INFLUENCES OF BIOCOMPONENTS (RME) ON REGENERATIONS OF DIESEL PARTICLE FILTERS

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Abstract

*The fatty acid methyl esters (FAME's) – in Europe mostly RME *) (Rapeseed methyl ester; Abbreviations see at the end of this paper) – are used in several countries as alternative biogenic Diesel fuels in various blending ratios with fossil fuels (Bxx). Questions arise often about the influences of these biocomponents on the modern exhaust after-treatment systems and especially on the regeneration of Diesel particle filters (DPF).*

In the present work different regeneration procedures of DPF systems were investigated with biofuels B0, B20 & B100.

The tested regeneration procedures were:
- *passive regenerations: DOC + CSF; CSF alone,*
- *active regenerations: standstill burner; fuel injections & DOC.*

During each regeneration on-line measurements of limited and unlimited emission components (nanoparticles & FTIR) was conducted.

It can be stated that the increased portion of RME in fuel provokes longer time periods to charge the filter with soot. This is due to the lower PM-emissions of the engine, as well as to the higher reactivity and higher SOF-portion of the particle mass from RME.

With the passive regeneration system with stronger catalytic activity (DOC + CSF) there is a stronger NO_2-production with B100 and due to the NO_2-supported oxidation of PM the balance point temperature is approx. 20°C lower, than with B0.

For the active regenerations the time courses of emissions and temperatures are closely connected with the chosen regeneration strategy – switching, timing and intensity (of burner, or fuel aerosol generator).

A higher portion of biocomponent causes usually a stronger break-down of the instantaneous DPF filtration efficiency during the regeneration procedure – this is an effect of stronger artifact of spontaneous condensation after DPF.

In summary there is no negative short term effect of bio-blended-fuels on the investigated regeneration procedures. Some recommendations for a successful long term operation, basing on other works and literature are given at the end of the paper.

Keywords*: Diesel particle filter, regeneration of DPF, biofuels, non-legislated emissions, nanoparticles*

1. Introduction

The passive DPF regenerations by means of catalytically coated DPF's (CSF ... catalyzed soot filter), or a combination of oxidation catalyst (DOC) upstream and a CSF downstream are preferred for retrofitting as simplest solution, if the conditions of engine operation allows it. Especially the engine application has to result in sufficient frequency of higher exhaust gas temperatures, which enable the light-off and sufficient duration of the catalytic oxidation of the collected particle mass. The low sulphur content of the fuel and the appropriate lube oil quality have to guarantee the long-duration efficiency of the catalytic coatings.

Active regeneration of DPF with burner has an advantage to be independent of engine operating conditions, catalytic coatings and fuel quality. It can be applicable for difficult situations, like low load operation with high sulphur fuel.

Regeneration with fuel injection (fuel aerosol generator) and oxidation catalyst (DOC) also offers the advantages of being mostly independent of engine operating conditions, but with the restriction of exhaust gas temperature, which has to be above the light-off temperature of the DOC. The catalytically supported fuel oxidation in DOC requires low sulphur fuels to enable the necessary long life of the catalytic coating.

In the present work the studies about the passive and active regeneration procedures were performed with different bio-contents (B0, B20 & B100).

The tests were conducted in the Laboratory for IC-Engines of the University of Applied Sciences, Biel, CH in close collaboration with the industry partners.

Tab. 1. Fuel properties as per EU-standards and further analysis of the test fuels

		Diesel	RME
Density at 15°C	g/m	0.842*	0.885*
Viscosity at 40°C	mm^2/s	2.0 - 4.5	4.6*
Flash point		above 55°C	143°C
Cloud point		max -10°C	-
Filterability CFPP		max -20°C	-15
Ash	%	max 0.010	Traces
Sulfur	ppm	<10	1.3*
Cetane Number		51	56
Calorific value	MJ/kg	42.7	37.2
C fraction	in %	86.7	77.5
H fraction	in %	13.3	11.8
O fraction	in %	0	10.7
Air_{min}	kg/kg	14.52	12.49
Boiling range 10-90% °C		180 - 340	315 - 360

* measured values

2. Test-engine and fuels

Manufacturer:	Liebherr Machines Bulle S.A., Bulle/Fribourg
Type:	D934 S
Cylinder volume:	6.36 Litters
Rated RPM:	2000 min^{-1}
Rated power:	111 kW
Model:	4 cylinder in-line
Combustion process:	direct injection
Injection pump:	Bosch unit pumps
Supercharging:	Turbocharger with intercooling

Following base fuels were used for the research (Tab. 1):
- Shell Formula Diesel fuel Swiss market summer quality (10 ppm S) according to SN EN 590,
- Rapeseed Oil Methyl Ester RME from Flamol, Berne, CH.

3. Tested DPF systems

For the research of impacts of the biocomponents on the DPF regeneration following DPF systems were supplied:
- HUG mobiclean RS, DOC+CSF (DPF with catalytic coating), Fig. 1,
- HUG mobiclean RS, CSF only,
- HUSS MK system with standstill burner regeneration,
- HUSS MD system with fuel injection+DOC.

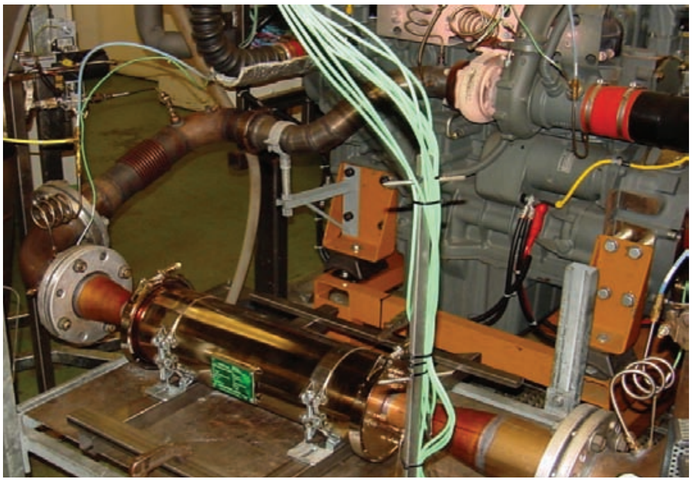


Fig. 1. HUG DPF with passive regeneration (DOC+CSF) on the Liebherr engine

All applied filter materials were SiC (silicon carbide) with a high average filtration efficiency PCFE > 99% fulfilling the VERT / OAPC quality criteria.

4. Regeneration procedures & results

According to the objectives each regeneration was performed at least 3 times in an identical test.

The soot loading of the filter is always to the same back-pressure (Δp = 105-115 mbar).

During the regeneration procedure several parameters were continuously registered: regulated & unregulated gaseous emissions (standard & FTIR), nanoparticles (CPC, PAS, DC) and several temperatures in the filter body.

Passive regenerations, HUG DPF's

The results of soot loading procedures give important information about the effects of bio-components.

All loading procedures, except of B100, were performed in identical way. For B100, which yielded very difficult conditions of soot loading, periodical switch-off for cool-down were necessary.

The soot loading with increased bio-content needed always a longer time period. This is represented for (DOC + CSF) and for CSF in Fig. 2.

The final particle mass, as product of engine-out emission and time, increases. Nevertheless the oxidized portion of PM during the soot loading procedure and the PM remaining in the DPF at the end of soot loading procedure are unknown.

The reasons for slower soot charging with bio-components are:

- lower engine-out PM-emissions,
- higher reactivity of PM and partial oxidation during soot loading with DOC,
- with high bio-content (here B100) lowering of exhaust gas temperature to the temperature-window of the highest NO_2-production in DOC, easier NO-NO_2 oxidation with B100 and the intensified NO_2-continuous regeneration.

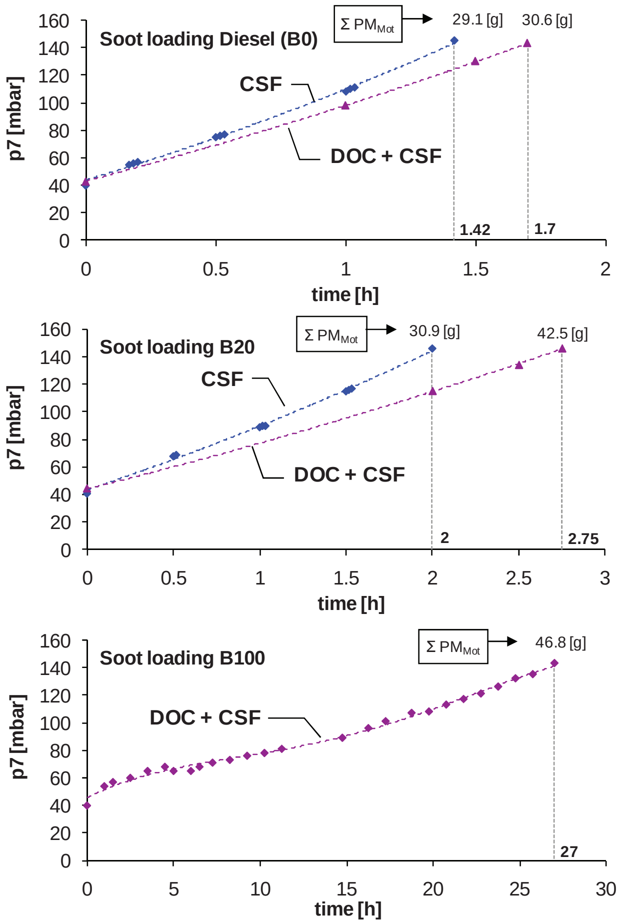


Fig. 2. Backpressure (p_7) during soot loading cycle

After the soot loading each regeneration attempt was performed in the same way: stepwise increasing of engine torque at a constant speed.

In Fig. 3 – the comparison of regeneration tests nbrs. 7, 11 & 10 (B0, B20 & B100 with DOC + CSF) shows with B100 following tendencies, which would not be visible with B20:

- there is more NO_2 with B100 because of lower texh (near to the maximum of NO_2-production), more NO_x and more easy NO-NO_2 oxidation,
- the intensity of regeneration with B100 from 5th step (approx. 300°C) is higher; the drop of backpressure quicker than with the other fuels,
- with B100 the N2O peak in 2nd step is a little bit higher, than with B20 (7ppm / 5ppm) and after start of regeneration NH3 increases with B100 up to 6ppm (during 1/2h), while with B20 it stays at zero-level.

Figure 4 gives the comparisons of the instantaneous NP filtration efficiencies (CPC & DC) for the test variants with (DOC + CSF) and B0, B20 & B100.

With the stronger catalytic system (DOC + DPF) B100 causes a drop of FE during the regeneration because of spontaneous condensation of heavy HC-compounds after DPF and a partially increased break-through of smallest size NP nuclei mode.

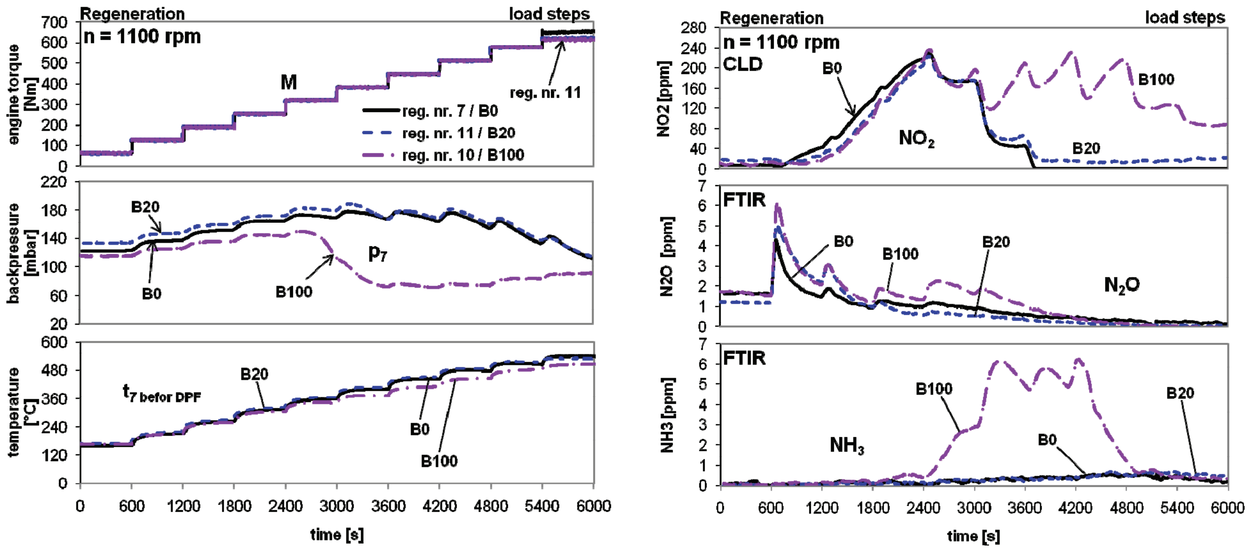


Fig.3. Regenerations with (DOC + CSF) & B0, B20 & B100

Figure 5 – the comparison of regeneration tests: (B0 & B20 with DOC + CSF) and (B0 & B20 with CSF) shows for the DPF-system with weaker catalytic activity (CSF only) following tendencies:

- start of regeneration later – in steps 6 & 7 (instead of step 5 like for the other system) at exhaust gas temperature approx. 100°C higher,
- higher values of CO and HC (little oxidation),
- no production of NO_2,
- no production of N_2O peak in the 2nd step (not represented here),
- increased NP-values with B20 comparing to B0 (this is not the effect with strongly catalytic system DOC+CSF),
- the DPF with DOC oxidizes more the precursor substances of spontaneous condensates yielding lower NP-concentrations since the DOC-light-off in the 2nd step (approx. 240°C).

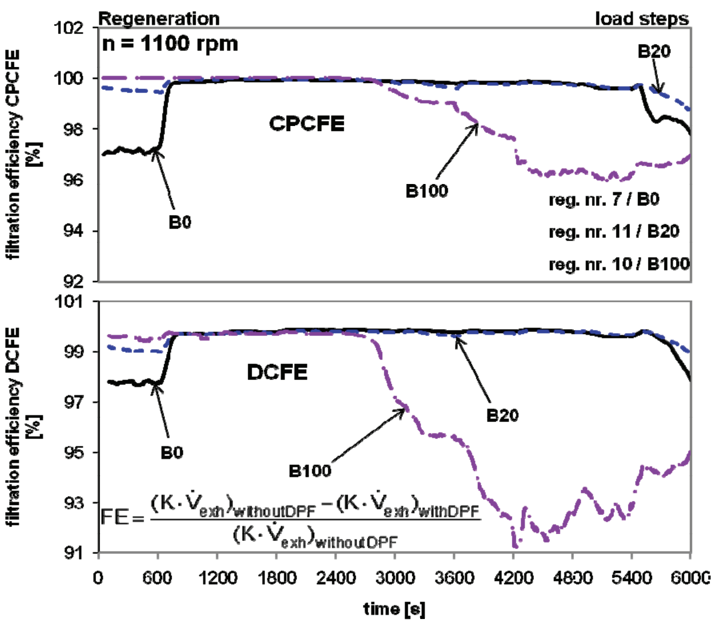


Fig. 4. Instantaneous nanoparticle filtration efficiency during the regeneration procedures with (DOC+CSF) & B0, B20, B100

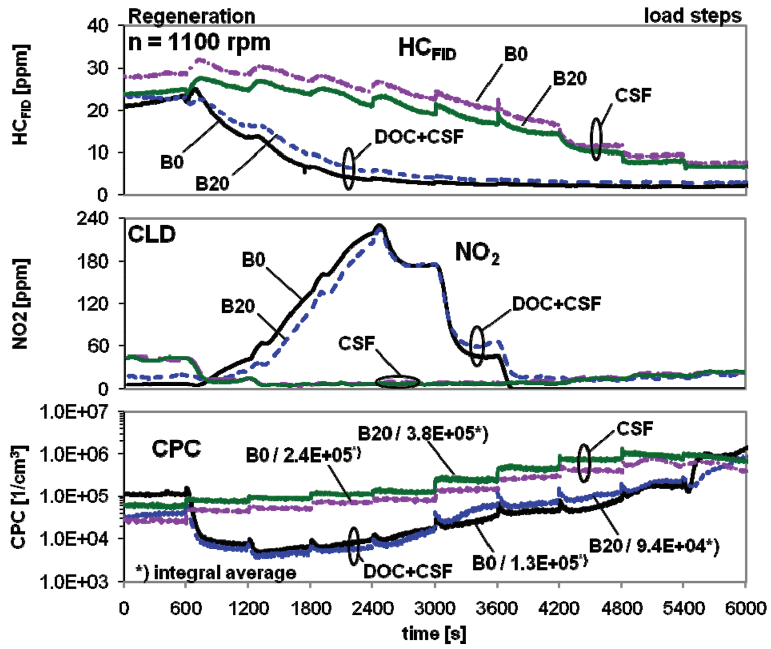
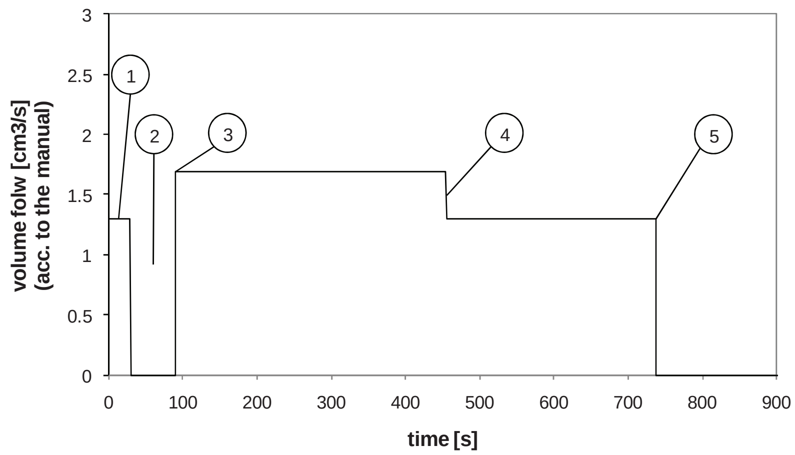


Fig. 5. Regeneration with (DOC + CSF) vs. (CSF) with B0 & B20

Active regenerations, HUSS DPF's

The regeneration procedure with standstill burner (system MK) is represented in Fig. 6. The represented points① to ⑤ are fixed in the ECU of the system and are a repetitive procedure. The air supply by the air pump is an important necessity at engine standstill.

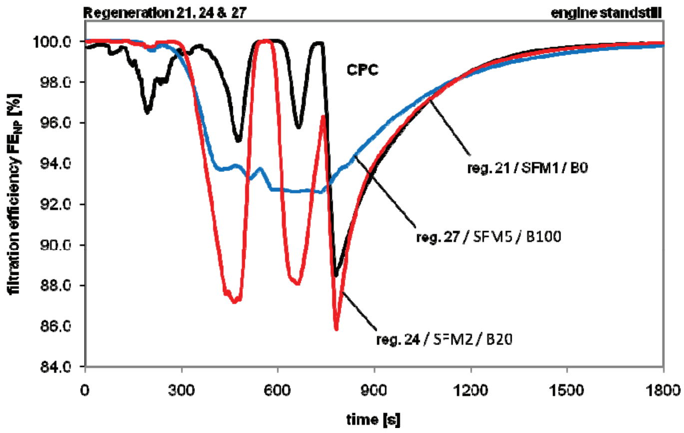


1. glow plug precooking, air pump on ~ 0.5 min
2. glow plug start (no air pump) ~ 1.0 min
3. start of fuel & air supply, ignition, flame ~ 6.0 min
4. switch off fuel (air pump on) ~ after 7.5 min
5. switch off air pump ~ after 12.5 min

Fig. 6. Regeneration procedure with standstill burner (system MK)

A definition of DPF filtration efficiency during engine standstill is not possible, since there is no engine-out emission entering the DPF.

Since the NP-values (CPC, DC & PAS) were measured during all regeneration procedures it was decided to calculate the instantaneous relative reduction rate of them as an equivalent of filtration efficiency. As reference the average concentrations of CPC, DC & PAS in the regeneration steps and engine without DPF were considered.



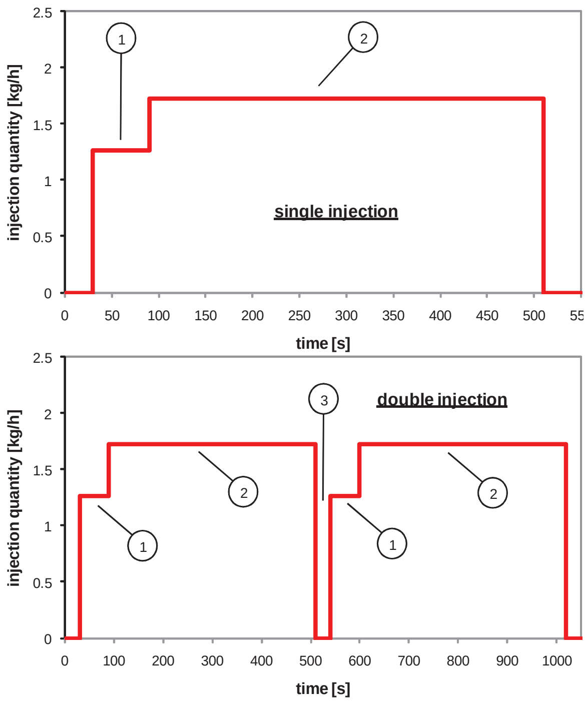
$$FE_{NP} = \frac{(K)_{withoutDPF} - (K)_{withDPF}}{(K)_{withoutDPF}}$$

Fig. 7. Comparison of instantaneous equivalent CPC-reduction rates during the standstill burner regeneration with different bio-contents (burner fuel B0 & B20); all reg. with burner fuel B0 except reg. 24 with B20

This equivalent filtration efficiency compares only the NP-concentrations [#/cm3]. A comparison of absolute particle counts as product of concentration [#/cm3] and volumetric flow [cm3/s] makes no sense, since the volume flow of the regeneration air supply is negligible comparing to the average engine volume flow.

Figure 7 shows some comparisons of instantaneous equivalent CPC- reduction rates with B0 / B20 & B100. It can be generally remarked, that the nanoparticle penetration during the flame period is stochastically increased – the equivalent filtration efficiency reduced. No influence of bio component content can be remarked.

The regeneration procedure with fuel injection and DOC consists of injecting the same amount of fuel during the same time at a constant operating point of the engine. This operating point can be chosen, but it should be in any case with an exhaust temperature, which is over the light-off of the DOC.



1. preinjection 60 sec
2. main injection 420 sec
3. pause 30 sec

Fig. 8. Fuel injection strategies for regenerations of system Huss MD

Figure 8 shows the fuel injection strategies for regeneration of the HUSS DPF, system MD. It can be programmed in the ECU of this DPF-system, that after the first FI-period, if the backpressure does not fall below a certain value, a second FI-period will be automatically activated.

In the present investigations some regenerations were performed with single, or with double FI.

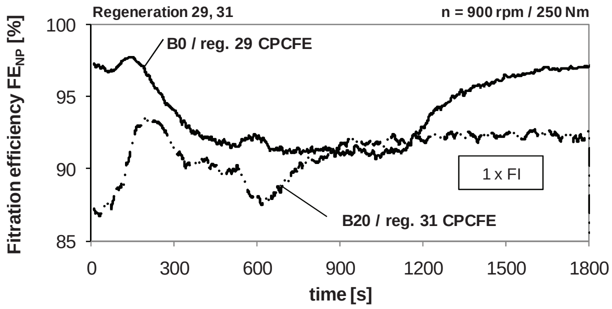


Fig. 9. CPC filtration efficiency during regeneration with B0 & B20

Figure 9 represents the comparison of the instantaneous CPC-filtration efficiency B0 & B20. It is confirmed that with B20 there is a significantly lower CPC FE in the first phase of regeneration procedure up to approx. 700s.

This observation can be explained with the fact, that the fuel injection is also conducted with B20 for the DPF, which was charged with B20. At the beginning of FI, when there is no oxidation in DOC the different HC-matrix from B20 (from both: DOC & DPF) enables more condensates after DPF. In the further phase, when the oxidation in DOC and in DPF becomes more intense, the influences of the products of this oxidation become similar for both fuels B0 & B20 and so they give origin to similar condensation effects afterwards.

5. Remarks and recommendations

The used equipment and procedures in the present project are those of VERT. There are several results concerning the use of bio-fuels.

Principally the filtration of solid particles (NP) of a DPF is independent of fuel B-content. Nevertheless with increasing share of bio-components there are more condensates after the DPF, which increase the particle count concentrations and simulate the lower overall PC-filtration efficiency (PCFE) of the DPF. This means, that to prevent the mistakes resulting from this artifact it is better to test the DPF with standard fuel.

The soot loading with biofuel, or biofuel-content, needs longer time because of less PM-emission of the engine and also because of stronger soot oxidation during the loading procedure. The regeneration is easier to ignite with Bio-content. In case of a stronger soot loading up to the limit of the capacity of the DPF, there is a danger of overloading DPF and getting too much heat value of the SOF deposited in the DPF. This effect with B100 caused, in one case of a non-catalytic DPF with an active regeneration help, an overheating and destruction of the filter material.

An important part of VERT quality testing procedure is the field durability test (2000h for VERT, 1000h for LRV). This was not an objective of investigations in present part of project, since the results concerning exhaust after-treatment are well known:

- the biofuels have historically a bad reputation concerning poisoning of catalytic coatings; this is true, if the content of sulphur, phosphorus and dirt is above the quality norm,
- the presence of biofuels quality norms and the fuels, which fulfil these norms are guarantee for satisfactory long life of catalytic coatings,
- the questions of lube oil durability and degradation with application of biofuels is always to consider and it was a subject of the part of investigations of INIG.

The fulfilment of biofuel quality requirements depends on supplier, transport, stocks conditions and time of storage.

Bio components have limited durability (validity) time because of oxidative degradation, water absorption and possible bacteria befall, or increased impurities, [1-4]. For these reasons the user of biofuel is recommend to periodically control the quality of supply chain and of the fuel.

Following recommendations can be given for the use of biofuels with DPF systems:

- the filtration efficiency is not influenced by the biofuel, but there can be artefacts of spontaneous condensates after DPF,
- performing VERT/LRV tests part 1 & 3 is recommended with a standard fuel,
- for long life of catalytic coatings and for sustainable engine operation control periodically the quality of fuel and fuel supply chain,
- for active regeneration systems with high bio-content set down the threshold for starting regeneration to the lower values of back-pressure, to prevent the danger of overheating of DPF during the regeneration,
- for burner regeneration, if biofuels are used for the burner, make sure the reliable ignition and operation of the burner,
- consider the general recommendation for the engine: durability of injection system and of lube oil; power reduction with fuels with lower heat value; limits of electronic regulation with changed heat value of fuel.

6. Conclusions

Regenerations with (DOC+CSF):

- with the same soot loading procedure the necessary time to load the DPF for Δp = idem increases with the bio-content of fuel (here for $\Delta p \approx 100$ mbar: B0 1,7h; B20 2,5h; B100 27h),
- the reasons for slower soot charging with bio-components are:
  - lower engine-out PM-emissions,
  - higher reactivity of PM and partial oxidation during soot loading with DOC,
  - with high bio-content (here B100) lowering of exhaust gas temperature to the temperature-window of the highest NO_2-production in DOC, easier NO-NO_2 oxidation with B100 and the intensified NO_2-continuous regeneration,
- the repeatability of regeneration results and of the instantaneous filtration efficiencies is very good, except for the 1st step,
- the differences in the 1st step can be explained with the dispersion of the preliminary state of soot loading at the beginning of respective regeneration,
- with B100 there are some effects, which would not be detectable with B20:
  - there is more NO_2 with B100 because of lower texh (near to the maximum of NO_2-production), more NO_x and more easy NO-NO_2 oxidation,
  - the intensity of regeneration with B100 from 5th step (approx. 340°C) is higher; the drop of back-pressure quicker than with the other fuels,
  - the increase of NP-emissions due to regeneration with B100 starts in the 4th step - spontaneous condensates after DPF and/or break-through of smallest size NP nuclei mode.

Regenerations with (CSF):

- soot loading with B20 needs longer time (2h), than with B0 (1,4h),
- soot loading with CSF takes a little shorter time, than with (DOC+SCF),
- the regeneration procedures and emissions are well repeatable,
- there is lower dispersion of curves of instantaneous FE and of temperature traces in step 8 with B20, than with B0.

Regeneration with standstill burner:

- the time-courses of emissions and temperatures are closely connected with the regeneration strategy,

- the nanoparticle penetration during the flame period is stochastically increased – the equivalent filtration efficiency reduced,
- the bio-components increase the NO_x - & NO_2 - values during the flame period.

Regeneration with fuel injection + DOC:

- longer duration of fuel injection (double FI) prolongs respectively the period of high temperature level for the regeneration,
- the longer regeneration period is depicted with the higher emissions of CO, HC, DC & NH_3, in the respective time interval,
- at higher OP there is a higher level of exhaust temperature and of NO_x,
- after stopping the fuel injection there is an intense production of NO_2 due to texh decreasing into the level of NO_2-maximum,
- during the regeneration period (period of FI) there is a break-down of NP-filtration efficiency, which correlates with the single, or double FI-period and which is more intense for DC,
- with B20 there is a lower NP-filtration efficiency in the first phase of regeneration procedure – this is an effect of stronger artefact of condensates after DPF, due to the changed HC-matrix of B20.

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Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
BAFU	Bundesamt für Umwelt, (Swiss EPA)
CNC	condensation nuclei counter
CPC	condensation particle counter
CSF	catalyzed soot filter
DC	Diffusion Charging sensor
DOC	Diesel Ox. Catalyst
DPF	Diesel Particle Filter
DMA	differential mobility analyzer
EMPA	Eidgenössische Material Prüf und Forschungsanstalt, CH
FAME	fatty acid methyl ester
FE	filtration efficiency
FI	fuel injection
FID	flame ionization detector
FOEN	Federal Office of Environment (BAFU), CH

FTIR	Fourier Transform Infrared Spectrometer
ICE	internal combustion engines
INIG	Institut Nafty I Gazu, Krakow, PL
LRV	Luftreinhalteverordnung, CH (OAPC)
MD19	heated mini-diluter
NanoMet	NanoMetnanoparticle summary surface analyser (PAS+DC+MD19)
NDIR	nondispercive infrared
NP	nanoparticles < 999 nm (SMPS – range)
OAPC	Ordinance on Air Pollution Control
OP	operating point
PAS	Photoelectric Aerosol Sensor
PC	particle counts
PCFE	particle counts filtration efficiency
PM	particulate matter, particle mass
PMFE	particle mass filtration efficiency
RME	rapeseed oil methyl ester
SMPS	Scanning Mobility Particle Sizer
SOF	soluble organic fraction
TTM	Technik Thermische Maschinen, CH
ULSD	ultra low sulphur Diesel
VERT	Verification of Emission Reduction Technology
WNRI	West Norway Research Institute