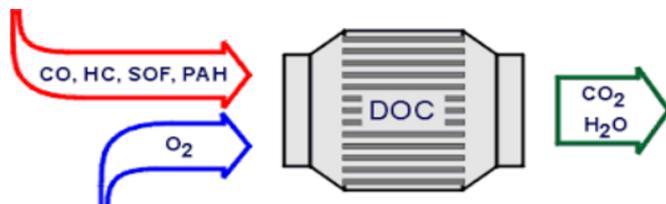
- Mixing and the reductant distribution are effectively improved by the turbulent vortices created by the mixer.
- Heat transfer via spraying onto a mixer's hot surface results in enhanced convective heat flux, and therefore, mixers are effective in reducing deposits.
- Increasing the inlet pipe diameter was found to be the most useful measure to increase the amount of evaporated droplet and vapor uniformity index at the substrate inlet plane.

## 4. 2 Abatement Measures for Diesel Particulates

### 4.2.1 Diesel Oxidation Catalyst

The primary function of the diesel oxidation catalyst (DOC) is to oxidize engine carbon monoxide (CO) and hydrocarbon (HC) emissions with the residual oxygen of the exhaust gas into H<sub>2</sub>O and CO<sub>2</sub>. In addition, DOC exhibits a high activity in the oxidation of the soluble organic fraction of particulate matter, thus reducing total particulate emissions. (Tschöke et al. 2010: 457)

The converter body consists of a ceramic or metallic honeycomb structure in which the exhaust gas is routed through many small parallel channels. The honeycomb structure enables a high catalytic contact area to exhaust gases. The inner channel walls are covered with an active catalytic coating containing catalytically active precious metal, generally platinum group metal. Exhaust gas components, CO and hydrocarbons, diffuse onto this coat when they flow through the converter body and are oxidized (Tschöke et al. 2010: 457) Reaction products, CO<sub>2</sub> and water vapour, desorb from the catalytic site and diffuse to the bulk of exhaust gas, as shown in Figure 10. (Majewski & Khair 2006: 408).



**Figure 10.** Conversion of pollutants in diesel oxidation catalyst (Majewski & Khair 2006: 404).

The level of particulate matter reduction is influenced in part by the percentage of soluble organic fraction in the particulate. DOC typically exhibits the total PM reduction efficiency of 15–30 %. The PM removed by DOCs is mainly soluble organic fraction from unburned fuel and oil. DOCs generally have insignificant impact on elemental carbon (EPA 2010).

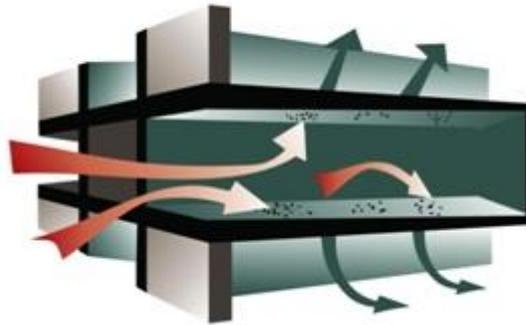
In addition, the DOC forms NO<sub>2</sub> due to the oxidation of NO. This step is conducive to nitrogen oxide reduction, especially for the selective catalytic reduction (SCR) process. Nitrogen dioxide can also be effectively used for passive soot filter regeneration. (Tschöke et al. 2010: 457–459)

### 4.2.2 Diesel Particulate filters

In order to remove insoluble particulate matter – elemental carbon and ash – from the exhaust gas, diesel particulate filters (DPF) are necessary (Merkisz & Pielecha 2015: 109). The function of DPFs is to physically capture a very large fraction of diesel particulates from the exhaust gas flow, thus preventing their release into the atmosphere (Tschöke et al. 2010: 458).

The substrate of the filtering systems can be made of many different materials and have different compositions. The most common design for a diesel particulate filter is the wall-flow monolith. A number of other, alternative filter designs and materials have also been developed. Examples include cartridges made of ceramic fibres, various types of ceramic foams, and metallic materials, such as metal fibre felts and sintered metal structures. (Majewski & Khair 2006: 460).

The wall-flow filter consists of several small parallel channels running axially through the part. Adjacent channels are alternatively plugged at each end in order to force the diesel exhaust gas flow through the porous substrate walls between the channels. These walls act as a mechanical filter, see Figure 11. (Majewski & Khair 2006: 460.)



**Figure 11.** Wall-flow monolith structure (Nett Technologies Inc. 2015).

Wall-flow monoliths are characterized by high filtration efficiencies from 70 to 95 % of total PM. Even higher efficiencies (>99 %) are observed for solid particulate matter fractions. (Konstandopoulos 2013: 25)

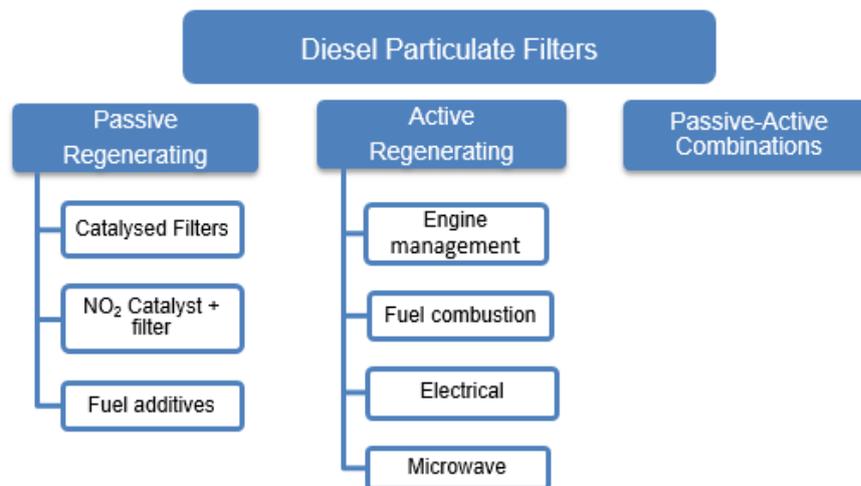
Drawbacks of monolith filters include a relatively high pressure drop. As the solid fraction of PM (soot) accumulates on the channel walls, the pressure drop across the filter increases, leading to increased back pressure to the engine and deteriorated fuel economy. Hence, regeneration of the filter by removal of the soot is a relevant part of wall-flow operation. (Konstandopoulos 2013: 8.) In addition, increased maintenance concerning wall-flow filters is related to ash emissions. As the incombustible ash particles cannot be removed from the filter through thermal regeneration, the accumulated ash must be physically removed from the DPF. This generally involves ash cleaning at a dealer or service centre. Ash is classified as a hazardous waste and must be handled and disposed of as such. (Sappok 2016.)

The oxidation of carbon in diesel soot can occur via reactions with the oxidizing agent  $O_2$  and  $NO_2$ .  $O_2$  is present in diesel exhaust gas at sufficient concentrations practically in all operating conditions. However, relatively high temperatures ( $600^\circ C$ ) are required to achieve appreciable regeneration rates with  $O_2$ . Thus, the  $O_2$ -based regeneration is mostly seen in active DPF systems.  $NO_2$  contains a much more active oxygen species for soot combustions than the  $O_2$  molecule itself, allowing filter regeneration at remarkably lower temperatures. (Guan et al. 2015).  $NO_2$  is present in the native diesel exhaust gas in very small quantities, but the  $NO_2$  concentrations can be increased by using a DOC or other methods. (Majewski & Khair 2006: 471.)

The temperature of the exhaust gas is too low to sustain auto-regeneration of the trap. This problem can be solved by 1) increasing the temperature of the trapped soot to a point where it starts oxidizing, 2) decreasing the required soot combustion temperature to a level that is reached during regular engine operation, or 3) by utilizing  $NO_2$  as a low-temperature agent. The first approach is used in active filter systems, the last two in passive (catalytic) filter systems. (Majewski & Khair 2006: 497.) A classification of DPF systems based on the principle of regeneration is shown in Figure 12.

In passive systems no external energy is applied for the regeneration process. In these systems the soot oxidation temperature is lowered to a level allowing auto-regeneration during regular engine operation. This can be achieved by introducing an oxidation catalyst to the system, either directly onto the filter media surface or added to the diesel fuel as a fuel additive. Passive systems that utilize  $NO_2$  as a low-temperature soot oxidation agent have also been introduced. (Johansen 2015; Majewski 2015a)

Any application in which the exhaust gas temperature cannot be guaranteed to be suitable for passive regeneration will require some active regeneration system. Active filter regeneration techniques operate by raising the temperature of the soot trapped in the filter to around  $600^\circ C$ , at which the soot will combust in oxygen. To achieve this, it is necessary to increase the exhaust gas temperature, or to increase the temperature of the filter itself. (Guan et al. 2015.)



**Figure 12.** Classification of filter systems by regeneration method.

For this, an outside energy source is needed. Hence, the active regeneration process of the filter will lead to increased fuel consumption. However, because active regeneration occurs periodically, the overall fuel penalty is approximately 2%. (Guan et al. 2015.)

In passive-active regeneration combinations the catalyst-based filter is also equipped with some kind of active regeneration system (Majewski 2015a). Passive-active combinations may be able to sustain fully passive operation during periods of increased exhaust temperature at high loads. In the case of idle operation, or continuous light-load conditions with low exhaust gas temperatures when the soot ignition temperature cannot be reached even with catalyst, active regeneration is utilized. (Guan et al. 2015.) The use of a catalyst allows performing regeneration at a lower temperature and shortening the regeneration time period, compared to non-catalytic active systems. In either case, the fuel economy penalty associated with active regeneration can be minimized. (Majewski 2015a.)

### 4.2.3 Integrated After-treatment Systems

#### Non-thermal Plasma

Non-thermal plasma (NTP) is believed to be a promising candidate for total engine exhaust emission control, including PM and NO<sub>x</sub> (Babaei et al. 2014). A plasma, known as the fourth state of matter, is a gas that has been ionised by passing an electrical current through it. There are several ways non-thermal plasma can be generated: dielectric-barrier discharge, corona discharge, electron beam irradiation and microwaves. The basic principle is that electron temperature and gas temperature greatly differ, so that the electron temperature is much higher than the gas temperature. (Manivannan et al. 2014.) High-energy electrons impact with gas molecules and produce various chemically active species, such as oxygen radicals, ozone and hydroxyl radicals (Babaei et al. 2014).

Both gaseous and PM emissions of exhaust gases undergo chemical changes when they are exposed to the plasma (Babaei et al 2014). For the removal of elemental carbon, there are two routes by NTP: 1) simple oxidation by means of oxygen and hydroxyl radicals, and 2) interaction between NO<sub>2</sub> and carbon soot. Hydrocarbons, including SOF and gaseous HC, initially react with O atoms, and are oxidized into CO and CO<sub>2</sub>. (Song et al. 2009.)

An important advantage of non-thermal plasma is its potential to oxidize particulates at low temperatures (Konstandopoulos 2013: 16). The typical reaction temperature is 200–300°C, which is relatively lower than that of DPF regeneration by thermal oxidization (Kuwahara et al. 2012). A critical issue with this method is the requisite energy consumption and, therefore, relatively high fuel penalty (Kontandopoulos 2013: 16).

### Wet Electrostatic Scrubber

In order to decrease the emission of particulate matter in the submicron size range (<1 µm), wet electrostatic scrubbers (WES) have been developed. A wet electrostatic scrubber is a spray tower equipped with an electrified spray unit for the generation of electrically charged water droplets, and a particle pre-charging unit. A spray of charged water droplets (collectors) is dispersed in the scrubber chamber, and the electrostatic forces among positively charged droplets and negatively charged particles lead to rapid and effective particle capture. (Jaworek et al. 2013; Di Natale et al. 2015.)

Wet electrostatic scrubbers inherit the structural and process advantages of conventional scrubbers, such as low-pressure drop and simple operation. An additional advantage of electrostatic scrubbers is their ability to also remove soluble gases. (Di Natale & Carotenuto 2015.) Experimental results published in the literature show that the removal of solid particles by water droplets is more efficient than with other mechanical methods. Experimental studies have also indicated that the energy consumption of the WES system is significantly lower than that of conventional scrubbers: an electrostatic scrubber requires 4–7 times less water than a conventional scrubber to remove the same amount of PM and SO<sub>x</sub>. (Jaworek et al. 2013.)

An innovative WES system for diesel particulate matter capture at pilot scale was recently developed and tested within the activity of the DEECON project (Innovative After-Treatment system for Marine Diesel Emission Control). Trial tests with a mono-cylinder diesel engine test rig indicated that the WES unit is capable of removing particles as fine as 10 nm. The reduction efficiency of total particle concentration in the range 10–500 nm was 70-95 % in number (Di Natale & Carotenuto 2015).

### Selective Catalyst Reduction and Filter

Meeting future emission regulations for inland navigation may require the use of both diesel particulate filter technology and the NO<sub>x</sub> reduction catalyst SCR. Typically, the reduction of NO<sub>x</sub> and PM emissions is performed by separate devices (Tronconi et al. 2015). Such sequential system configurations, however, have several drawbacks:

- 1) Large volume of the whole exhaust cleaning system
- 2) Insufficient temperature for SCR catalyst during cold start when DPF is placed in front of the SCR
- 3) Unfavourable conditions for passive soot regeneration – lower temperature and lower NO<sub>2</sub> – if SCR is placed upstream of the DPF. (Johansen 2015.)

In order to solve these problems, catalyst manufacturers have recently showed a lot of interest in the development of combined SCR-DPF devices, often referred to as SCRF®, or SDPF, in which the porous walls of the DPF are saturated with SCR catalytic material (Tronconi et al. 2015).

An important issue for the viability of the SDPF concept is the cross-interaction between the SCR and DPF functions. The fast SCR reaction  $4\text{NH}_3 + 2\text{NO} + 2\text{NO}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$  competes for NO<sub>2</sub> with passive soot regeneration reactions. (Johansen 2015.) As the NO<sub>x</sub> reduction by SCR occurs much more rapidly than the NO<sub>2</sub>–soot reaction, there is less NO<sub>2</sub> available to react with soot, leading to slower regeneration (Watling et al. 2012). In experiments performed by Tronconi et al. (2015), the influence of SCR reactions on passive soot oxidation were shown to be quantitatively prominent, and therefore this concept has to be carefully considered especially in applications which rely on continuous regeneration strategies.

Another aspect of the competitive interactions taking place in SDPF is the effect of soot presence on NO<sub>x</sub> conversion. The reaction of NO<sub>2</sub> with soot to form NO alters the in situ NO<sub>2</sub>/NO<sub>x</sub> ratio, which is known to be a controlling factor in the NO<sub>x</sub> reduction performance. (Tronconi et al. 2015.)

Taking into account these cross-interactions, the integration of the SCR and DPF functionalities into a single after-treatment device poses a major technological challenge which requires further

extensive experimental work. An additional challenge of using this concept is the trade-off that needs to be made when choosing the optimal wash-coat loading to find a balance between NO<sub>x</sub> reduction performance, filtration efficiency and the pressure drop behaviour (Tronconi et al. 2015).

## 4.2 Particulate Filtering System for Dual Fuel Engine

The engine exemplified in this study is a 1 MW, 6-cylinder, four-stroke, medium speed dual fuel engine with direct injection of liquid fuel and indirect injection of gas fuel. As a dual fuel engine, it can be run in either gas mode or liquid-fuelled diesel mode. In IWT applications, the ultra-low sulphur diesel fuel EN590 (<10 ppm S) is used.

Based on the PM emission measurements of the engine, the target reduction efficiency for exhaust after-treatment system is >90% for PM and >99% for PN in diesel operation mode. Thus, the highest efficiency wall-flow particulate filter is required. Other targets for particulate filtering system were defined as follows:

- Low pressure drop and parasitic load. Maximum pressure drop over the filter system 30–40 mbar.
- High availability, i.e. only little maintenance is needed. Ash cleaning interval >4000 h.

In order to find an optimal DPF-system for 1 MW dual fuel marine engine, numerous companies active within the exhaust gas after-treatment field were contacted and asked to submit suggestions for the particulate filtering system for a 1 MW dual fuel engine. Several well-prepared proposals were received.

## 5 Results

### 5.1 Modern and compact SCR solutions

Mandated by the EU Stage V standard, different exhaust after-treatment technologies will be coupled closely in order to meet both the new emission limits and the space saving requirements. A DOC upstream of a DPF followed by a SCR and ammonia slip catalyst (ASC) is likely to be the most common arrangement in the heavy machineries with engine powers from 56 to 560 kW. (Nathan 2016) The most promising ideas among the compact after-treatment systems are presented in following sections.

Caterpillar Inc. unveiled 2016 the 6-cylinder turbocharged heavy-duty engine (Cat C9.3B) which had an engine-mounted after-treatment system, in Figure 13. The engine meets the EU Stage V, and U.S. Tier 4 emission standards. The units of DOC, DPF and SCR have placed into a common platform, which was mounted above the engine. The weight of the after-treatment package was 95 kg while the engine net dry weight was ca. 860 kg. (Caterpillar 2016; Gehm et al. 2016b)



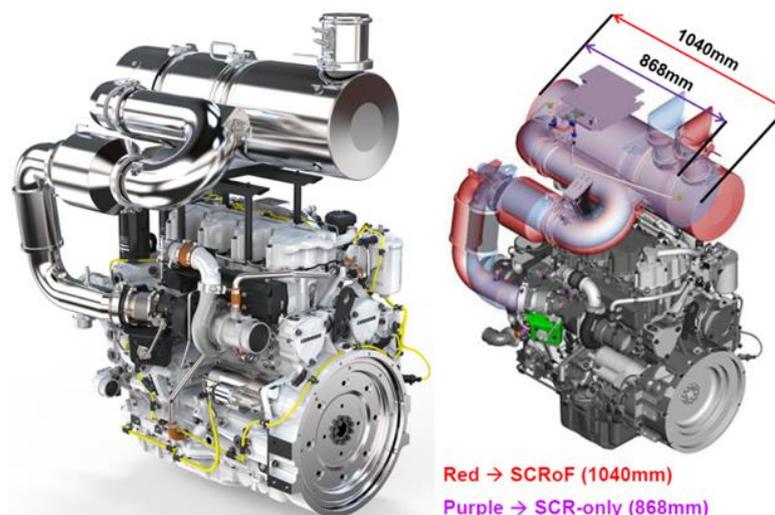
**Figure 13.** Cat C9.3B heavy-duty engine with a compact engine-mounted after-treatment system (Gehm et al. 2016b.)



**Figure 14.** Cummins Single Module™ unit consisting of a DOC, DPF, SCR, and ASC (Gehm 2016a).

According to Gehm (2016a), the reduced size and weight of single unit, Figure 14, is enabled by a helical urea decomposition or mixing chamber. Passive regeneration is used for DPF and the service cleaning interval is expected to be more than 5,000 operating hours. The single unit system has a high degree tolerance to sulphur in fuel, up to 5,000 ppm. Varying diameters and lengths are allowed for the modular designed system. (Cummins 2016) However, the separate DPF and SCR units are used in the engines of above 9 liter in order to meet the EU Stage V standard.

Liebherr has a compact exhaust after-treatment system in which a SCR catalytic converter and a particulate filter are combined (SCRFilter). A 4-cylinder in-line heavy-duty engine with SCRFilter system is in Figure 15, on the left. Dimensions and comparison of installation space and between two different after-treatment versions, which were available, is in Figure 15, on the right. In the other version, there is a DOC, an SCR-coated particulate filter and an SCR. In the other, there is only SCR (Liebherr 2015). The engines equipped with this system will meet the EU Stage V emission standard.



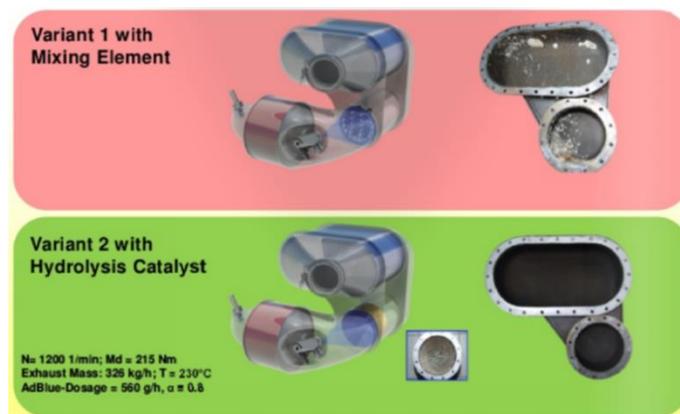
**Figure 15.** Installation space comparison and dimensions of a compact exhaust after-treatment system by Liebherr, modified (Liebherr 2015; Vonarb 2015).

Despite the system configuration (Figure X9, on the right), either SCR and filter or SCR only, the component installation is the same concerning the after-treatment system fixation, the sensors, and the urea supply system alike. The system is compatible with Liebherr's D93, D94 and D95 engine series including I4, I6, V8, V12 configurations. (Liebherr 2016.) The dimensions and weight of the whole after-treatment package depend on the SCR technology and engine injection strategy. Depending on the system utilization profile, periodically cleaning of ashes is needed as maintenance. Service intervals are over 4,500 operating hours. (Kloecker, 2016; Liebherr 2016)

As in the Caterpillar system, the after-treatment system of Liebherr has been installed above the engine. The after-treatment system of Liebherr can be assumed to be light due to the lightweight supporting structure, as can be seen in Figure 15. If the supporting structures are compared, they are probably much heavier above the Caterpillar engine than the Liebherr one. Therefore, vibrational features of the after-treatment systems could be different.

Continental AG has offered a commercial version of a compact SCR system from 2016 onwards. In the system, additional particulate filters, or combination filters with an SCR coating are used. The Stage V compliant exhaust system is applicable for engines from 130 to 560 kW from 2019 onwards (Continental 2014, 2016).

For the system, the effects of a mixer and a hydrolysis catalyst on urea deposit accumulation into the SCR catalyst at low exhaust temperature is presented in Figure 16. Less urea deposits are accumulated when the hydrolysis catalyst is used instead of plain mixer at low exhaust temperature. Therefore, e.g. Zebo (2012) has also concluded that the decomposition of urea-water solution can be enhanced by using hydrolysis catalyst technology in this after-treatment system.



**Figure 16.** Comparison of a mixer and a hydrolysis catalyst (Zebo 2012).

The largest space envelope is needed if a combination of DOC, DPF and SCR is demanded. For the smallest machines, this combination is difficult to accommodate. Cost penalties may arise if the separate canning has to be made. System downsizing can also mean the penalties to the service intervals as in the case of DPF. (Nathan 2016)

Many of the studied compact after-treatment systems, used in heavy-duty machinery, are located above the engine. These kinds of solutions cannot be directly used in marine engines because the needed maintenance space has generally been guaranteed for the overhauling of the pistons. However, the broader the independence of the after-treatment system package of the location, the more extensive is the range of applications where the system can be used. Depending on the application, the different factors, as vibrational effects, weight, need of space, pressure drop, urea mixing length, thermal upkeep, price, have to be carefully taken into account. Urea mixing is also one of the major factors.

As in the marine-SCR systems, static mixing has been found to be effective for mixing together two (or more) fluid streams. A wide variety of different baffle and plate designs with different shapes and geometric configurations have been proposed and used in connection with static mixers. With the evidences from several studies, it has proved that mixing and the reductant distribution are effectively improved by the turbulent vortices created by the mixer.

## 5.2 Particulate Filtering System for Dual Fuel Engine

Based on the inquiry, the following types of particulate filtering systems were proposed:

- passive systems with catalytic coated ceramic wall-flow filter elements
- passive system with DOC + uncatalysed ceramic wall-flow filter element

- passive systems with DOC + catalytic coated ceramic wall-flow filter elements
- passive-active system with catalytic coated ceramic wall-flow filter element + full-flow fuel burner

When assessing the proposals, special attention was paid to high filtration efficiency, reliability and durability of the filter system, regeneration method and adequate regeneration temperatures, maximum pressure drop over the filter, and maintenance requirements. An overview of the proposed filter types and ranges of the key parameters are presented in Table 1.

The filter substrate is a key component of the diesel filter system, affecting both its performance and durability. Both cordierite and silicon carbide filter elements were proposed. Cordierite is characterized by a very low thermal expansion coefficient and high resistance to extreme thermal cycling. The disadvantage of cordierite compared to silicon carbide is a lower melting point, which is considered insufficient under certain uncontrolled regeneration conditions. In contrast, silicon carbide is characterized by a superior thermal durability. (Majewski 2015b)

**Table 1.** Overview of the proposed filter systems.

Filter types	wall-flow cordierite, wall-flow SiC
Regeneration methods	catalytic coating, DOC + catalytic coating, catalytic coating + burner, NO <sub>2</sub> from DOC
Reduction efficiency	
• PM (%)	90-97.9
• PN (%)	97-99.5
Pressure drop	
• clean (mbar)	20-40
• operation (mbar)	30-73
Ash cleaning interval (h)	1000-5000

The demerits of silicon carbide are a higher thermal expansion coefficient (less resistant to extreme thermal cycling) and higher cost. (Majewski 2015b)

A number of fully passive systems were proposed. The advantage of passive systems is that no external energy is needed for the regeneration process. Regeneration at lower temperatures also reduces thermal stress, resulting in a longer life span of the filter media.

A critical issue with fully passive systems is that passive filters require operating temperatures high enough to initiate combustion of collected soot. Lower loads and exhaust temperature may lead to poor regeneration and higher pressure drop. The minimum regeneration temperature for the proposed passive systems ranged from 200 °C to 340 °C.

A noble metal based catalyst – a DOC or a catalyst coating with precious metal – provides the additional advantage of a high conversion rate for gaseous CO and HCs. On the other hand, formation of toxic components or secondary particles which were not originally in the exhaust gas, so-called secondary emissions, has also to be kept in mind. It is known that catalytic converters containing platinum may increase the NO<sub>2</sub> emissions. (Weltens & Vogel 2008: 221, 225)

A passive-active system was also proposed. The advantage of this method is that it is less dependent on exhaust gas heat. The regeneration can be triggered to occur actively with light loads and lower exhaust temperatures. The demerits of this kind of system are increased fuel consumption and increased thermal stress during active regeneration periods, higher maintenance requirements, and more complex and expensive control units.

A very important parameter is the maximum pressure drop through the exhaust system, caused by the hydraulic resistance of filtering system components (Majewski 2015a). The pressure drop over the filter system should stay below the maximum allowable engine back pressure specified by the engine manufacturer. In this study, 30–40 mbar was applied. The maximum pressure drop across the filter system was  $\leq 40$  mbar in all alternatives at clean conditions. Low pressure drop during engine operation, i.e. with some soot and some ash load, seems to be critical for many solutions, but some proposals meet the targeted 30–40 mbar also in saturated conditions. However, in most cases the pressure drop can be tailored by using the correct filter volume or by installing more filters.

The targets for DPF included high availability, i.e. only little maintenance should be needed. The ash cleaning interval was expected to be  $>4000$  hours. The suppliers reported surprisingly large differences in expected ash cleaning intervals: 1000–5000 hours. Differences in ash storage capacities may be explained, to some extent, by cell designs. Filter designs with asymmetric cells in which the inlet cell is larger than the outlet cell have demonstrated a considerable increase in ash storage capacity for the same nominal filter volume, by simply increasing the size of the inlet cells to accommodate the ash (Sappok 2016). Also, some differences were found in calculating methods. Some suppliers informed that they can offer an ash cleaning service. Generally, passive particulate filter systems do not require frequent maintenance, except for ash removal. Some suppliers stated that after approximately 10,000–12,000 hours the cartridges must be removed and maintained (renew coating).

The suppliers were also asked to specify if the DPF system was significantly different in gas operation only. In general, the suppliers reported that the design of the filtering system would not be significantly different for gas mode only. The permissible maximum pressure drop over the filter system is the primary parameter here. Most systems were said to be scalable to higher engine power, but bigger engines may require some special attention.

## 6 Conclusions

The objective of the present study was to explore both the compact SCR system solutions and available after-treatment methods for the removal of exhaust PM. Literature reviews were conducted concerning the pressurized SCR concepts, urea mixing length optimization, and PM reduction systems.

A number of SCR manufacturers and PM reduction system suppliers were contacted. Because of the delicate information related to the topic, gathered information from the SCR system manufacturers was minor. However, some fresh and new ideas and latest innovations were collected by investigating commercially available compact exhaust after-treatment systems, particularly used in off-road heavy machineries. A survey of commercially available static mixers for a compact design marine-SCR system was also carried out.

Concerning the removal of exhaust PM, the potential companies were asked to send a proposal for the particulate filtering system for a 1 MW dual fuel engine. Several well-prepared proposals were received. The response rate (62%) was sufficiently high to allow generalizing of the results.

Based on the evidences from several studies and on the replies from the companies, the following conclusions could be made:

- Many of the studied compact after-treatment systems, used in heavy-duty machinery, are located above the engine. These kinds of solutions cannot be directly used in marine engines because the needed maintenance space has generally been guaranteed for the overhauling of the pistons. However, the broader the independence of after-treatment system package of the location, the more extensive is the range of applications where the system can be used. Depending on the application, the different factors, as vibrational effects, weight, need of space, pressure drop, urea mixing length, thermal upkeep, price, have to be carefully taken into account.

- Mixing and the reductant distribution are effectively improved by the turbulent vortices created by the mixer.
- Heat transfer via spraying onto a mixer's hot surface results in enhanced convective heat flux, and therefore, mixers are effective in reducing deposits.
- Increasing the inlet pipe diameter was found to be the most useful measure to increase the amount of evaporated droplet and vapour uniformity index at the substrate inlet plane.
- It is possible to find commercial mixer which is characterized by a very simple design with the lowest available head loss for any static mixer. A whole range of static mixers can also be found which may meet the targeted pressure drop and mixing quality requirements. With some mixers, a mixing length of 3-4 tube diameters may be achieved. With some mixer solutions, lowest ammonia slip can be achieved at conversion efficiencies of up to 95%. At the same time the total pressure loss applied to an entire SCR system is in a range of only a few mbar.

Based on the replies, the following conclusions and guidelines for the selection of particulate filtering systems for inland waterway vessels could be made.

- 1) Diesel particulate filters with catalyst coating and/or upstream DOC can be regarded as the primary choice for particulate filtering systems in IWT applications. The advantages of fully passive systems are their low operational and low maintenance requirements. Passive systems also showed low operational costs, because no external energy is applied in the regeneration process. In general, passive systems are also relatively inexpensive. On the negative side, regeneration with fully passive systems is dependent on exhaust heat. However, with adequate catalyst formulation and/or with DOC upstream of the filter, the regeneration temperature can be adjusted to meet the minimum temperature of the exhaust.
- 2) Catalysed filters with active regeneration support in low temperature conditions can also be seen as an advisable solution for particulate emission reduction. The advantage of catalysed filters with active regeneration support is that they are less dependent on exhaust gas heat. The regeneration can be triggered to occur actively with light loads and lower exhaust temperatures. On the negative side, the demerits of CDPF + burner systems are linked to increased fuel consumption and increased thermal stress with active regeneration periods, higher maintenance requirements, and more complex and expensive control units. However, catalysed filters with active regeneration support in low temperature conditions can be seen as the most reliable method for particulate emission reduction.

Noble metal based catalysts – a DOC and/or a catalyst coating with precious metal – provide the additional advantage of high conversion rate for gaseous carbon monoxide and hydrocarbon emissions. Platinum group metal free catalysts, such as mixed metal oxide catalysts, showed lower activity for the oxidation of gaseous HCs. PGM free catalysts also required higher regeneration temperatures compared to noble metal based catalysts. On the other hand, attention should also be paid to secondary emissions. It is known that catalytic converters containing noble metals may increase NO<sub>2</sub> emissions.

The above mentioned guidelines for the selection of particulate filter systems are limited to applications with ultra-low-sulphur fuel. As the sulphur content of diesel fuel is critical to DOC applications and noble metal catalysts, the applicability of these methods in, e.g., marine applications with high sulphur fuel is restricted. Further research on the effect of high sulphur content in the fuel on filter design and filter regeneration is recommended. In addition, further research on combining diesel particulate filters with other after-treatment devices, mainly SCRs, is needed. Moreover, the development status of integrated systems for exhaust gas after-treatment should be followed.

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