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Analysis of lubricating oil degradation and its influence on brake specific fuel consumption of a light-duty compression-ignition engine running a durability cycle on a test stand

ARTICLE INFO

The Euro 6 emission standard requires compliance with tough legal exhaust emissions limits for newly registered vehicles and obligates light-duty vehicle manufacturers to respect the 160,000 km durability requirements for in-service conformity. Although there is no legal limit set for fuel consumption, manufacturers are obligated to decrease the carbon footprint of vehicle fleets in order to obtain carbon neutral mobility beyond 2035.

The aim of this paper is to analyse the impact of various oils' and viscosity grades' degradation on the change in break specific fuel consumption (BSFC) measured over a standardized durability test cycle. Each oil candidate underwent 300 h of durability test running performed on a test bed without any oil changes. The purpose of the laboratory test was to reproduce the worst-case operating conditions and degradation process of the long-life engine oil type that can be experienced during extreme real life driving of a vehicle.

In order to define the influence of the engine oil deterioration on the BSFC profile, the engine operation parameters were continually monitored throughout the test run. Additionally, chemical analysis of the oil was performed and the solid deposits formed on the turbocharger's compressor side were evaluated.

The test results revealed differences up to 5% in the BSFC values between the oil candidates tested over the durability cycle. The observed BSFC increase was directly related to the decrease in engine efficiency and can cause higher fuel consumption of the engine, which in turn has an adverse effect on environmental protection goals.

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Key words: *oil degradation, fuel efficiency, durability cycle, oil aging, diesel engine*

1. Introduction

Emissions limits for carbon dioxide (CO_2) and toxic exhaust compounds aim to achieve a carbon neutral and emission-free transportation sector in the coming decades.

Vehicle manufacturers have been developing new engine technologies with reduced friction and pumping losses, improved engine combustion and thermal efficiency. Coupled with such engine technologies are highly efficient exhaust aftertreatment systems (ATS) with primary operation focused on engine cold start emission and in-service conformity (ISC) compliance over the full useful lifetime of vehicle operation [1].

Modern engines and ATS technologies have to be combined with dedicated lubricating oil solutions that are enhanced with dedicated oil additives formulations. The primary role of engine oil is to protect the engine parts from deterioration due to friction, wear, corrosion, deposits, and oxidation – while at the same time providing the expected fuel efficiency effects. Anti-wear additives can protect metal surfaces from wear due to close contact. Antioxidants maintain oxidation stability and reduce the impact of oxidative decomposition. A friction modifier can reduce the coefficients of friction, improving fuel economy and helping to protect against wear. Detergent is vital in maintaining engine cleanliness from combustion contaminants and other impurities. Dispersants suspend and separate insoluble particles from fuel combustion or oil degradation [4, 11]. With a drive to lower viscosity oils for fuel economy benefits, viscosity modifiers provide more flexibility to meet those requirements [15]. To provide satisfactory performance requirements at low temperatures, pour point depressant is often blended to improve the flow properties under cold operation. When engine oil is contaminated with water, emulsifiers prevent phase separation for specific applications [7, 9, 10].

The performance of engine lubricant is expected to maintain optimum performance throughout the entire service interval – therefore, this also applies to aged oil conditions.

The term oil aging means a combination of various processes that result in changes in the chemical and physical properties of engine oil [5, 12]. Oil aging occurs for two main reasons: internal – caused by destabilization of oils (oxidation, polymerization) and external – caused by contamination of oil with mechanical impurities, as well as water or fuel [3, 8, 13]. The main lubricating oil parameters, such as: viscosity, acidity, soot content and oil dilution with fuel, change over the in-service operation of the vehicle.

Engine oil particles enter the combustion chamber through the cylinder liner-piston rings set and are burned, forming harmful side-products. [2, 6] A fraction of air-the fuel mixture or combustion gasses pass through the cylinder liner-piston rings to the engine crankcase (blow-by gas) and are recirculated back to the air intake system to reduce emissions [14]. Blow-by gasses can contaminate the intake ducts, including the compressor side of the turbocharger, causing deterioration of engine operational parameters.

This paper analyses comparative test results of eight various lubricating oils of two viscosity grades: 0W20 and

0W30, tested on an engine test bed under a durability cycle. Each oil sample was tested under a standardized durability test cycle performed on a modern light-duty Euro 6 diesel engine. The attention was paid mainly to the oil aging impact on BSFC change during the test, thus the indication of the overall deterioration in engine efficiency.

2. Test method and facilities

2.1. Test object description

The test objects were eight lubricating oils, divided into two viscosity grades and complying with the specifications listed in Table 1.

Table 1. Description of lubricating oils under test

Oil code	SAE viscosity grade	ACEA specification
Oil A	0W20	C5
Oil B	0W20	C5
Oil C	0W20	C5
Oil D	0W20	C5
Oil E	0W30	C2
Oil F	0W30	C2
Oil G	0W30	C2
Oil H	0W30	C2

For the purposes of the test, each engine oil was identified by a letter from A to H. The lubrication oils were randomly selected for the test program and derived from various manufacturers. All of them were developed for light-duty vehicles complying with Euro 6 emission requirements and were designated both for compression ignition (CI) and spark ignition (SI) engines.

The test activities were carried out on light-duty diesel engines complying with Euro 6 emission standards. The engine was installed on a test bed equipped with an eddy-current dynamometer and automation system capable of test cycle execution, engine parameters monitoring and data storage. The engine installation layout is shown in Fig. 1.

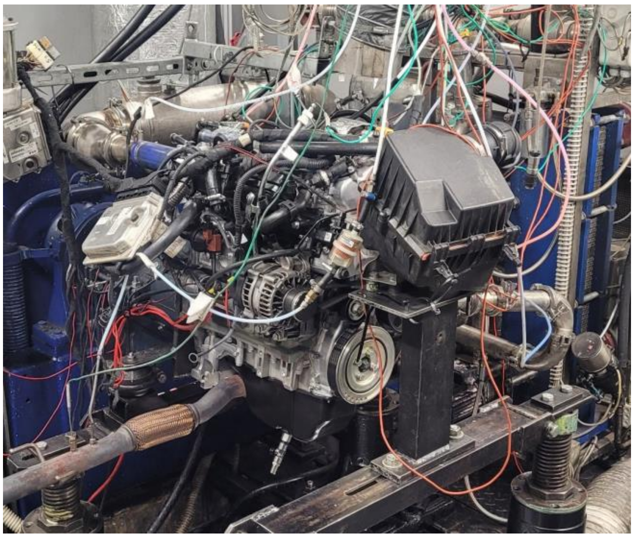

Fig. 1. Engine installation on the test bed

The engine and ATS were instrumented with temperature and pressure sensors to monitor and analyze the variations in engine operation parameters. The base engine parameters are presented in Table 2.

Table 2. Engine parameters

Engine parameters	Unit	Value
Displacement	cm^3	1248
Maximum power	kW	70
Maximum torque	Nm	200
Number of cylinders	–	4

2.2. Test methodology

Each lubricating oil under test underwent established test procedure executed on the engine dynamometer. The test procedure consisted of engine break-in, elementary durability cycle repeated for defined number of times and power curve measurement performed at the start and end of the test for engine performance verification.

The elementary durability cycle was composed of a sequence of steady-state points including engine operation at maximum power, maximum torque, partial load for emission components' loading and finally a step consisting of engine running at overspeed conditions for engine components mechanical stress.

The main criterion for lubrication oil evaluation during durability test was that the operating parameters did not exceed the engine protection limits. Another key criterion for an oil assessment was the air temperature profile at the compressor outlet, which was likely to increase due to blow-by sediments collected inside the compressor housing of the turbocharger.

The durability cycle on the test bench lasted 300 h and aimed at reproducing in an accelerated manner the distance of 30 000 km covered by the vehicle on the road.

The lubricating oil properties and elemental composition were defined based on chemical analysis performed at fresh oil conditions and during the durability cycle. The parameters analyzed included: soot content according to DIN 51452:1994 method, kinematic viscosity at 40°C and 100°C according to PN-EN ISO 3104:2021-03, TAN and TBN values.

Additionally, a chemical analysis of deposit composition collected inside the compressor housing was performed.

In order to ensure the desired repeatability of the test procedure, a brand new diesel engine unit was procured for each oil sample under test.

3. Test results and discussion

3.1. Specific brake fuel consumption results and engine performance for 0W20 lubricating oils

Four different SAE 0W20 oil samples (named A-D, respectively) were subjected to the 300 h durability cycle run on a test bed.

Figure 2 presents the variation in BSFC traces as a function of test time for A-D oil samples. Engine oil A completed the cycle; however, it did not meet the requirements due to exceeded limit of air temperature at compressor outlet. It resulted in a steady increase in the delta compressor temperature after 120 test hours, as shown in Fig. 3. The delta compressor temperature was the calculated difference between the compressor inlet and outlet temperatures.

The BSFC value of oil A was found to be increased by around 3.5% at the end of the test (EOT) compared to the best performed on oil sample C.

In the case of oil B, the durability cycle was terminated at 230 h due to activation of the engine protection limit of air temperature at compressor outlet. The temperature difference between the input and output of the compressor reached 180°C, which was an increase of over 30% compared to the start of test (SOT) condition. The increase in BSFC (compared to oil C) at the stage of test termination was near 5%.

Oil samples C and D did not reveal a significant increase in BSFC profile throughout the durability test. Also, the delta compressor temperature was found to be at a stable level for those oils.

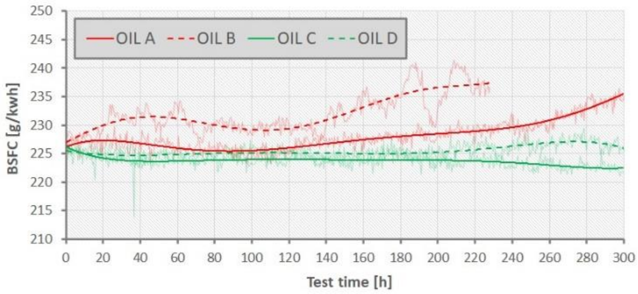

Fig. 2. BSFC change in function of the test time

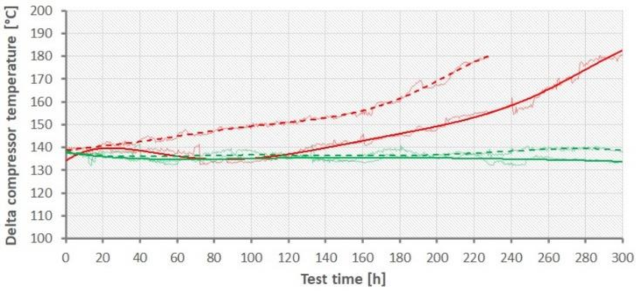

Fig. 3. Difference between compressor inlet and outlet temperature change as a function of test time

Figure 4 compares the exhaust gas pressure traces at the turbine inlet of the turbocharger. It can be noted that for oil sample A, the inlet turbine pressure exceeded 2500 mbar at EOT i.e. increasing by 25% compared to the SOT value.

Considering engine oils C and D, the exhaust gas pressure inlet turbine remained at a stable level for the entire test.

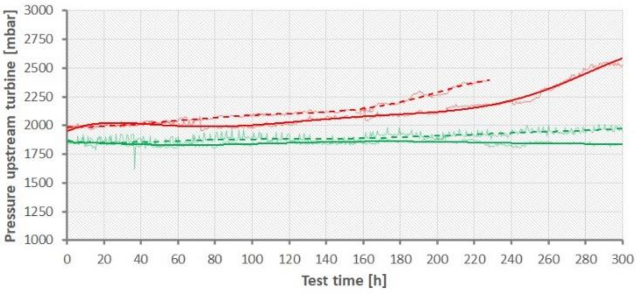

Fig. 4. Pressure upstream turbine change as a function of test time

The engine torque profiles throughout the test hours for A-D oil samples are presented in Fig. 5. For oil A that completed the test (but exceeded engine boundary condition), the relative decrease in torque was nearly 5% compared to oil C. Around 6% of engine torque deterioration was seen for oil B at the point of test termination. Engine oils C and D did not reveal a significant decrease in engine torque as a function of test time.

Figure 6 compares the calculated values of compressor efficiency for the turbocharger. The highest drop in efficiency from 0.73 to 0.54 was noticed for oil A, and it was similar in range to oil B (which did not complete the test run). The efficiency profiles for the compressor also remained almost constant in the case of oils C and D.

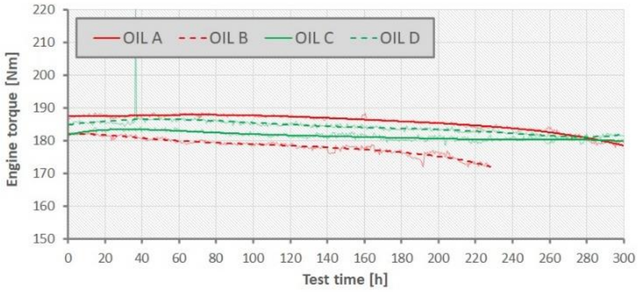

Fig. 5. Engine torque change as a function of test time

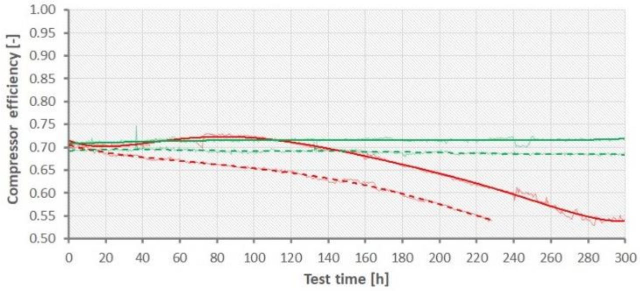

Fig. 6. Calculated compressor efficiency change as a function of test time

During the execution of durability testing, the air inlet temperature was maintained in the range of 18–22°C, as illustrated in Fig. 7. This approach was essential for test condition repeatability. Fluctuation or increase in air inlet temperature above the target values can intensify the deposit formation inside the compressor housing.

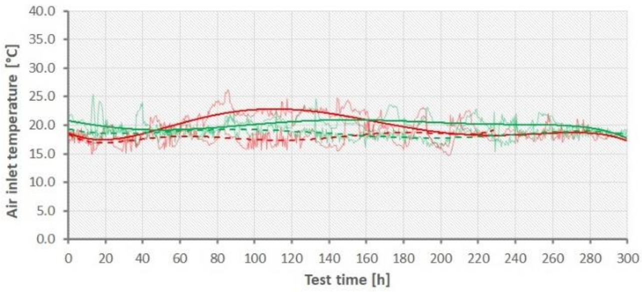

Fig. 7. Compressor air inlet temperature change as a function of test time

3.2. Brake-specific fuel consumption results and engine performance for 0W30 lubricating oils

Further lubricating oils samples named as E-H were of 0W30 viscosity grade.

Figure 8 compares the variation in BSFC behavior as a function of the durability test. Engine oils E and F did not show relevant fluctuation in the BSFC.

Oil G completed the durability test although did not meet the engine boundary conditions due to elevated air temperature at the compressor outlet. For that oil sample, the BSFC increased slightly (by around 1.5%) at EOT (compared to oil E, which was taken as a reference).

The last oil sample (code H) did not complete the durability cycle because of exceeded engine protection limit of the air temperature at the compressor outlet. This test run was terminated at 195 h. The delta compressor temperature sharply increased after 150 h and reached a value 160°C, as shown in Fig. 9. The increase in BSFC at the point of test termination was about 5% in relation to the SOT condition.

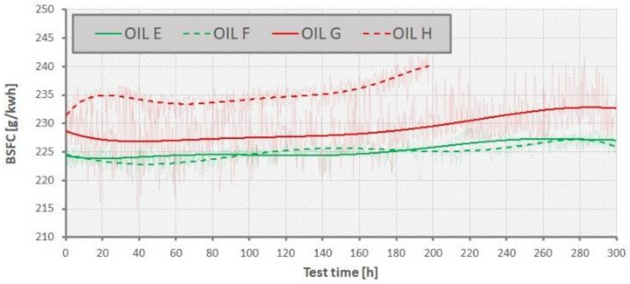

Fig. 8. BSFC change as a function of test time

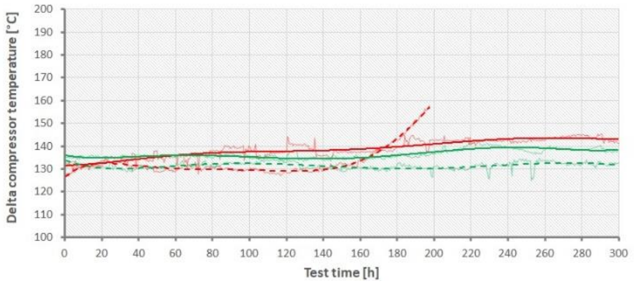

Fig. 9. Difference between compressor inlet and outlet temperature change as a function of test time

The traces of exhaust gas pressure upstream of the turbine are shown in Fig. 10. For oils E, F and G, the pressure were aligned with each other and increased by 11% at the EOT.

In terms of oil H, the pressure profile initiated from a higher level of 2050 mbar and ended up on 2300 mbar at the point of test termination (an increase of 12%).

Figure 11 illustrates the engine torque traces as a function of the test time. Oils E, F and H did not reveal a significant decrease in engine torque, in contrast to oil G for which torque decrease was 9.5% and the EOT.

Calculated compressor efficiency lines are set in Fig. 12. The greatest deterioration of compressor performance was found for oil H corresponding to values of 0.68 at SOT and 0.54 at the EOT.

The compressor air inlet temperature were adjusted in the range of 18–22°C, as shown in Fig. 13.

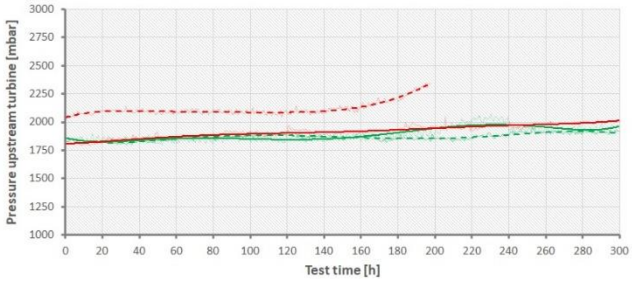

Fig. 10. Pressure upstream turbine change as a function of test time

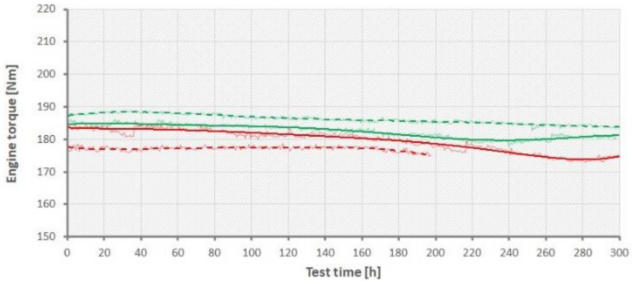

Fig. 11. Engine torque change as a function of test time

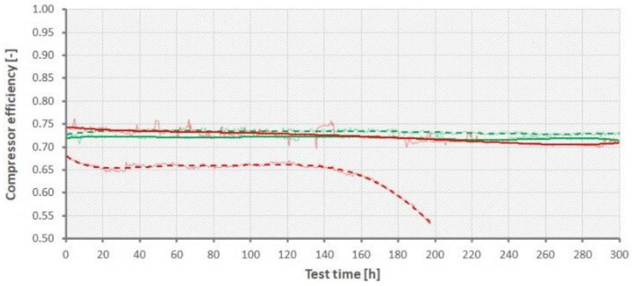

Fig. 12. Compressor efficiency change as a function of test time

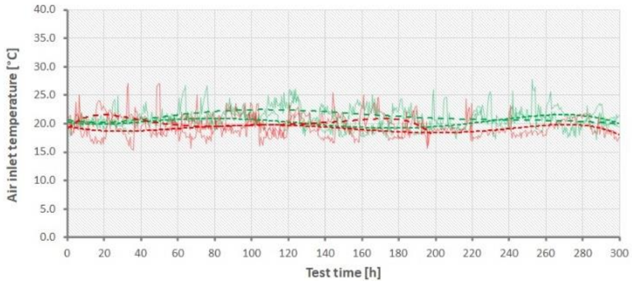

Fig. 13. Compressor air inlet temperature change as a function of test time

3.3. Chemical analysis of 0W20 engine oils

Chemical analysis of all engine oils under test were carried out periodically. Figure 14 shows a trend of soot content measured for oils A–D. The soot content did not exceed 1% for any of the oil samples A–D.

Kinematic viscosity was analyzed at oil temperature of 40°C and 100°C. In each case an increasing trend was visible over the durability test (Fig. 15 and 16).

Further investigation concerned the change in total base number (TBN) and total acid number (TAN) values over the cycle. In the case of oil A, the traces of TAN and TBN already intersected after 85 hours of testing (Fig. 17).

The test run on oil B was stopped due to the activation of engine protection limits but the TAN/TBN traces had not yet intersected at that point.

The best performing oils (C and D) did not show any tendency for the TAN/TBN traces to intersect. This indicates that those two engine oils showed the best acid-neutralizing properties (defined by TBN), which counteracts the acidic products formed during fuel combustion and harsh operating conditions.

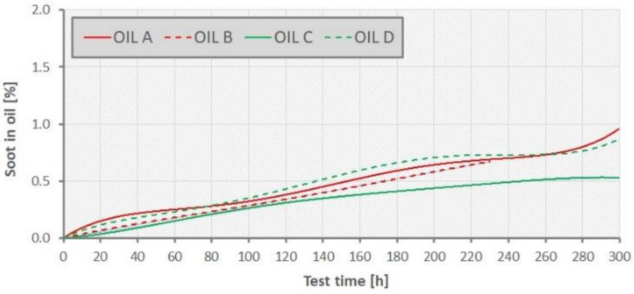

Fig. 14. Soot content change as a function of test time

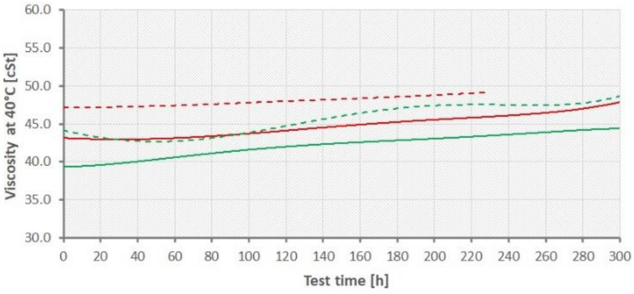

Fig. 15. Viscosity at 40°C change as a function of test time

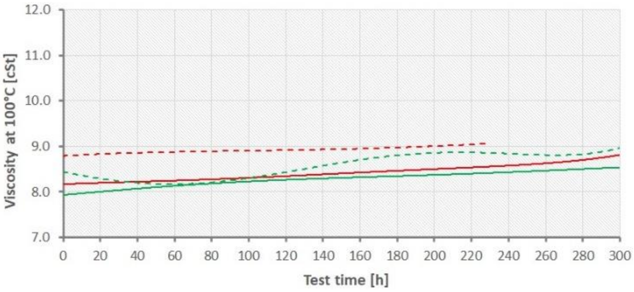

Fig. 16. Viscosity at 100°C change as a function of test time

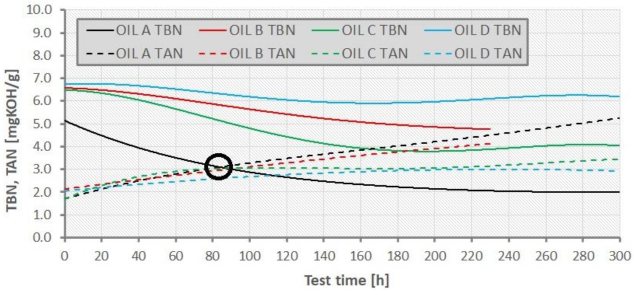

Fig. 17. TBN and TAN numbers change as a function of test time. (TBN and TAN crossover marked with a circle)

3.4. Chemical analysis of 0W30 engine oils

Figure 18 presents the trend of soot content for lubricating oils E-H. In case of oil H, the soot concentration increased by 2.5% even though the test was terminated at 240 h. For other oils, the soot level did not exceed 1% at EOT.

It was noticed that the viscosity values at 40 and 100°C were elevated for oil H, which was explained by its high soot content (Fig. 19–20).

TBN and TAN traces are presented in Fig. 21. For oils G, H and F, the crossover of TBN/TAN occurred at 150 h, 190 h, and 220 h (respectively), whereas oil E maintained the best properties in that respect.

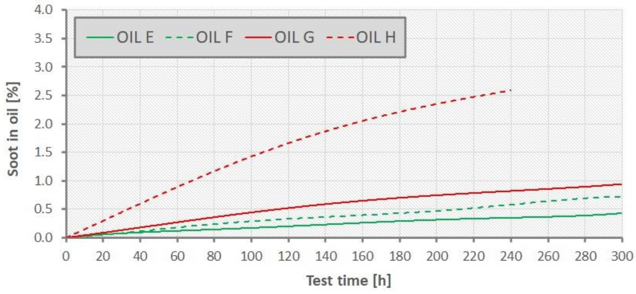

Fig. 18. Soot content change as a function of test time

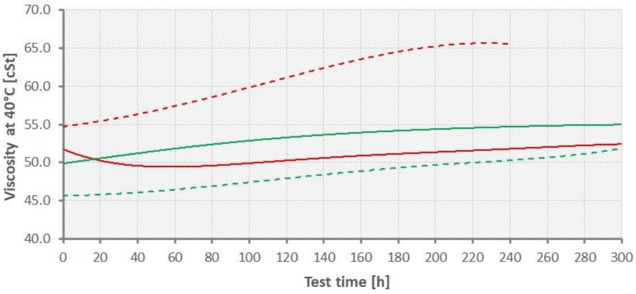

Fig. 19. Viscosity at 40°C change as a function of test time

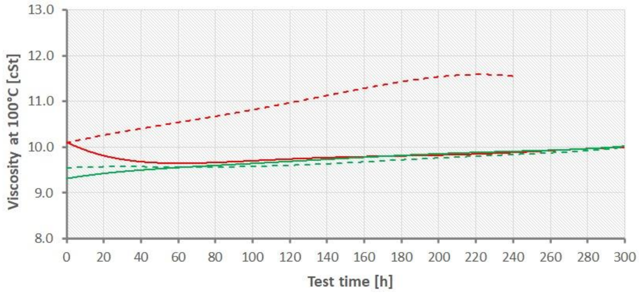

Fig. 20. Viscosity at 100°C change as a function of test time

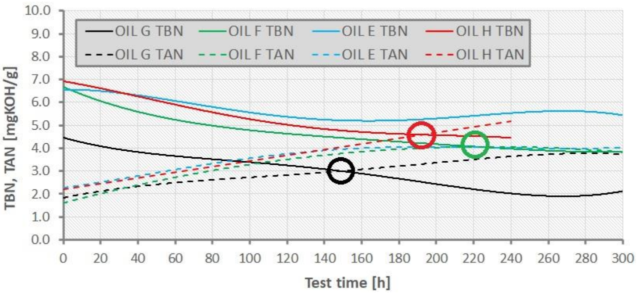

Fig. 21. TBN and TAN numbers change as a function of test time. (TBN and TAN crossover marked with circle)

3.5. Chemical analysis of lubricating oil deposits inside the turbocharger's compressor

Chemical analysis of the composition of the deposits collected inside the compressor housing revealed that nearly 92% of the material consists of carbon. The other elements found were: iron, molybdenum, calcium, phosphorus, sulfur, zinc and others, as presented in Fig. 22. The elemental composition derived mainly from the formulation of the oil additives. The analysis performed for oil H.

In principle, the reason for deposit formation inside the compressor housing is blow-by gas vapor introduced at the compressor inlet that carries over from the engine crankcase the oil fog, impurities and remnants from the combustion process. An example of a severely contaminated compressor housing and cover is shown in Fig. 23 and Fig. 24.

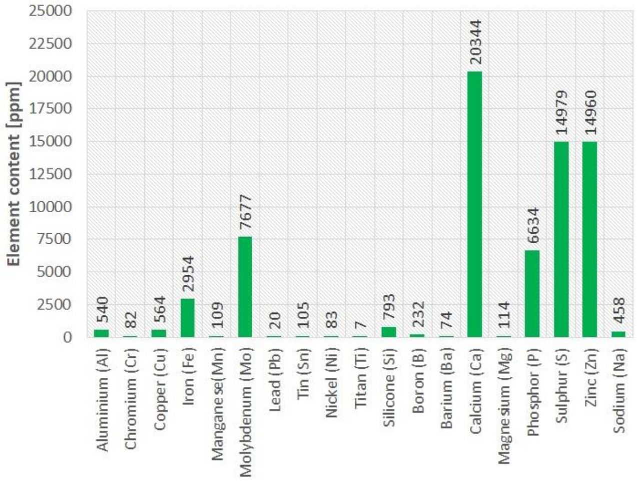

Fig. 22. Elemental content of compressor deposits after the test

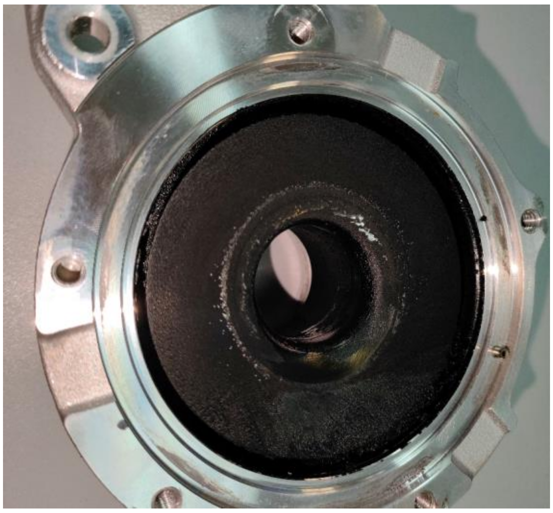

Fig. 23. Deposits collected on compressor cover after the durability test

4. Conclusion

An engine oil's resistance to aging process throughout in-service operation has an important impact on the engine operating parameters and its overall efficiency, which can be referred to as BSFC value.

Eight randomly selected oil samples of two viscosity grades (0W20, 0W30) were subjected to a 300 h durability test run, meant to reproduce in an accelerated method the distance of 30 000 km of vehicle on-road usage.

Fig. 24. Contaminated compressor housing after the durability test

It was found that within a selected batch of engine oils the maximum deterioration of BSFC reached 5%, while the decrease in engine torque was up to 6%.

Moreover, two oil samples (B and H) out of eight did not complete the durability cycle. The reason for cycle termination was exceedance of the limit for charge air temperature measured at the turbocharger's compressor outlet under full load conditions.

Elevated charge air temperature was caused by contamination of the inside of the compressor with oil-derived deposits, resulting in the deterioration of compressor efficiency.

Oil samples (C-F) successfully passed the durability run, maintaining engine operating parameters including: BSFC, engine torque, and charge air temperature at a stable level. For those oils, the engine protection limits were not surpassed.

During the durability test, physical and chemical properties of engine oils were analysed in terms of lubrication oil degradation monitoring.

In the case of four engine oil candidates (samples: A,F,G,H) crossover of TAN/TBN parameters occurred. The equilibrium of TAN and TBN values indicates that the organic and inorganic acid-neutralizing properties of the oil (as defined by the TBN value) are at its borderline value. Acidic products are mainly formed during fuel combustion and under harsh operating conditions.

A chemical analysis of the composition of deposits found inside the compressor revealed that nearly 92% of the material consisted of carbon.

From a vehicle operation perspective, inadequate quality engine oil can lead to severe contamination build up inside the turbocharger's compressor and an increase in charge air temperature. At engine full load conditions, a heavily contaminated compressor has generated charge air temperature exceeding protection limits and also a significant increase in exhaust backpressure was measured. That in turn may result in the turbocharger overstressing and its premature failure. The issue of compressor contamination can be enhanced for extended engine oil change intervals; for such applications the lubricating oil quality requirements are of key importance for faultless engine operation.

Nomenclature

ATS	after-treatment system
BSFC	break specific fuel consumption
CI	compression ignition
CO_2	carbon dioxide
EOT	end of test
ISC	in-service conformity
SI	spark ignition
SOT	start of test
TAN	total acid number
TBN	total base number

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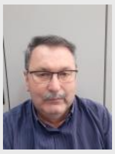

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