

# Chapter 2

## SCR Technology for Off-highway (Large Diesel Engine) Applications

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### Abbreviations

BMEP	Break Mean Effective Pressure
BSO	Bodensee-Schifffahrts-Ordnung (local regulation for ships on Lake Constance)
CPSI	Cells per Square Inch
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EPA	Environmental Protection Agency
EU	European Union
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
NRTC	Non-Road Transient Cycle
PGM	Precious Group Metals
PLC	Programmable Logic Controller
PM	Particulate Matter
SCR	Selective Catalytic Reduction

### 2.1 Introduction

The term *Off-highway* includes a great variety of diesel engine applications like propulsion of ships, mining trucks, harvesters, trains, power generation and pump drives, e.g. for hydraulic fracturing (see Fig. 2.1). In a broader sense, even power generation and pump drives need to be considered *mobile*, as they are often mounted into containers or onto trailers.

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**Fig. 2.1** Off-highway applications for diesel engines (*Pictures MTU*)

Diesel engines for off-highway applications can be heavy-duty derivatives, mainly for the power range below 560 kW, or special designed diesel engines. Engines with a power output of more than 560 kW are referred as *large diesel engines*. The power output of these large engines reaches up to 100 MW. Based on their speed of rotation, large diesel engines are divided into high-speed engines (>1,000 rpm), medium-speed engines (400–1,000 rpm) and low-speed engines (<400 rpm). Typically, the displacement increases as the rotating speed of the engines decreases. Usually, medium- and low-speed engine displacements range from 30 to 2,000 L/cylinder (e.g. large two stroke engines), whereas those for high-speed engines typically lie between 0.2 and 20 L/cylinder. An example of a high-speed engine and a medium-speed engine can be found in Figs. 2.2 and 2.3.

A further differentiation is the fuel. Most high-speed engines are using high-quality standard diesel fuel like trucks or passenger cars. However, heavy fuel oil (HFO), which can contain a significant amount of sulfur (up to 5 %) [1], is the preferred fuel for medium- and low-speed engines.

Exhaust emissions from off-highway diesel engines have to comply with more and more stringent emission regulation. Similar to diesel engines used in heavy-duty trucks or passenger cars, the reduction of exhaust emissions requires a combination of engine-internal measures and aftertreatment technology. Corresponding to the engine size and application, exhaust gas aftertreatment technologies for off-highway diesel engines combine on-highway as well as power plant technology (see Fig. 2.4).

The dimensions can range from SCR boxes well known from on-highway trucks up to house-like industrial systems for diesel engine power plants (see Fig. 2.5).

Engine Configuration	
cylinder numbers	8V,12V, 16V, 20V
displacement per cylinder	4.77 l
power range	1 to 3 MW
max. power per cylinder	150 kW
rated speed	1800 rpm
rated BMEP	21.0 bar

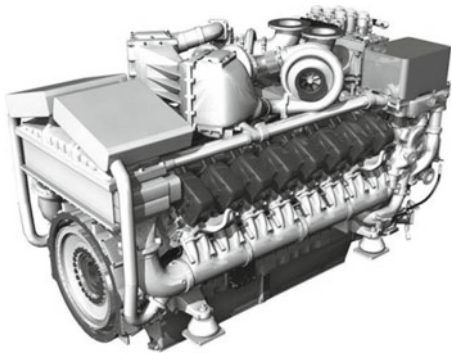


Fig. 2.2 Example of a large high-speed engine (MTU S4000) (Picture MTU)

Engine Configuration	
cylinder numbers	6,8, 9, 12, 16
displacement per cylinder	32 l
power range	3 to 8 MW
max. power per cylinder	500 kW
rated speed	750 rpm
rated BMEP	24.9 bar

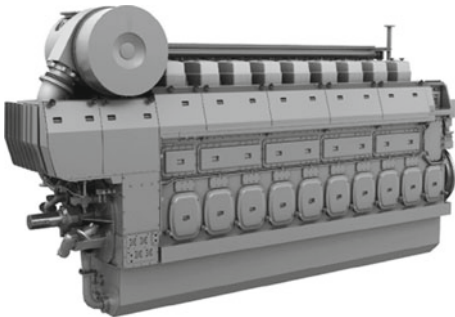


Fig. 2.3 Example of a large medium-speed engine (Bergen B32:40) (Picture Bergen Engines AS)

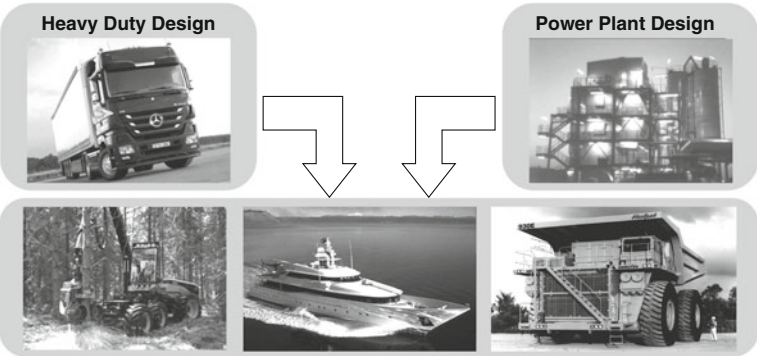
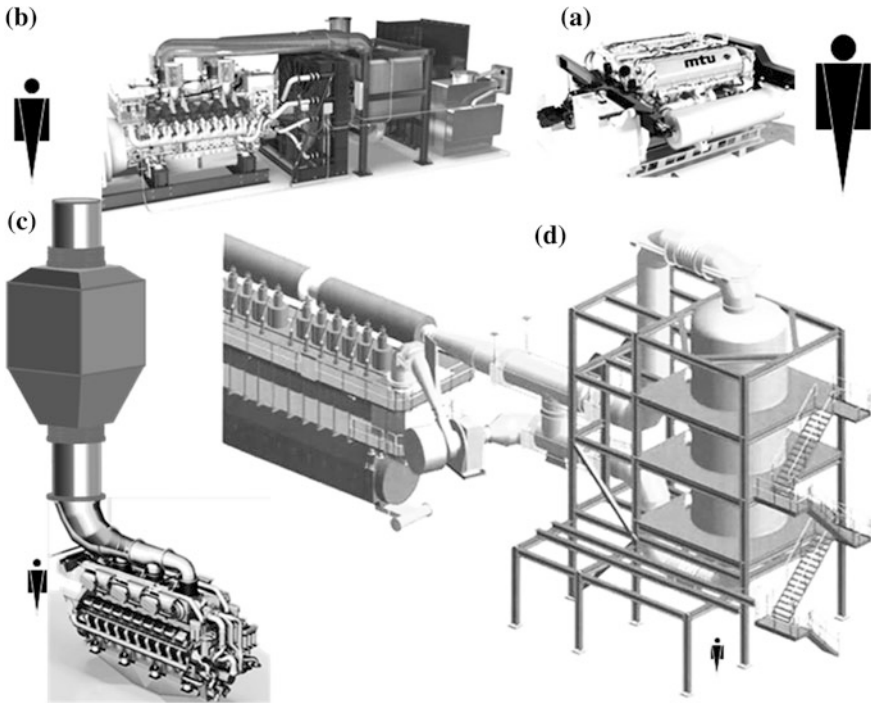


Fig. 2.4 Influences and roots of off-highway exhaust gas aftertreatment systems (Pictures MTU)



**Fig. 2.5** Off-highway diesel engines with SCR range from truck-like mobile systems up to stationary power plants: **a** Railcar 700 kW, **b** Container Genset 3 MW, **c** Ship Propulsion 7 MW, **d** Stationary Two-Stroke Engine 50 MW (Pictures MTU and Johnson Matthey)

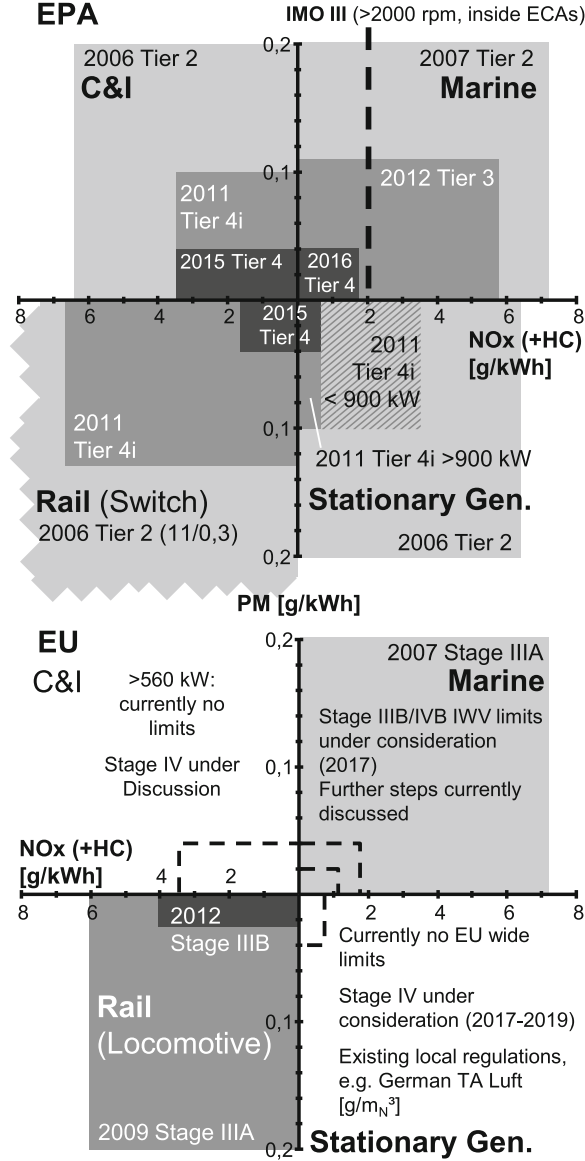
Because the SCR technology for smaller engines can directly be derived from available on-highway technologies, this chapter will focus mainly on the specific requirements of large diesel engines with a power output larger than 560 kW.

## 2.2 Off-highway Emission Legislation

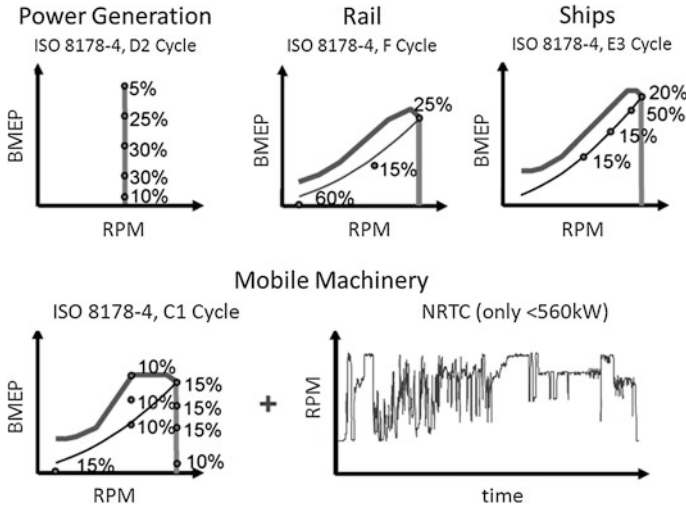
Due to the increasing awareness of air quality, stricter emission limits have been introduced, which will be even further tightened for off-highway diesel engines in the coming years. Depending on the application and the location, different emission limits apply. The most stringent emission regulations are currently imposed by the European Union (EU) and the Environmental Protection Agency (EPA) in USA. Off-highway diesel engines have to fulfill different emission standards, depending on the application.

Nitrogen oxides ( $\text{NO}_x$ ) and particulate matter (PM) are the main pollutants, which are in the focus of the current emission legislations. Figure 2.6 gives an overview of emission limits for engines with a power output higher than 560 kW. It should be noted, that especially EPA Tier 4 will require very low exhaust emissions.

**Fig. 2.6** EPA and EU emission legislation for engines >560 kW (Emission limits taken from [2])



An additional challenge arises from the fact that, depending on the application, different test cycles have to be used for the certification of engines. The test cycles shown in Fig. 2.7 reveal that engines are operated only in selected areas of the engine map during respective certification runs. Only steady state test cycles are used for off-highway engines with a power output greater than 560 kW. For mobile machinery engines with a power output below 560 kW, the NRTC is added



**Fig. 2.7** Engine operating points of different off-highway test cycles (Data taken from [3])

as a transient test cycle. On-highway heavy-duty engines with SCR exhaust gas aftertreatment always have to pass a transient and mostly additionally a steady state test cycle.

During the steady state test cycle, the engine is operated at constant speed and load while the emission measurement is conducted. After each emission measurement, the operating point is changed and the next measurement will be performed. Finally, the overall test cycle result is calculated by a weighted sum of all measurements. During the NRTC test, the engine is operated fully transient, with a continuous measurement of the emissions. Therefore, the aftertreatment system has also to be able to perform under transient conditions. This fact leads to specific requirements, e.g. highly accurate urea dosing. More details on emission legislation and certification procedures can be found in [2].

As a consequence, different engine and aftertreatment calibrations are required with respect to the corresponding application. Furthermore, depending on the application and the required emission limits, different exhaust gas aftertreatment technologies have to be used. Examples are DPF only, SCR only and combined DPF + SCR aftertreatment systems.

### 2.3 SCR Systems for High-Speed Engines

Up to a few hundred kW of power output, on-highway engines or derivatives are used also for off-road applications. For most of these applications, the exhaust technology is very similar if not equal to on-highway systems. Yet, engines with a higher power output or applications with special regulations require different solutions.

### 2.3.1 Small Ship Applications

Due to worldwide-applicable IMO III regulation coming into force within the next few years, aftertreatment will come into focus for ocean going vessels. Local regulations have also led to the development of NO<sub>x</sub> reduction systems for smaller ships. For example, the Bodensee-Schiffahrts-Ordnung (BSO) is setting NO<sub>x</sub>-limits for ships on Lake Constance in Germany, Switzerland and Austria. In addition to the specific emissions in [g/kWh], the absolute amount of emitted NO<sub>x</sub> in [g/h] is limited, too, requiring sport boats to use exhaust gas aftertreatment. For such small applications on-highway SCR-technology is suitable. While urea dosing and catalyst systems can be sourced from mass produced on-highway components, catalyst housing and insulation have to be adapted to the available space on board as well as to other requirements, such as maximum surface temperature and thermal protection.

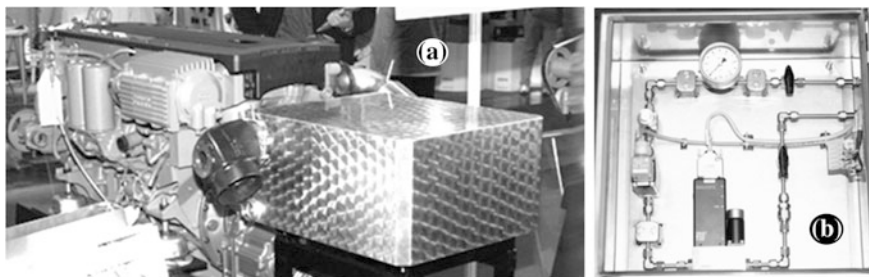
As the necessary storage capacity for reducing agent is small, it might be reasonable to use NH<sub>3</sub> gas as reducing agent instead of aqueous urea. Figure 2.8 shows a system realized by H+H Umwelt und Industrietechnik for a 300 kW engine. The reducing agent dosing system consists of a mass flow controller and a shut-off valve only. While the local authorities have allowed this kind of solution for the Lake Constance, NH<sub>3</sub> gas bottles are not allowed for most applications due to safety reasons. Solutions for solid storage of NH<sub>3</sub> are being developed and allow direct dosing of gas without the inherent danger of compressed ammonia [4]. Reductant supply systems are discussed in detail in Part VI of this book.

### 2.3.2 Rail Applications

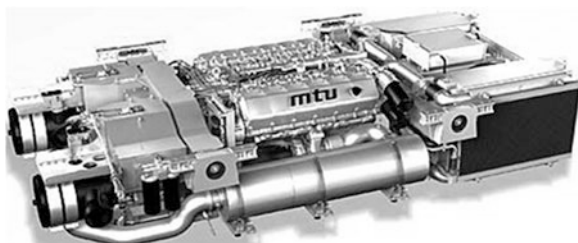
Stringent emission limits for EU and US railroads have forced the introduction of exhaust gas aftertreatment for rail diesel engines. While the most complete pollutant reduction could be achieved with a combined particulate filter and SCR system, an alternative way to meet legislation could be through tuning the engine to meet PM emission limits without a particulate filter and use SCR for NO<sub>x</sub> reduction.

Severe packaging constraints force a high integration of engine and exhaust gas aftertreatment. For railcars, for example, engines, aftertreatment including urea tank, generators and coolers are combined into so called power-packs. Figure 2.9 shows an MTU power pack with a 700 kW diesel engine. The SCR system is replacing the silencers mounted left and right to the engine. Figure 2.10 depicts the integration of urea dosing and mixing, as well as the silencing function into the aftertreatment box [5]. On-highway technology is used for urea dosing as well as for catalyst and canning. Power-packs with derivatives of truck engines even use truck silencers with minor modifications.

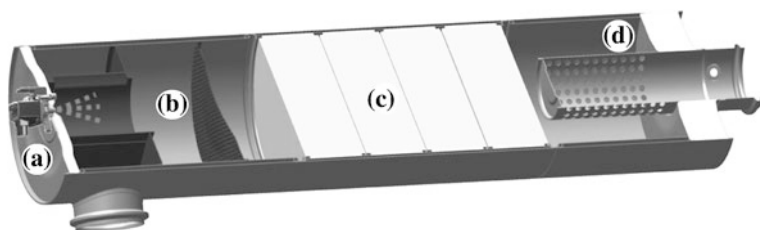




**Fig. 2.8** SCR system for a 300 kW engine with **a** engine and catalytic reactor and **b** gaseous NH<sub>3</sub>-dosing from a compressed gas cylinder (Pictures H+H Umwelt und Industrietechnik)



**Fig. 2.9** Diesel-electric power-pack with MTU 12 V 1600 R80L and SCR aftertreatment. Diesel engine, generator, exhaust-system, tanks and other auxiliary systems are packaged on a frame for under-floor mounting on railcars (Picture MTU)

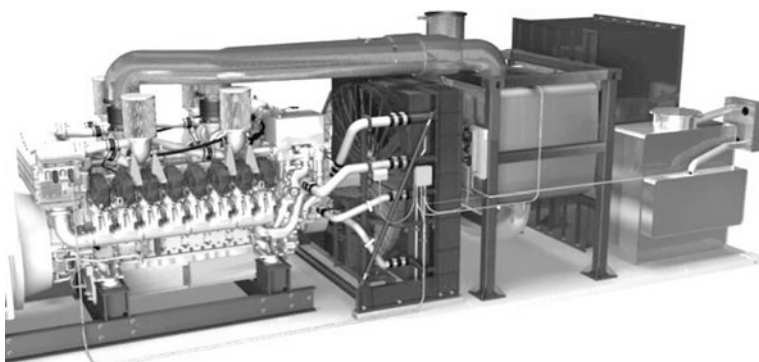


**Fig. 2.10** SCR system for the EU III B certified MTU 12 V 1600 R80L engine for railcars with **a** urea dosing and **b** mixing section, **c** catalyst and **d** silencing integrated into a compact housing (Picture MTU)

### 2.3.3 Gensets

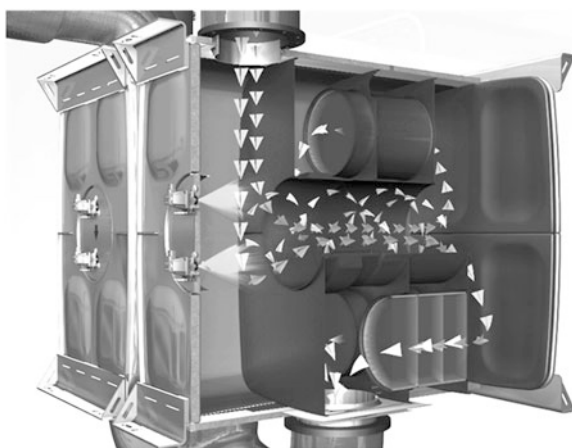
With high-speed engines up to a power output of a few MW, electrical power generation is available as containerized systems [6]. Figure 2.11 gives an example of such a genset. Mostly used as emergency and peak power systems, such engines are characterized by fast load response. The dynamic of exhaust temperature and





**Fig. 2.11** MTU 16 V 4000 genset with SCR aftertreatment integrated into a container (Picture MTU)

**Fig. 2.12** SCR System for a containerized genset with MTU 16 V 4000 engine, using on-highway-derived technology for dosing, canning and catalyst (Picture MTU)



flow is comparable to on-highway applications or mobile machinery. Aftertreatment systems have to be highly integrated in order to fulfill the space requirements. Since these demands are similar to on-highway applications, technology derived from heavy-duty trucks is used for pumping and dosing of reductant fluid, most commonly a 32.5 % urea solution.

Catalyst canning and housing technology have their roots in heavy-duty truck-systems, preferably with a mixing section integrated into the catalyst housing as shown in Fig. 2.12. Depending on the allowable pressure drop, the catalyst cell density can go up to 400 cpsi and the space velocity can reach 50,000 1/h.

For engines with very high power density, the temperatures downstream of the turbo charger may exceed 550 °C. The usage of on-highway vanadium-type catalysts is limited by the maximum exhaust temperatures and has to be evaluated carefully. For temperatures above 450 to 500 °C, ammonia oxidation as an undesired side reaction may reduce the NO<sub>x</sub> conversion capacity. At temperatures

above 550 °C, the catalyst formulation has to be tested to guarantee that the catalyst possesses sufficient aging resistance [7]. The optimum vanadium content of a catalyst for those engines may therefore be lower than for an on-highway application where low temperature activity is more important. Also zeolite-type catalysts may be an alternative. However, sulfur free fuels are mandatory to allow the use of zeolite technologies as well as PGM catalysts for pre-oxidation and for reduction of NH<sub>3</sub> slip. Systems run for emergency-power or peak-shaving will in general have lower temperature profiles than systems for continuous power. This may lead to a different catalyst and system design depending on the exhaust temperature profile. Details about different catalyst formulations and their application range are discussed in Part II of this book.

## 2.4 Medium and Low-Speed Engines

Derived from power plant technology, first medium- and low-speed diesel engines for gensets were equipped with SCR technology in the late 1980s. Cell density of power plant catalysts is normally given in cells per 150 mm edge length while for automotive catalysts cells per square inch (CPSI) is used. Power plant catalysts usually are square-type honeycombs with 150 mm edge length and less than 40 × 40 cells (≈46 cpsi). Since the introduction of NO<sub>x</sub> aftertreatment for heavy-duty vehicles, round-shaped catalysts with up to 15 inch in diameter and higher cell densities are available, which are also used for small stationary engines.

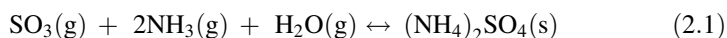
### 2.4.1 Fuels and Sulfur

An important difference between high-speed and low- or medium-speed engines with respect to the exhaust system is the fuel.

Medium-speed engines can run with lower-quality fuels than high-speed engines. Lower-grade distillates as well as residual fuels (HFO) are used. As described in Table 2.1, for the SCR technology, important fuel characteristics are the content of ash, sulfur and for residual fuels also vanadium.

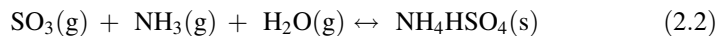
Zeolite-type catalysts will deactivate very rapidly with high-sulfur fuels. Vanadium-type catalysts are sulfur tolerant. To a certain degree, the SCR activity is increased by the presence of sulfur-oxides as the catalyst surface will be acidified. But two other mechanisms are limiting: Possible formation of ammonium salts and oxidation of SO<sub>2</sub> to SO<sub>3</sub> [8].

The following equations describe the sum of possible reactions with ammonia and SO<sub>3</sub> leading to ammonium sulfate (Eq. 2.1) and ammonium hydrogen sulfate (Eq. 2.2):



**Table 2.1** Fuel characteristics with importance to SCR technology

Ash	Catalyst pitch to be adapted: Residual fuels: $\leq 35$ cells / 150 mm (35 cpsi) + installation of soot-blowers On-highway quality: $\geq 300$ cpsi ( $\approx 100$ cells / 150 mm)
Sulfur	Minimum temperature for reductant dosing depends on $\text{SO}_3$ -concentration in the exhaust gas (see Fig. 2.14) Catalyst partly converts $\text{SO}_2$ into $\text{SO}_3$ . Dew-point of exhaust and acidity of condensate are changed Low-sulfur fuel enables the use of oxidation catalysts and the use of zeolite-type SCR-catalysts
Vanadium	Vanadium from residual fuels is captured in the catalyst. Catalyst activity increases with time also for undesired reactions: $\text{SO}_2$ conversion, risk of ammonia salt formation and $\text{NH}_3$ oxidation increase



Ammonium hydrogen sulfate is highly hygroscopic and leads to sticky deposits which will not only block the catalyst pores but also the channels. Ammonium sulfate is not as dangerous as it builds a dry ash-like salt and will decompose before melting [9]. Small quantities of pure ammonium sulfate can be handled by soot blowers. Figure 2.13 shows the gas phase conditions at which ammonium sulfate or ammonium hydrogen sulfate will form.

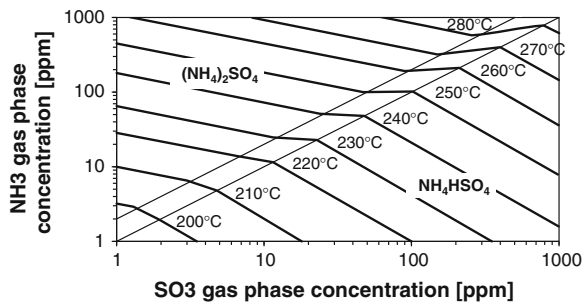
Due to capillary condensation, salts may form on the catalyst up to 350 °C [8]. For exact calculations, the local gas-phase concentration of  $\text{SO}_3$ ,  $\text{NH}_3$  and  $\text{H}_2\text{O}$  along the catalyst and the pore distribution of the catalyst are necessary [11]. The dew-point of sulfuric acid calculated according to [12] is shown in Fig. 2.14.

While  $\text{NH}_3$  is consumed by the SCR-reaction over the length of the catalyst, the  $\text{SO}_3$  concentration increases as the catalyst enhances the oxidation of  $\text{SO}_2$  to  $\text{SO}_3$  according to Eq. (2.3):



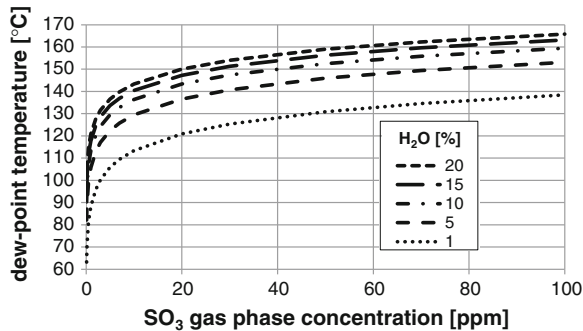
The risk of salt formation depends on the local maximum of the product of  $\text{NH}_3$  \*  $\text{SO}_3$  along the catalyst. Higher vanadium content of the catalyst increases the SCR activity but also the  $\text{SO}_x$  conversion. Therefore, the sulfur content of the fuel limits the minimum dosing temperature as well as the low temperature SCR activity. Figure 2.15 is an estimate of the minimum temperature before catalyst for reductant dosing with regard to fuel sulfur content.

To control the catalyst bed temperature in high sulfur fuel applications, as shown in Fig. 2.16 a bypass is often installed for the SCR catalyst as well as for the boiler [14]. This keeps the catalyst at high temperatures even during low-load operation or idling and avoids condensation of sulfuric acid in the catalyst during start-up.

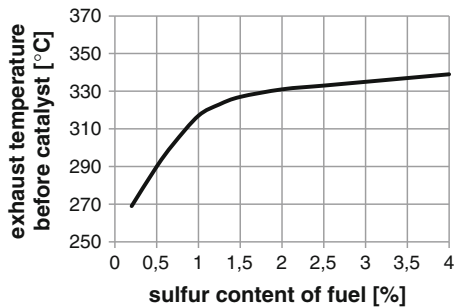


**Fig. 2.13** Conditions for ammonium sulfate salt build-up on the catalyst (Data according to [10]). With a  $\text{NH}_3$  to  $\text{SO}_3$  ratio with less than 1:1, formation of  $\text{NH}_4\text{HSO}_4$  (ammonium hydrogen sulfate) will dominate. Whereas with a ratio of greater than 2:1 preferably  $(\text{NH}_4)_2\text{SO}_4$  (ammonium sulfate) and with a ratio between 1:1 and 2:1 a mixture of both will form. With increasing temperature higher concentrations of  $\text{NH}_3$  and  $\text{SO}_3$  are necessary for salt formation

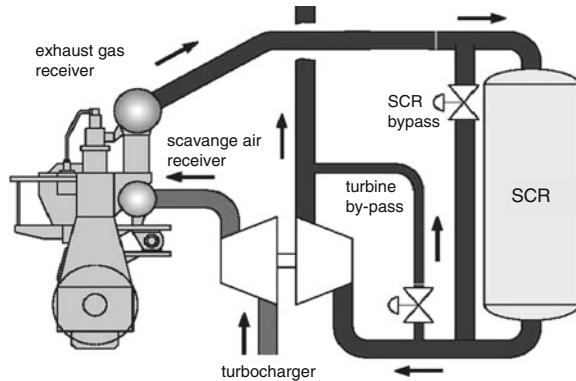
**Fig. 2.14** Dew-point temperature of sulfuric acid as function of  $\text{SO}_3$  and  $\text{H}_2\text{O}$  concentration in the exhaust gas (Calculated according to [12])



**Fig. 2.15** Minimum exhaust temperature before catalyst for  $\text{NH}_3$ -dosing as function of fuel sulfur content based on empirical data according to [13]



**Fig. 2.16** Typical arrangement of pre-turbo SCR for a two stroke engine with an exhaust bypass around the catalytic reactor (Picture Johnson Matthey)



### 2.4.2 SCR Technology for Marine Applications

First commercial ships were equipped with SCR technology in the early 1990s (e.g. MS Aurora 1992 by ABB/HUG and RoRo Ferry Nils-Dacke of TT-Line in 1995 by Siemens [15, 16]).

Since then, the introduction of local emission regulations have led to the development of SCR technology for ships of various sizes and with various engines [17, 18].

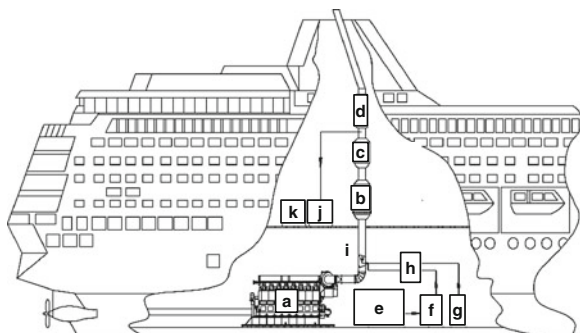
$\text{NO}_x$ -tax in Norway and emission-dependent fairway, as well as port dues in Sweden [19] have led to numerous installations of exhaust cleaning systems on commercial ocean going ships, especially in the Baltic Sea and North Sea. Thus,  $\text{NO}_x$  levels of ships with SCR installation are below the limits of IMO III and are therefore realized far earlier than when this worldwide regulation will go in effect.

For low-speed and medium-speed engines the main technology is derived from diesel engine power plant systems. Whereas in power plants the reducing agent can also be ammonia-water, on bigger ships only urea-water solution is used for safety reasons. In marine applications, special care has to be taken regarding the vibration resistance of urea tubing. Pumping and dosing systems, as well as urea supply tubes should use welding connections wherever possible to avoid urea leakage. A second difference to land-based applications is the demand for classified systems. Classification societies, e.g. Germanischer Lloyd, have included exhaust gas aftertreatment in their rules [20].

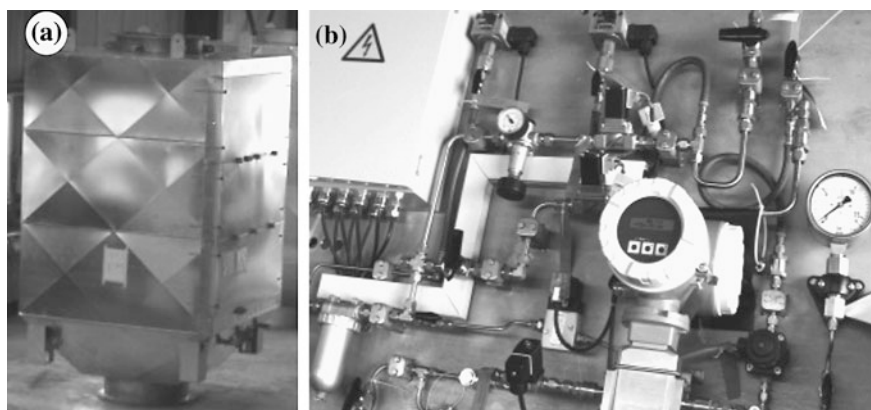
Figures 2.17 and 2.18 show a typical setup and details of a SCR exhaust gas aftertreatment system for a HFO-fueled vessel. The SCR catalyst is placed before the boiler as close to the engine as possible to allow high temperatures at the catalyst for high  $\text{NO}_x$  conversion and to avoid building of ammonium sulfates.

### 2.4.3 Low-Speed Engine Genset

The high efficiency of low-speed two stroke engines is coupled with low exhaust temperatures. Big stationary or marine engines have temperatures downstream of



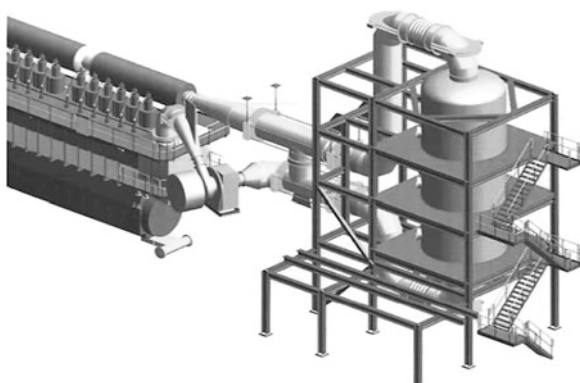
**Fig. 2.17** Overview of an SCR installation on an ocean going ship with a heavy fuel engine. The SCR is installed before the boiler to allow high temperatures at the catalyst for high  $\text{NO}_x$  conversion and to avoid building of ammonium sulfates. **a** Diesel engine, **b** SCR reactor, **c** boiler, **d** silencer, **e** urea tank, **f** urea pump skid, **g** compressor (working air), **h** dosing unit, **i** two-phase nozzle, **j**  $\text{NO}_x$ -analyzer (optional), **k** PLC control cabinet (Pictures H+H Umwelt und Industrietechnik)



**Fig. 2.18** **a** Catalyst housing and **b** urea dosing panel for a medium-speed engine ship application (Pictures H+H Umwelt und Industrietechnik)

the turbine all the way down to  $150\text{ }^{\circ}\text{C}$ , making catalytic exhaust gas aftertreatment impossible. To apply SCR with such engines, the catalyst has to be placed upstream of the turbo charger where temperatures are high enough for exhaust gas aftertreatment. Figure 2.19 shows such an installation with a stationary two stroke engine. The design of the catalyst housing has to regard the exhaust pressure of several bar above ambient [14, 21]. A positive side effect is that this higher pressure is increasing the catalytic reaction but it also enhances the undesired side reactions. As low-speed engines normally run with bunker fuels containing higher amounts of sulfur and vanadium, an important criterion for the catalyst layout is

**Fig. 2.19** SCR pre-turbo in a pressurized vessel installed at a 50 MW two stroke engine  
(Picture Johnson Matthey)



the allowed conversion of  $\text{SO}_2$  to  $\text{SO}_3$ . Even with the SCR catalyst's very low initial vanadium concentration, vanadium from the fuel loads the catalyst and the  $\text{SO}_x$  conversion will rise over time until the catalyst has to be exchanged due to its increasing activity. As for medium-speed engines, a bypass can control the catalyst temperature. In contrast to low-load temperature control for SCR installations after turbo, for pre-turbo installations the maximum catalyst temperature has to be controlled as the  $\text{SO}_2$  oxidation significantly increases at higher temperatures.

## 2.5 Combined Systems

### 2.5.1 DPF + SCR

The combination of a DPF and a SCR aims at the reduction of  $\text{NO}_x$  and PM simultaneously. The combination of both technologies (SCR + DPF) is already used in modern Euro 6, JP09, and US EPA 2010 certified heavy-duty trucks and has undergone comprehensive examination [22–27]. However, for the off-highway application it cannot be considered a standard technology, yet.

An example of a prototype installation on a shunting locomotive, see Fig. 2.20 [22], is presented in this section. Because of the highly variable operating conditions and frequent idling of a shunting locomotive, this example represents a very critical and challenging application for an aftertreatment system.

#### 2.5.1.1 Reactor Concept

As space is limited in a locomotive, especially if it is not designed for the integration of an aftertreatment system, the reactor has to be fitted in place of the silencer. Hence, a very compact reactor, which is able to act as a silencer too, is required. A further challenge arises for aftertreatment systems that are combined





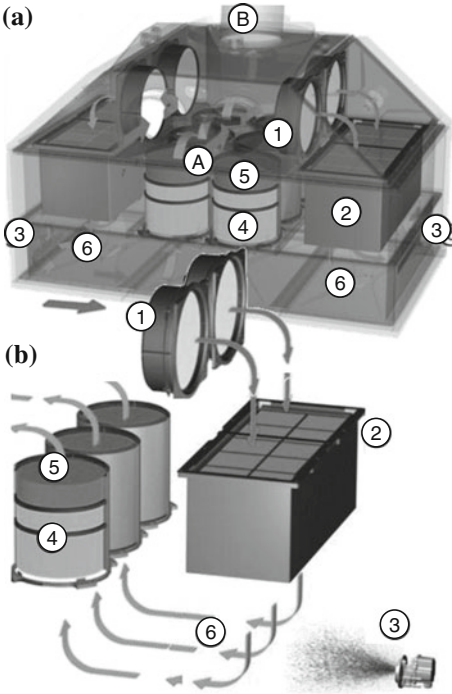
**Fig. 2.20** Shunting locomotive from Deutsche Bahn AG with **a** combined DPF + SCR installation (Picture MTU)

with older engines. This poses some limitations on the backpressure in order to prevent an excessive increase in fuel consumption. In the presented example, 130 mbar were set as the maximum backpressure for the total aftertreatment system, which mainly determines the required DPF volume and the design of the exhaust flow paths in the reactor.

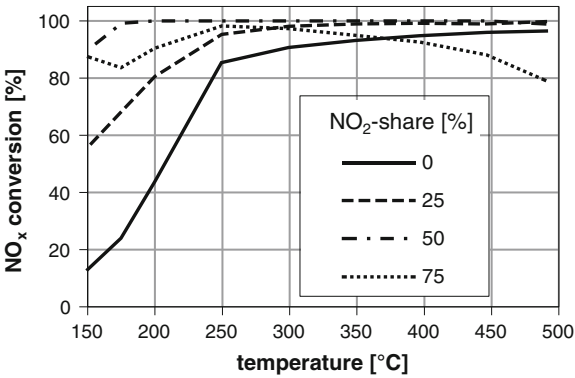
Figure 2.21 shows the cross-section of the installed DPF + SCR reactor. After entering the inlet chamber, the exhaust flow is divided into a right and a left path. First, the exhaust flows through a diesel oxidation catalyst (DOC) to convert some NO to NO<sub>2</sub>, which is a prerequisite for a continuous soot oxidation within the diesel particulate filter (DPF) and which additionally improves the SCR conversion rate, (see Fig. 2.22) [22]. The DPF placed behind the DOC reduces particulate matter (PM) with high efficiency. Downstream of the DPF, a special designed mixing chamber gives the injected urea solution sufficient time for evaporation, mixing and thermolysis before entering the SCR catalyst. Finally, an ammonia slip catalyst is used to prevent any NH<sub>3</sub> slip to the environment.

Due to the required low backpressure, rectangular DPF substrates are used to optimize the exhaust flow cross-section. The utilization of rectangular substrates is not common in mobile applications. Hence, no “mobile” canning technology is available and the canning known from power plant systems (see Sect. 2.6) does not meet the requirements. Therefore, a dedicated canning technology had to be developed. Further details on this can be found in [22]. The integration of round and rectangular substrates is a good example of how heavy-duty vehicle technology and industrial design are combined in aftertreatment systems for off-highway applications.

**Fig. 2.21** Combined aftertreatment system for a shunting locomotive:  
**a** DPF + SCR installed in one reactor housing, **b** gas flow (Picture MTU) with A exhaust gas inlet, 1 diesel oxidation catalyst (DOC), 2 diesel particulate filter (DPF), 3 urea solution Injection, 4 SCR catalyst, 5 ammonia slip catalyst (ASC), 6 urea mixing area, B exhaust gas outlet



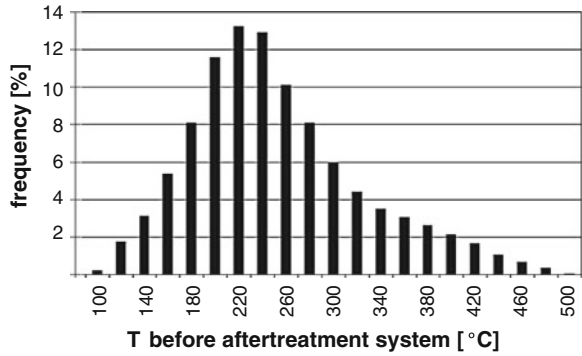
**Fig. 2.22** NO<sub>x</sub> conversion as a function of temperature and NO<sub>2</sub>/NO<sub>x</sub> ratio (synthetic gas test bench measurements) (Data MTU)



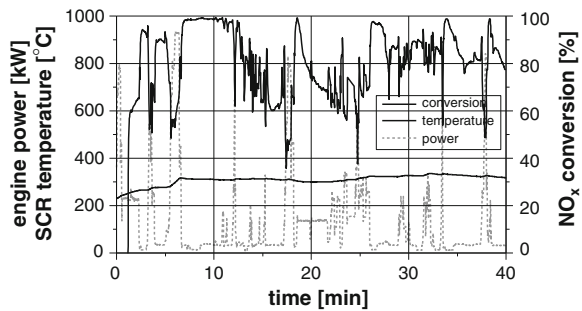
2.5.1.2 Field Experience

In the ISO-F acceptance test the system revealed an overall NO<sub>x</sub> conversion efficiency of more than 70 %. Based on the engine out emissions the NO<sub>x</sub> emissions after the aftertreatment system stayed well below 3.5 g/kWh required by the EU-IIIb legislation. At the same time NH<sub>3</sub> emissions were kept at an absolute minimum.

**Fig. 2.23** Measured temperature distribution in front of the DPF + SCR Reactor (*Data MTU*)



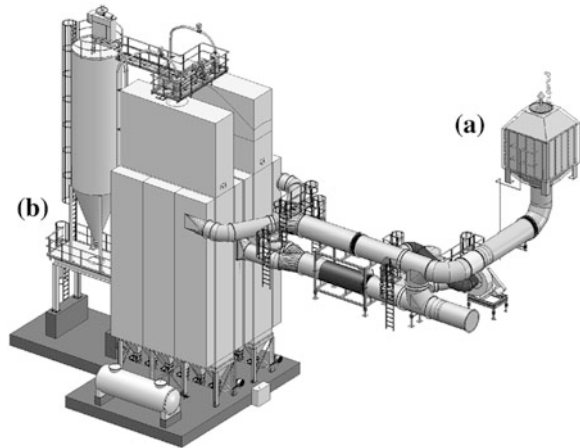
**Fig. 2.24** NO<sub>x</sub> conversion during field operation of the shunting locomotive (*Data MTU*)



Because the typical operating conditions in the field includes 70 % idling, the aftertreatment system is exposed a significant amount of time to low temperatures. Figure 2.23 displays a representative exhaust temperature distribution in front of the exhaust gas aftertreatment system. It is revealed that the average inflowing exhaust gas temperature typically is in the range of 250 °C, which seems quite low, because for this system urea dosing is enabled only for temperatures higher than 250 °C (many on-highway applications are using already 200 °C as threshold). However, due to the high thermal mass of the DOC and the DPF, the temperature before the SCR catalyst is significantly higher. The transient measurements of NO<sub>x</sub> conversion and temperature of the SCR catalyst during operation, displayed in Fig. 2.24, reveal an average SCR operating temperature around 300 °C. The NO<sub>x</sub> conversion efficiency is typically in the range of 80 % or higher, which confirms the efficiency of such a system even under transient conditions. A prerequisite for this performance is also a precise control of the amount of injected urea solution.

It has to be noted, that a combined aftertreatment system requires a high engineering and integration effort and cannot directly be derived from available on-highway technology.

**Fig. 2.25** Combined exhaust gas aftertreatment system for a low-speed engine with **a** SCR and **b** dry  $\text{DeSO}_x$  (DryEGCS) (Picture Couple Systems GmbH)



### 2.5.2 Combination of DeNoxation and DeSulfurization

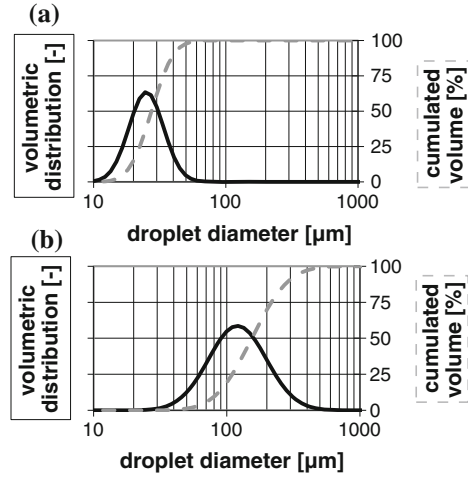
For bunker fuels with high sulfur levels, a combined system would mean to consolidate the  $\text{NO}_x$  and  $\text{SO}_x$  aftertreatment. For  $\text{SO}_x$  reduction wet systems are known from stationary coal and diesel power plants. Wet scrubbers are further developed for exhaust gas aftertreatment on ships [28, 29]. With those systems the SCR is normally installed upstream of the  $\text{SO}_x$  reduction system. Recently, also systems where the desulfurization is done with a dry absorption process have been successfully installed on ships [30]. Figure 2.25 shows a combined system for a stationary engine. Beneficial for dry systems is the smaller heat loss compared to wet systems. This enables the placement of the SCR downstream of the  $\text{DeSO}_x$  without the need of heating up the exhaust again. Without  $\text{SO}_2$  present in the exhaust gas, the V-content as well as the cell density of the SCR-catalyst can be increased. A SCR system installed downstream of a desulfurization will therefore be smaller than it has to be for the engine out  $\text{SO}_2$  concentration. Additionally problems with ammonium-salt formation will not occur and the overall  $\text{NO}_x$ -conversion can be higher due to a lower minimum allowed urea dosing temperature. The downside of dry desulfurization is the much higher space requirement needed for this installations compared to wet systems.

## 2.6 System Integration

### 2.6.1 Reductant Supply

One precondition for high  $\text{NO}_x$  reduction with  $\text{NH}_3$ -SCR-Systems is proper mixing of the reducing agent with the exhaust gas, as well as a good thermolysis of urea.

**Fig. 2.26** Droplet diameter of different spray systems (based on [31]): **a** hollow cone nozzles (airless) and industrial two phase nozzles (air assisted), **b** spray systems derived from gasoline injectors (airless)



Spray systems and mixing devices build a closely coupled system which has to be designed carefully.

### 2.6.1.1 Spray Systems

First for on-highway truck applications and later also for passenger cars, several airless systems have been developed. Up to now, the maximum amount of reducing agent per dosing system is around 10 to 20 L/h. Above this, industrial spray systems are customized and available to deliver much larger quantities. Air assisted nozzles or airless nozzles with good atomization (e.g. hollow cone nozzles) lead to droplet diameters below 100 μm and volumetric mean diameters down to 20 μm. Spray systems derived from gasoline injection valves are characterized by a rather coarse spray (see Fig. 2.26).

### 2.6.1.2 Mixing Concepts

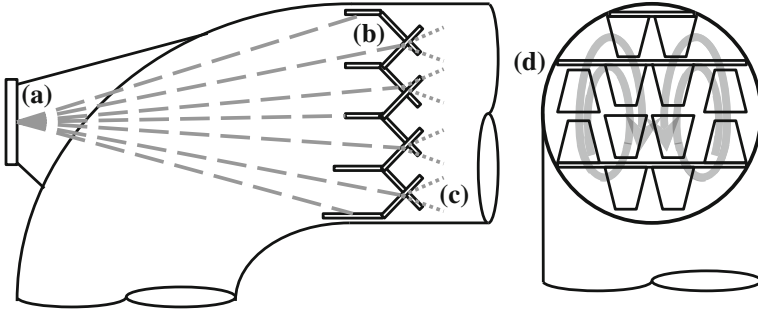
In analogy to the flow uniformity which has first been defined in [32], a uniformity index  $\gamma$  is commonly used also to describe the ammonia distribution across the exhaust pipe or the catalyst cross section. The concentration distribution is defined according to Eq. (2.4):

$$\gamma = 1 - \frac{1}{2A \cdot \bar{c}} \cdot \int_A \sqrt{(c - \bar{c})^2} dA \quad (2.4)$$

with  $c$  and  $\bar{c}$  being the local and average  $\text{NH}_3$ -concentration respectively, and  $A$  being the cross-section of the relevant plane, e.g. the front face of the catalyst.

**Table 2.2** Functionalities included in mixing devices

Measure	Effect
Generation of small scale turbulence	Enhancement of evaporation
Generation of large scale turbulence	Mixing across entire pipe diameter
Droplet catching	Avoiding wall wetting
Providing a hot surface	Heat exchange for evaporation and urea decomposition
Providing surface by a baffle plate	Secondary atomization of droplets



**Fig. 2.27** Baffle plate mixing element for coarse urea spray with the main functionalities **a** spray generation, **b** droplet catching and heat exchange, **c** secondary atomization, **d** large scale mixing (Drawings based on [34])

For discrete measurement points with concentration  $c_i$  representing an area  $A_i$  the uniformity index is defined as

$$\gamma = 1 - \frac{1}{2A \cdot \bar{c}} \cdot \sum_{i=1}^n A_i |c_i - \bar{c}| \quad (2.5)$$

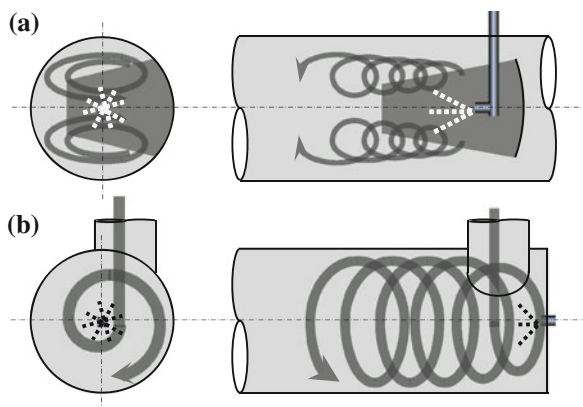
$\text{NO}_x$  reduction of more than 95 % with  $\text{NH}_3$  slip below 10 ppm needs a  $\text{NH}_3$ -distribution of  $\gamma > 95$  %. Good mixing systems for passenger cars and trucks are able to achieve  $\gamma > 99$  %.

Functions included in mixing devices are shown in Table 2.2.

Several mixing technologies are commercially available. Depending on the reductant injection, two general types of mixers can be defined: (a) Mixers for secondary atomization combined with small scale turbulence for droplet breakup and (b) swirl or vortex generators for large scale distribution [31, 33].

For droplets with diameters  $\gg 50 \mu\text{m}$ , a secondary atomization is necessary as such large droplets would otherwise not evaporate properly and would lead to wall wetting downstream of the injection point. Therefore, mixing concepts for coarse spray primarily consist of small-scale turbulence generators and baffle plates for droplet breakup and evaporation (see Fig. 2.27) and have to be installed downstream of the injection location [31]. Additionally large-scale turbulence generators may be integrated for mixing.

**Fig. 2.28** Working principle of **a** vortex mixer and **b** swirl generator



Droplets smaller than 50  $\mu\text{m}$  easily follow the exhaust flow. As the evaporation of small droplets is fast enough, secondary atomization is not necessary, i.e. mixers for fine spray (and self-evident for gaseous reductant) can be installed directly upstream of the injection location. Literature describes several geometric forms, which can be classified into two general groups shown in Fig. 2.28: (a) turbulence wings, mostly delta-wings [33, 35], or round plates installed into the exhaust pipe generating a pair of counter-rotating vortices. (b) swirl generators, which induce one single swirl over the entire exhaust pipe or mixing chamber.

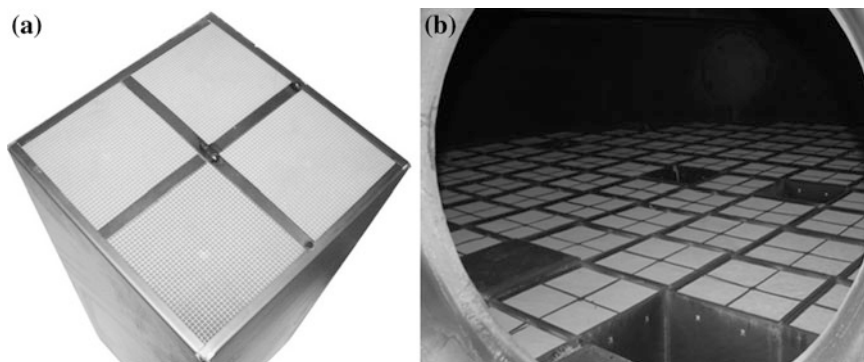
Vortex mixers are well known from power plant systems where they are used with grids of injection nozzles for gaseous ammonia or aqueous ammonia solutions. The mixer is installed upstream of the injection point and the reducing agent is sprayed into the vortex system. The nozzle itself can be placed directly behind the mixer in a zone with low flow in order to have an optimum initial breakup of the spray. Adapted to the exhaust flow of a diesel engine, vortex mixer can be placed together with a single air assisted nozzle in the center of the exhaust pipe. The vortices as a result of large scale turbulence, distribute the reducing agent across the entire exhaust cross section.

In combination with airless on-highway dosing systems which produce a fine spray, vortex mixers allow placement of the nozzle close to the wall of the exhaust pipe from where the droplets are transported away from the wall into the exhaust flow. Without mixer, the impulse of the fine droplets would not be enough to penetrate into the center of the exhaust stream.

Instead of two or more vortices a single swirl is often used for applications where the dosing system is placed at a front face of a catalytic reactor or at a  $90^\circ$  bow of the exhaust pipe. The reductant is sprayed in the center of the swirl.

For both types care has to be taken that centrifugal forces are not too high to avoid wall wetting downstream of a urea dosing system.





**Fig. 2.29** **a** Canning of square catalyst bricks into metal frames and **b** loading of a catalytic reactor (*Pictures Johnson Matthey*)

### 2.6.2 Canning Concepts

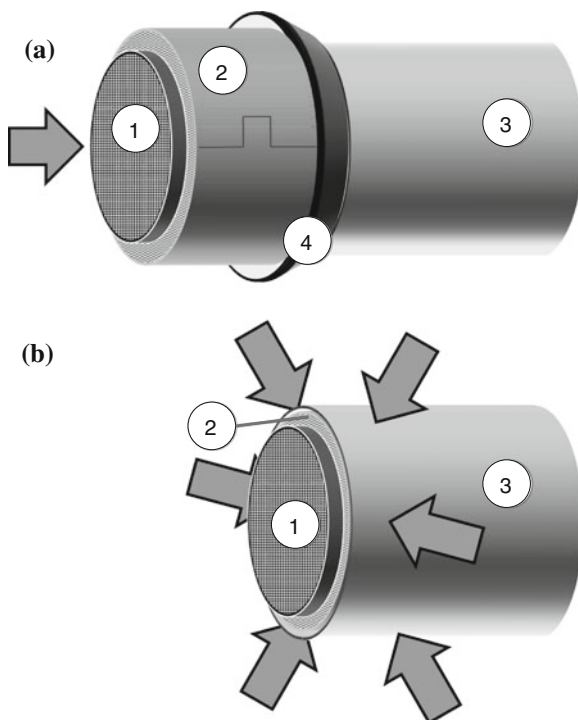
Depending on the exhaust mass flow, which first of all is related to the engine size, two completely different technologies are applied for mounting the catalyst bricks into the exhaust system. For exhaust flows higher than 10,000 to 20,000 Nm<sup>3</sup>/h, the technology is derived from power plant applications. Square catalyst bricks are grouped into metal frames. The catalysts are held in place by the geometric structure of these metal frames. The frames are packed into the catalytic reactor through a manhole and are supported by a metallic structure within the reactor (see Fig. 2.29). To avoid mechanical damage of the catalyst bricks, a fiber mat is packed between catalyst and metal frame. But in contrast to automotive canning technologies, the mats do not have to hold in place the catalyst.

An advantage of this technology is the optimal usage of the available cross-section and the possibility of exchanging the catalysts or reloading catalysts if a spare layer is foreseen in the reactor. For large engines being built and commissioned on site, catalysts are normally put in place just after the engine is running properly, in order to avoid catalysts deterioration due to excess temperature or other exceptional conditions during commissioning of the engine.

Because of the rectangular geometry, the holding forces between canning and catalyst are low and systems with this power plant-like canning can withstand only small g-forces. The technology is appropriate for stationary or quasi-stationary applications like big ships.

For smaller engines and mobile applications, canning technologies known from on-highway systems are preferred. Most of the time, the catalyst bricks are canned into round metal cans. Stüttem [36] describes the principle technologies used for automotive catalysts. Stuffing and shrinking are the typical processes. First, the size of the catalyst substrates is measured and the support mats are weighed. Second the necessary diameter of the metallic canning is then calculated to reach the optimum pressure within the support mat. The target is to guarantee the

**Fig. 2.30** Principle of the canning technologies  
**a** stuffing and **b** shrinking  
 with 1 catalyst, 2 support mat,  
 3 metal canning, 4 stuffing  
 cone



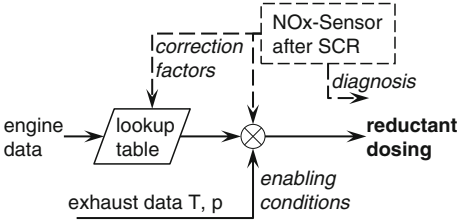
necessary holding force over the lifetime without over-pressing either the mat or the catalyst brick. In the final step with the stuffing process, the catalyst and the support mat are pressed into a readily sized canning. With the alternative shrinking process, the catalyst and mat are put into an oversized canning which than is shrunk to the demanded size (see Fig. 2.30).

## 2.7 Control Strategies

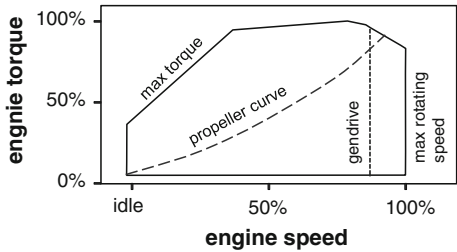
Depending on the dynamic behavior of the engine exhaust as well as the size of the SCR system and the necessary  $\text{NO}_x$ -conversion, different control strategies are used for correct urea dosing.

Systems for low- or medium-speed diesel engines used as gendrive or for propulsion of ships with fixed propellers often work with look-up tables or a characteristic curve as input for an open-loop reductant dosing control (Fig. 2.31). As the engines only use a small band within the engine map (Fig. 2.32) the  $\text{NO}_x$ -emission and thus the reductant dosing rate has a fixed correlation to either engine speed or load.

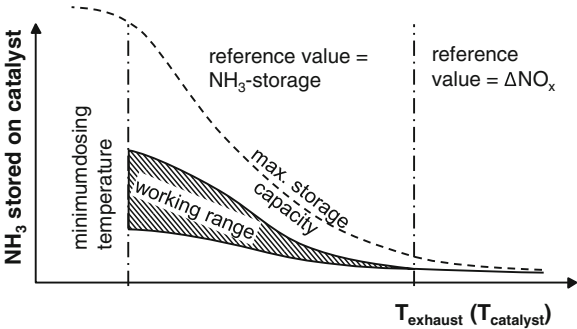
**Fig. 2.31** Feed forward reductant dosing control based on a lookup table



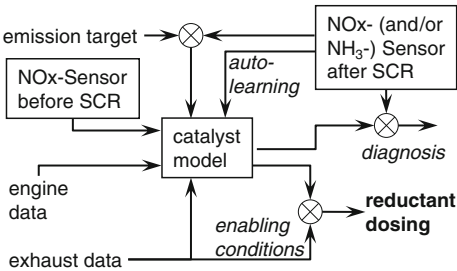
**Fig. 2.32** Diesel engines used as gendrive or for propulsion ships with a fixed propeller use only a narrow band within the engine map. This enables the use of look-up tables for reductant dosing control



**Fig. 2.33** Temperature dependency of possible reductant dosing control strategies



**Fig. 2.34** Reductant dosing control scheme for transient systems with high NO<sub>x</sub>-conversion including exhaust sensors and catalyst model



For applications which demand a high NO<sub>x</sub>-reduction but which have slow changes in exhaust temperature and massflow, a feed-back control based on NO<sub>x</sub>-measurement downstream of the SCR is additionally used. Depending on the volume of catalyst installed and on the operating temperature, the response time of

the SCR-system may be too slow for a closed-loop control. In such applications the  $\text{NO}_x$ -signal may be used to adapt the lookup tables and to improve the feed-forward control (see Fig. 2.31).

To allow high  $\text{NO}_x$ -reduction and fast transient response within the entire engine map, a model based control strategy as outlined in Fig. 2.34 has to be applied [37]. A common way is to operate with the ammonia storage level on the catalyst as reference value [38]. Provided that the system is tuned to negligible  $\text{NH}_3$ -slip the actual  $\text{NH}_3$ -storage level on the catalyst surface can be calculated from  $\text{NO}_x$ -input,  $\text{NO}_x$ -conversion and urea dosing. Depending on the transience of a given application a certain safety margin is set between the physical storage capacity of the catalyst and the target value. The reductant dosing rate is then controlled to keep the  $\text{NH}_3$  filling level as high as possible for maximum  $\text{NO}_x$ -conversion efficiency. Only for high temperatures where the  $\text{NH}_3$  storage capacity of the SCR catalyst is low, the demanded  $\text{NO}_x$ -conversion can be directly used as reference value for the reductant dosing (Fig. 2.33).

For truck-like systems with an electronic engine control providing a lot of emission relevant data, e.g. the actual exhaust massflow, the control algorithm from on-highway trucks can directly be applied also for off-highway applications. In addition to the above mentioned feed-back signal, literature describes other possibilities to include exhaust concentration sensors into the control algorithm [39, 40]. Instead of calculating the  $\text{NO}_x$ -input from engine data it can directly be measured with a  $\text{NO}_x$ -sensor upstream of the catalyst. A  $\text{NH}_3$ -sensor for slip control allows to reduce the safety margin between physical ammonia storage storagecapacity and the actual storage level [41]. Detailed discussion on control strategies can be found in Chap. 14 of this book.

## 2.8 Outlook

It is expected that despite of further engine optimizations, even stricter future emission limits worldwide will lead to an increase in exhaust gas aftertreatment applications for off-highway engines. SCR is currently considered as the main path of technology for  $\text{NO}_x$  aftertreatment in this market. However, development work has still to be done to adapt this technology further to meet all off-highway conditions and requirements. Especially in the mid-power range, where neither on-highway nor power plant technologies meet the constraints of operating temperature, as well as packaging and mechanical durability. Off-highway engines can run up to 35 years, which is far beyond the typical operating life-time of on-highway vehicles. Therefore, a specific challenge is the prevention of aging of the catalyst technology. Due to the great variety of applications, modular and compact packaging concepts are needed to adjust the aftertreatment system in regards to the application-specific requirements in a cost effective way. These challenges have to be addressed and solved, because it is expected that in the future many off-highway diesel engines will be equipped with an SCR system.

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