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"Optimisation of the Engine–internal Late Post–injection in the Regeneration Mode of a Passenger Car Diesel Engine for Reducing the Oil Dilution during Operation with the Fuel Blends B7, B10 and B30"

Concluding Report on the Research Project: **UFOP No. 540/093**

Supported by: Union zur Förderung von Oel- und Proteinpflanzen e. V. (UFOP), Volkswagen AG Wolfsburg

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Magdeburg, 31.08.2010

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG
FAKULTÄT FÜR MASCHINENBAU
LEHRSTUHL KOLBENMASCHINEN
INSTITUT FÜR MOBILE SYSTEME

Institute for Mobile Systems
Chair of Reciprocating Machines

"Optimisation of the Engine-internal Late Post-injection in the Regeneration Mode of a Passenger Car Diesel Engine for Reducing the Oil Dilution during Operation with the Fuel Blends B7, B10 and B30"

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The effects of changes to the engine-internal “late” post-injection in regeneration mode during operation with the fuel blends B7, B10 and B30 on the fuel entry into the engine oil as well as on the change in the oil viscosity and the limited gaseous emissions were examined in a passenger car diesel engine 2.0 l TDI with common rail system, oxidation catalyst close to the engine and diesel particle filter (DPF) in stationary test runs at the Institute for Mobile Systems IMS, Chair in Piston Engines, at the Otto-von-Guericke University Magdeburg. The soot measurement was omitted owing to the use of a DPF.

The diesel engine as well as the application control unit and exhaust gas after-treatment system etc. were provided by Volkswagen AG for the tests.

The standard late post-injection was divided into 2 parts. However, only the injection time point and the fuel volume of the first partial amount could be varied. The second partial amount of the late post-injection was automatically adjusted by the control unit in order to reach an exhaust gas temperature of 640 °C before the DPF. The two early post-injections could not be changed. The second partial amount of the early post-injection was automatically adjusted by the control unit (together with the automatic adjustment of the second later partial amount).

In addition to the task included in the UFOP project, the fuel entry and the decrease in engine oil viscosity were also determined by early post-injections subsequent to the main injection.

The engine tests were carried out with the engine oil approved by the engine manufacturer “Titan GT1 Longlife III 5W-30“ made by Fuchs Europe Schmierstoffe GmbH.

The stationary test bench tests revealed that

- the entire fuel entry into the engine oil increased with a rising RME component of the fuel,
- at the same time, the RME concentration in the oil rose and the DF concentration fell,
- no significant concentration differences were discernible in the oil with 5 injections with the series application "old" and 6 injections with the series application "new" in regeneration mode,
- the splitting of the late post-injection during operation with B30 lowered the entire fuel, RME and DF entry in comparison to the series application "new" by 27 % and reduced the decrease in the oil viscosity resulting during the test run at 100 °C by approx. 10 %,
- the early post-injections subsequent to the main injection (preheat mode without late post-injection) during operation with B10 and B30 yielded almost the same fuel entry and the same viscosity decrease in the engine oil as the regeneration mode with the optimised, split late post-injection,
- the splitting of the late post-injection in regeneration mode in comparison to the series application “new” did not have any negative effects on the particle filter regeneration and the limited gaseous exhaust gas emissions.

The stationary test bench tests revealed that optimisation of the late post-injections in the area of the exhaust stroke can significantly reduce the fuel entry into the engine oil. However, they also clearly demonstrated that the early post-injections subsequent to the main injection can have a considerable share in the engine oil dilution if partial amounts of the fuel jets encounter the cylinder wall. The early post-injections should therefore also be incorporated in future tests for further reduction of the fuel entry into the engine oil.

B_e	Hourly fuel consumption
BDC	Bottom dead center,
bmep	Brake mean effective pressure
B7	Fuel mixture comprising 7 vol.% RME and 93 vol.% DF
B10	Fuel mixture comprising 10 vol.% RME and 90 vol.% DF
B30	Fuel mixture comprising 30 vol.% RME and 70 vol.% DF
CA	Crank angle
CO	Carbon monoxide
CO_2	Carbon dioxide
CAT	Oxidation catalyst
DF	Diesel fuel, without RME component
DPF	Diesel particle filter
dp	Differential pressure of the diesel particle filter
fuel total	Total fuel, consisting of RME and DF components
h	Operating hours
ITDC	Ignition top dead center
kW	Kilowatt
NO_x	Nitrogen oxide
n	Speed
n	Number of measurements
OP	Operating point
Oxi-Kat	Oxidation catalyst
O_2	Oxygen
P	Probability
P_e	Effective engine power
p_{ca}	Charge air pressure (absolute) after charge air cooler
p_{exh}	Exhaust gas counter pressure after exhaust turbocharger
p_{exh}	Exhaust gas counter pressure after DPF
PI	Post-injection
RME	Rapeseed methyl ester, biodiesel, B100
s	Standard deviation
T	Torque
TDC	Top dead center
TC	Exhaust gas turbocharger
Texh	Exhaust gas temperature after exhaust turbocharger or after DPF
THC	Hydrocarbon emission
T_R	Temperature of the ambient air
T_{cw}	Cooling water temperature at engine outlet
T_{ca}	Charge air temperature after charge air cooler
T_b_TC	Exhaust gas temperature before the exhaust gas turbocharger
T_b_PF	Exhaust gas temperature before the particle filter (after oxidation catalyst)
T_a_PF	Exhaust gas temperature after the particle filter
T_{oil}	Oil temperature in the oil pan
t	Student factor
v	Confidence interval

Introduction

The market launch of biodiesel as an admixture component in diesel fuel is continuing apace throughout the world. However, the increase in the admixture content of biodiesel from 7 %-vol. (B7) to 10 %-vol. (B10) or higher is increasingly encountering reservations on the part of car manufacturers [1].

The reason for this is that driving profiles at low speeds, as typically occur in urban traffic, are extremely critical for cars equipped with diesel particle filters, because only very low exhaust gas temperatures result here in the normal operating mode of the diesel engine. In order to nevertheless ensure regeneration of a charged particle filter in these operating states, the exhaust gas temperature must be increased to > 550 °C before entry into the particle filter.

Cylinder post-injection strategies are applied as standard for this. This is designated as late post-injection on account of the late position of this inner-engine injection in relation to the cylinder top dead centre. Because this injection is not very efficient during expansion in the combustion stroke due to physical reasons, the exhaust gas temperature either increases directly or via a downstream oxidation catalyst. In some engines, fuel is also injected into the exhaust stroke in a targeted way inside the engine, which then only combusts in the downstream oxidation catalyst and increases the exhaust gas temperature to the extent that this is sufficient for ignition of the soot deposits in the downstream diesel particle filter.

A major problem when using post-injection is the fact that the fuel can impinge on the cylinder walls, thereby leading to an engine lubrication oil dilution. The oil dilution results in a decrease in viscosity with the risk of operating conditions conducive to wear. The oil dilution can lead to engine damage if a definite limit value is exceeded.

Although diesel fuel without admixed components of biodiesel can evaporate out of the engine oil, the biodiesel components that have entered the engine oil remain there owing to the higher boiling temperatures of e.g. RME in comparison to diesel fuel in lubricating oil and thus result in a permanent oil dilution [2].

Besides the particle filter system with active particle filter regeneration through engine-internal fuel post-injection, which is currently used without additives among all German car manufacturers, there are also systems supported with additives which essentially work with low fuel volumes during the post-injection for the regeneration. In these systems, biodiesel content of up to 30 percent (B30) can be approved under particular conditions (e.g. reduction in the oil change interval) [3]. Systems in which the additive fuel required for the regeneration is injected directly before the oxidation catalyst, however, do not principally have any problems with lubrication oil dilution caused by this.

In order to reduce the irreversible engine lubrication oil dilution in car engines with engine-internal post-injection at a further increase in the biodiesel component in the diesel fuel beyond 7 %-vol., an attempt must be made to reduce the fuel entry above all in regeneration mode through optimisation of the late post-injection in respect to the number of post-injections, the injection volume and the injection time points. The test bench tests described below are carried out with this objective in mind.

2 Task

The lubrication oil dilution in the regeneration mode of a modern car diesel engine is to be reduced by optimising the engine-internal late post-injection during operation with the fuel blends B7, B10 and B30. The tests are to be conducted on a diesel engine 2.0-l-TDI with common rail injection of Volkswagen AG.

On the basis of the current series application with a total of 6 injections, the effects of splitting the volume post-injected in regeneration mode into two parts (7 injections in total) as well as the variation of these partial injection volumes and their injection time points on the fuel entry into the engine oil are to be examined. At the same time, the exhaust gas temperature intended for regeneration of the diesel particle filter in the current series application before the filter must also be retained with the split late post-injection. The RME and DF components as well as the influence of the fuel contained in the lubrication oil on the oil viscosity must be determined in all test runs.

The results obtained with the optimised late post -injection (7 injections per cycle) are to be compared with the fuel entry values measured with the current series application (6 injections per cycle). The results determined with B10 fuel must be compared with the values documented in the FNR/UFOP Project (FKZ: 22010007) [2], which were measured with the previous series application (5 injections per cycle) for this engine design.

The progression of the filter regeneration as well as the limited gaseous exhaust emissions in regeneration mode when using the split late post-injection and the current series application are to be compared.

The tests are to be carried out stationary on the engine test bench.

An oil approved by the engine manufacturer is to be used as engine oil.

The fuel entry tests to be performed in regeneration mode as well as the regeneration of the charged particle filter are to be carried out with the engine operating point OP1 contained in **Tab. 2-1**. The particle filter is to be charged at the engine operating point OP2.

Tab. 2-1: Operating points of the engine 2.0 l TDI CR 4V, 103 kW

OP	n [rpm]	T [Nm]	bmep [bar]	
1	2140	30	1,9	Regeneration
2	2000	65	4,2	Charging

Potential measures for reducing the fuel entry into the engine oil are to be proposed as a result of the tests.

3 Operating Media
3.1 Test fuels

Diesel fuel

Diesel fuel free of RME components was procured from Mundt + Thoms GmbH in Magdeburg for the tests.

Biodiesel B100 (RME)

The biodiesel B100 provided for the tests intended in this project was a rapeseed methyl ester (RME) in winter quality with cold additive.

Fuel blends B7, B10 and B30

The fuel blends were mixed in the IMS from biodiesel (RME) and RME-free DF. The mixing and storage of the blends was performed in 200 l vats, from which the fuel was taken during implementation of the tests. The RME and DF components of the blends are shown in the following **Tab. 3-1**:

Tab. 3-1: Fuel blends used

Fuel blend	B7	B10	B30
RME component [%]	7	10	30
DF component [%]	93	90	70

3.2 Boiling characteristic curves of the fuels

The boiling characteristics of the fuels B0, B7, B10 and B30 were recorded by ASG Analytik-Service Gesellschaft mbH and documented in the test reports 161935 and 181697. The test method DIN EN ISO 3405 was used for B0, B7 and B10, while ASTM D 1160 was used for B30. The results are shown in **Figure 3-1**.

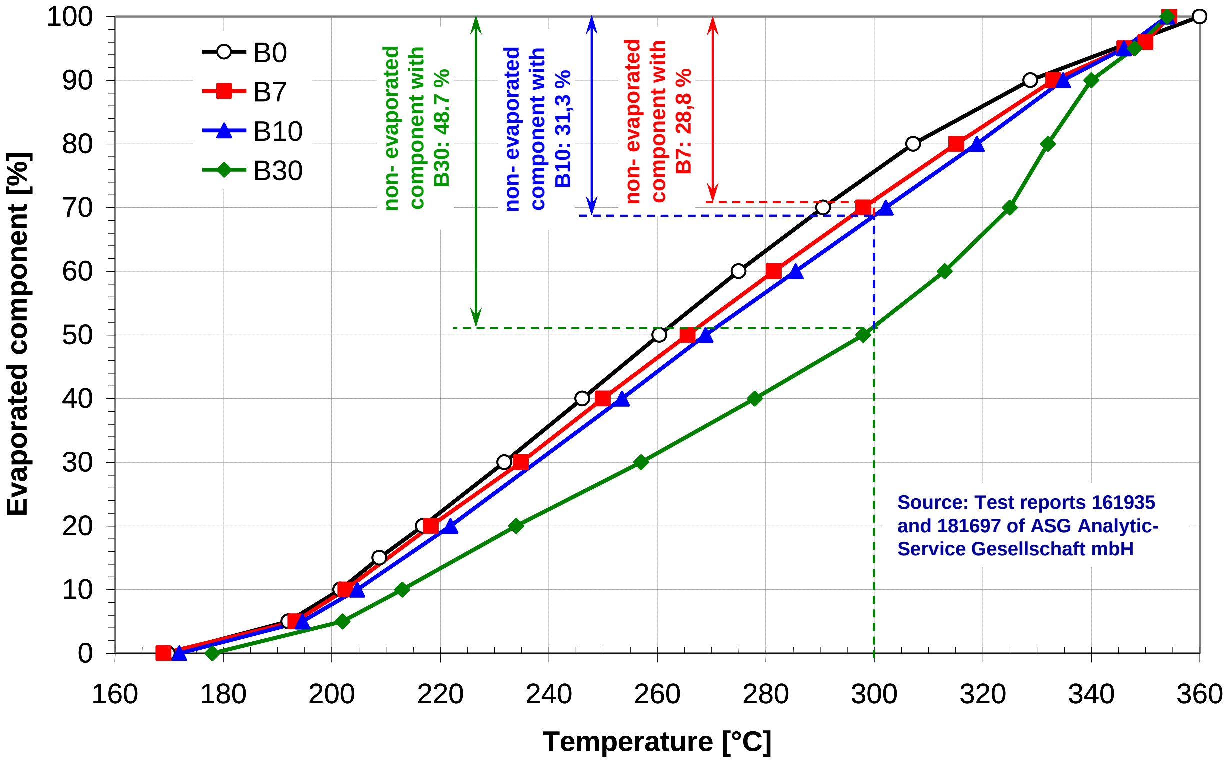


Figure 3-1: Boiling curves of the fuels B0, B7, B10 and B30

The figure shows that the evaporated fuel component decreases while the non-evaporated component increases at the same boiling temperature with increasing RME component in the fuel blend. Thus for the boiling temperature of 300 °C, for example, the non-evaporated component is determined at 24 % for B0, 28.8 % for B7, 31.3 % for B10 and 48.7 % for B30. The distillation end of the three fuel blends was 354 °C.

3.3 Engine oil

The engine was operated with the engine oil approved by the engine manufacturer with the designation “Titan GT1 Longlife III 5W-30”, which corresponds to the VW standard VW 507 00. The oil was procured from Fuchs Europe Schmierstoffe GmbH.

4 Test Setup

4.1 Test engine

A diesel engine 2.0-l-TDI-CR-4V with a rated power of 103 kW provided by Volkswagen AG Wolfsburg served as a test engine.

Table 4-1 below describes the technical data of the exhaust-turbocharged, charge-air-cooled 4-cylinder diesel engine.

Table 4-1: Technical data of the test engine 2.0-l-TDI-CR-4V

Engine type	Four cylinder diesel engine
Engine number	CBA 0634448
Engine code letter	CBAB
Manufacturer	Volkswagen AG
Injection system	Common rail, injection pressure: 1800 bar 8-hole injection nozzle, Piezo inline injectors
Engine control	EDC 17
Valves per cylinder	4
Displacement	1,968 cm³
Bore/stroke	81.0 / 95.5 mm
Geometric compression ratio	16.5 : 1
Exhaust turbocharging	Exhaust turbocharger VNT, charge air cooling
Exhaust gas purification	EGR with low temperature cooling, oxidation catalyst and DPF close to engine
Max. power	103 kW at 4200 rpm
Max. torque	320 Nm at 1750 – 2500 rpm
Fuel	Diesel fuel according to EN 590
Emission class	Euro 5

The high standards of the exhaust gas standard Euro 5 are achieved by the engine with a connected low-temperature EGR cooling for optimisation of the untreated emission and a diesel particle filter (**Figure 4-1**) close to the engine with upstream oxidation catalyst [5].

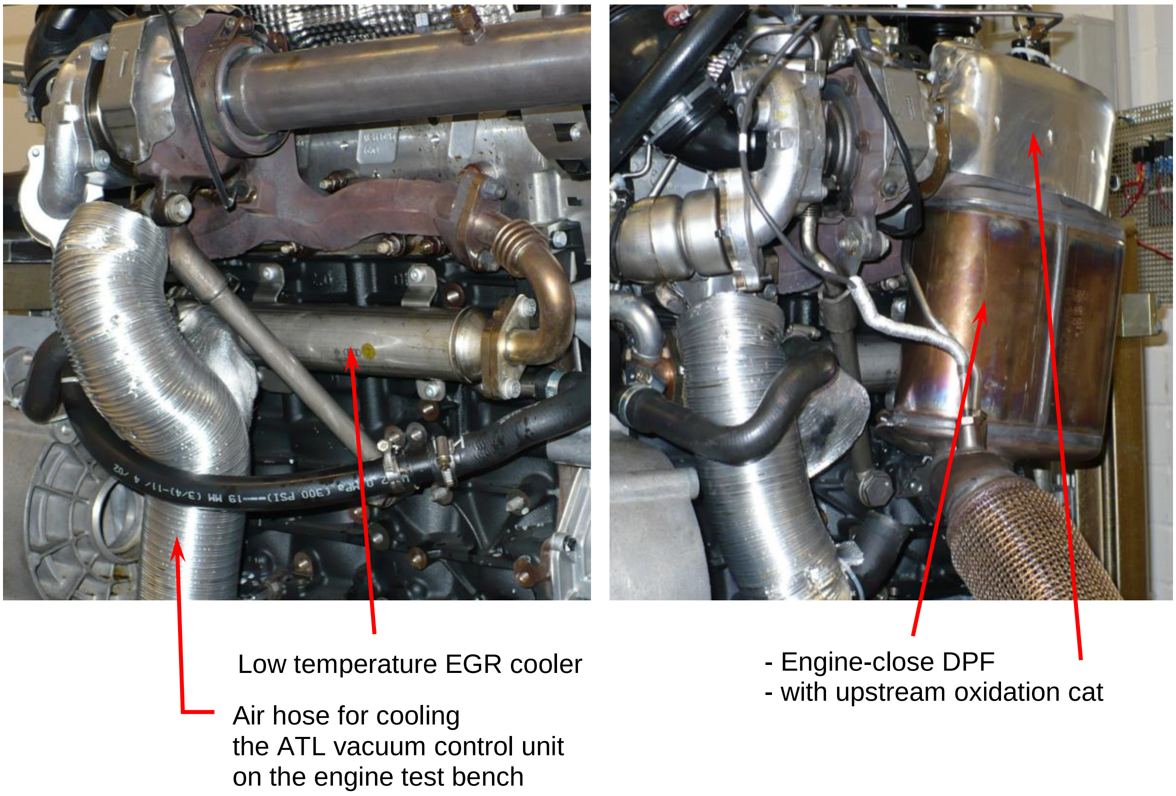


Figure 4-1: Low-temperature EGR cooler (left) and engine-close DPF with oxidation catalyst (right)

4.2 Engine test bench

The principle structure of the engine test bench is shown in **Figure 4-2**.

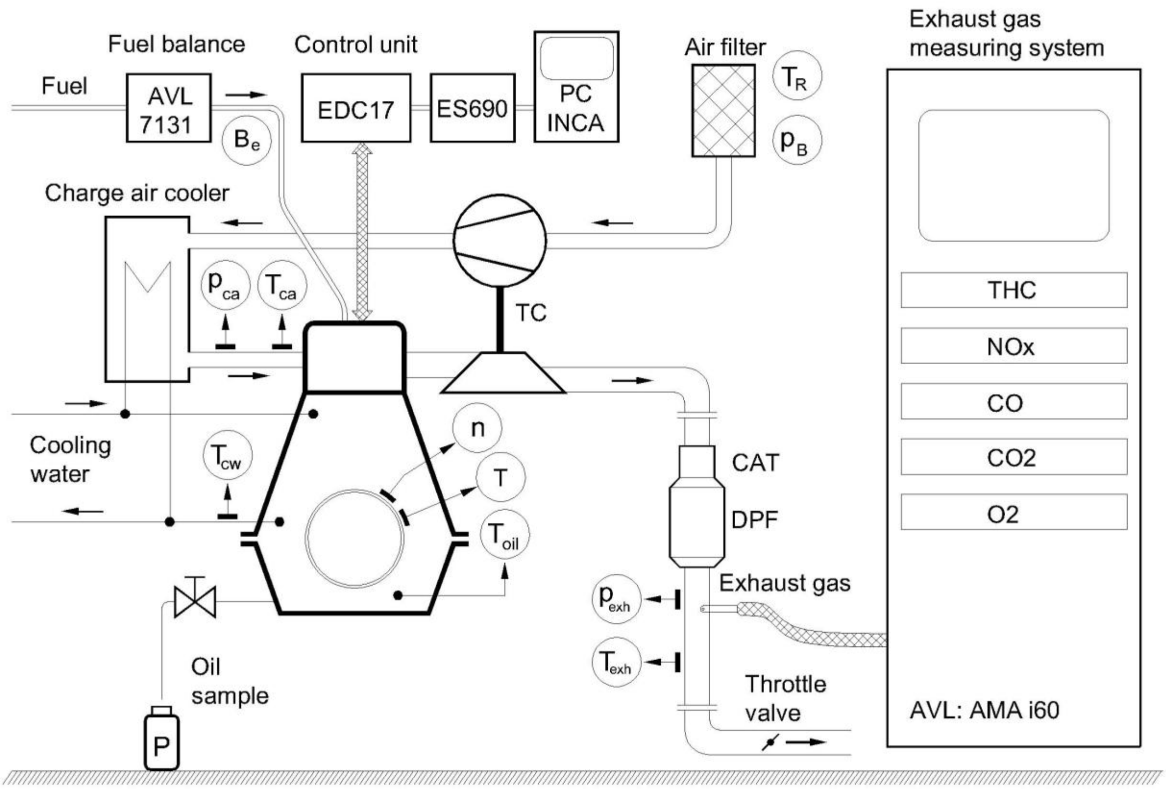


Figure 4-2: Engine test bench with exhaust gas after-treatment and measuring system

The engine 2.0-l-TDI-CR-4V was connected to the Schenck eddy current brake W 230 via an elastic propeller shaft. The engine was started with a three-phase trailing motor, which was connected to the brake device during starting and which accelerated the engine to a speed of 1450 rpm.

Important engine parameters, e.g. speed, torque, cooling water and oil temperature as well as charge air temperature and charge pressure after the water-cooled charge air cooler, the exhaust gas counter pressure and exhaust gas temperature after the particle filter, the hourly fuel consumption and the test room temperature, were logged via measuring points which were connected to the test bench computer.

The engine control was implemented with an application control unit (control unit EDC 17). The engine data significant for the tests was read out with the interface module ES690 and the ETAS software INCA V5.4 and displayed on the PC.

The engine exhaust gas analysis system of the AVL AMA i60 was used for determining the gaseous exhaust gas components nitrogen oxides (NO_x), hydrocarbons (CH), carbon dioxide (CO_2), carbon monoxide (CO) and oxygen (O_2). The exhaust gas was extracted via a multi-hole probe that was installed radially in the exhaust gas system after the particle filter and fed to the analysis system via a heated hose.

The fuel supply for the engine was realised via a separate pump, which pumped fuel from a 200 litre vat into the fuel system of the test bench. The AVL fuel balance 7131-03 was used for measuring the gravimetric fuel consumption.

The engine cooling and water-cooled charge air cooler were connected to the external cooling system of the engine test bench. The engine was operated with the thermostats integrated in the coolant circuit of the engine.

The diesel particle filter shown in Figure 4-2 with upstream oxidation catalyst was located close to the engine directly at the outlet of the exhaust gas turbocharger. In order to protect the vacuum control unit of the exhaust turbocharger against impermissibly high temperatures, a fan also had to be used whose air flow was directed towards the seal of the adjusting rod on the vacuum control unit owing to the absence of an air stream on the engine test bench which cools the engine compartment sufficiently (Figure 4-1).

4.3 Test implementation

4.3.1 Project stages

The test bench tests carried out in the project were divided into 6 stages:

- *Stage 1:*

  Determination of the fuel entry in regeneration mode with 6 and 7 injections at the engine operating point OP1 with late post-injection and the fuel blend B7. The aim was to determine the entry of RME and DF over a period of 8 operating hours and its influence on the engine oil viscosity. This test sequence was carried out three times.

- *Stage 2:*

  As stage 1, but with the fuel blend B10.

- *Stage 3:*

  As stage 1, but with the fuel blend B30.

- *Stage 4:*

  Determination of the engine oil viscosity in regeneration mode with 7 injections at engine operating point OP1 with variation of the late post-injection. The injection volume of the third post-injection and the injection start of the third and forth post-injection during engine operation with the fuel blend B30 was varied.

- *Stage 5:*

  Charging of the diesel particle filter over 7 hours at operating point OP2 without post-injection and regeneration at operating point OP1 with 6 and 7 injections during engine operation with the fuel blend B10 as well as regeneration at operating point OP1 with 7 injections and the fuel blend B30. The aim was to determine the effect of the split late post-injection on the regeneration sequence of the diesel particle filter.

- *Stage 6:*

  Determination of the fuel entry in the preheat stage with 5 injections at operating point OP1 (without late post-injection) and the fuel blends B10 and B30. The aim was to determine the entry of RME and DF over a period of 8 operating hours and its influence on the engine oil viscosity. This test sequence was carried out twice.

4.3.2 Test sequence

Time sequence:

The project was planned to take place between August 2009 and the end of April 2010. However, the project start was delayed cost neutrally by 4 months with confirmation by the project initiator owing to the need to provide a new engine including application control unit.

The test bench tests were commenced in December 2009 with introduction of the new engine over 20 operating hours and subsequent logging of the full load curves with diesel fuel in filling station quality as per EN 590 and with the fuel blend B30.

After provision of the data records necessary for the test by Volkswagen AG Wolfsburg in December 2009 with the late post-injection used as standard and with split post-injection, the fuel entry tests in regeneration mode with fuel blend B7 were commenced in January 2010.

It is pointed out at this stage that the regeneration time in the stationary tests on the engine test bench lasted 8 hours in order to clearly reveal the differences in the fuel entry. However, the individual regeneration of the filter in the vehicle is significantly shorter. In addition, a DF discharge also occurs between the individual regenerators, which could not be considered here.

The time sequence of the test bench tests carried out in the project in 2010 can be seen in **Table 4-2**.

Table 4-2: Overview of the test bench tests carried out in the project in 2010

Stage	Test	Task	from/to:	January	February	March	April	May	June
1	1 - 6	Regeneration 6 i und 7 i Fuel: B7, 8 h/d	14.01.-27.01.						
1	1 - 3	6 i - BP1: 2140 rpm; 30 Nm	19.01.-21.01.						
1	4 - 6	7 i - BP1: 2140 rpm; 30 Nm	22.01.-26.01.						
2	1 - 6	Regeneration 6 i und 7 i Fuel: B10, 8 h/d	28.01.-10.02.						
2	1 - 3	6 i - BP1: 2140 rpm; 30 Nm	28.01.-01.02.						
2	4 - 6	7 i - BP1: 2140 rpm; 30 Nm	02.02.-08.02.						
3	1 - 6	Regeneration 6 i und 7 i Fuel: B30, 8 h/d	11.02.-12.03.						
3	1 - 3	6 i - BP1: 2140 rpm; 30 Nm	15.02.-17.02						
3R	1 - 3	6 i - BP1: 2140 rpm; 30 Nm	09.03.-11.03.						
3	4 - 6	7 i - BP1: 2140 rpm; 30 Nm	18.02.-23.02.						
4	1 - 5	Variation late post-injection Fuel: B30 Regeneration 7 i	22.03.-08.04.						
5	1 - 3	Charging DPF, 7 h/d Fuel B7, B30 Regeneration 6 i, 7 i Weigh DPF	22.04.-30.04.						
5	1	6 i - B7	26.04.-27.04.						
5	2	7 i - B7	28.04.-30.04.						
5	3	7 i - B30	22.04.-23.04.						
6	1 - 4	Preheat stage (early post-inj.), 5 i 8 h/d, Fuel: B10, B30	08.06.-18.06.						
6	1 - 2	5 i - B10	10.06.-14.06.						
6	3 - 4	5 i - B30	16.06.-17.06.						

R: Repetition
i : Injections per cycle

Oil filling:

The engine oil filling was 3,600 cm³ Titan GT1 Longlife III 5W-30 for each test run, except in stage 4. Only in stage 4 was the engine operated with an oil filling reduced to 2.2 litres, in order to obtain analysable viscosity differences in the variants to be evaluated in the test time reduced to only 4 hours per variant.

Taking the oil samples:

An oil sample was taken from the engine oil pan at the start and end of each test run. The oil drain plug in the engine oil pan was replaced by a hollow screw for this. The oil could therefore be drained into the sampling tank through a ring piece via the drain cock. **Figure 4-4** shows the oil extraction device.

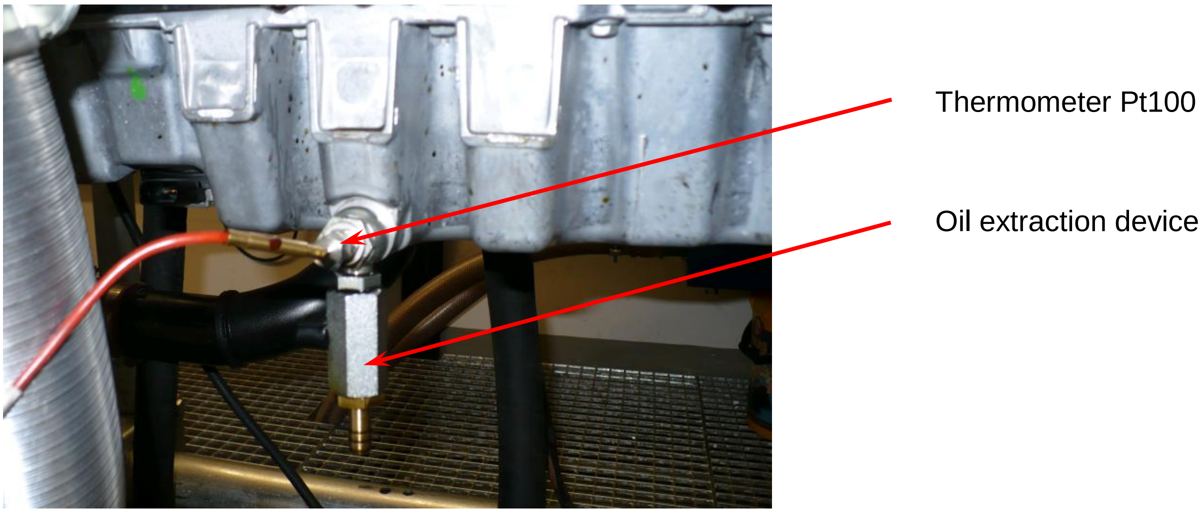


Figure 4-4: Oil sampling from the engine oil pan

The oil temperature was measured in the engine oil pan with the resistance thermometer Pt100 led through the hollow screw.

The engine was operated in idling mode during the oil sampling in all test runs. The first 50 to 100 cm³ of the drained oil were supplied to the engine immediately after the subsequent extraction of the oil sample to be analysed via the oil filler neck. In this way, it was ensured that no stale oil from the extraction device was used.

The oil sample volumes constantly taken from the engine were limited to 50 cm³/sample, in order to reduce the engine oil filling as little as possible.

Oil change:

After each test run, the engine oil was drained with the engine operationally warm and the engine oil filter replaced. The oil could drip out over approx. 30 minutes. The engine was filled with 2.5 litres of fresh oil three times afterwards for rinsing and operated each time for about 15 minutes. After the rinsing operation, the engine oil was drained, the oil filter housing being vented for complete emptying after the first and second rinsing. As no venting of the filter housing occurred in earlier tests after the last rinsing operation, the oil filter housing was also not vented after the third rinsing operation, in order to enable a comparison with the results for the test runs of the previous project [2]. The oil could drip out of the engine for at least 12 hours after the last rinsing.

The engine was then refilled with 3,600 cm^3 or, in stage 4, with only 2,200 cm^3 fresh oil of the brand Titan GT1 Longlife III 5W-30.

Oil analyses:

The 57 oil samples taken from the engine during the test runs were sent to Fuchs Europe Schmierstoffe GmbH for analysis after completing each run. The gas chromatographic analysis in accordance with DIN 51380 was carried out there for the quantitative determination of the RME and DF components in the engine oil. The viscosity testing of the oil samples was also carried out. After all samples of a test run were analysed, the results were transferred to the IMS.

Charging and regeneration of the diesel particle filter:

To determine the mass increase of the diesel particle filter resulting during the charging and for validation of the successful regeneration, the filter was weighed immediately before and after the charging as well as after completion of the regeneration (**Figure 4-5**).

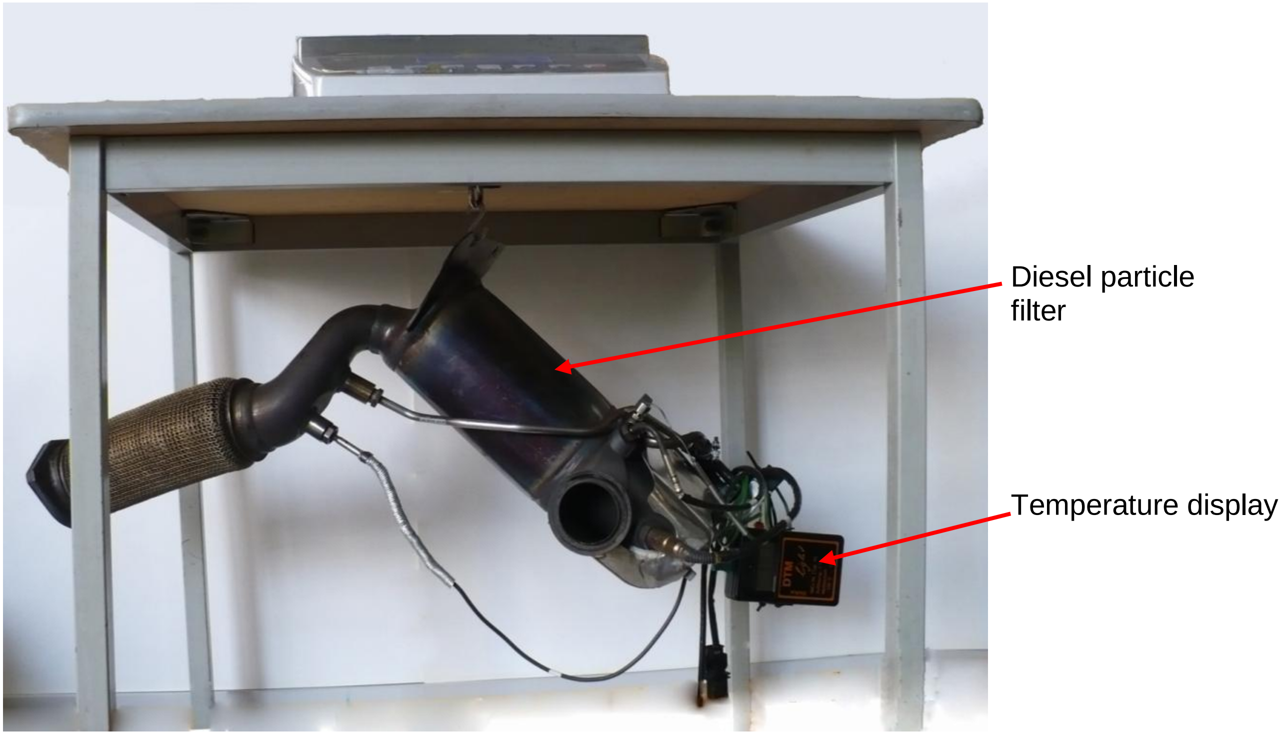


Figure 4-5: Weighing the diesel particle filter

The filter was always removed with the upstream oxidation catalyst installed in the same housing and the integral temperature and pressure sensors and fastened hanging freely on the weighing device standing on a table. The filter was removed immediately after stopping the engine for this and completed with the digital temperature measuring device. The weighing was only carried out at a constant temperature of the measuring point T_v_PF = 140 °C.

4.3.3 Operating points of the engine

The operating points envisaged in six stages as well as the full load curves of the engine recorded with the usual filling station DF and with fuel B30 are shown in **Figure 4-5**.

Operating point OP1 was in a very low load range with T = 30 Nm (bmep = 1.9 bar) at n = 2140 rpm. All tests that were planned in regeneration and preheat mode were carried out at this operating point.

At operating point OP2 with T = 65 Nm (bmep = 4.2 bar), the engine was only operated during the tests for charging the particle filter. This operating point was selected as a significant filter load was to be expected owing to the high exhaust gas recirculation rate.

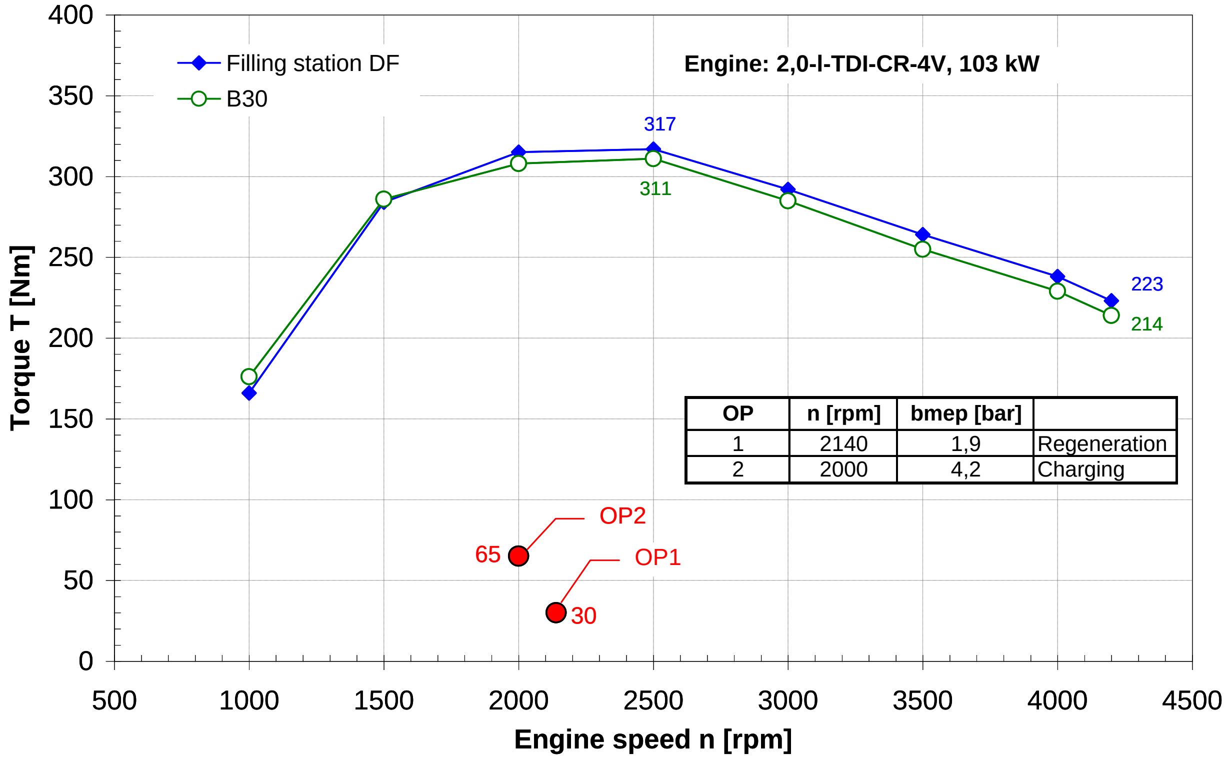


Figure 4-5: Operating points and full load curve of the engine with B10

The progression of the full load curve with the two fuels reveals that the full load torques were slightly below the values measured with filling station DF at an identical injection volume specification, i.e. without adjustment to the special fuel with the fuel blend B30. The difference was measured at approx. 2 % with maximum torque and at approx. 4 % at the rated power point.

4.3.4 Operating characteristic values of the engine

Table 4-3 contains the averaged operating characteristic values of the engine recorded during the stationary test bench runs for the various fuels with 6 and 7 injections in regeneration mode, with 3 injections during particle filter charging and with 5 injections per cycle in preheat mode. The measured values were logged by the test bench computer and recorded manually.

The tests for the fuel entry in regeneration mode with 6 and 7 injections per cycle at operating point OP1 were performed with the fuel blends B7, B10 and B30. The variation of the late post-injection at operating point OP1 occurred with the fuel blends B30. The charging and regeneration tests were carried out with the fuel blends B7 and B30 and the tests in the preheat stage (5 injections per cycle) with B10 and with B30.

The measured engine oil, cooling water and exhaust gas temperatures only had very low variance and hence demonstrate a stable engine run.

The test runs of stage 5 reveal that the late post-injection at OP1 increased the exhaust gas temperature in comparison to the charging at operating point OP2 by approx. 300 °C to approx. 566 °C and hence to the level necessary for the filter regeneration. The temperature measuring point was installed in the exhaust line of the test bench approx. 15 cm after the particle filter. Consequently, this temperature value was lower than the temperature value measured before the particle filter at approx. 640 °C and communicated to the control unit.

The exhaust gas counter pressure values were determined approx. 50 cm after the particle filter and the charge pressure values approx. 45 cm after the charge air cooler. At operating point 1, absolute values of 1.59 to 1.76 bar were measured in preheat and regeneration mode for the charge pressure.

The hourly fuel consumption values in regeneration mode were B_e = 4.9 to 5.2 kg/h.

The rail pressure values p_{Rail} exhibit relatively large fluctuations. In stage 3, values of 514 to 609 bar were measured in the 6 test runs with the fuel B30 at OP1. These values were read out with the interface module ES690 and the ETAS software INCA V5.4 and displayed on the PC. Different rail pressure values can lead to different injection volumes and hence presumably also to fluctuating fuel entries into the engine oil at the same injection duration.

The rail pressure values measured in stage 4 also exhibit significant fluctuations from 555 to 606 bar. The causes for the rail pressure fluctuations could not be analysed.

Table 4-3: Measured values of the engine corresponding to the measuring point plan

Stage	Test	Description	Fuel	Number of injections	n [rpm]	T [Nm]	T_{oil} [°C]	T_{cw} [°C]	T_{exh} [°C]	p_{exh} [mbar]	T_R [°C]	T_{ca} [°C]	p_{ca} [bar]	p_{Rail} [bar]
1	1 - 3	Regeneration	B7	6	2140	30	106	97	560	38	29	38	1,63	n/a
	4 - 6	Regeneration		7			106	97	561		28	39	1,75	n/a
2	1 - 3	Regeneration	B10	6	2140	30	105	97	559	38	26	37	1,60	n/a
	4 - 6	Regeneration		7			106	97	560		26	38	1,74	n/a
3	1 - 3	Regeneration	B30	6	2140	30	104	97	557	38	28	30	1,59	514 – 533
	4 - 6	Regeneration		7			106	97	563		26	40	1,73	603 – 609
4	1 - 5	Variation of the late post-injection	B30	7	2140	30	105	97	568	41	27	33	1,72	555-606
5	1 - 2	DPF charging	B7	3	2000	65	102	94	268	25	27	30	1,20	n/a
		Regeneration		6 / 7	2140	30	105	97	567	55	26	38	1,76	n/a
	3	DPF charging	B30	3	2000	65	102	94	260	25	27	28	1,20	n/a
		Regeneration		7	2140	30	105	97	566	42	27	34	1,76	n/a
6	1 - 2	Preheating	B10	5	2140	30	106	97	485	34	29	37	1,70	558 – 592
	3 - 4	Preheating	B30	5	2140	30	106	98	484	38	27	37	1,74	585 – 589

4.3.5 Injection sequence

As an application control unit was available for the tests, the operating states and data contained in **Figure 4-6** could be continuously monitored on the PC and read out. The figure shows two instantaneous records of the injection volumes and the exhaust gas temperatures before the exhaust gas turbocharger, before and after the DPF at operating point OP1 in four different operating modes or injection strategies of the engine.

Number of injections	3 (without Regeneration)	5 (Preheat stage)	6 (Regeneration)	7 (Regeneration)		
InjCrv_qPil2Des_mp	0.9	1.2	1.2	1.2	[mg/stroke]	Pilot-injection
InjCrv_qPil1Des_mp	1.0	1.4	1.4	1.4	[mg/stroke]	Pilot-injection
InjCrv_qMI1Des	6.0	4.0	4.0	3.6	[mg/stroke]	Main injection
InjCrv_qPoI3Des_mp	0.0	1.0	1.0	1.0	[mg/stroke]	1st post-injection
InjCrv_qPoI2Des_mp	0.0	11.1	10.7	10.3	[mg/stroke]	2nd post-injection
InjCrv_qPil3Des_mp	0.0	0.0	0.0	2.0	[mg/stroke]	3rd post-injection
InjCrv_qPoI1Des_mp	0.0	0.0	2.7	0.8	[mg/stroke]	4th post-injection
Exh_tAdapTTrbnUs	283	686	684	695	[deg. C]	Exhaust gas temperature before TC
Exh_tAdapTPFltUs	253	562	640	644	[deg. C]	Exhaust gas temperature before DPF
Exh_tAdapTPFltDs	237	509	590	590	[deg. C]	Exhaust gas temperature after DPF

Figure 4-6: Engine data of the application control unit at OP1 in different operating modes

In normal operation, the engine operated with 3 injections per work cycle. In order to prepare a requisite regeneration of the particle filter, the engine was operated with 5 injections per cycle, i.e. with 2 additional early post-injections (first and second post-injection) close to the main injection, so as to increase the exhaust gas temperature in the preheat stage, if necessary. In regeneration mode, the engine in the current series version was operated with 6 injections per cycle, i.e. besides two pilot-injections and the main injection two early and one late post-injection occurred (third post-injection). Splitting this third post-injection into two partial injection volumes (third and fourth post-injection) allowed the engine to be operated for test purposes with 7 injections per cycle. The individual injection volumes reveal fluctuations with the result that mean values were used for the further evaluations.

Figure 4-7 shows the injection in normal, preheat and regeneration mode at operating point OP1 for three different applications of the engine control unit.

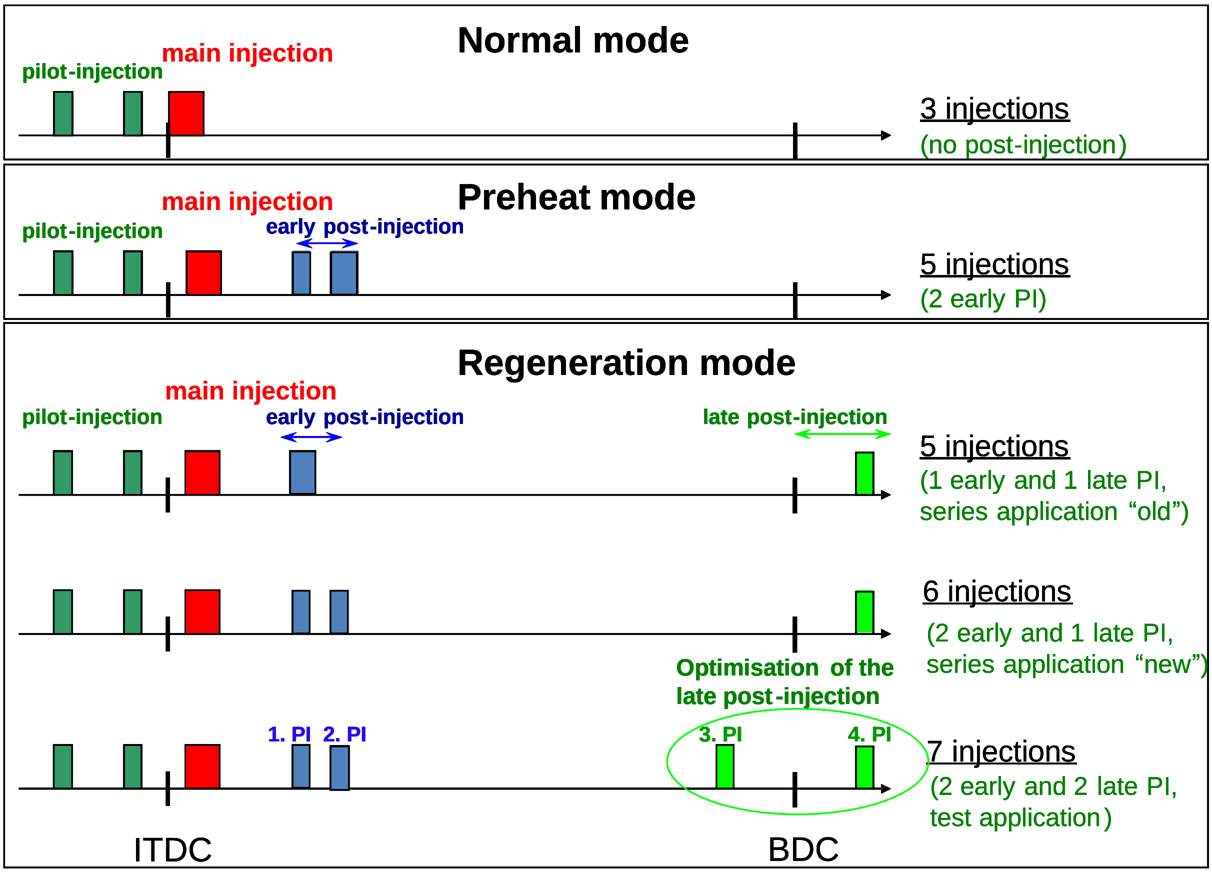


Figure 4-7: Injection sequence in normal, preheat and regeneration mode at OP1 for three different applications of the engine control unit

No post-injection occurred in normal mode with 3 injections per cycle. Two post-injections subsequent to the main injection, which are referred to as early post-injections here, were realised in preheat mode.

For comparison of the fuel entry into the engine oil with the results shown in [2] from the year 2008, the regeneration mode was also shown with 5 injections per cycle in Figure 4-7. No tests were carried out with the series application "old" in this project. An early and a late post-injection were included in the application. The late post-injection only occurred at the start of the upwards movement of the piston in the exhaust cycle.

In the current series application "new" provided by VW AG, two early post-injections and one late post-injection were realised, the late post-injection occurring at the same crank angle as in the series application "old".

The test application with 7 injections per cycle was provided by VW AG for examining the effects of the split late post-injection.

Besides the existing late post-injection, a further injection, designated as the third post-injection in Figure 4-7, also occurred in the series application “new”. This third post-injection was triggered towards the end of the work cycle a few degrees crank angle before the lower dead centre of the piston.

The injection time points of the third and fourth post-injection and the injection volume of the third post-injection were released by VW AG for the variation within the optimisation tests. All other labels, e.g. the injection volume of the forth post-injection could not be adjusted manually. To ensure the high exhaust gas temperature for the regeneration of the particle filter, which was specified in this application at approx. 640 °C, the second and fourth post-injection volumes were automatically adjusted without access from outside.

The exact values of the injection angle and injection volumes cannot be given in this report for reasons of confidentiality.

5 Confidence Interval for the Mean Values

The confidence interval that is shown for the mean values in the following results diagrams is the range in which the true mean value of a parent population lies with a specified probability. It is entered in the following diagrams as an error bar above the mean value calculated from the random samples. For the confidence level P, also referred to as statement probability, the usual value in technology of 95 % was selected.

The confidence interval v shown around the calculated mean value as an error bar, in which the true mean value is located, was calculated according to the following formula:

$$v = \pm \frac{t \cdot s}{\sqrt{n}}$$

t: Student factor for P = 95 %
s: Standard deviation of the random sample
n: Number of measured values in the random sample

In the case of an overlap of the confidence intervals in the mean values to be compared, significant mean value differences cannot be assumed.

6 Results of the Tests

6.1 Results in regeneration mode

6.1.1 Fuel impingement on the cylinder walls

In order to create active regeneration conditions at the DPF inlet, post-injection strategies with up to four post-injections per cycle were used in regeneration mode in the VW engine examined. These were investigated in respect to their effect on the fuel entry into the engine oil as well as the kinematic oil viscosity.

It is known that post-injections make a major contribution to oil dilution during regeneration. In particular during the late injection, where the piston is far from the cylinder head, the high fuel penetration results in impingement of the fuel on the cylinder walls [4]. However, the early post-injection subsequent to the main injection can also contribute to oil dilution if the injection start is at a time when the piston is already far enough from the upper dead centre that the fuel jets no longer reach the piston and partial amounts of the fuel jets encounter the cylinder wall.

Figure 6-1 shows that the fuel jet axes at crank angles over approx. 30° after the cylinder top dead centre no longer reach the piston but encounter the cylinder wall in the present engine.

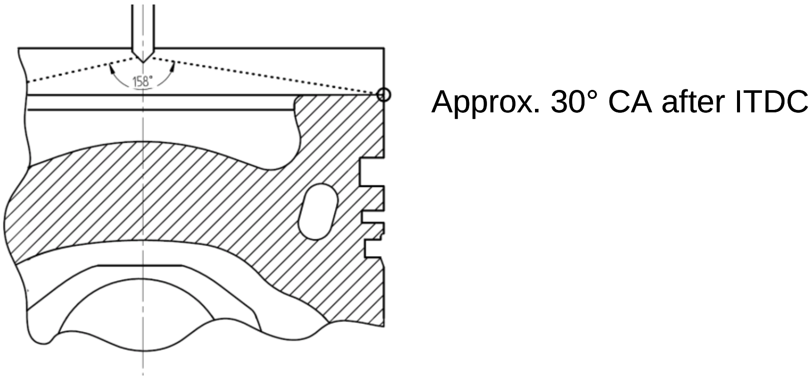


Figure 6-1: Crank angle limit for avoiding the jet impingement on the cylinder wall

The injections occurring later in the cycle, which therefore extend beyond the limit of approx. 30° crank angle after the cylinder top dead centre, can contribute to oil dilution. In this engine, the early post-injections subsequent to the main injection also occurred later (> 30° crank angle after cylinder top dead centre).

An option for reducing the oil dilution involves reducing the jet pulse, which can be achieved by dividing the after-injected volume into two parts. The reduction in the oil dilution by splitting the post-injection is explained as follows in [4] on the basis of two main phenomena:

- Reduction in the injection volumes at the two injections results in shorter injection times and hence a reduced jet pulse. The fuel impingement on the cylinder wall is reduced and the oil dilution decreased.
- The “seat throttle effect” results twice instead of once through the split late post-injection. The seat throttle effect during the opening and closing of the nozzle leads to a lower average injection pressure and hence to a reduction in the jet pulse and penetration, thereby resulting in a decrease in the oil dilution.

6.1.2 Optimisation of the split late post-injection

The aim of optimising the split late post-injection involved realising an injection sequence with the lowest fuel entry into the engine oil in regeneration mode, whereby the regeneration efficiency should be retained as with the series application “new” (6 injections per cycle).

The tests were carried out with the test application provided by VW AG and shown in Figure 4-7 with a total of 7 injections per cycle. This application of the control unit data record contained two early post-injections subsequent to the main injection (first and second post-injection) and two late post-injections (third and fourth post-injection).

The data record corresponded to variant V5 indicated below in **Figure 6-2** when delivered. This figure shows the principle of the examined 5 settings of the injection start for the third and fourth post-injection as well as the injection volume of the third post-injection for operating point OP1. The exact values of the injection angles and injection volumes are confidential.

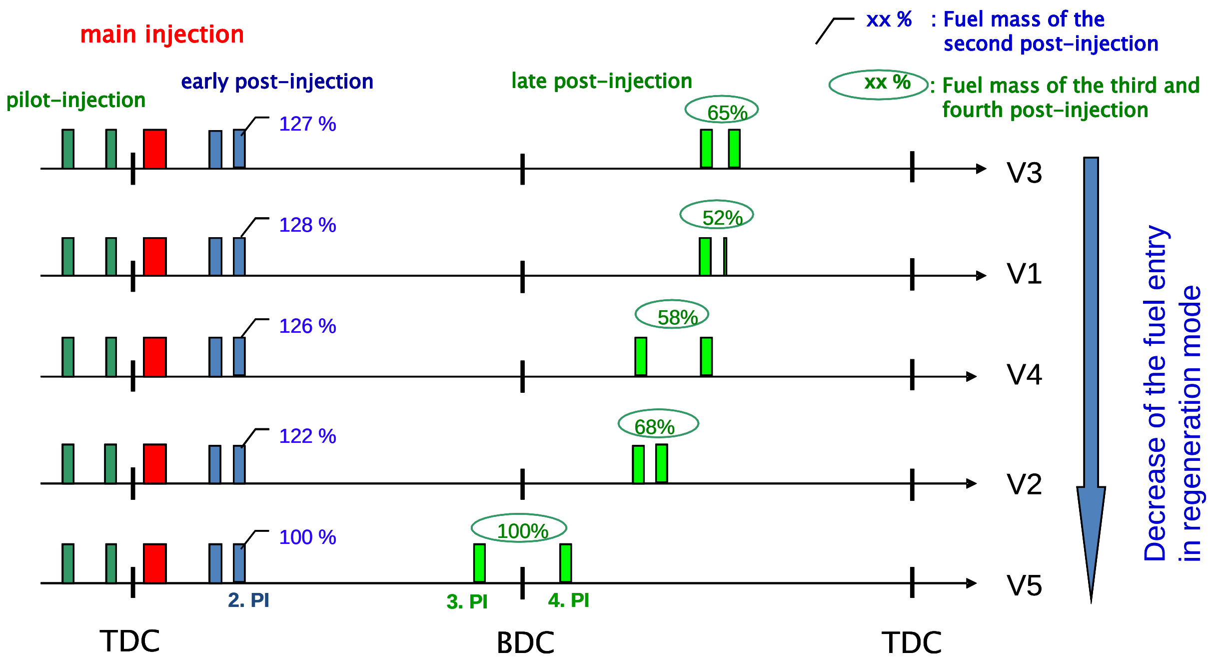


Figure 6-2: Variation of the late post-injection

To evaluate the level of the fuel entry, the kinematic viscosity of the engine oil samples was determined after the test runs with 5 different injection sequences.

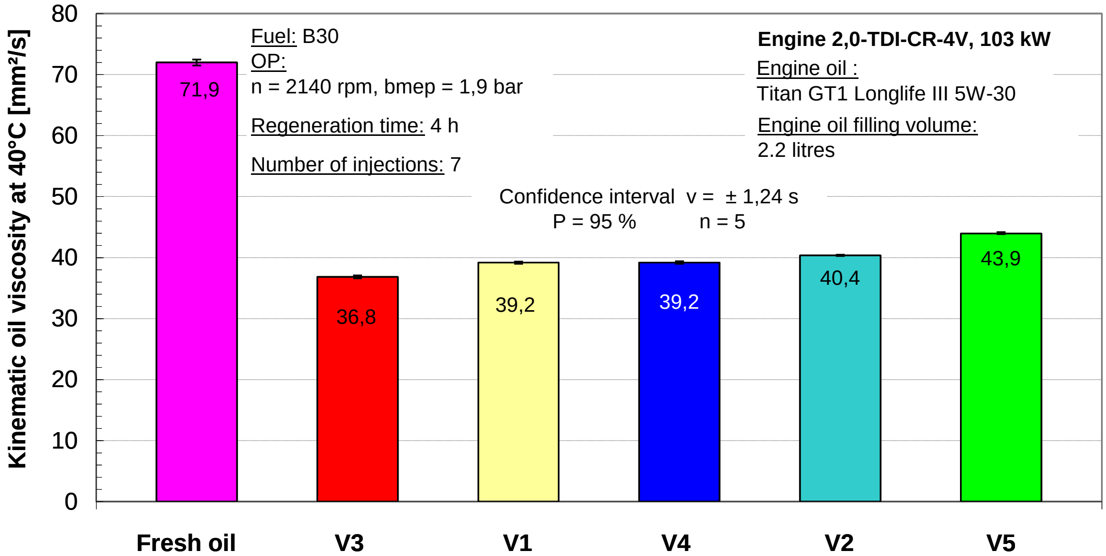
The total fuel masses of the split late post-injection selected in variant V5, i.e. the third and fourth post-injection was determined at 100 %. The fuel masses in the variants V2, V4, V1 and V3 were considerably less than in variant V5. At the same time, the injection time points were also changed in addition to the fuel masses.

The fuel mass of the second early post-injection was also determined at 100 % in variant V5 per cycle. A considerably higher fuel mass of the second post-injection per cycle of 122 % to 128 % was determined in variants V2, V4, V1 and V3. However, the first post-injection remained unchanged in all variants.

The changes to the post-injection in respect to the fuel injection volumes and the injection time points revealed that the fuel entry into the engine oil was the greatest in variant V3. It became less in variants V1, V4, V2 to V5, which was also determined on the basis of the increasing viscosity values of variants V3 to V5.

Figure 6-3 shows the results of the oil viscosity measurement for the five variants examined with the split late post-injection for an oil temperature of 40 °C. A test run at operating point OP1 was performed over 4 hours in regeneration mode for each variant. The engine had a reduced oil filling of only 2.2 litres in these tests, in order to ensure sufficiently high oil dilutions for measurement of the kinematic viscosity of the various variants despite a shorter test run time. 5 viscosity measurements were conducted with each of the oil samples taken after 4 hours.

The mean values of these measurements and a fresh oil sample from the engine reveal in Figure 6-3 that the oil viscosity has decreased to almost half the fresh oil value after just 4 hours in regeneration mode.



	Fresh oil	V3	V1	V4	V2	V5
Total 2nd to 4th post-injection mass/stroke [%]	-	**111,9**	**109,5**	**109,5**	**108,7**	**100**

Figure 6-3: Kinematic oil viscosity at variation of the split late post-injection

If we consider the viscosity values of the variants which increase from V3 to V5 and the total of the fuel masses read out from the control unit in the second, third and fourth post-injection (fuel mass of the first post-injection constant), it becomes apparent that the kinematic oil viscosity rises with decreasing fuel mass of the early and late post-injection, i.e. the fuel entry falls.

The determination that the fuel entry into the engine oil has increased despite the reduction in the fuel mass of the third and fourth post-injection and the resultant increase in the early injected fuel mass in the second post-injection in the examined variants V2, V4, V1 and V3 allows us to conclude that the early post-injection subsequent to the main injection must play a not insignificant role in the oil dilution. The confirmation for this is given in point 6.2.

All further tests described with 7 injections per cycle, i.e. the tests with split late post-injection, were carried out with variant V5, as this demonstrated the lowest fuel entry.

6.1.3 Fuel entry into the engine oil

6.1.3.1 Fuel entry with 6 injections per cycle (series application "new")

The stationary test runs in regeneration mode were performed three times at operating point OP1 with every fuel blend. The test run time was 8 hours each. After the engine start and a short warm-up phase, the engine was operated over 8 hours in regeneration mode. The oil sampling was conducted at 0 and 8 hours. The engine was operated in idling mode during the sampling.

The results determined gas-chromatographically from the oil samples for the fuel concentration of the test runs with 6 injections per cycle can be seen in **Figure 6-4**.

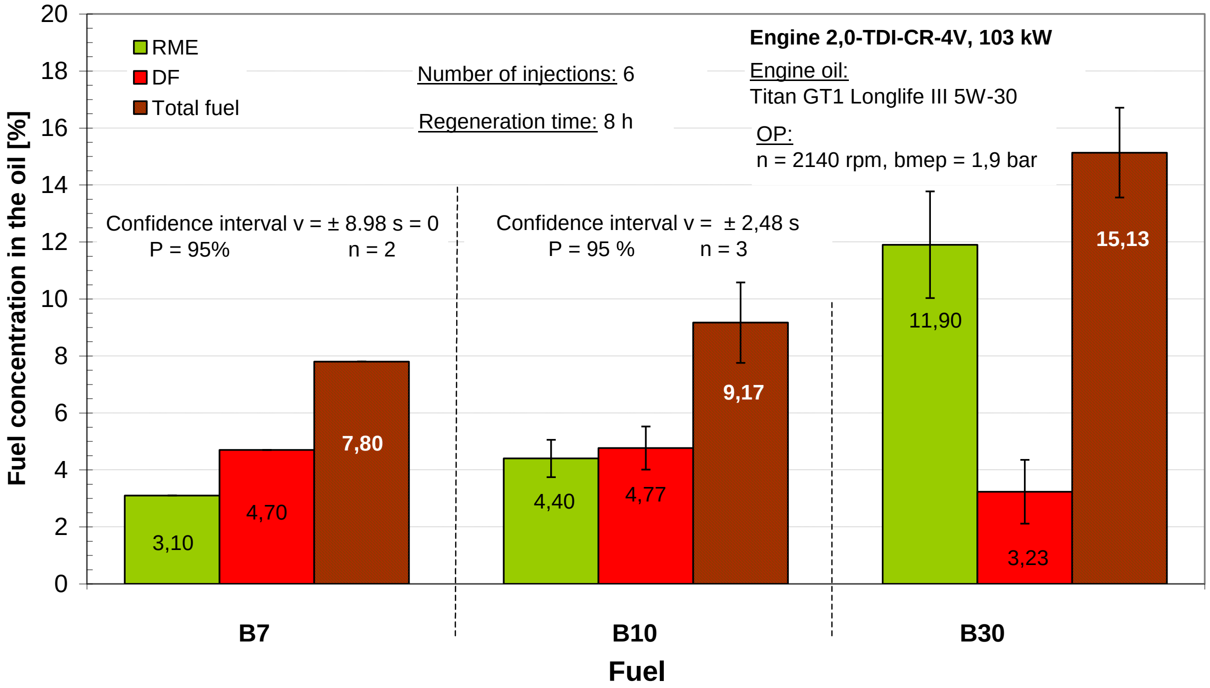


Figure 6-4: Concentration of RME, DF and total fuel in the engine oil after 8 hours engine operation in regeneration mode with 6 injections per cycle at OP1 with B7, B10 and B30

The figure reveals that the fuel entry into the engine oil significantly increased after increasing the biodiesel content in the fuel blend from B7 to B10 and B30. Although the concentration of the total fuel comprising the RME and DF content was 7.8 % in the engine oil during stationary engine operation in regeneration mode over 8 hours with B7, it increased during operation with B10 to 9.17 % and with B30 to 15.13 %. During operation with B30, the entry of the total fuel is thus 94 % higher than with B7. This resulted in a concentration increase due to the increases in the RME concentration determined in the oil. These rose from 3.10 % during operation with B7 to 4.40 % with B10 and 11.90 % with B30. In other words the RME entry during operation with B30 was 284 % higher than during operation with B7. The DF concentration of 4.70% with B7 and 4.77 % with B10 did not reveal any significant differences.

The low DF concentration in the engine oil of only 3.23 % during operation with B30 is due to the significantly lower DF component in the fuel blend B30 in comparison to B7 and B10.

6.1.3.2 Fuel entry with 7 injections per cycle (split late post-injection)

Figure 6-5 shows the results of 3 test runs each in regeneration mode with 7 injections per cycle, i.e. with split late post-injection (variant V5) at operating point OP1 during operation with B7, B10 and B30.

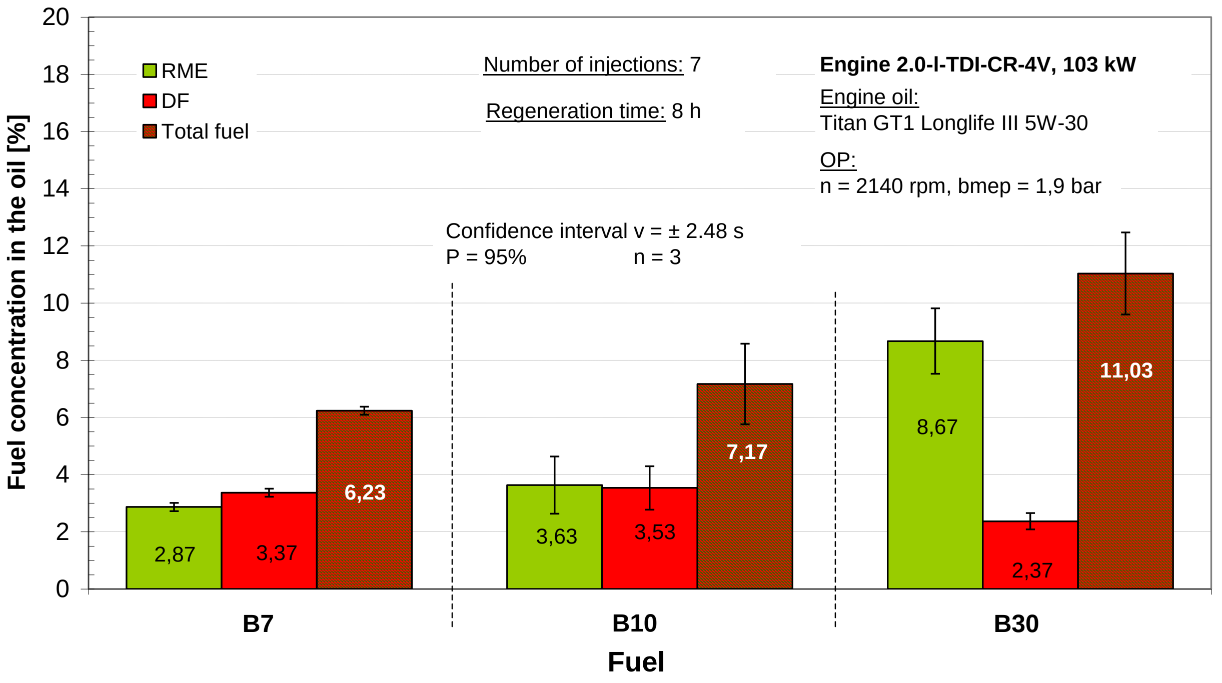


Figure 6-5: Concentration of total RME, DF and fuel in the engine oil after 8 hours engine operation in regeneration mode with 7 injections per cycle at OP1 with B7, B10 and B30

In principle, a similar pattern results in regeneration mode with 7 injections per cycle as that with 6 injections. Nevertheless, the level of the gas-chromatographically ascertained fuel concentrations in the engine oil was considerably lower. Here too, it can be determined that the RME entry into the engine oil increased as the RME component in the fuel blend increased. With B7, the RME concentration was only 2.87 % with an average of three test runs per fuel blend after a test duration of 8 hours, but this figure was 3.63 % with B10 and 8.67 % with B30. In other words, the RME entry with B30 was 202 % higher than with B7. The DF concentration with B7 of 3.37 % did not reveal any significantly different value to operation of the engine with B10, in which the DF concentration was 3.53 %. The low DF concentration in the engine oil of only 2.37 % during operation with B30 is, in turn, due to the significantly lower DF component in the fuel blend B30 in comparison to B7 and B10.

The increase in the concentration of the fuel of 6.23 % in total with B7 and 7.17 % with B10 through to 11.03 % with B30 is to be explained by the higher RME component in the fuel blend with increase in the RME entry – as also in regeneration mode with 6 injections per cycle. The total concentration of fuel is consequently 77 % higher with B30 than with B7.

6.1.4 Fuel entry into the engine oil during operation with B10 in relation to the injection strategy

Figure 6-6 shows the fuel concentration values during engine operation with 6 injections per cycle (series application "new") and 7 injections per cycle (split late post-injection variant V5) for RME, DF and fuel in total during engine operation with B10 at OP1. In addition, the results from the previous FNR/UFOP project [2] with 5 injections per cycle (series application "old") for the fuel blend B10 were compared with the results of this project. In doing so, it is to be noted that the results from the previous project were determined with another diesel engine of VW AG but with the same construction.

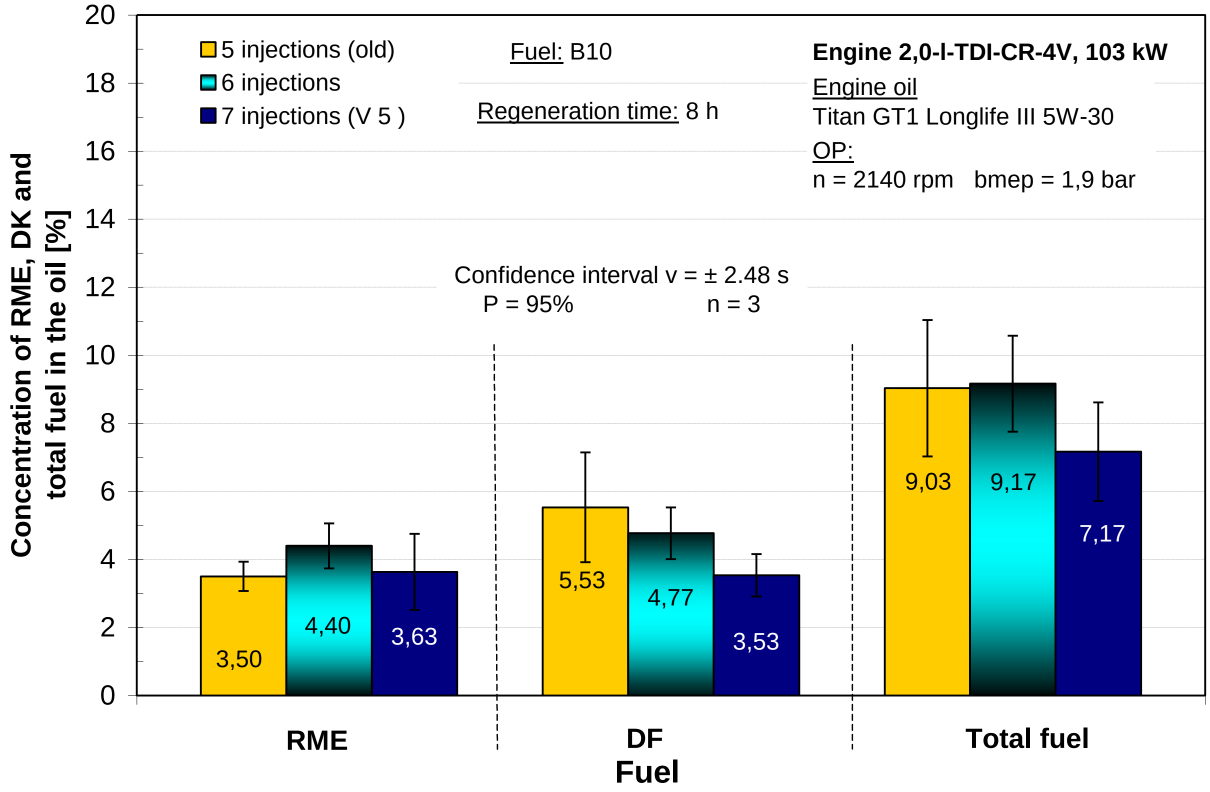


Figure 6-6: Concentration of total RME, DF and total fuel in the engine oil after 8 hours engine operation in regeneration mode with 5, 6 and 7 injections per cycle at OP1 with B10

The concentration values of the series application "old" with 5 injections and the series application "new" with 6 injections per cycle did not reveal any significant differences. The RME concentration in the series application "new" tended to be somewhat higher at 4.40 % in comparison to the series application "old" at 3.5 %. The reverse was the case for the DF concentration. Here a higher DF concentration value was determined in the series application "old" at 5.53 % in comparison to the series application "new" with only 4.77 %. The concentrations of total fuel were almost identical at 9.03 % and 9.17 %.

During operation of the engine with B10, the RME concentration with the split late post-injection was reduced from 4.40 % to 3.63 % and the DF concentration from 4.77 % to 3.53 % in comparison to the series application "new", with the result that the lowest concentration value of the fuel resulted at 7.17 %.

6.1.5 Drop in the engine oil viscosity in relation to the injection strategy

Figure 6-7 shows the mean values of the viscosity decrease in regeneration mode after test run times of the engine lasting 8 hours each with the fuels B7, B10 and B30 with 6 injections (series application "new") and 7 injections per cycle (split late post-injection variant V5). In addition, the viscosity decrease identified in the previous FNR/UFOP project [2] with 5 injections (old) is indicated for B10, which was measured during operation of the engine with the series application "old".

The viscosity measurements were carried out at an oil temperature of 100 °C.

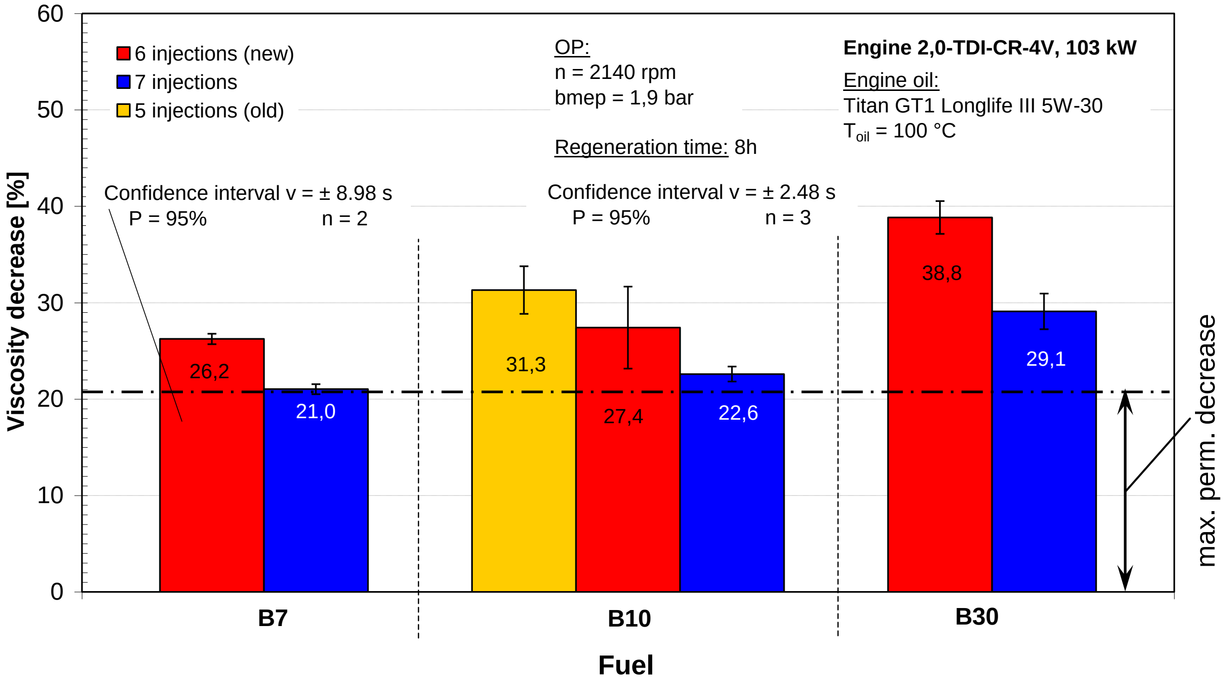


Figure 6-7: Decrease in the oil viscosity at 100 °C in regeneration mode over 8 hours at engine operation with 5, 6 and 7 injections (variant V5) with the fuels B7, B10 and B30

The permissible upper viscosity limit for an SAE 30 oil at an oil temperature of 100 °C is 12.45 mm²/s. The lower limit value is given as 9.3 mm²/s. The viscosity of the oil samples taken from the engine before stating the test run was 11.75 mm²/s on average and hence in the permissible range. On the basis of this value, the lower permissible viscosity limit is reached upon a decrease in the viscosity by approx. 21 %. This value was exceeded in all test runs with the exception of the test runs carried out with B7 and with split late post-injection.

The viscosity decrease rose with increasing RME component in the fuel blend both with 6 and 7 injections per cycle. At the same time, the values determined with the split late post-injection were below the values measured with the series application "new" with 6 injections per cycle. This difference is significant for B30.

The viscosity decrease with the fuel B10 determined with the series application "old" with 5 injections in the previous project [2] tended to be greater, but was not significantly greater than with the series application "new".

6.1.6 Improvements by splitting the late post-injection in comparison to the series application "new"

6.1.6.1 Reduction in the fuel entry

Figure 6-8 shows the percentage decrease in the fuel entry into the engine oil through splitting the late post-injection (variant V5) in relation to the series application “new” with 6 injections per cycle (100 %).

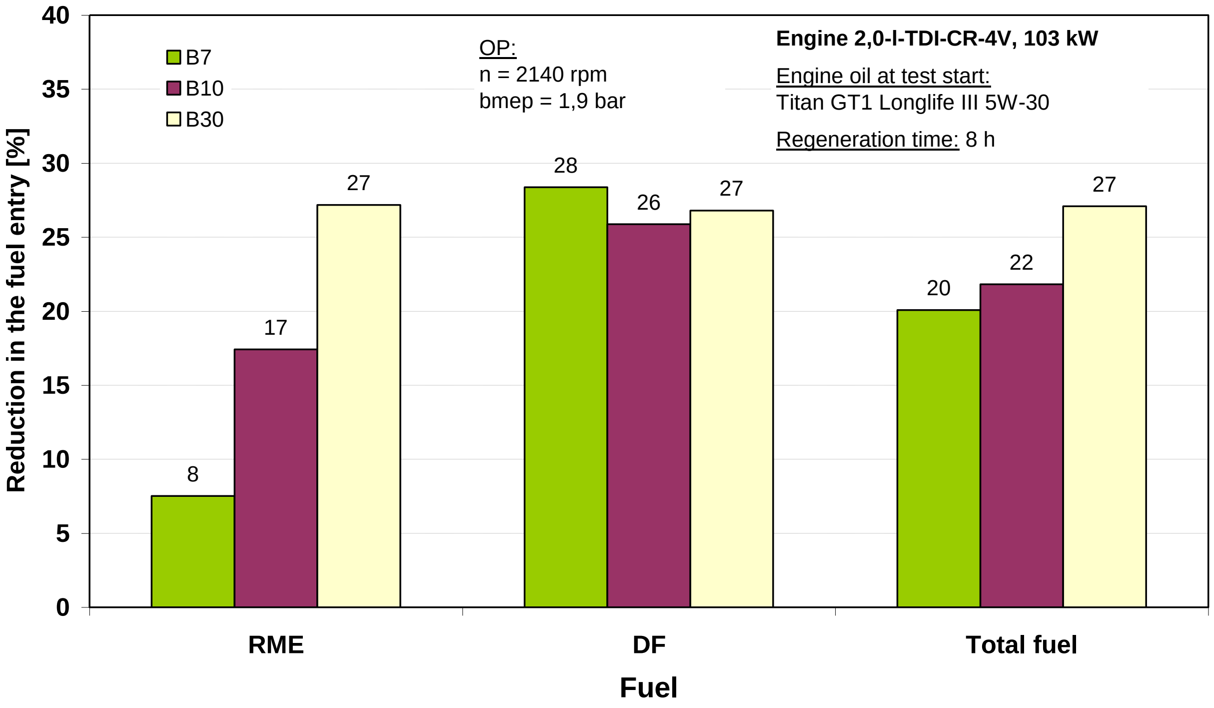


Figure 6-8: Reduction in the fuel entry through the split late post-injection (variant V5), in relation to the series application “new” with 6 injections per cycle

The results were determined from three stationary test runs per fuel at operating point OP1 over 8 hours in non-interrupted regeneration mode.

The DF entry was reduced during operation with the three fuel blends by approx. 26 to 28 %. However, the reduction in the RME concentration increased with increasing RME component in the fuel blend of B7 to B10 and B30. It was approx. 27 % for B30. No explanation can be found why the reduction in the RME entry exhibited lower values than for B30, with 8 % for B7 and 17 % for B10.

The reduction in the RME concentration increasing from B7 to B10 and B30 through the split late post-injection had the result that the concentration reduction of the total fuel rose from 20 % for B7 to 22 % for B10 and 27 % for B30.

The improvement in the oil dilution by dividing the late after-injected fuel volume into two parts on the engine test bench is indicated at 25 % in [5], there being no data provided on the fuel composition. In real urban driving during journeys from door to door, this only led to an oil dilution lower by 20 %.

As the tests described here were carried out in stationary test bench operation, results divergent from this are to be expected in practical application involving driving profiles at low speeds and idling times in urban traffic.

6.1.6.2 Reduction of the drop in engine oil viscosity

Splitting the late post-injection meant the engine oil was diluted less during the 8-hour test runs in regeneration mode than with the series application “new” with 6 injections per cycle (Figure 6-7).

Figure 6-9 clearly reveals the improvement, i.e. the reduction in the viscosity decrease through splitting the late post-injection in comparison to the engine operation with the series application “new”. The figure indicates the difference of the viscosity decrease given in percent between the operation with 6 and 7 injections per cycle.

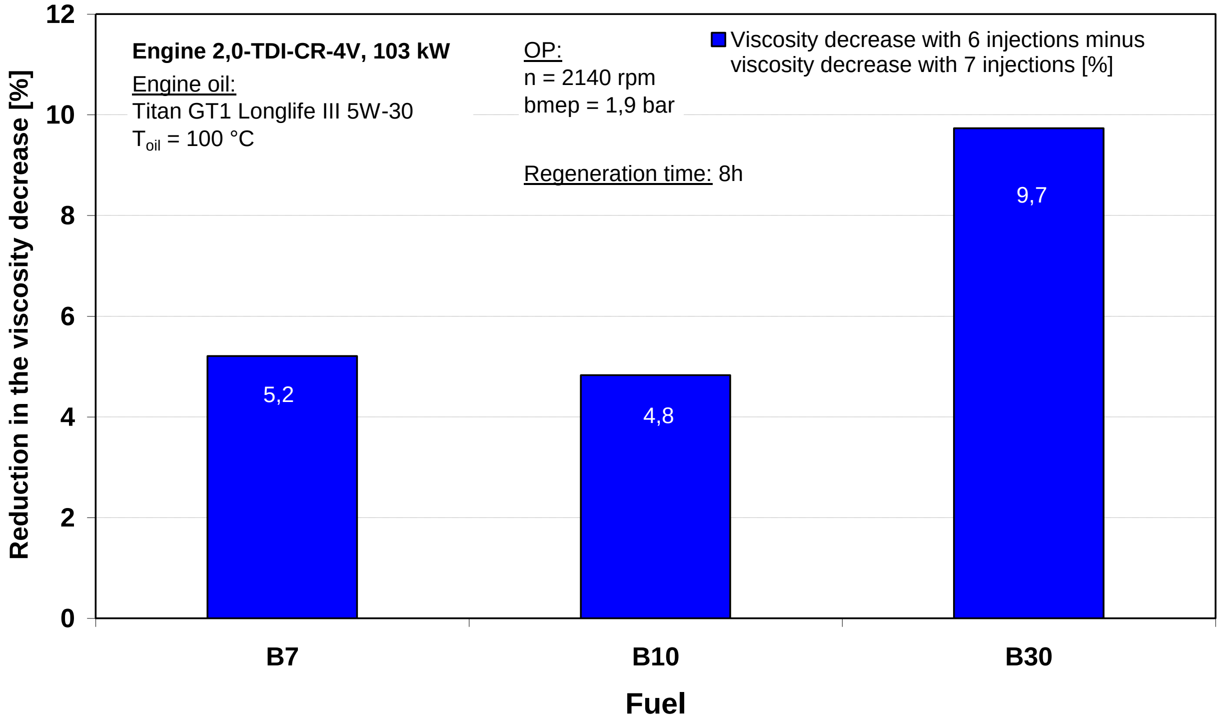


Figure 6-9: Reduction in the viscosity decrease through the split late post-injection (variant V5), in comparison to the series application “new” with 6 injections per cycle

The viscosity decrease that was determined with the split late post-injection was approx. 5 % below the values measured with the series application “new” with 6 injections per cycle with B7 and B10 and approx. 10 % below these values with B30. With the exception of B7, the permissible lower viscosity limit value was exceeded during the 8-hour test runs with the split post-injection despite the determined improvement.

6.2 Results in preheat mode

6.2.1 Fuel entry through early post-injections

The result of the optimisation of the late post-injection described in point 6.1.2 allows us to conclude that the late post-injection subsequent to the main injection must also play a not insignificant role in the oil dilution.

Figure 6-10 shows the fuel entry which was measured during engine operation with B10 and B30 in the preheat stage after a test run duration of 8 hours. The mean values of two test runs each per fuel are shown in the figure.

In the preheat stage, the engine was operated with 5 injections, two early post-injections occurring close to the main injection (first and second post-injection in Figure 4-7). The injection start for these two post-injections and the injection volume of the first post-injection are the same both in the preheat and regeneration mode with 6 and 7 injections. Only the injection volume of the second post-injection was approx. 5 to 17 % greater in the preheat mode than in the regeneration mode with 6 and 7 injections.

However, as both post-injection events occur at a time when the piston is already more than 30° crank angle after the cylinder top dead centre, it must be assumed that parts of the fuel jet encounter the cylinder wall, thereby diluting the engine oil.

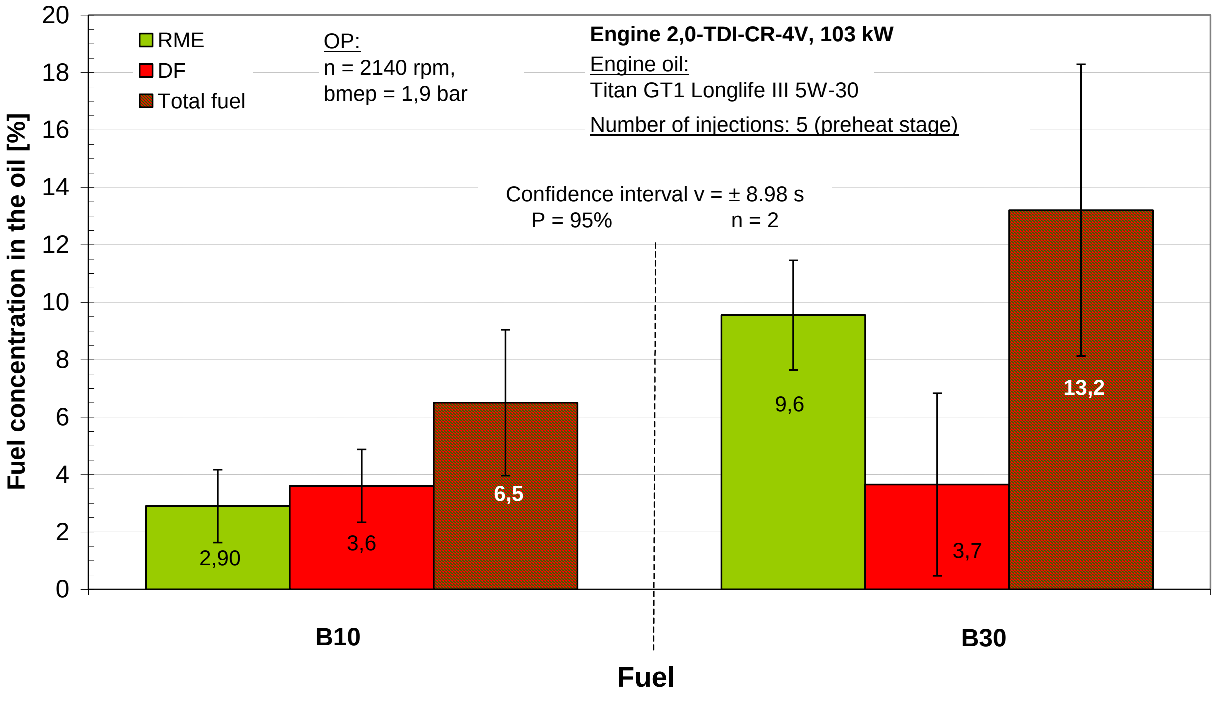


Figure 6-10: Fuel concentration in the engine oil after 8 hours engine operation in preheat mode with 5 injections per cycle at OP1 with B10 and B30

As already determined during engine operation in regeneration mode, the fuel entry into the engine oil increased as the RME component of the fuel blend increased. Although the concentrations measured were 2.9 % for RME and 3.6 % for DF during engine operation with B10, the concentration values for RME were 9.6 % and 3.7 % for DF with B30. This low DF value of 3.7 % is – as already determined in the regeneration mode of the engine – due to the lower DF component in the fuel blend B30 in comparison to B10.

The total concentration of fuel for B10 at 6.5 % and for B30 at 13.2 % was calculated by summation of the relevant RME and DF values.

For comparison, the concentration values which were measured during engine operation with B10 in the preheat stage with 5 injections as well as in regeneration mode with 6 and 7 injections are shown opposite one another in **Figure 6-11**. The concentration values of the preheat stage are the mean values from two test runs. The mean value from three test runs was formed in regeneration mode.

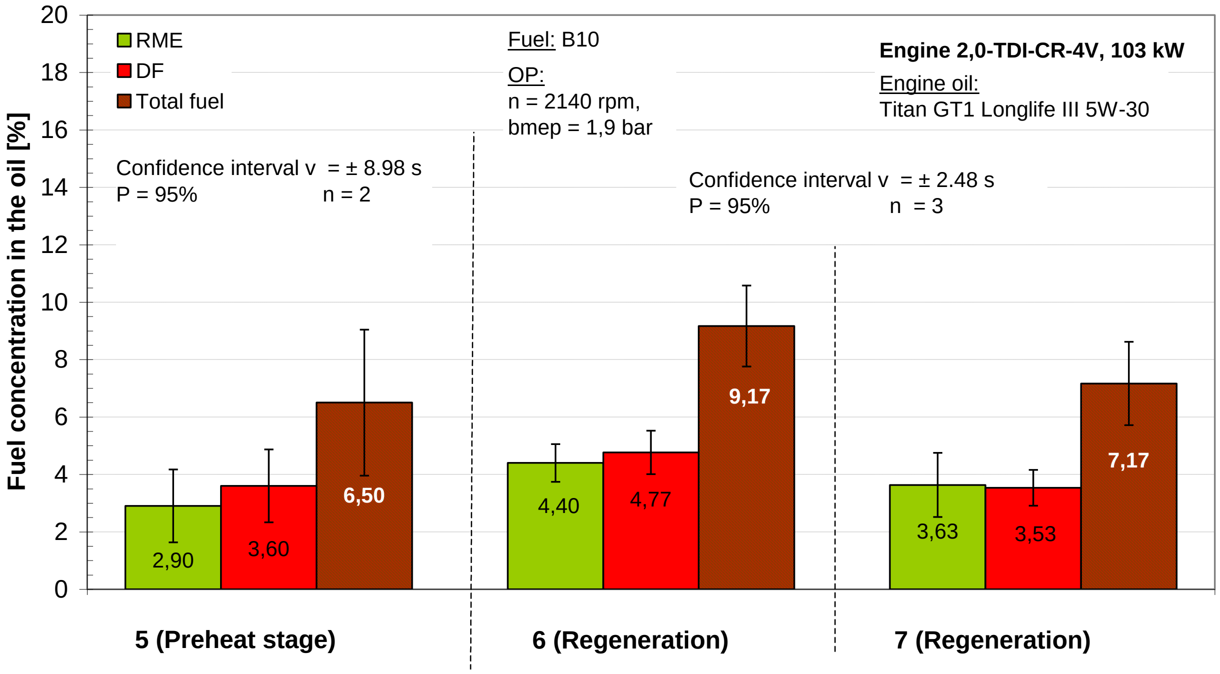


Figure 6-11: Fuel concentration in the engine oil after 8 hours engine operation with B10 in preheat mode with 5 injections and in regeneration mode with 6 and 7 injections per cycle at OP1

This figure reveals that the two early post-injections in the preheat stage almost caused the same fuel entry as measured in regeneration mode, in particular with the split late post-injection (7 injections per cycle). The differences between preheat and regeneration mode are not significant. The RME and DF concentration values are almost the same in each operating mode.

In **Figure 6-12** below, the concentration values of the engine operation with B30 in the preheat stage with 5 injections are compared with the concentration values in regeneration mode with 6 and 7 injections.

No significant concentration differences are demonstrable during engine operation with B30 either. It is discernible that the RME concentrations in each operating mode exhibit 2.6 to 3.7 times the value of the DF concentrations. The concentration values from operation with the preheat stage tended to be greater than in regeneration mode with 7 injections per cycle (split late post-injection). The highest fuel entry was determined in regeneration mode with 6 injections per cycle (series application “new”).

That allows us to conclude that the early post-injection must be taken into consideration during further attempts to reduce the fuel entry in regeneration mode.

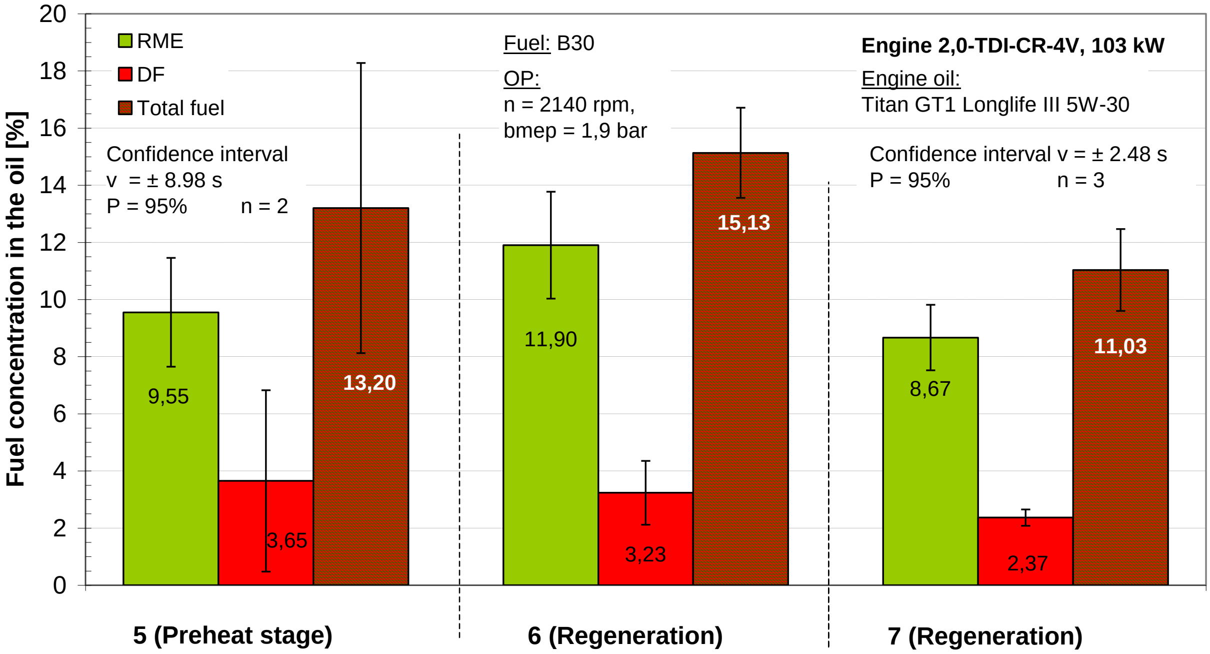


Figure 6-12: Fuel concentration in the engine oil after 8 hours engine operation with B30 in preheat mode with 5 injections and in regeneration mode with 6 and 7 injections per cycle at OP1

6.2.2 Drop in the engine oil viscosity through early post-injections

Figure 6-13 compares the decrease in the oil viscosity after 8-hour engine operation at operating point OP1 with B10 and B30 in preheat mode with 5 injections with the viscosity decrease in regeneration mode with 6 and 7 injections.

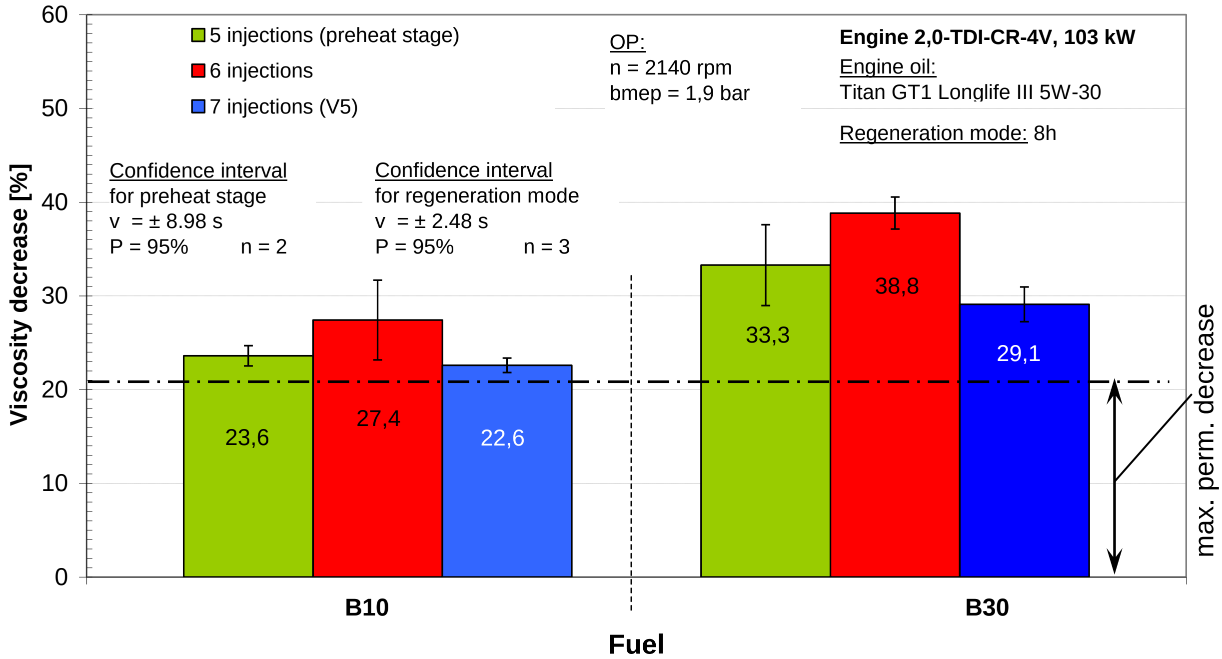


Figure 6-13: Decrease in the oil viscosity after 8 hours engine operation with B10 and B30 in preheat mode with 5 injections and in regeneration mode with 6 and 7 injections per cycle at OP1

The figure confirms the findings regarding the fuel entry made in 6.2.1 with the following statements:

- The greatest viscosity decrease trend in the engine oil was measured with both fuels in regeneration mode with 6 injections (series application “new”),
- The lowest viscosity decrease was determined in regeneration mode with 7 injections per cycle (split late post-injection),
- The viscosity decrease in preheat mode tends to be greater than in regeneration mode with split late post-injection and less than in regeneration mode with the series application "new".

6.3 Examination of the exhaust gas after-treatment with different injection strategies in regeneration mode of the engine

6.3.1 Charging and regeneration

The change in the injection strategy should not reduce the efficiency of the exhaust gas after-treatment system. The following figures therefore show the results of the examination of the particle filter regeneration during operation of the engine with the series application “new” (6 injections per cycle) and the test application with the optimised split post-injection (7 injections per cycle, variant V5).

Figure 6-14 outlines the records of the exhaust gas temperatures read out during the charging with the interface module ES690 and the ETAS software INCA V5.4 before the exhaust gas turbocharger, before and after the DPF as well as the differential pressure of the DPF during engine operation at operating point OP2 with the fuels B7 and B30. The charging occurred for each of the three indicated charging processes over 7 hours in normal mode of the engine with a total of 3 injections per cycle (Figure 4-7).

In each charging process, the accumulated particle mass was determined by weighing the filter before and after the charging, after which the filter was regenerated.

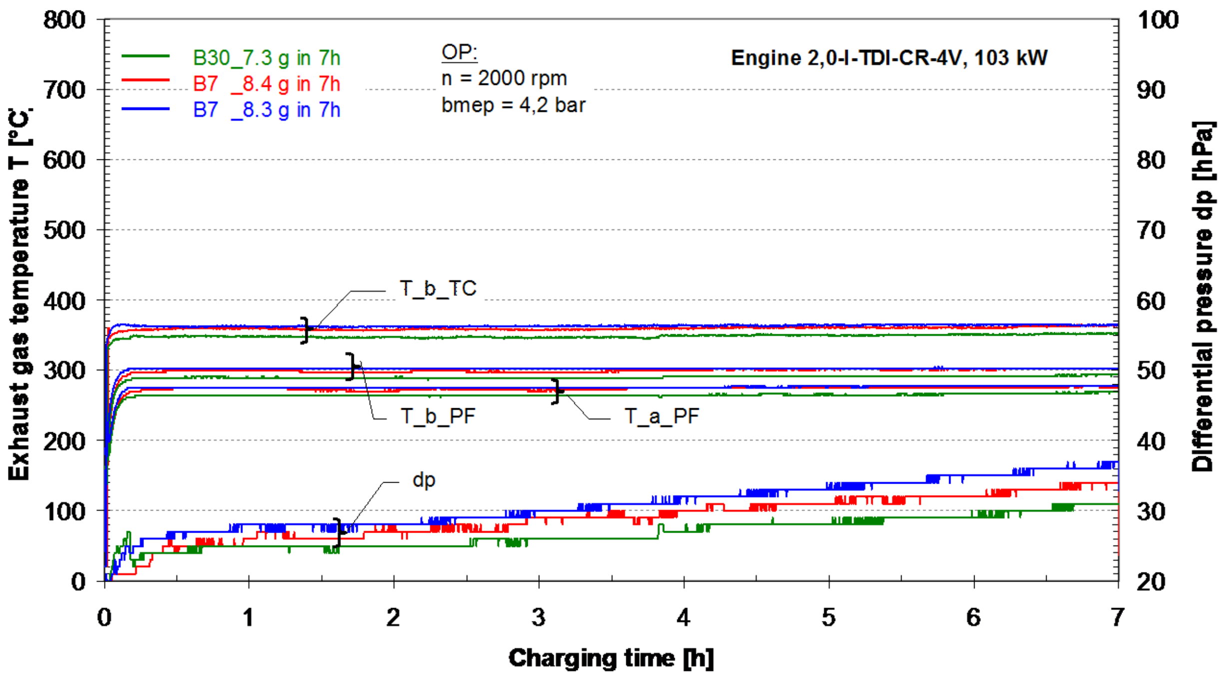


Figure 6-14: Exhaust gas temperatures and differential pressure of the DPF when charging the filter during engine operation at OP2 with B7 and B30

The exhaust gas temperature T_v_PF measured during the charging at OP2 (n = 2000 rpm, p_{me} = 4.2 bar) before the filter of approx. 290 to 303 °C is still way below the temperature that is necessary for burning off the soot before the filter. The differential pressure of the filter continuously increased during the charging.

The particle mass accumulating in the filter during the charging over 7 hours and the differential pressure rise of the filter can be seen in **Figure 6-15**.

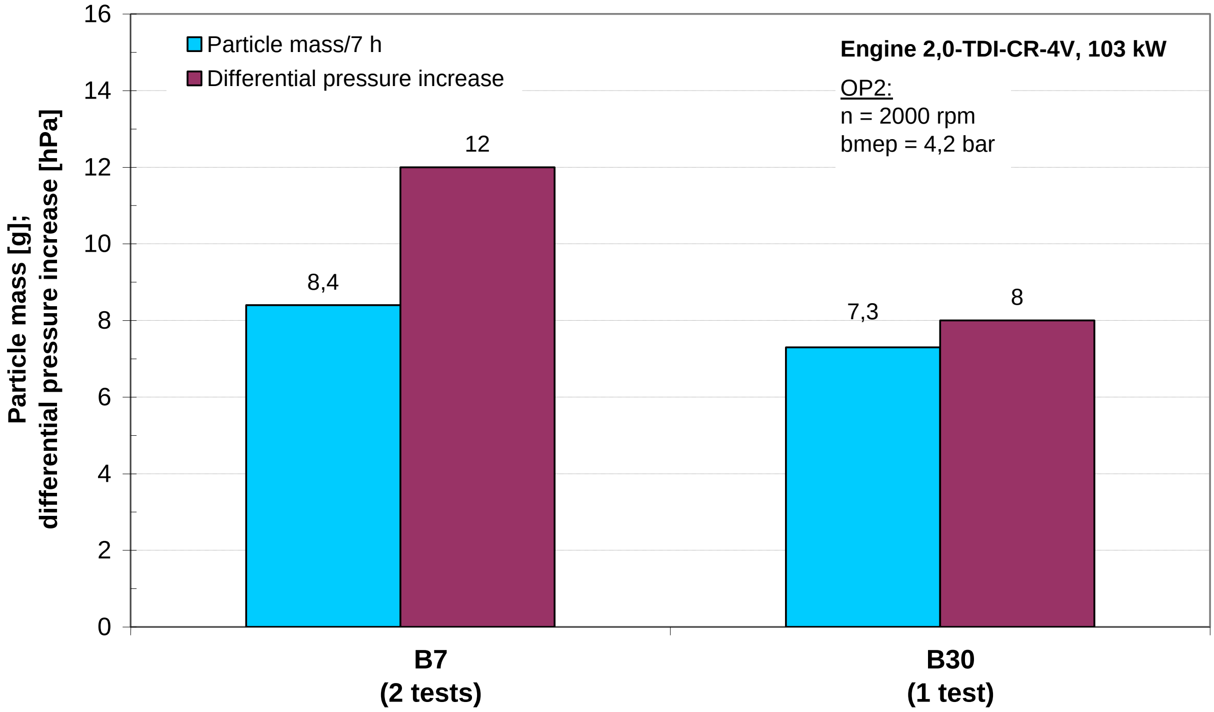


Figure 6-15: Accumulated particle mass and differential pressure of the DPF after charging the filter over 7 hours during engine operation at OP2 with B7 and B30

The mean value of the particle mass of two charging processes accumulating in the filter was 8.4 grams during engine operation with the fuel B7 at a differential pressure increase in the filter of approx. 12 hPa. As was to be expected, a lower particle mass accumulated with B30 owing to the known lower soot formation at a higher RME content in the fuel. 7.3 grams were measured in a test with B30 at a differential pressure increase of approx. 8 hPa.

The charging occurred in all three test runs with the same injection strategy (normal mode with 3 injections). The differences are thus only due to the different fuels.

Figure 6-16 shows the regeneration progression during engine operation in regeneration mode with 6 injections per cycle (series application “new”) with the fuel B7 and one regeneration progression each with 7 injections per cycle (test application with split late post-injection variant V5) with B7 and B30. The regeneration was carried out at operating point OP1.

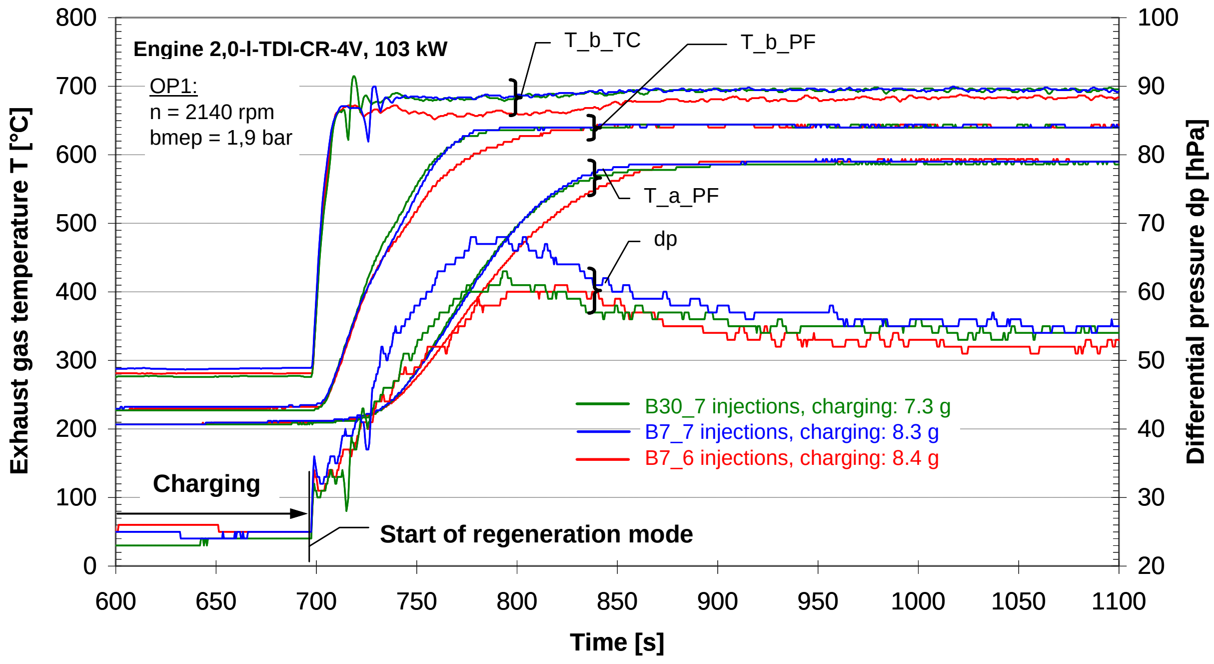


Figure 6-16: Regeneration of the particle filter during engine operation at OP1 with B7 and B30 in regeneration mode with 6 and 7 injections per cycle

After charging the filter at OP2, the engine was operated over approx. 5 minutes before the start of the regeneration at OP1 indicated in the figure with charging mode (normal mode). This was necessary for a smooth progression in the switchover of the operating mode from charging to regeneration mode, which was envisaged at OP1.

This figure reveals that the regeneration with the two injection strategies of the regeneration mode progress almost identically:

- The exhaust gas temperature specified for the regeneration before the particle filter T_b_PF was reached in all three test runs, with the split late post-injection even approx. 40 seconds earlier than with the series application "new".
- The regeneration was completed after approx. 250 seconds in all three test runs, which can be discerned from the fact that no further differential pressure drop occurred.

The results clearly reveal that the sequence of the particle filter regeneration by splitting the late post-injection while retaining the exhaust gas temperature before the particle filter of 640 °C was not adversely affected.

6.3.2 Exhaust gas emissions

Figure 6-17 shows the results of the gaseous exhaust gas emissions measured with the engine exhaust gas analysis system of the AVL AMA i60. The measurement was carried out immediately before the switchover from the charging to regeneration mode at OP1 with the fuel B7. The emissions do not exhibit any significant difference.

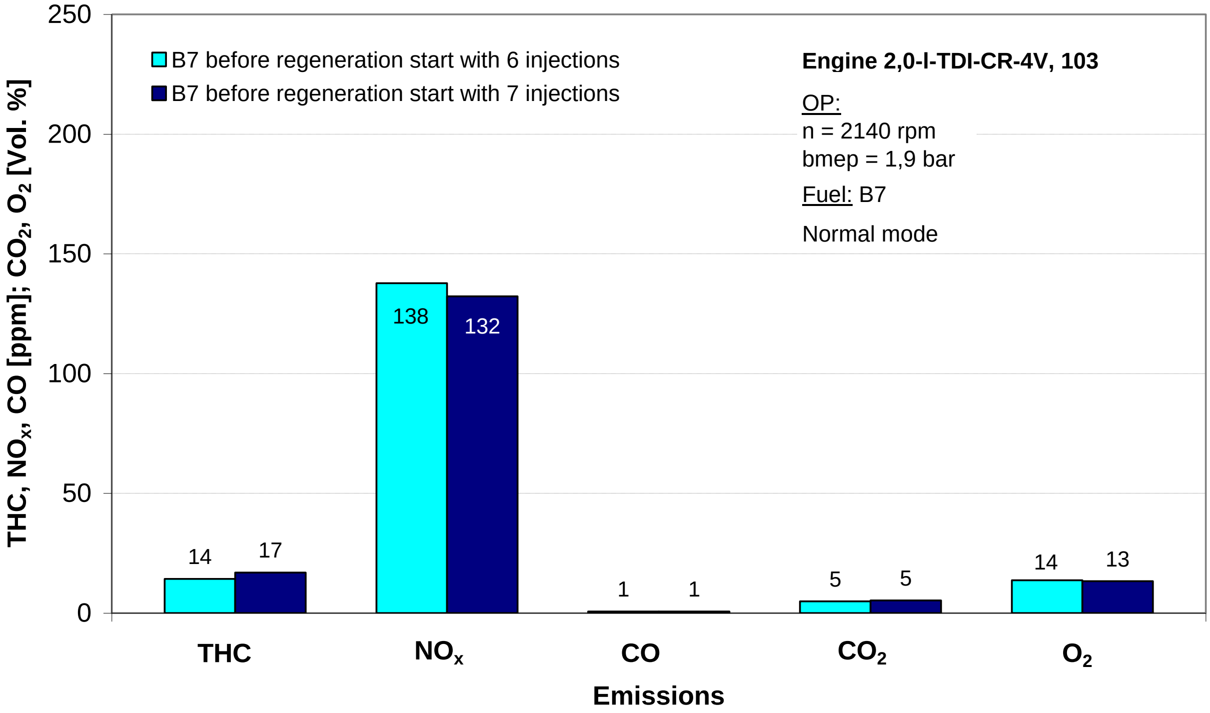


Figure 6-17: Exhaust gas emissions after DPF immediately before start of the regeneration of the particle filter during engine operation at OP1 with B7 in normal mode with 3 injections per cycle

Figure 6-18 shows the results of the gaseous exhaust gas emissions which were measured during engine operation with B7 in regeneration mode with 6 and 7 injections per cycle immediately after ending the regeneration. Here too, no significant differences can be discerned in the measured values between operation of the engine with the series application "new" and the test application with split late post-injection.

The stationary test bench operation at operating point OP1 therefore revealed that engine operation in regeneration mode with split late post-injection did not have any negative effects on the regeneration of the particle filter and the gaseous exhaust emissions.

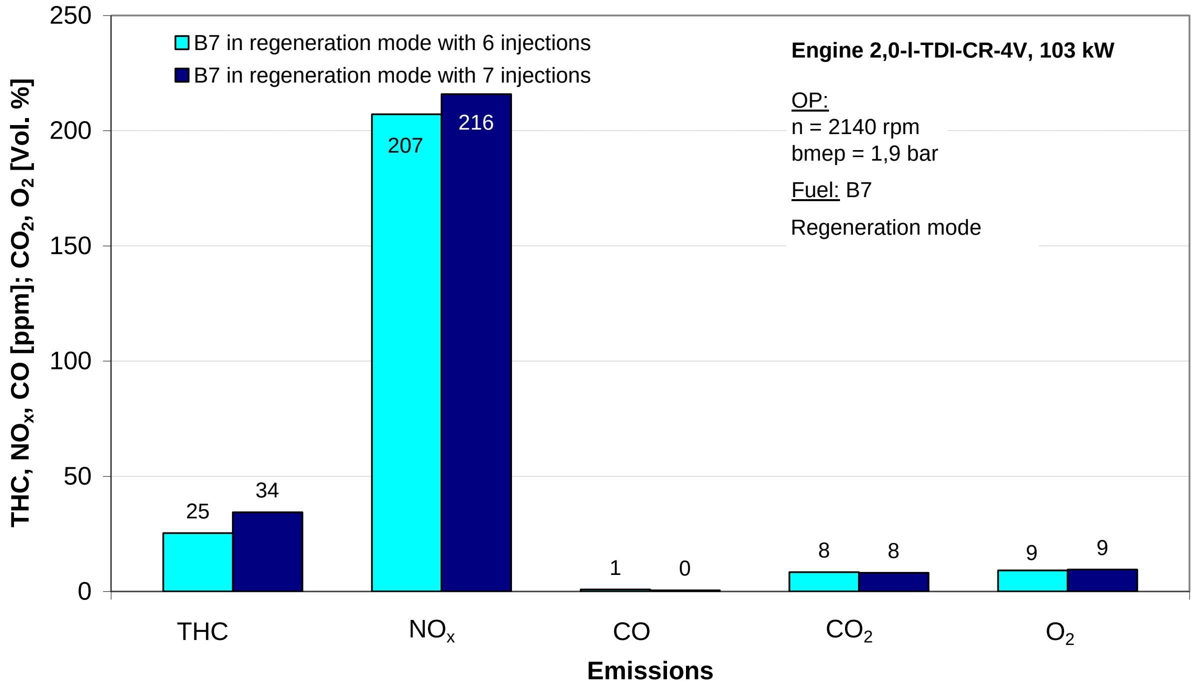


Figure 6-18: Exhaust gas emissions after DPF immediately before end of the regeneration of the particle filter during engine operation with B7 in regeneration mode with 6 and 7 injections per cycle at OP1

7 Summary

The effects of changes to the engine-internal “late” post-injection in regeneration mode during operation with the fuel blends B7, B10 and B30 on the fuel entry into the engine oil as well as on the change in the oil viscosity and the limited emissions were examined in a passenger car diesel engine 2.0 l TDI with common rail system, oxidation catalyst close to the engine and diesel particle filter in stationary test runs at the Institute for Mobile Systems IMS, Chair in Piston Engines, at the Otto-von-Guericke University Magdeburg.

In addition to the task included in the UFOP project with the no. 540/093, the fuel entry and the decrease in engine oil viscosity were also determined by early post-injections subsequent to the main injection.

The diesel engine as well as the application control unit and the exhaust gas after-treatment system etc. were provided by Volkswagen AG for the tests.

The current data record for this engine version with 6 injections per cycle (series application “new”) was also provided with the application control unit. The change to the engine-internal late post-injection was made by splitting the late post-injection volume into two parts. This division was enabled by VW AG by handing over a test application of the control unit data record with 7 injections per cycle.

An attempt was made to minimise the fuel entry into the engine oil and the oil dilution by varying the injection volume and injection start of the split late post-injection. In doing so, changes to the early post-injections and the second partial volume of the split post-injection were not possible manually for the application control unit used. These were automatically corrected to ensure the exhaust gas temperature before the particle filter of 640 °C.

The engine oil approved by the engine manufacturer and used in the engine tests with the designation “Titan GT1 Longlife III 5W-30” was procured from Fuchs Europe Schmierstoffe GmbH, which also performed the gas chromatographic oil analyses for determining the fuel concentrations in the engine oil samples and the viscosity determinations.

To ascertain the fuel entry in regeneration mode with 6 and 7 injections per cycle, three test runs each lasting 8 hours at operating point OP1 were carried out during engine operation with the fuels B7, B10 and B30 at a speed of 2140 rpm and a mean pressure of 1.9 bar.

The fuel entry in preheat mode with 5 injections per cycle was examined during engine operation with the fuels B10 and B30 at the same operating point in two test runs each lasting 8 hours.

The exhaust gas after-treatment in the regeneration mode of the engine was examined with the series application “new” and the test application with optimised, split late post-injection with the fuels B7 and B30.

The following results were obtained in the present project:

- The boiling characteristic curves of the fuel blends B7, B10 and B30 revealed that the non-evaporated fuel component increased with rising RME content in the fuel at the same fuel temperature. At a temperature of e.g. 300 °C, the non-evaporated component with B30 was approx. 69 % higher than with B7.
- In the regeneration mode of the engine, the total fuel entry into the engine oil increased as the RME content in the fuel rose. In the case of the series application “new” with 6 injections per cycle, the total fuel entry with B30 was 94 % higher than with B7 and 77 % in the test application with optimised, split post-injection, i.e. with 7 injections per cycle in variant V5.
- The rise in the total fuel concentration in the regeneration mode of the engine resulted from the significant rise in the RME concentration at a falling DF concentration. The RME entry with B30 was 287 % higher than for B7 with 6 injections per cycle and 202 % higher than for B7 with 7 injections per cycle.
- The DF concentration in the engine oil was approx. 30 % less for B30 than for B7 and B10 in regeneration mode with 6 and 7 injections per cycle.
- There was no significant difference in respect to the fuel entry between the series application “old” with 5 injections from the previous project [2] and the series application “new” with 6 injections per cycle during operation with B10.
- The division of the late post-injection (7 injections per cycle) reduced the total fuel entry in comparison to the series application "new"

  - with B7 by approx. 20 %
  - with B10 by approx. 22 %
  - with B30 by approx. 27 %

  Although the DF concentration values for the three fuels were reduced by approx. 26 to 28 %, the split reduced the RME entry very differently:

  - with B7 by approx. 7 %
  - with B10 by approx. 18 %
  - with B30 by approx. 27 %.

  This shows that a split has an especially positive effect at high RME contents.
- The reduction in the viscosity decrease occurring during the test runs was approx. 5 % in regeneration mode with the late post-injection in comparison to the series application “new” at an oil temperature of 100 °C for B7 and B10 and approx. 10 % for B30.
- The two early post-injections subsequent to the main injection almost caused the same fuel entry in the preheat stage with 5 injections per cycle as was measured in regeneration mode, especially with the split late post-injection. The RME concentration reached 0.81 times the value of the DF concentration for B10 and 2.62 times the value of the DF concentration for B30.
- The oil viscosity was reduced by approx. 24 % with B10 and by approx. 33 % with B30 during the test runs in the preheat stage. The viscosity decrease in preheat mode thus tended to be greater than in regeneration mode with split late post-injection and less than in regeneration mode with the series application "new".
- The charging and regeneration of the particle filter occurred without problems in the test runs with B7 and B30 with the series application “new” and the test application with split injection. A lower particle mass accumulated with B30 owing to the lower soot formation at a higher RME content in the fuel. The split late post-injection did not have any negative effects on the regeneration of the particle filter and the gaseous exhaust gas emissions.

The stationary test bench tests revealed that optimisation of the late post-injections in the area of the exhaust stroke can significantly reduce the fuel entry into the engine oil. However, they also clearly demonstrated that the early post-injections subsequent to the main injection can have a considerable share in the engine oil dilution if partial amounts of the fuel jets encounter the cylinder wall. The early post-injections should therefore also be incorporated in future tests for further reduction of the fuel entry into the engine oil.

8 Literature

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