Diesel Particle Filters for GPU

Contents

1. Introduction

Zurich Airport is continuously working on improving the air quality at the airport and in its surrounding area. Legislative requirements as well as our own efforts often supported by technological developments have shown improvements in concentrations of criteria air pollutants such as NO_2, PM10 or ozone.

Zurich airport's approach to local air quality comprises the development and update of detailed and accurate emission inventories, sophisticated concentration modelling for airport sources, concentration measurements of all regional sources and the development and implementation of mitigation options.

In line with international recommendations [1], emission sources are grouped into four categories: aircraft, including APU (Auxiliary Power Unit and aircraft frame), aircraft handling (ground support equipment, de-icing, airside traffic), airport infrastructure (building maintenance, aircraft maintenance, area maintenance, fire services, construction) and landside access traffic.

This study addresses the Ground Power Units (GPU), part of the aircraft handling category.

2. Airport Air Quality Mitigation Plan

In the context of the national clean air act of 1986 and the Canton of Zurich's mitigation plan 1992, Zurich airport developed its air quality mitigation plan in 1993, addressing all relevant emission sources. With the development of the airport and when obtaining the operating license in 2001, Zurich airport is bound to take all measures feasible to reduce emissions in the areas of air traffic, handling and infrastructure.

A range of measures have been implemented since 1995 by all airport partners. These include, but are not limited to:

- Aircraft: Emission related landing charges (based on NOx and HC); implementation of A-CDM to reduce taxi times and queuing
- APU: Fixed ground energy systems (AGES) on all terminal stands and some open stands
- GSE: Continuous replacement of ground support equipment and change from diesel to electric or natural gas
- Buildings: insulation and retrofits for lower heating requirements
- Landside traffic: increase of public transportation share

Despite all efforts to the local air quality in the past, the longer term concentration developments reveal the potential to further reduce emissions of NOx and particles.

3. Diesel Particle Filters for Ground Power Units (GPU)

3.1. Ground Power Units at Zurich Airport

GPU are providing electrical energy at 115V with 400Hz to aircraft. The electrical energy is needed for aircraft during ground time to run electrical appliances like computers, communication and navigation instruments, lights or motors. However, GPU cannot provide energy to heat or air-condition the aircraft. At Zurich airport, all GPU are diesel powered.

Ground Power Units at Zurich airport are owned and operated by the various handling agents. The GPU are used on open stands where there are no fixed aircraft ground energy systems available. They are also used in the aircraft MRO facilities (Maintenance, Repair and Overhaul). In total, there are 47 GPU in operation. They produced a total of 52,300 operating hours per annum, consuming 300,000 litres of diesel. This amount constitutes approximately 10% of all diesel used for ground support equipment and airside traffic (all data from 2014).

Based on the current GPU fleet, 15 were selected to receive an emission reduction retrofit. Their selection was based on the economic service time and usability.

3.2. Emission Reduction Technologies

3.2.1. DeNOx and diesel particle filter (DPF)

Initial ideas included the technology to reduce NOx emissions alongside the particle emissions. As such, a DeNOx and particle filter (DPF) system has been envisaged.

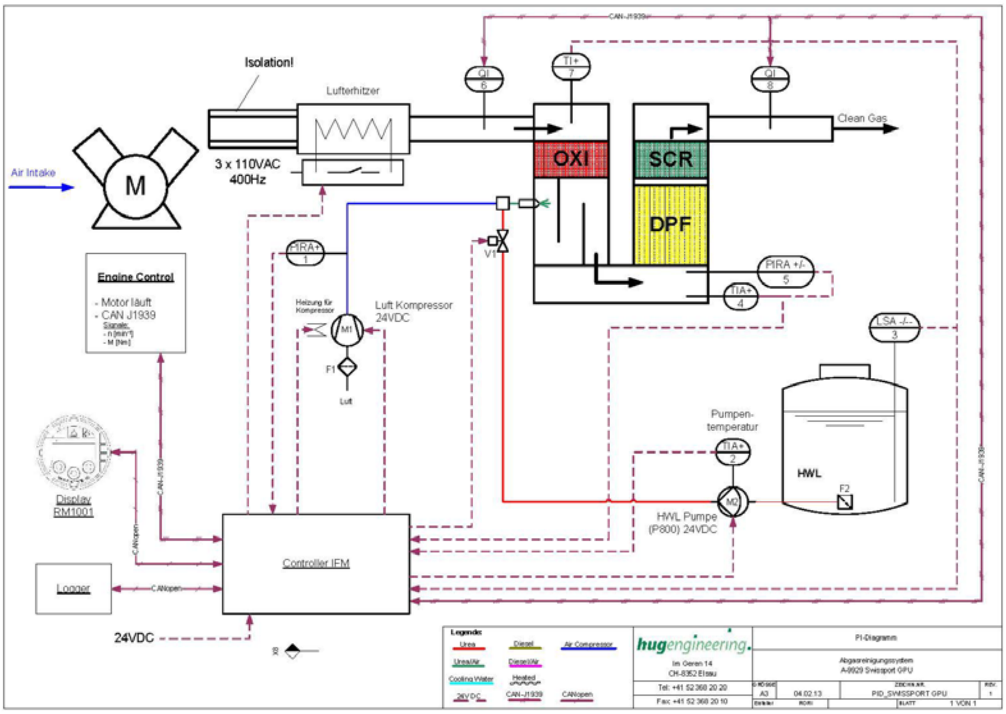


Figure 1 Schematic design of DeNOx and DPF [2]

Figure 2 DeNOx and DPF system used for field testing

Comprehensive tests have shown that the average load of the generator significantly influences the potential NOx reduction. However, the actual load – ranging from 10-15 kW with occasional peaks of 30-40 kW for narrow body aircraft – is low compared to the engine power of 97-125 kW. The reason for this lies in the narrow tolerance of the frequency of 400Hz for short term peaks.

The overall NOx emission reduction potential has been modelled to be less than 20%. As the required heating of the DeNOx part leads to an increase of fuel of 1.5 l diesel/hour (plus 20% CO_2 emissions), the option for a DeNOx system was not found to be feasible.

Furthermore, installation of an urea tank and supply on the GPU and provisions for securing a frost-proof design as well as defrosting capabilities, are very demanding and finally rather expensive.

3.2.2. Diesel Particle Filters (DPF)

System

The particle filter system used is a wall flow filter made of porous ceramic substrates with an upstream connected heating coil, mounted on top of the GPU (see Annexe for details).

Figure 3 Diesel particle filter (left part) with heating coil (right part), Hug Engineering [2]

Operation and regeneration

The DPF system works with a small two stage preheating system 30/40 kW (2x15kW / 2x20kW) that heats up the exhaust to a load-independent regeneration temperature of approx. 550°C. The regeneration is triggered by the exhaust counter pressure and lasts approximately 20 minutes per cycle. Regeneration is typically taking place every 10 operating hours.

Retrofit and maintenance

The retrofit has been done on existing GPU, taking them out of operation for approximately 2-3 days. The system does not require special maintenance for the DPF itself.

Figure 4 Retrofitting a GPU with a DPF

4. Environmental Achievements

4.1. Technology development

Engine technology for non-road mobile machinery has evolved over time and has become cleaner. Combustion engines have to meet the EU regulations (EU NRMM-Directives) that have become more stringent over time as well. The following table reflects this development between 2005 [3] and 2012 [2], where over seven years, NOx emission factors have been reduced by almost two thirds. The values in the following table represent actual measured values from several ground power units for both survey years.

Criteria		**2005**	**2012**
Technology range	(GPU model years)	1994-2004	2006-2011
Fuel Consumption	(l/h)	7.93	6.49
NOx	(ppm)	647	233
CO	(ppm)	108	160

Table 1 Development of GPU emission factors 2005-2012 (measured, [2, 3])

As such, the technology development in itself delivers ecological benefits. At the same time, the initially estimated potential to further reduce emissions becomes smaller. This is particular the case for NOx.

4.2. DPF benefits

A comprehensive testing has been set up to assess the benefits of the DPF in actual operation. As the GPU data logger records the actual load during a typical operating cycle, the data has been used on the testbed for emission measurements. While one set of measurements has been done before the DPF system, the second set of measurements has been done after the DPF (figure 5).

Figure 5 GPU emission measurement set-up

The testing was performed in November 2015 at Zurich Airport, using two different GPU, both equipped with the DPF (see table 2). Particle numbers were measured using a TSI CPC 3772 with a thermal conditioner and a raw gas dilutor. Particle mass was measured with an AVL Micro Soot Sensor Measuring Unit (cf. table 3).

Specifications	GPU #116	GPU #132
Rated electrical Power [kVA]	90	90
Engine Capacity [l]	4.8	4.5
Number of Cylinders	4	4
Operating Hours [h]	13,791	6,263
Year built	2006	2010
Diesel Fuel	EN590	EN590

Table 2 Measured GPU models

Measuring Device	Particulate Mass	Particulate Number	Exhaust Gas (NO, NO_2, O_2, CO)
Manufacturer	AVL	TSI	Testo
Type	Micro Soot Sensor	CPC 3772	Type 350
Principle	Photo Acoustic	Condensation Particulate Counter	Electrochemical cells, dry measurement
Range	0.001 – 50 mg/Nm^3	0 – 10,000 particles/Ncm^3	

Table 3 Measurement devices for GPU emission measurements Zurich Airport.

Based on a load profile and temperature series before DPF of GPU as measured on October 15/16, 2015 for a 24h operational period (figure 6), a synthetic load profile has been derived for the testing purposes: The electrical load was controlled by using a load bank, with adjusted base load of 10 kW$_e$ and switchable load steps of 8 kW$_e$ (figure 7). As can be seen, the power demand is fairly low with only few peaks above 15 kW$_e$. The exhaust gas temperature ranges from 150°C to 250°C and is thus below any temperature range where passive regeneration of a DPF is feasible.

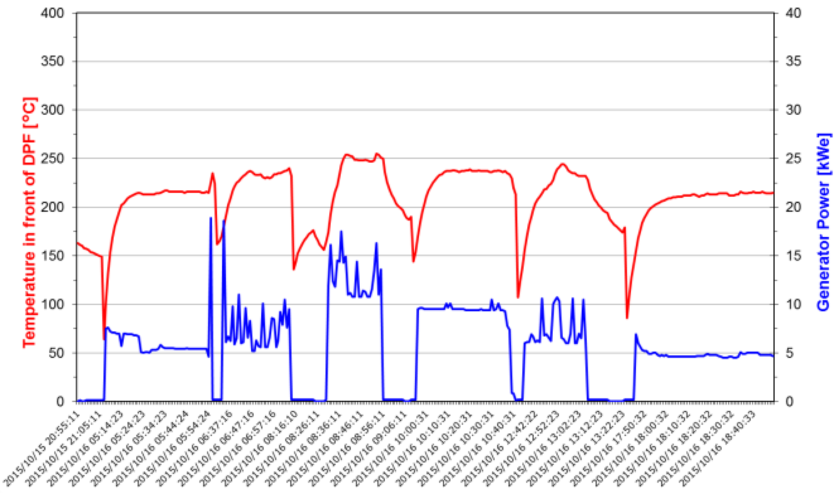


Figure 6 GPU actual load profile and exhaust temperature (October 15th-16th, 2015, 24 hour period)

This load profile has been used to perform two measurements each, of both GPU and before/after the DPF (detailed data can be seen in the annex).

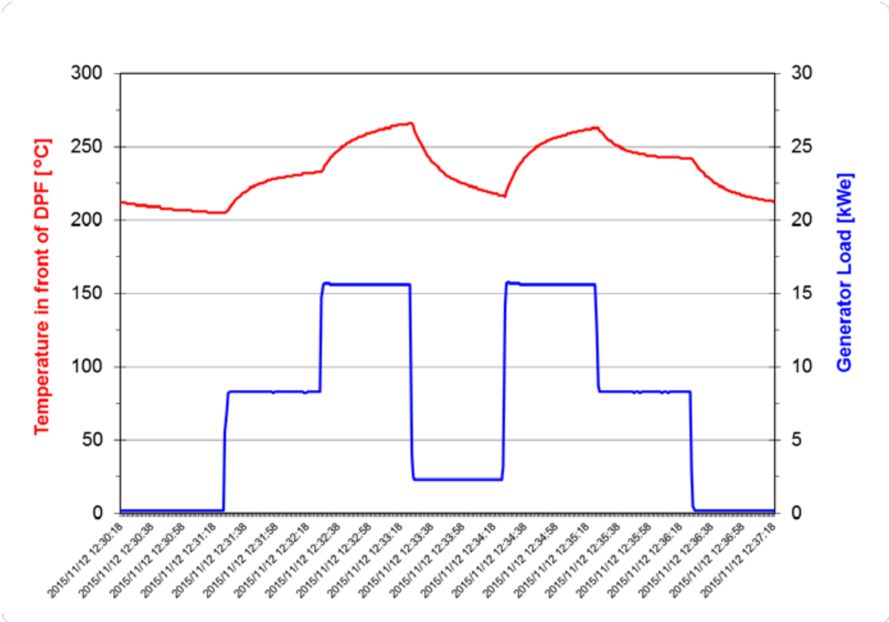


Figure 7 Synthetic GPU load profile and typical exhaust temperature during measurements

The results are displayed in the following figure 8. It shows a GPU operating cycle over 20 minutes with the loads and load changes indicated. Before the DPF, the particle numbers range from $1.6x10^7$ to $3.2x10^7$ #/Ncm³, while the mass itself gives a total of 3-25 mg/Nm³. NO ranges typically between 100 and 290 ppm.

After the DPF filter, the particle numbers range from 590 to 1,120 #/Ncm³ (>99.99% reduction) and no mass is detected. The NO emissions don’t change much and remain between 120 and 360 ppm.

As shown in the following figure, the trace of Particulate Number before DPF is nicely following the load profile pattern as shown in the previous figure and is showing a good repeatability of the load steps.

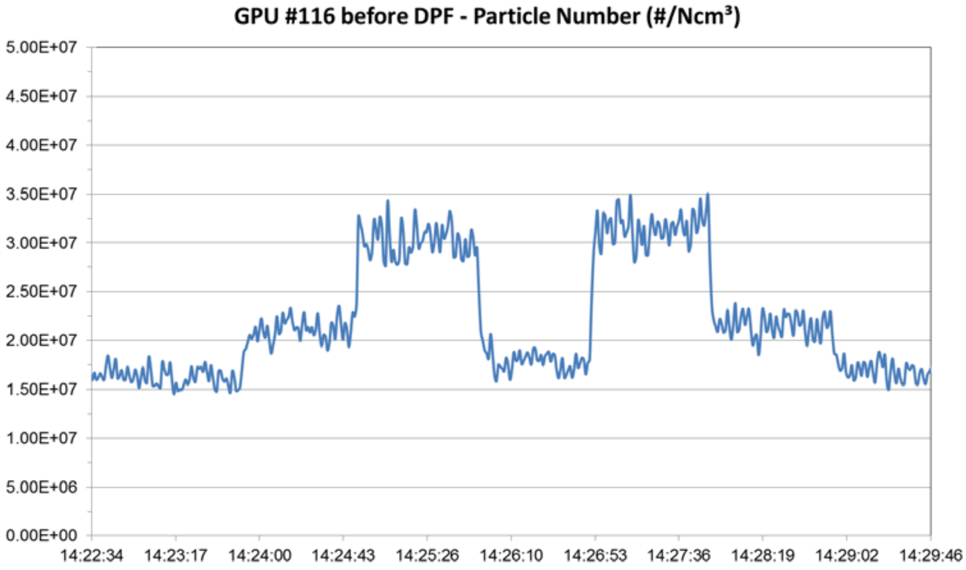


Figure 8 Measured trace of number of particles of GPU#116 before DPF

Emission Factors

Based on measurement results for emissions of particle mass and number as well as for fuel consumption values, emission factors could be calculated. These emission factors are providing an indication what emissions are generated under typical operational conditions (average load). Since the fuel consumption of GPUs is electronically traced, emission factors based on consumed amount of fuel per time period are most convenient.

Emission Factors		**2006 engine**	**2010 engine**
		Average Load	Average Load
Values without DPF			
Soot	(mg/kg Diesel)	224	1125
Particle number	(#/kg Diesel)	$9.4x10^{14}$	$2.3x10^{15}$
NOx (as NO_2)	(g/kg Diesel)	25	16
Values with DPF			
Soot	(mg/kg Diesel)	0	0
Particle number	(#/kg Diesel)	$3.3x10^{10}$	$9.9x10^{8}$
NOx (as NO_2)	(g/kg Diesel)	25	16

Table 4 Derived GPU emission factors

5. Outlook

5.1. Retrofitting existing machinery

The approach of Zurich airport has demonstrated the feasibility of taking technical measures to improve the emissions on existing machinery. Given the long life-time ad the large number of equipment in use at airports, this method could yield significant reductions of particles in the engine exhaust.

Main requirements:

- Sufficient long remaining life-time of the equipment or sufficiently recent purchase: The definition depends on company and site specific assumptions or agreements. A remaining life-time of 10 years or an age of approximately 5 years seems reasonable to consider a retrofit.
- High usability: the best return and environmental benefit comes from a high usage of the equipment. Again this depends on local circumstances, but an operation time of approx. 700 hours per year should be envisaged.

5.2. New engine emission standards

On September 25, 2014, the European Commission proposed Stage V emission regulations. The proposed Stage V emission limits for engines in nonroad mobile machinery (category NRE) are shown in the following table. These standards are applicable to diesel (CI) engines from 0 to 56 kW and to all types of engines above 56 kW.

Category	Ign.	Net Power	Date	CO	HC	NOx	PM	PN
		kW		g/kWh				1/kWh
NRE-v/c-1	CI	P < 8	2019	8.00	7.50[a,c]		0.40[b]	-
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.60	7.50[a,c]		0.40	-
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.00	4.70[a,c]		0.015	1×10^{12}
NRE-v/c-5	All	56 ≤ P < 130	2020	5.00	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.50	0.19[c]	0.40	0.015	1×10^{12}
NRE-v/c-7	All	P > 560	2019	3.50	0.19[d]	3.50	0.045	-

[a] HC+NOx
[b] 0.60 for hand-startable, air-cooled direct injection engines
[c] A = 1.10 for gas engines
[d] A = 6.00 for gas engines

Table 5 Proposed Stage V Emission Standards for Nonroad Engines [4]

Stage V regulations would introduce a new limit for particle number emissions. The PN limit is designed to ensure that a highly efficient particle control technology—such as wall-flow particulate filters—be used on all affected engine categories. The Stage V regulation would also tighten the mass-based PM limit for several engine categories, from 0.025 g/kWh to 0.015 g/kWh. GPU would generelly fall into the category NRE-v/c-5.

Annexe

A.1. Abbreviations

A-CDM	Airport Collaborative Decision Making
AGES	Aircraft Ground Energy Systems (providing electricity and/or air-conditioning to the aircraft)
APU	Auxiliary Power Unit (kerosene powered turbine, built into aircraft)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRT	continuously regenerating trap
DeNOx	Denitrification
DPF	Diesel Particle Filter
GPU	Ground Power Unit (diesel powered electricity generator)
GSE	Ground Support Equipment (vehicles and machinery used to service aircraft at ground)
HC	Hydrocarbon
Hz	Hertz
kVA	Kilovolt-Ampère – nominal electrical power of generator
kW	Kilowatt – engine mechanical power
kWe	Kilowatt – generator electrical power
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NOx	Subsumes NO and NO_2 as Nitrogen oxides
NRE	Non road engines
PM	Particulate Matter
ppm	parts per million
SCR	Selective Catalytic Reduction

A.2. Diesel Particle Filter Specifications

	mobiclean™ R EP30	**mobiclean™ R EP40**
Generator power	65-90 kVA	90-120 kVA
Engine power	85-120 kW	120-150 kW
Temperature (low load)	180°C	180°C
Temperature (regeneration)	530°C	530°C
Filter type	R20 basic	R20 basic
Max generator power at regeneration	75%	75%
Duration of regeneration	15 min	15 min
Additional fuel consumption	max. 1.5%	max. 1.5%

Table 6 Diesel particle filter specifications [2]

A.3. Measured/calculated emission values for GPU

Note: the 2006 and 2010 engines are not the same engine manufacturer. As such, the values cannot directly be compared.

Fuel and Emission Data		2006 engine		2010 engine	
		No load: idle-2 kW	Load: 10-18 kW	No load: idle-2 kW	Load: 10-18 kW
Fuel Flow	(l/h Diesel)	4.3	7.5	4.0	7.7
O_2	(Vol%)	17	16	17	16
Values before the DPF					
NOx ($NO+NO_2$)	(ppm)	231	325	130	160
CO	(ppm)	225	210	148	187
Soot	(mg/Nm^3)	3.4	7.3	19.1	24.3
Particle number	(#/Ncm^3)	1.69E+07	2.62E+07	3.94E+07	5.11E+07
Values after the DPF					
NOx ($NO+NO_2$)	(ppm)	220	335	136	163
CO	(ppm)	225	212	151	184
Soot	(mg/Nm^3)	0	0	0	0
Particle number	(#/Ncm^3)	652	860	19	18

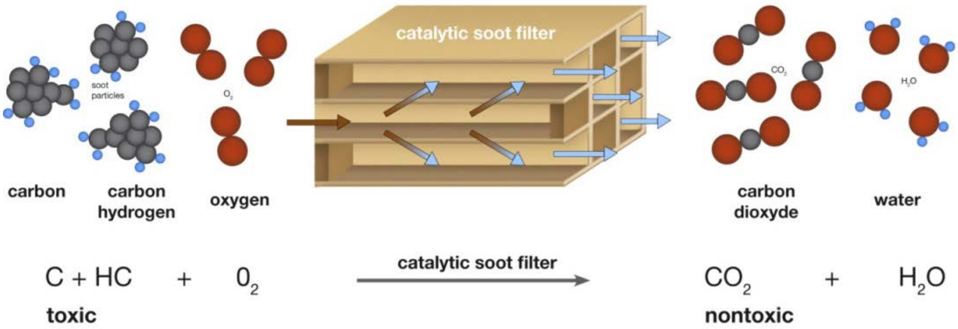
Table 7 Measured fuel and emission indices for GPU (Nov. 2015, Zurich Airport)

A.4. Glossary

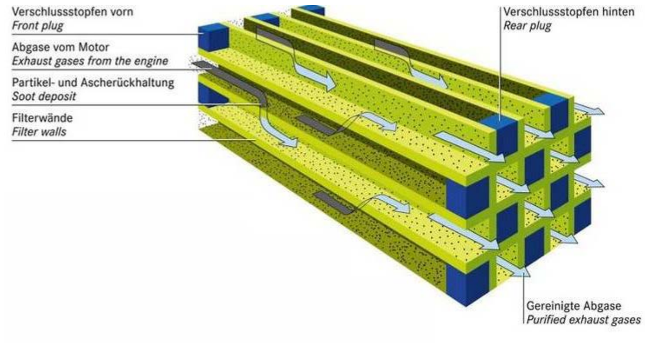
DPF (Diesel Particulate Filter)

The diesel particulate filter – also known as a soot particulate filter – is a component of the exhaust system of diesel engines. It is filtering harmful soot particles generated by the combustion process in the engine and converting it into carbon dioxide and water (-> DPF-Regeneration). Among the numerous concepts developed for this purpose, wall flow filters made of porous ceramic substrates – such as silicon carbide – have established themselves as the standard choice, with high filtration efficiency of >98% for particulate mass and particulate numbers.

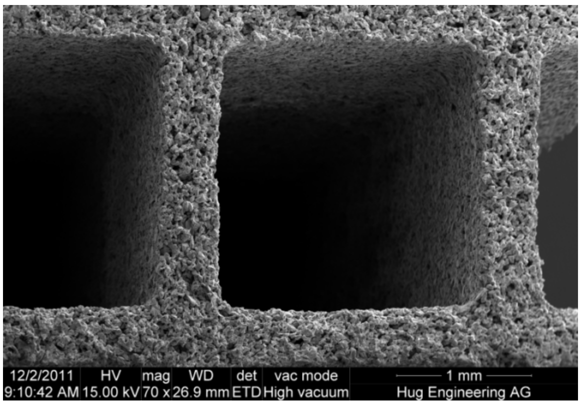
The European emission standards for on-road vehicles are requiring the installation of a DPF. Today, all new passenger cars and commercial vehicles in the EU are fitted with a DPF. New regulations for off-road applications are in preparation and will also require a DPF to be used on this kind of engines in the future.



Filtration of soot particles and conversion into carbon dioxide and water



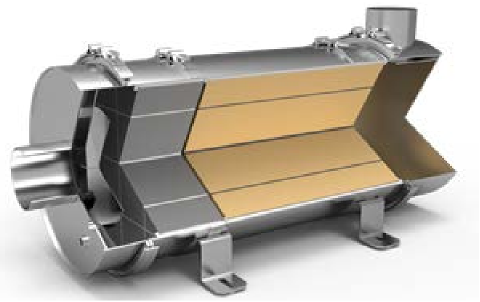
Schematic of a wall-flow Filter



X-Ray Microscope Picture of porous ceramic wall of a DPF

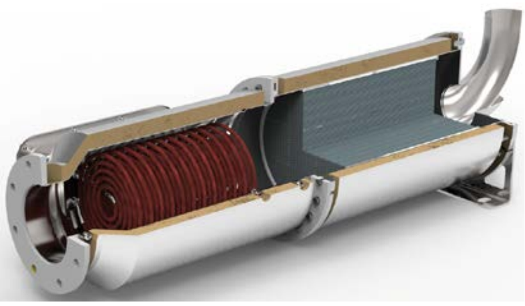
DPF-Regeneration
DPF-Regeneration is describing the soot-burn-off of the accumulated soot in the filter. There is a ‘passive’ and an ‘active’ regeneration.

Passive regeneration is using special coatings on the DPF for catalytically burning-off the soot particles. The basic principle is called CRT (continuously regenerating trap) and it uses nitrogen dioxide to oxidize the soot particles. Depending on the catalytic coating, passive regeneration is starting at exhaust gas temperatures of around 250°C and sufficient burn-off rates are achieved at exhaust gas temperature above 350°C. Though the prerequisite to implement passive regeneration is that exhaust gas temperatures are periodically well above 350°C. Furthermore, nitrogen dioxide is generated by using nitrogen monoxide (typically about 95% of all emitted NOx of an engine) and oxidizing it in an oxidation-catalyst installed in front of the DPF. This oxidation-catalyst is very susceptible to poisoning by sulphur and sulphur content in diesel fuel should not exceed 50 ppm.



Passive Regeneration: Pre-Oxidation-Catalyst (grey) and DPF (yellow) combined in one DPF-Housing

Active Regeneration is using heated exhaust gas to activate the burn-off of soot particles. To heat up the exhaust gases a diesel fuel burner or an electric heater could be used. For achieving sufficient burn-off rates, catalytically coated DPF’s are used and exhaust gas temperatures have to be periodically above 450°C. On GPU’s the implementation of an electric heater is most preferred. Due to the electric load created by the heating coils on the generator and the engine, the exhaust gas temperature is naturally increased and is supporting the burn-off process.

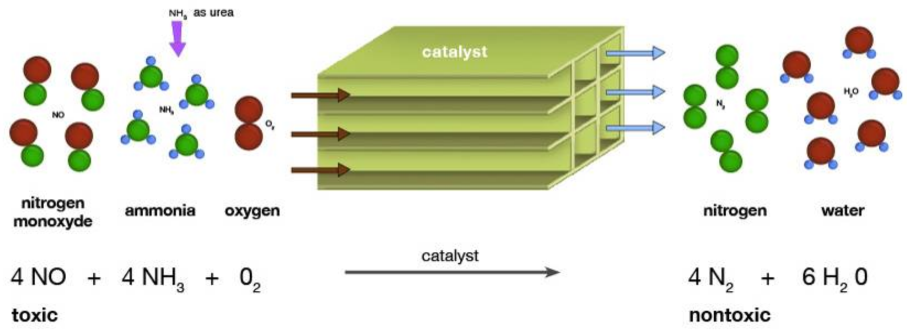


Active Regeneration: electrical Heating (heating coils in red colour) and DPF (grey) combined

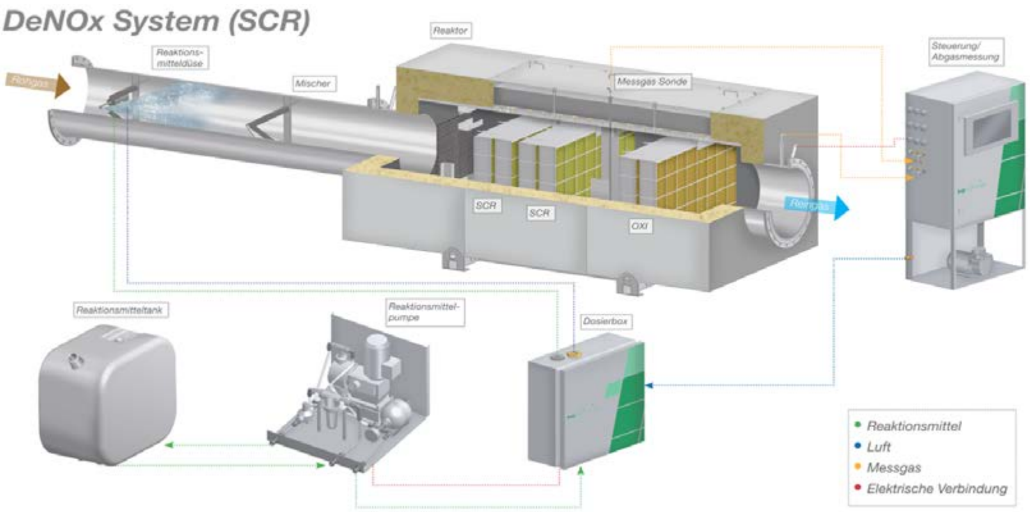
Selective catalytic reduction (SCR)

SCR is a technology for the reduction of toxic nitrogen oxides (NOx). This technology is transforming harmful NOx into harmless N2. The basic principle is that an urea water solution (usually referred to as “AdBlue” in the automotive industry) is injected into the exhaust gas, where the urea is transformed into ammonia, carbon dioxide and water. This mixture of ammonia and exhaust gas is flowing into a so called SCR-Catalyst, where the ammonia is chemically reducing mainly nitrogen monoxide and nitrogen dioxide into elementary nitrogen. For securing a proper urea transformation into ammonia and sufficient catalytic activity, exhaust gas temperature must be above 250°C. State of the art SCR-Systems are able to convert >99% of NOx into nitrogen.

The European emission standards for on-road vehicles are requiring the installation of a SCR-System. Today, all new passenger cars and commercial vehicles in the EU are fitted with a SCR-System. For this a supply chain for urea solution is established. New regulations for off-road applications are in preparation and will also require SCR-Systems to be used on these kind of engines in the future.



Chemical reduction of NOx into Nitrogen



SCR-System for Power Plant

Figures

Tables

Sources

No.	Document Name
[1]	International Civil Aviation Organization, ICAO: Airport Air Quality Manual. ICAO Doc 9889, 1st edition, 2007.
[2]	Hug Engineering: Project documentation and personal information. 2012-2015.
[3]	Flughafen Zürich AG: Ground Power Unit (GPU) Exhaust Emissions at Zurich Airport. Sept. 2006.
[4]	https://www.dieselnet.com/standards/eu/nonroad.php (visited 30.10.2015)

Version	Date	Name	Modifications
1.0	21.1.2016	Fleuti	First Edition
2.0	19.3.2018	Fleuti	Correction of table 4 (EI for PN before DPF)

Authors:	Emanuel Fleuti	Thomas Walter
Division/Unit:	Environmental Protection	Hug Engineering

emanuel.fleuti@zurich-airport.com
Phone +41 (0)43 816 21 81, Fax +41 (0)43 816 47 60

Flughafen Zürich AG
P.O. Box, CH-8058 Zurich-Airport
www.zurich-airport.com

thomas.walter@hug-engineering.ch
Phone +41 (0)52 368 23 72, Fax +41 (0)52 368 20 10

Hug Engineering AG
Im Geren 14, CH-8352 Elsau
www.hug-eng.ch