



2nd VegOil

Demonstration of 2nd Generation Vegetable Oil Fuels in Advanced Engines

Workpackage WP2
Engine development

Deliverable N° 2.1: Survey on state-of-the-art technologies and impact of plant oil fuels

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1 Summary

In diesel engines the main components of exhaust gas, that have to be reduced to meet the exhaust emission standards, are carbon-based particulates (PM) and nitrogen oxides (NO_x). To meet the current and future emission standards an exhaust aftertreatment system has to be used.

Exhaust aftertreatment systems can be divided into:

- Diesel particulate filter systems (DPFs) to reduce the particle emissions
- DeNO_x-systems (denitration exhaust aftertreatment systems) to reduce the nitrogen oxides emissions

DPFs filter the particulate matter out of the exhaust stream. After a certain time, DPFs reach their loading capacity and have to be regenerated. The DPF can be continuously regenerated if the exhaust temperature is constantly high enough to burn off the soot. This type of regeneration is called passive regeneration. If the exhaust temperature is not high enough for a passive regeneration, the DPF needs to be actively regenerated. This is done by injecting additional fuel into the combustion chamber or the exhaust pipe. Then the heat is generated over a diesel oxidation catalyst (DOC) upstream of the DPF. During regeneration the soot oxidizes to carbon dioxide.

To reduce nitrogen oxide, SCR-systems (selective catalytic reduction) are common. In SCR-systems ammonia reacts with the nitrogen oxides (NO, NO₂) in the exhaust gas to nitrogen (N₂) and water (H₂O).

Due to the operational conditions of agricultural machines, special demands are required for exhaust aftertreatment systems:

- Inured to crashes and vibrations
- Compact design
- Emitted heat must not enflame combustible material such as straw, etc.
- No line-of-sight obstruction for the operator
- Various operating profiles

Biofuels for diesel engines contain alkali and alkaline earth metals as well as phosphorus. Calcium, magnesium, sodium and potassium cause ashes, which cannot be removed during regeneration and therefore shorten the service intervals of the DPF. Sodium, potassium and phosphorus are toxic for the DOC and damage the structure of ceramic DPFs.

2 Introduction

This report gives an overview and a summary of common exhaust aftertreatment systems for diesel engines. It describes their design, their function in general and especially their operation with biofuels like plant oils.

3 Exhaust emission from diesel engines

3.1 Emissions with diesel

For diesel engines there are four different groups of exhaust emissions limited by law.

- Hydrocarbons (HC) like:
 - Aromatic hydrocarbons
 - Alkanes
 - Alkenes
 - Polycyclic aromatic hydrocarbons (PAH)
- Carbon monoxide (CO)
- Nitrogen oxides (NO_x) like:
 - Nitric oxide (NO)
 - Nitrogen dioxide (NO₂)
- Particulate matter (PM)

Additional there are several other emissions in the exhaust gas of a diesel engine like:

- Aldehydes
- Sulfur dioxide
- Sulfates
- Ammonia
- Cyanide [1]

3.2 Emissions with rapeseed oil

An important difference of the emissions from diesel fueled engines in comparison with engines operating with rapeseed oil is the quantity of each group of emissions. Looking at the results of different emission tests, PM emissions in converted diesel engines are lower when biofuels are used, whereas the NO_x-emissions are normally higher.

Especially the PM from diesel engines can increase the mutagenic disposition of cells and thus cause cancer. Investigations [2] have shown that the mutagenicity of exhaust gas from a

converted engine fueled with rapeseed oil complying with DIN V 51605 has a lower mutagen effect in most points of an 8-Mode cycle.

3.3 The formation of diesel emissions

Emissions in a combustion engine are combustion products of the fuel as well as the lubricant and the components of the air. Depending on the conditions during the combustion different sorts of emissions occur:

1. Emissions due to incomplete combustion:
 - Unburned hydrocarbons
 - Fractional burned hydrocarbons (e.g. CO)
 - Thermal cracked products and their derivatives (e.g. soot)
2. Emissions due to complete combustions
 - Combustion with fuel and air components (e.g. NO)
3. Combustion of the lubricant [3].

Lubricants can contain sulfur, phosphorus and ashes. Sulfur and phosphorus are known as catalysis toxins. Ashes are causing deposits in the DPF which might lead to an increasing exhaust gas pressure.

3.4 Diesel emission standard

Depending on the date of the type approval of an engine and its power, different levels of legal exhaust gas limits are effective in the EU (Table 1).

Table 1: Exhaust emissions requirements for tractors in the EU

Engine Cat.	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
18kW - 37kW	Stage II			Stage IIIA											
	CO: 5,5 g/kWh HC: 1,5 g/kWh NO _x : 8 g/kWh PM: 0,8 g/kWh			CO: 5,5 g/kWh HC+NO _x : 7,5 g/kWh PM: 0,6 g/kWh											
37kW - 56kW	Stage II			Stage IIIA				Stage IIIB							
	CO: 5 g/kWh HC: 1,3 g/kWh NO _x : 7 g/kWh PM: 0,4 g/kWh			CO: 5 g/kWh HC+NO _x : 4,7 g/kWh PM: 0,4 g/kWh				CO: 5 g/kWh HC+NO _x : 4,7 g/kWh PM: 0,025 g/kWh							
56kW - 75kW	Stage II			Stage IIIA				Stage IIIB			Stage IV (01.10.2013)				
	CO: 5 g/kWh HC: 1,3 g/kWh NO _x : 7 g/kWh PM: 0,4 g/kWh			CO: 5 g/kWh HC+NO _x : 4,7 g/kWh PM: 0,4 g/kWh				CO: 5 g/kWh HC: 0,19 g/kWh NO _x : 3,3 g/kWh PM: 0,025 g/kWh			CO: 5 g/kWh HC: 0,19 g/kWh NO _x : 0,4 g/kWh PM: 0,025 g/kWh				
75kW - 130kW	Stage II			Stage IIIA				Stage IIIB			Stage IV (01.10.2013)				
	CO: 5 g/kWh HC: 1 g/kWh NO: 6 g/kWh PM: 0,3 g/kWh			CO: 5 g/kWh HC+NO _x : 4 g/kWh PM: 0,3 g/kWh				CO: 5 g/kWh HC: 0,19 g/kWh NO _x : 3,3 g/kWh PM: 0,025 g/kWh			CO: 5 g/kWh HC: 0,19 g/kWh NO _x : 0,4 g/kWh PM: 0,025 g/kWh				
130kW - 560kW	Stage II			Stage IIIA				Stage IIIB			Stage IV				
	CO: 3,5 g/kWh HC: 1 g/kWh NO _x : 6 g/kWh PM 0,2 g/kWh			CO: 3,5 g/kWh HC+NO _x : 4 g/kWh PM: 0,2 g/kWh				CO: 3,5 g/kWh HC: 0,19 g/kWh NO _x : 2 g/kWh PM: 0,025 g/kWh			CO: 3,5 g/kWh HC: 0,19 g/kWh NO _x : 0,4 g/kWh PM: 0,025 g/kWh				

From stage 3B on the emission limits cannot be achieved with engine internal modifications (e.g. adjustment of the injection timing) only. Exhaust aftertreatment systems will be necessary to comply with future emission standards.

Every new emission stage includes a stricter emission limit and so an adaption of the exhaust gas aftertreatment system. The typical systems for each emission level are shown in Table 2.

Table 2: Exhaust gas treatment depending of the emission

Emission standard	exhaust gas treatment system
Stage 3A	engine modification, EGR *)
Stage 3B	DPF or SCR
Stage 4	DPFand SCR

* EGR = exhaust gas recirculation

4 Exhaust after treatment with diesel engines

4.1 Diesel Particulate Filter Systems (DPF)

4.1.1 Particulate matter (PM)

Particulate matter (PM) includes all exhaust components that are deposited on a characteristic filter below a temperature of 51.7 °C. It mainly consists of soot, carbon hydrides, sulfates, additives from fuel and lubricating oil, abrasion and corrosion products. The size distribution for different engines fueled with diesel is fairly uniform. Usually a log-normal distribution is found around a value of approximately 80-100 nm. Relevant to health are mainly particulate matters which enter the Alveoles of the lungs, linger there, not being digested by macrophages and insoluble in body fluids. This PM is mainly in a size-range of 10-20 nm. The smaller the PM size is, the easier it can enter the blood and lymphatic system of the body. The particles can absorb and transport toxic substances such as polycyclic aromatic hydrocarbons (PAH). PAH are considered as carcinogenic [1].

4.1.2 Layout and function of a DPF

The goal of diesel particulate filter systems is to reduce particulate emissions from the exhaust of diesel engines. A difference can be made between filter principle, structure, material and regeneration.

Theoretically, DPFs can be divided into:

- Surface-type filter
- Volume filter

Filters on which deposited PM forms a filter cake are called surface-type filters. Surface-type filters have increasing filter efficiency, but also increasing pressure losses with increasing particle setting. Volume filters refine over the whole volume. The efficiency of volume filters is decreasing with their loading. Today most filter systems are a combination of both filter principles [4].

Regarding their layout, DPFs can be separated into:

- Honeycomb filters
- Filters with filter pockets
- Filter foams

Honeycomb filters consist of parallel quadratic channels which are closed mutually. Due to this structure, the aerosol is forced to cross the separating walls between the channels. Thus the PM precipitates on the surface of the inlet side of the separation wall.

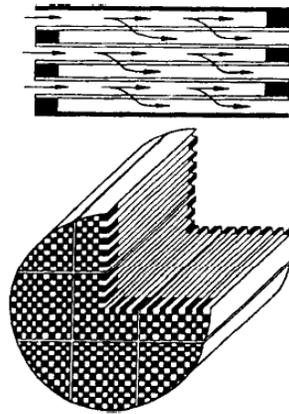


Figure 1: Honeycomb filter [1]

Filters with filter pockets have star arranged separating walls. The flow direction of the exhaust is from the outside to the inside. The PM mainly precipitates on the surface of the separation walls.

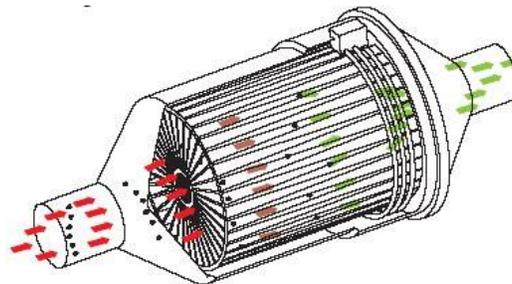


Figure 2: Filter with filterpockets [5]

Filter foams are volume filters. They have a spongy structure [1].

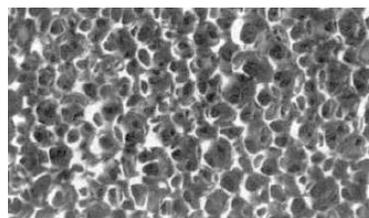


Figure 3: Filter foam [1]

DPFs can be made of different materials. Typical are:

- Ceramic extruded material
- Sintered metal
- Ceramic or metal foams

Important properties for DPFs and their filter materials are:

- Pressure loss
- Behavior during regeneration
- Durability

The porosity of the filter material and the layout of the filter determine the pressure loss. Regeneration is influenced by thermal properties like the heat capacity. The filter material itself is important for the durability [1][6][7][8].

Due to filter loading by particulate matter and ashes, the backpressure is increasing during the operation. Therefore, the filter has to be regenerated at specific intervals. The influence of biofuels on filter loading is discussed below. On the test bench the influence will be investigated more properly, also the differences in regeneration behavior with different fuels. Also the durability of DPFs will be evaluated with different fuels. A shorter service interval is expected due to higher ash contents of biofuels compared to fossil fuels.

4.1.3 Regeneration

For the regeneration of a DPF there are two basic methods:

- Passive regeneration
- Active regeneration [4]

To determine the setting of the DPF, the pressure loss of the filter is measured. It is important that the pressure loss is not higher than the maximum exhaust back pressure value given by the engine manufacturer.

For the active regeneration strategy, it is necessary to boost the temperature of the DPF above the ignition temperature of soot (about 600°C). Above this temperature, soot and adhering hydrocarbons oxidize to carbon dioxide and water. To boost the temperature of the DPF, there are several options:

- Fuel post-injection in the combustion chamber with subsequent oxidation in a DOC.
- Fuel injection in the exhaust pipe with subsequent oxidation in a DOC.
- Restricting the intake air [1][6].

In comparison to the active regeneration which increases the exhaust temperature, the passive regeneration decreases the soot ignition temperature. There are two methods:

- Decreasing the soot ignition temperature with a catalyst.

- NO₂ as oxidizing agent (continuous regeneration trap, CRT-method) [1].

There are two catalytic regeneration strategies, depending on the catalyst:

- The catalyst is in the fuel (fuel additive).
- DPFs with catalytic coating (coated soot filter, CSF).

Fuel additives are usually made of iron oxide. The latter remains as ash in the particulate filter. Thus, depending on the ash capacity of the filter, it has to be cleaned periodically to avoid an excessive exhaust back pressure [7].

A Continuously Regeneration Trap (CRT) uses NO₂ as oxidizing agent. In comparison to oxygen, it is a stronger oxidizing agent. Thus, the soot oxidation starts earlier at a temperature of about 230°C [1]. In addition to the right temperature, a NO₂ to soot ratio of at least 8:1 is necessary. Therefore, there is an upstream diesel oxidation catalyst, in which NO is converted into NO₂ [8].

Modifying the mapping of the injection time for integrating a post injection is very difficult. So aftermarket kits have often a passive regeneration strategy.

4.2 DeNOx

DeNOx technologies can be separated into

- SCR-method (selective catalytic reduction)
- NSC (NO_x storage catalyst) [8].

Due to the different cost trend per engine displacement, the SCR-system is used in vehicles with a huge cylinder capacity and the NSC is for compact cars [7]. Therefore only the SCR-system will be described below.

4.2.1 Layout of components of a SCR-system

SCR-systems consist of several components:

- A diesel oxidation catalyst (DOC)
- A dosing system for the injection of urea in the exhaust stream.
- A hydrolysis catalyst to crack urea into ammonia
- A SCR catalyst to reduce NO_x
- A guard catalyst to oxidize the ammonia slips to nitrogen. A NO_x-sensor or a NH₃-sensor is used if a controlled urea dosing system is used.

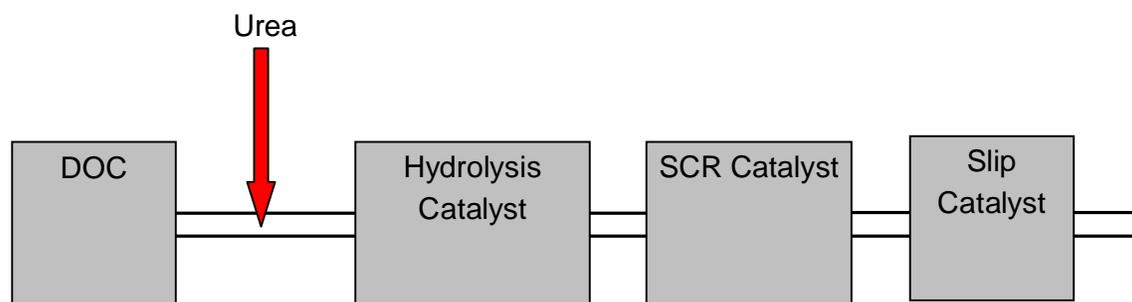


Figure 4: Illustration of the assembly of a SCR-system

4.2.2 Function of a SCR-Catalyst

The SCR-method reduces NO_x with ammonia (NH₃) to nitrogen (N₂) and water. Depending on the exhaust temperature and the NO to NO₂ ratio the reactions can be different.



Below 300°C the reaction will be predominantly like in (2). If the NO to NO₂ ratio is about 1:1 the reaction will be like (1). This reaction has the highest rate of conversion [7]. Due to the fact, that the amount of NO₂ in diesel exhaust is below 10%, an upstream DOC is necessary to increase the NO₂ amount.

Because of its chemical aggressiveness and toxicity ammonia cannot be carried along in vehicles directly. It has to be stored in a non-hazardous carrier substance like urea (CO(NH₂)₂, trade name Adblue). Urea is dosed upstream of the reduction catalyst in front of the hydrolysis catalyst, where it is cracked into ammonia and water. The amount depends on the NO_x concentration in the exhaust gas [8]. Either it is calculated on model calculations basing on different engine parameters (regulated urea dosing) or it is controlled by the nitrogen or ammonia concentration in the exhaust gas, measured downstream of the SCR-catalyst, with a sensor (controlled urea dosing) [8] [9]. The consumption of Adblue can vary from 3-7% of the diesel consumption.

The reduction of NO_x takes place in the reduction catalyst according to (1) and (2).

In order to avoid ammonia slip (ammonia which has not been oxidized in the SCR-catalyst), a guard catalyst is mounted downstream of the SCR-catalyst in which the unneeded ammonia is reduced to nitrogen and water. A further opportunity to avoid ammonia slip is the use of a NO_x- or a NH₃-sensor. It is measuring the NO_x- or NH₃-concentration, so that the amount of urea will be adapted [6] [9].

4.3 Exhaust gas treatment in non-road vehicles

Due to the operational conditions of agricultural machines, special requirements exist for exhaust aftertreatment systems:

- Inured to crashes and vibrations
- Compact design
- Heat emission must not enflame harvest
- No line-of-sight obstruction

4.4 Exhaust aftertreatment systems and biofuels

Generally, new DPFs have the potential to lower the particle emissions of biofuel-powered engines. Also, a reduction of CO emissions from oxidation catalysts or DPFs with a particularly effective catalytic coating is detectable. These reductions decrease greatly during running time [12].

Biofuels for diesel engines contain alkali and alkaline earth metal as well as phosphorus. Calcium, magnesium, sodium and potassium cause ashes, which cannot be removed during regeneration and therefore shorten the service intervals. Sodium, potassium and phosphorus are toxic for the DOC and damage the structure of ceramic DPFs [13].

Former tests [12] at a rapeseed oil fired combined heat and power plant with different DPFs have shown: The elements which accumulate mainly during operation are phosphorus and calcium. These elements come either out of the fuel or out of the engine oil. Each tested DPF had to be cleaned externally every 200 hours or even at shorter intervals. So the target service intervals of 1000 hours could not be achieved. Causal for this were the disposed ashes which caused increasing exhaust back pressure or alloyed the catalytic coating, and thus, constrained the regeneration.

Because of the lower exhaust temperature of engines running with biofuels, the regeneration could be reduced or could be prohibited.

In the past, the Vereinigte Werkstätten für Pflanzenöltechnologie (VWP) did some research in order to investigate the coherence between the phosphorus content in rapeseed oil and the

deposits in a DPF. At the beginning of the test, the maximum ash capacity of the DPF was determined. It was about 25 g ash. Figure 5 shows a charged and an uncharged DPF.



Figure 5: Charged and uncharged DPFs [14]

Figure 6 shows the development of ash deposits during 1200 hours with two fuel qualities (10 ppm and 15 ppm phosphorus).

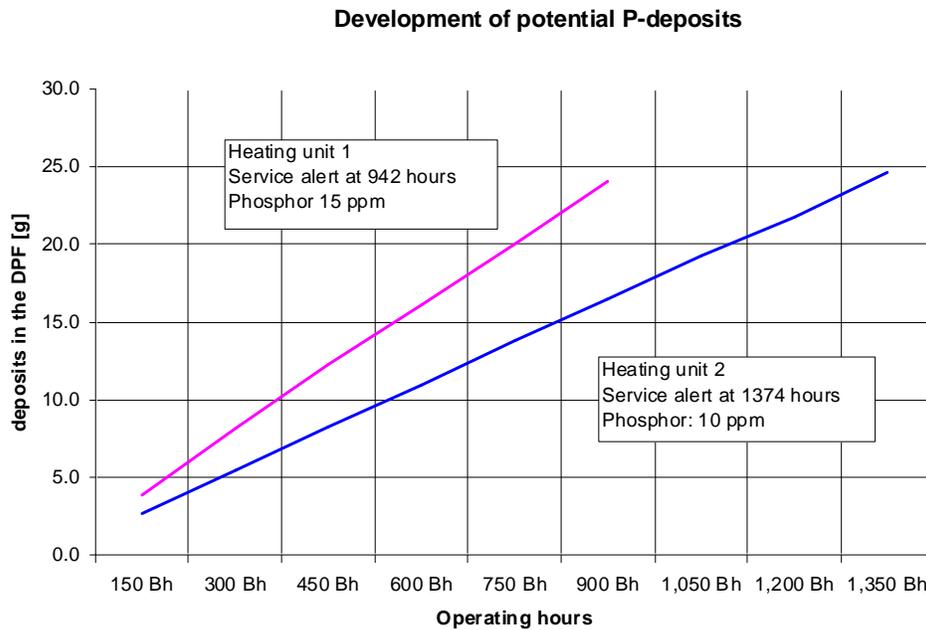


Figure 6: Process of soot deposit during 1200h and with different fuel qualities [14]

Obviously, the use of the fuel with 10 ppm P leads to a longer period until the DPF is loaded, and thus, to an extended service interval. Hence, for exhaust aftertreatment systems and for modern diesel engines in general the amount of ash producing elements in the fuel should be as low as possible [14].

Due to this, it is important, that DPF-systems for biofuels have the following features:

- High ash capacity;
- Opportunity for an easy external cleaning;
- The position of the DPF should match the low exhaust gas temperature of bio-fuels;

5 Conclusions

Exhaust aftertreatment technologies in on-road vehicles are state of the art. From 2011 on, lower emission levels will be effective for non-road engines as well (EU stage 3B). Therefore, technologies like DPF and SCR will be implemented in non-road vehicles like agricultural tractors as well. Additionally, the demand for alternative fuels like vegetable oils is increasing due to increasing fossil fuel prices and CO₂ reduction strategies.

The impact of biofuels on these technologies will have to be investigated precisely. Former studies have shown that biofuel exhaust gases tend to plug DPFs because of the fuel's content of ash forming elements. Therefore, different fuel qualities will be tested on an engine test bench within this project (see deliverable 2.2).

Furthermore, it is of high importance to establish a standard for biofuels that limits the ash-building and DOC-toxic elements to a level that ensures the same performance and reliability of an engine no matter if biofuel or fossil diesel is used.

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