Lubricants



Engine Oil-derived Emissions and their Balance for the DI Diesel Engine

Due to the increasingly demanding emission limits the understanding of the contributions of the lubrication oil sources to the engine emission becomes more important. The reduction of these contributions allows the decrease of particulate emissions through their oil and ash fractions. The Institute for Internal Combustion Engines (Lehrstuhl für Verbrennungskraftmaschinen, VKA) at the Technical University Aachen (RWTH Aachen, Germany) has examined the influence of the oil consumption of individual engine components in a FVV research project. Conclusions on the particulate emission of a diesel engine due to engine oil consumption have been achieved with the aid of detailed particulate analysis. The influence of the emissions of ash-forming elements on engine oil component deposits has been examined with a complementing endurance run with an exhaust aftertreatment system. Also, the contributions of the engine oil-derived emissions have been balanced.

1 Introduction

One of the goals of the optimisation and the innovative development of modern diesel engines is the compliance with the increasingly more demanding exhaust gas emission limits. Engine control measures and the use of exhaust aftertreatment components allowed a significant reduction of the diesel engine exhaust gas emissions during the past few years according to the current standards. Even more stringent regulations for the emission behaviour of diesel engines are planned for the future by the legislators. These regulations will contain further limitations in particular regarding particulate and nitrogen oxide emissions. An influencing factor which has not been examined in much detail is the emission resulting from the engine oil. These emissions not only affect the efficiency of exhaust aftertreatment systems but also have a significant influence on the particulate emissions of the engine.

2 Experimental Setup and Execution

Several studies have been performed on a direct injection 1.9 l passenger car diesel engine with exhaust aftertreatment and on a heavy duty engine in the Institute for Internal Combustion Engines to assess the influence of the engine oil on

the emissions. Abbrevations and formulae are shown in Table 1. The effects of emissions of ash-forming elements on deposits of engine oil components on engine components, which were exposed to combustion and exhaust gas, and on exhaust aftertreatment components were examined with 500 h continuous tests at alternating operating points, Table 2, of the passenger car diesel engine with exhaust aftertreatment system. Also, an emission balance was established. The investigations at the heavy duty engine were aimed at determining the oil consumption of individual components and drawing conclusions on the engine oil particulate emissions of a heavy duty diesel engine with the aid of detailed chemical particulate analysis. Apart from the operating conditions of the engine the formulation of the lubrication oil was a test parameter, too. The focus of the analyses was placed on the consumption source of the piston, the piston rings and the cylinder.

2.1 Passenger Car Engine

After 250 h continuous operation an oil change was performed. Consumed oil was refilled during operation with fresh oil. The element concentrations of the research oil supplied by the company Lubrizol are shown in **Table 3**.

The exhaust aftertreatment system consisted of a combination of oxidation





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Table 1: Abbreviations and formulae

DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
ELR	European load response
ICP-OES	Inductively coupled plasma optical emission spectrometry
NAC	NO _x adsorber catalyst
NOAK	Evaporation loss in special test
NSF	Non soluble fraction
NSOF	Non soluble organic fraction
P _e	Effective power
SCR	Selective catalytic reduction
SOF	Soluble organic fraction
TC	Exhaust gas turbocharger
WSF	Water soluble fraction
Ψ	Mass fraction

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catalyst (DOC, from Umicore, ceramic carrier 5,66" x 3", 400 cpsi, 90 g Pt/ft³), NO_x adsorber catalyst (NAC, from Umicore, ceramic carrier 5,66" x 6", 400 cpsi, BaO), diesel particulate filter (DPF,

from Ibiden, silicon carbide, cell density of 200 cpsi; dimensions 5,66" x 6"; porosity of 42) and a second downstream NAC for the detection of sulphur breakthrough.

Table 2: Operating points for the continuous operation of the passenger car engine

Operating Points Passenger Car Engine	Duration	Engine Speed	Brake mean effective pressure	Temperature Down- stream of Turbine
Unit	min	1/min	bar	°C
1	15	2250	2	360
2	25	2750	2	350
3	15	2250	12	500
4	15	2750	11	620
5	25	3250	10	590
6	15	3850	13	660
7	15	2250	2	360
8	15	2750	2	350
9	15	3250	2	350
10	40	3750	2	350
11	15	3850	13	660

Table 3: Mass fraction of the elements of the fuel and the lubrication oils used

	BTL Fuel	Passenger Car Engine Oil	Zinc-free Oil	Oil Containing Zinc	Unit
engine	heavy duty engine / passenger car	passenger car	heavy duty engine	heavy duty engine	
AI	<0.03	5	<5	<5	ppm
Са	<0.03	2017	2570	4589	ppm
Cu	<0.05	<5	7	<5	ppm
Fe	0.1	<5	<5	<5	ppm
Mg	<0.03	491	52	43	ppm
Mo	<0.05	135	<5	<5	ppm
Р	<0.2	727	700	1117	ppm
S	<1	1931	1500	3383	ppm
Si	<0.05	<10	<25	<20	ppm
Zn	0.2	794	9	1229	ppm

Table 4: Heavy duty engine operating points

Operating Point	Engine Speed	Torque
-	1/min	Nm
A25	1200	533
A100	1200	2133
C25	1800	422

The regeneration intervals of the NAC were chosen such that at the beginning of the continuous operation test a conversion rate of more than 70 % could be achieved in the first NAC. To exclude a desulphurisation during the NAC regeneration no regeneration was performed at the operating points 3, 4, 5, 6 and 11 because it was impossible due to the load to reach a temperature below 500°C during rich operation. The particulate filter was regenerated during the full load phases at the operating points 6 and 11.

2.2 Heavy Duty Engine

A six-cylinder straight-type engine from MAN, type D20, supplied by the company MAN AG, was used as heavy duty engine with Euro III adjustment. Being a modern heavy duty engine, this engine is equipped with a CR injection system and a fuel lubricated CR pump. Due to the high portion of the high pressure injection pump at the oil consumption (up to 70 % [3]), today fuel-lubricated injection pumps are used ever more frequently.

For the investigations at the heavy duty engine an oil containing zinc (ash content approximately 1.8 %) as well as a zinc-free lubrication oil (ash content approximately 0.9 %) were used to assess the potential of reduction of the oil ash. Both of these oils supplied by the company Fuchs, Table 3, are most modern oils with an evaporation loss (according to NOAK) of 7.8 % (oil containing zinc) and 11 % (zinc-free oil) respectively. The NOAK index represents the weight loss of an oil sample kept in an evaporation crucible at a temperature of 250 °C over 60 min. The oil consumption was determined with a continuous measuring system ÖVM4 of the company IAVF.

Three stationary operating points and abrupt ELR load alterations of the heavy duty engine were investigated. Two partial load points (A25, C25) and one full operating point (A100) are described in **Table 4**.

Individual oil sources were deactivated and others varied to determine the fractions of the oil consumption and the particulate emissions of the individual sources. This was achieved through the following measures:

- Exclusion of the oil ingression through the valves by introducing barrier air in the valve stem guide Table 5: Test matrix with examined configurations (* turbocharger with low mileage; ** additional test C25 and A100)

Configuration	Oil Type	Liner	Deactivated Sources	Oil Consumption Measurement
base*	zinc-free	series	-	yes
series production liner, w/o oil sources	zinc-free	series	TC; valves; blowby	yes
base*	containing zinc	series	-	yes
series production liner, w/o oil sources	containing zinc	series	TC; valves; blowby	only ELR
base; TC with 600,000 km	containing zinc	series	-	no
base; TC with 600,000 km	zinc-free	series	-	yes
liner finely honed, w/o oil sources	zinc-free	finely honed	TC; valves; blowby	yes
liner finely honed, w/o oil sources	containing zinc	finely honed	TC; valves; blowby	only ELR
liner finely honed with valves **	zinc-free	finely honed	TC; blowby	yes

- exclusion of the oil source turbocharger by independent external air charging
- open crankcase breather for the blowby gases with gravimetric measuring of the oil from the blowby
- usage of different liners (serial production honing and finely honed with approximately only half the roughness)
- turbocharger with 600,000 km mileage.

To be able to consider all oil sources separately the tests were performed according to the following test matrix, see **Table 5**. All operating points of each configuration were tested three times to confirm of the analysis results. With the turbocharger with 600,000 km mileage no ELR load cycles were examined.

3 Analytics

To associate the lubrication oil-derived particulate fractions with the individual oil consumption sources a differentiated analysis of the collected particulate matter by various analytical methods is required. For this reason the samples for the particulate analysis in the exhaust were taken in parallel with the aid of a probe and a quadruple branching. In parallel, particulate samples were taken from two Pallflex filters as well as one quartz and one Teflon filter.

Hydrocarbons are organically soluble and therefore form the SOF emissions (Soluble Organic Fraction). The determination of the SOF fraction was performed with Pallflex filters which were – after being conditioned and weighed - exposed to a cyclohexane solution (organic solvent). After the solution process, they were weighed again. The WSF fraction was separated from the NSOF through solution with distilled water.

Esters, salts and their acids belong to the nitrates, nitrites, phosphates and sulphates. Non-soluble or hardly soluble salts as well as the esters are counted as NSF emissions (Non Soluble Fraction). The biggest fraction of the NSF consists of highly condensed hydrocarbons and elemental carbon. Soluble salts, for example the nitrate salts ammonium nitrate (NH_4NO_3) and aluminium nitrate ($Al(NO_3)_3$) and their acids can be found in the WSF (Water Soluble Fraction). Sulphates are formed from oil- and fuelbased organic sulphur compounds [4].

Ashes, mainly resulting from oil and wear deposits, predominantly consist of oxides and salts which are largely nonwater soluble or hardly water soluble and non-organically soluble and therefore are counted as NSF emissions. However, the fraction of the ashes is small compared to the fraction of highly condensed hydrocarbons and elemental carbon. Components in the oil additives, for example Ca and Zn, wear deposits from the engine (Fe, Al, etc.) as well as fuel additives can causes these ash emissions.

The deposits on the engine components and Teflon filters were examined regarding their individual elements through dissolution with nitric/hydrochloric acid and with the aid of ICP-OES. The exhaust aftertreatment systems (monoliths) were completely pulverised for the determination of the element concentration.

4 Oil Consumption of the Heavy Duty Diesel Engine

For the determination of the influence of the oil on the emission behaviour the oil consumption was measured for the respective operating points and configurations. The total quantity of filled oil was about 35 l. The two oils did not lead to a significant change in the oil consumption during the investigation of the basic configuration. The oil consumptions of the individual configurations are shown in Figure 1. The error bars shown in the diagrams do no represent the total measurement error but the 95 % confidence interval from the linear regression of the continuous oil consumption measurement. The actual measurement error can be higher under adverse conditions due to influences of temperature, and pressure as well as a potential measurement device drift.

From the mean (arithmetic mean of the consumption ratio) of the operating points A25, C25, A100 as well as the ELR load cycles the following fractions of the individual sources for the total oil consumption can be concluded: The biggest fraction of the oil consumption (78 %) is due to the source piston/piston rings/liner. The turbocharger with low mileage contributes the oil consumption significantly stronger with a fraction of 18 % than the blowby with 4 %. For the configurations examined an oil consumption due to the valves could not be proven within the measurement accuracy.

To conclude precise statements regarding the influence of the lubrication oil on the particulate emissions the loca-



Figure 1: Oil consumption heavy duty engine

tion of the oil ingression in the engine and the respective oil consumption mechanism are of great importance. The consumed lubrication oil can contribute to almost all fractions of the particulate emission. The unchanged and evaporated fractions of the lubrication oil are found in the organically soluble SOF if they have not been burned. The unchanged burnt lubrication oil contributes to the particulate mass via the oil ash portion of the non carbon containing fraction. Unburnt lubrication oil (modified or not modified) can contribute to the ash formation through the afterburning in the exhaust gas system. The contribution of the changed or evaporated and burnt lubrication oil to the soot particles cannot be uniquely assigned as it is due to the operating point of the engine. In Figure 2 the contributions of the oil consumption sources to the emissions (burnt, unburnt, changed for example through cracking or polymerisation) are shown.

5 Engine Oil Particulate Emissions

For all operating points the heavy duty engine shows overall an increase of the total particulate emissions with increasing oil consumption. These can be ascribed to the increasing SOF emissions since no change of the mass flow of the NSF and WSF emissions can be determined within the measurement accuracy. Considering the ratio of the oil consumption to the fuel consumption is not surprising that we find that no or only a very small, not measurable influence of the oil consumption on the NSF emissions can be detected. For the present investigations at the heavy duty engine the fuel oil consumption ratio is up to 3000:1.

The water soluble fractions of the particulate mass flow also do not show any change with increasing oil consumption. Since the sulphate or phosphate fractions of the oil are hardly or non water soluble and therefore only account for a very small portion of the mass of the WSF it has to be assumed that the WSF emissions mainly consist of nitrites and nitrates. Therefore no measurable influence of the oil consumption on the WSF emissions is to be expected.

All changes in the configuration influence burnt as well as unburnt fractions, compare **Figure 3**. The different formulations of the lubrication oil did not show any significant influence on the total particulate, NSF and SOF emissions as well as the emissions of organic and elementally bound *C*. The mean unburned emitted fraction of the oil emissions can be deter-



Figure 2: Contribution of the oil consumption sources to the emissions



Figure 3: Trend of the emission changes as a function of the oil consumption variation

Figure 4: Ca and Zn emissions as a function of the oil consumption

mined by the changes of the SOF emissions, Figure 3. It is about 20 %.

5.1 Emissions of Ash-forming Elements in the Heavy Duty Diesel Engine

The elemental emissions were examined in the raw exhaust gas. For the chosen elements Ca and Zn (only for oil containing zinc) the mass flows were calculated at the respective operating points. In addition, a balance for these elements was drawn up. The input variables were elements from consumed oil and fuel. The output variables were determined with an ultimate analysis of the particulate mass on the Teflon filters. The difference between input and out variables is due to the change in the element concentration in the oil sump, slip of the Teflon filters, deposits, analysis inaccuracies as well as formation of surface layers. All operating points showed an increase of the Ca and Zn emissions with increasing oil consumption. These are directly proportional to the oil consumption (within the measurement accuracy), Figure 4.

The gradients in Figure 4 as well as the element concentrations in the oil yield the mean mass fraction of the output variables shown later. The mass fraction of the output variables is the ratio of the measured emission and the emission expected due to the oil consumption. They are:

$$\begin{split} \Psi_{\text{output_variables_Ca}} &= 45 \ \% \ at \ \Psi_{\text{Ca}} = 2570 \ ppm \\ \Psi_{\text{output_variables_Ca}} &= 38 \ \% \ at \ \Psi_{\text{Ca}} = 4588 \ ppm \\ \Psi_{\text{output_variables_Ca}} &= 50 \ \% \ at \ \Psi_{\text{ZN}} = 1229 \ ppm. \end{split}$$

Differences in the fraction of Ca and Zn can be explained by the different discharge of the elements from the oil sump, different separation efficiencies of the analysis filters, formation of surface layers and analysis inaccuracies. Differences in the emission behaviour of the elements due to different oil consumption sources could not be determined within the measurement accuracy.

For the calculation of the total specific mass flow of the ash total factors were computed for zinc-free oil and oil containing zinc which lead to the ash mass flow when multiplied with the Ca mass flow which had been deposited on the analysis filter in theory. Here it is assumed that the fraction of all output variables corresponds to those of Ca. The total factors consist of two partial factors, the fraction of the Ca of the total elements in the oil as well as a factor which results from the formed oxygen compounds. The following assumptions have been made for the formation of oxygen compounds: A sulphate formation of 1:1 with Ca has been assumed. The remaining Ca was calculated as CaO. Zn formed ZnP₂O₇. The remaining P formed FePO₄ with Fe. The remaining Fe as well as Cu Mg Mo oxidised to Fe₂O₂, CuO, MgO and MoO₂. Another possibility of estimation is the use of the ash content of the lubrication oil of about 0.9 % for zinc-free and approximately 1.8 % for oil containing zinc. The difference of the two calculations is less than 1 %. Since the ash quantity calculated from the oxygen compounds of the elements and the ash quantity resulting from the sulphate ash content are the same, the specific ash emission can be calculated in g/kWh in approximation according to the following equation:

$$\frac{\dot{\mathbf{m}}_{ash}}{\mathbf{P}_{e}} = \frac{\dot{\mathbf{m}}_{oil_consumtion}}{\mathbf{P}_{e}} \cdot \boldsymbol{\Psi}_{output_variable} \cdot \boldsymbol{\Psi}_{oilash}$$

With a recovery rate of 45 % and an oil ash content of 0.9 % for example a specific ash emission of 0.36 mg/kWh results. The fraction of the emissions to the total particle emission is at the examined engine operation points (oil ash content 0.9 %) approximately 1 %.

5.2 Balance of Engine Oil Deposits in the Passenger Car Engine

In previous works [1, 2, 5] the mass fraction of the output variables of individual components due to the engine oil on components exposed to combustion and exhaust gases were significantly lower than 100 % except for sulphur and phosphorus. To explain the disposition of the remaining fractions the deposits in the combustion chamber, the exhaust gas pipes, the turbocharger, the EGR system, the oil filter as well as the exhaust aftertreatment components were examined in the passenger car engine. The total balance considers the input variables fed oil and fuel. On the output side the analysed components as well as the drained oil are accounted for. Losses can occur



through the exhaust but also through analysis inaccuracies and the formation of surface layers, Figure 5.

In these investigations about 87 % of the emissions of the source oil could be attributed to the individual deposit locations of combustion chamber, drained oil, exhaust gas pipes, turbocharger, exhaust gas recirculation system (EGR system), oil filter, diesel oxidation catalyst (DOC), nitrogen adsorber catalyst (NAC) and diesel particulate filter (DPF). The bulk part of the elements resulting from the oil was found after 500 h continuous operation in the drained oil (approximately 60 to 70 %). About 15 % of the elements were found in the DPF. As an example this is illustrated for Ca in

Figure 6. The elements molybdenum and phosphorus were also deposited in the DOC and the NAC. The only element that was increasingly deposited in the oxidation catalyst (8.6 %) was phosphorus, and these deposits mainly occurred at the catalyst entrance, Figure 7. In contrast to all other elements resulting from the engine oil sulphur, Figure 8, was bound up to 50 % in the NAC (approximately 94 % of the emitted sulphur) due to the good adsorption capacity of the NAC. An analysis of combustion chamber, EGR pipe, EGR valve, exhaust pipe, turbocharger and oil sump was impossible due to the high sulphur blank values of the solvent.

The disposition of the ash-forming elements could not be fully explained in the investigations. Possible loss mechanisms are the formation of surface layers which are not soluble with the sovent, slip as well as analysis inaccuracies.

6 Summarv

Due to the increasingly more stringent emission limits the understanding of



engine and exhaust system



Figure 8: Sulphur balance of engine and exhaust system

the contribution of the lubrication oil sources to the emissions as well as their disposition in the engine and the exhaust aftertreatment systems is of ever growing importance. Within this framework and with the aid of two FVV projects the oil consumption sources and the disposition of the consumed engine oil were examined in detail. The influence of the oil consumption sources of piston/piston rings/liners, turbocharger, blowby as well as valves on the particulate emissions was investigated in a heavy duty engine at the Institute for Internal Combustion Engines (Lehrstuhl für Verbrennungskraftmaschinen,

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VKA) at the Technical University Aachen (RWTH Aachen, Germany). It proved that the oil consumption is affected particularly by the group of piston/ring/liners. The used oil is burnt to a large extend. The element emissions of the ashforming elements Ca and Zn increased proportionally to the oil consumption and the oil ash content. A significant increase was also observed for the fraction of the soluble organic fraction (SOF) with increasing oil consumption.

During the balance of elements resulting from engine oil in a passenger car engine with exhaust aftertreatment about 87 % of the emissions of the source engine oil could be attributed to individual deposit locations (drained oil, combustion chamber, exhaust pipes, turbocharger, exhaust gas recirculation system, oil filter, diesel oxidation catalyst, NO., adsorber catalyst and diesel particulate filter). This represents a very high attribution rate. Only the non attributed remains of the elements resulting from engine oil have to be assigned to the not specifically classified gaseous elements, slip of the oil ash as well as the formation of surface layers which were not detected by the analysis.

These results represent an important foundation for the development of future oils, in particular regarding the requirements of the particulate emissions as well as the effects on exhaust gas aftertreatment components.

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