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Chemical decarbonisation of diesel engine and its impact on engine oil degradation

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Modern diesel combustion engines are sensitive to damage to the fuel system and to pollution by carbon deposits. Decarbonisation procedures significantly increase engine life and reduce exhaust emissions. In this experiment, decarbonisation was carried out using the chemical set BG 109 EPR, BG 112 DOC and BG 245 on a Skoda Octavia II with a 2.0 TDi diesel engine type CFFB 103 kW (Common Rail). The vehicle had a current odometer reading of 164.882 km. The effect of decarbonisation was monitored during the operation of the vehicle (7 measurements during 7 calendar months during work of 12.716 km). Two mail goals of the long-term experiment were to investigate the effect of chemical decarbonisation of the engine on the degradation of the Shell HELIX HX7 5W-30 oil filling and the condition of the fuel system (nozzle injection). The aim of the research was to confirm the hypothesis that cleaning additives have an impact on the rapid degradation of engine oil, especially in heavily worn diesel engines with high mileage.

Key words: *technical diagnostic, fuel system, decarbonisation, injectors, tribology*

1. Introduction

Chemical engine decarbonisation without disassembly is considered the cheapest type of decarbonisation. It is advisable to perform it in regular cycles (approx. 15.000 km) as a prevention against pollution of the combustion chamber. It is also suitable for minor degrees of engine pollution. A significantly dirty engine can be decarbonized just by disassembling it with the use of chemistry, ultrasound or mechanical cleaning. The latest trend is hydrogen decarbonisation without disassembly. Regular decarbonisation is a prerequisite for reliable operation and a long service life of the combustion engine.

The presented work fills the diagnosed gap in the literature on the subject, as it has been observed that there are few works presenting the degradation processes of engine oils during actual operating conditions [27].

Important notice: The research involves the application of commercial products from the brands Škoda, Shell, BG and modern diagnostic equipment. Any marketing promotion of these products is excluded throughout the article. Any attempt to damage the reputation of these brands is also excluded. These commonly used products served exclusively as necessary objects of measurement during research experiments.

2. The issue of nozzle injectors

2.1. The problem of carbonization of injectors

The results of experimental studies obtained by PC processing showed that the aggregate with new EDC units is more economical [2] than mechanical injection units without EDC. Analyses of injection processes in fuel supply systems with common rail systems have shown differences between the time of injection as preset by the controller and the time of injection accomplished in reality by the injection system [11]. The injectors of the Common Rail system make it possible to control the start of the injection and the injected quantity. The opening and closing of the nozzles are solved using an electromagnetic valve or a piezoelectric element [19]. Only orifice nozzles are used for direct injection of diesel engines. There are two types of orifice nozzles – with a channel and with a seat [7]. The final shape of the orifice nozzle is determined based on engine tests. The hole nozzle is produced with a maximum number of 12 holes with a minimum diameter of 0.2 mm [6]. Among the most thermally stressed and carbon-contaminated parts of the nozzle is the front of the nozzle with holes that extend into the combustion chamber. The temperature of the nozzle face should not fall below 120–140°C during operation, because there is an increased formation of carbon (especially long-term engine idling and low engine speeds are harmful).

Fig. 1. Fuel nozzle operation before and after the use of additives (illustrative photograph) [2]

Fig. 2. Damaged pistons (illustrative photograph)

When fuel is supplied to the engine with air, the temperature of the working medium in the engine cylinder decreases [26, 29]. On the contrary, the optimal performance of the nozzle can also be disturbed by its overheating, especially temperatures exceeding 250°C [29]. The influence of the driver skills was often identified as a previously overlooked factor [3]. Another related factor is the design of the engine's crank mechanism. The piston kinematics parameters can be influenced by adjusting the distance between the crankshaft axis and the axis of the cylinder [14]. Polluted nozzles cause a sharp, uneven jet of the fuel shown in Fig. 1, which may cause melting off of the piston material and consequently damage the engine (Fig. 2) [8, 16]. The quality of the fuel injection also has a great influence on the ignition delay and the roughness of the engine [28]. The starting dose of fuel with the participation of biocomponents causes the penetration of the unburnt part of the atomized fuel into the engine crankcase, and thus into the oil pan, causing destructive secondary reactions with engine oil. [12].

To understand the main function of the nozzle, it is necessary to state its simplified calculation. It assumes that the fuel is incompressible and the injection pressure remains constant [6]:

The nozzle is designed for the fuel dose V_{pal} according to equation (1) [24].

$$V_{pal} = \int_0^{\tau_d} \mu S_{Tr}\, w_{Tr} d\tau \tag{1}$$

According to equations (2) and (3), the mass flow of fuel in the nozzle - Q_m is calculated. Before that, it is necessary to calculate the speed of the fuel in the nozzle – c (4) [6].

$$Q_m = \mu \cdot \rho_P \cdot S \cdot c \tag{2}$$

$$Q_m = \mu \cdot S\sqrt{2\rho_p(p_v - p_k)} \tag{3}$$

$$c = \sqrt{\frac{2}{\rho_P}(p_v - p_k)} \tag{4}$$

According to equations (5) and (6), the total area of the nozzle openings – S and the diameter of the nozzle openings – d_D are calculated [6].

$$S = \frac{Q_m}{\mu\sqrt{2\rho_p(p_v - p_k)}} \tag{5}$$

$$D_D = \sqrt{\frac{4 \cdot S}{\pi \cdot z_o}} \tag{6}$$

It follows from equations (1) to (6) that carbon deposits result in a decrease in the diameter of the nozzle openings, which significantly decreases their performance parameters. Even a small contamination of the holes has a very sensitive effect on the fuel flow and the quality of the injection.

2.2. The issue of engine oil degradation

Chemical decarbonisation is good for the engine, but may not be good for the oil fill. Aggressive decarbonizing preparations are added to the oil filling and fuel, which can significantly accelerate the degradation of engine oil. Another factor is dissolved carbon deposits that accumulate in the oil fill. Manufacturers of decarbonisation sets declare that their products do not affect the quality of the oil filling. But reality may be different. Here, there is a large scope for the investigation of engine oil, which is directly and indirectly exposed to chemical decarbonisation.

In tribology, engine oil degradation is expressed by many physical and chemical parameters. The most fragile parameters is, in most cases, kinematic viscosity, TBN and AW additives. And it is necessary to pay great attention to these parameters.

TBN – parameter, which is used to assess the ability to dissolve acid sludge, its level also reflects the life of motor oil. Do not allow the operation of motor oil when the TBN value decreases by more than compared to the value of the reference sample and the manufacturer's motor oil recommendation TBN – the parameter should not fall below the value of 3.5 mg KOH/g [15].

AW additives – total engine oil additives. Engine oil must be usable in the working parts of the engine under all conditions. Ingredients are chemicals of complicated composition. They improve the performance of the base oil. They meet the demanding conditions of modern engines. Reducing the content of additives below 50% is unacceptable [15].

Kinematic viscosity is the primary and essential property of the suitability of a motor oil in a vehicle engine. Motor oil is only suitable for viscosity in the range ±20% of the reference sample and the manufacturer's motor oil recommendation [17]. Fretting in the tribological kinematic pairs under analysis comprises mainly wear products in the form of material build-ups which become softened, oxidised and fragmented over time. Worn products hardened by oxidation as they move around cause further damage in the form of surface abrasion and micropits [1].

For the study of mutual degradation processes, it is appropriate to use statistical-mathematical operations. A proven tool is the application of correlation analysis with the correlation coefficient – r according to equation (7), or of statistical covariance – k (8).

Table 1. Cohen's interpretation of correlation coefficients

Cohen's correlation coefficient scale	
|r|	correlation level
|0.0| – |0.1|	trivial correlation
|0.1| – |0.3|	small
|0.3| – |0.5|	medium
|0.5| – |0.7|	big
|0.7| – |0.9|	very large
|0.9| – |1.0|	almost perfect

$$r(x, y) = \frac{k(x,y)}{s_x s_y} \tag{7}$$

$$k(x, y) = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y}) \tag{8}$$

Assessing the tightness of the dependence using some characteristic that describes to what extent the variable x explains the variability of the variable y is called correlation analysis [9].

3. Experiments, results and discussion

3.1. Characteristics of the experiment objects

Technical diagnostics provide a lot of valuable data about the technical condition of the vehicle and its changes during use. If repeated diagnostic measurements are consistently managed and archived, it is possible to establish a prognosis based on development trends [18].

Our experiment was focused on monitoring the effects of chemical decarbonisation on the injection nozzles and the oil filling of a diesel engine. It had two goals. The first goal was long-term monitoring of the fuel injectors of the 2.0 TDi CFFB 103 kW engine (Fig. 4) and monitoring the fuel supply of individual injectors on the Škoda Octavia II vehicle (Fig. 3). The hypothesis was that chemical decarbonisation would ensure a balanced fuel supply. The second goal was long-term monitoring of the engine oil charge Shell HELIX HX7 5W-30 (Fig. 5) with monitoring of the most sensitive parameters and how they reacted to chemical decarbonisation

Fig. 3. Skoda Octavia II 2.0 TDi

Fig. 4. Engine of the Skoda II 2.0 TDi CFFB

Within this experiment, we would like to draw attention to the fact that the specificity of chemical decarbonisation and thus also of our monitoring is the long-term achievement of the effect (added cleaning additives in oil and fuel) – the effect of decarbonisation was monitored during 7 calendar months during a mileage run-in of 12,716 km. Data were collected from the diagnostic measurements, which were interpreted in tables, graphs and verbal evaluation through mathematical-statistical analysis.

From the point of view of diagnostic means, diagnostic systems are divided into OFF-LINE test diagnostic systems (diagnosed object out of operation) and ON-LINE operational diagnostic systems (diagnostic object in operation) [4, 29].

Fig. 5. Used engine oil and decarbonisation set in the experiment

In our case, tribodiagnosis of the oil filling is an OFF-LINE method, and injector diagnostics is an ON-LINE method. The means of chemical decarbonisation was (commonly available on the Slovak market) a 3-part set of type BG 109 EPR, BG 112 DOC and BG 245 (Fig. 5).

The process of the cleaning procedure consisted of three successive steps:

Step 1: Application of BG 109 EPR preparation into the old oil filling and subsequent operation of the engine for 20 minutes at idling speed. Then followed the draining of the oil filling from the engine with engine flushing.

Step 2: Applying a new oil filling to the engine with the addition of BG 112 DOC preparation.

Step 3: Application (mixing) of the preparation BG 245 into the fuel in the fuel tank.

The vehicle set up in this way was monitored at irregular kilometer intervals (Table 2, Table 2, Table 3) during the run-in of 12,716 km.

Fig. 6. Tribodiagnostic devices Q-1000, Q-3050 and EOBD – Gutmann Mega Macs PC

Tribotechnical diagnostics was carried out in the tribological laboratory (Department of Mechanical Engineering) A. O. S. Gen. M. R. Štefánik in Liptovský Mikuláš. SpectroVisc Q-3050 and FluidScan Q-1000 optical electronic devices were used for this purpose (Fig. 6). Diagnostics of the fuel system was carried out on the measuring station Gutmann Mega Macs PC (Fig. 6), which communicates with the control unit of the vehicle (ECU).

3.2. Diagnostics of injectors

The measuring station, through connectivity via the on-board EOBD port (OBD II), diagnoses active electronic circuits and passive components in the car in accordance with regulation 98/69/EC valid from 1.1.2000 [20].

Gutmann Mega Macs PC enables a wide range of diagnostics. It has a large library of almost all brands and types of cars. As part of the diagnostics of the fuel system, the device offers numerical and graphical measurements of the performance of the injection nozzles over time (dynamic characteristics).

Table 2. Performance monitoring of injectors

vehicle operation				fuel quantity deviation			
time interval	initial state (km)	end state (km)	total sum (km)	injector No. 1	injector No. 2	injector No. 3	injector No. 4
08.06–09.06.2021	164,882	165,033	151	1.0	–0.8	0.2	–0.4
09.06–17.06.2021	165,033	165,525	492	1.0	–0.7	0.2	–0.5
17.06–25.06.2021	165,525	166,810	1 285	1.0	–0.6	0.0	–0.4
25.06–08.08.2021	166,810	169,863	3053	0.5	–0.4	0.0	–0.1
08.08–13.09.2021	169,863	170,831	968	0.3	–0.2	0.1	–0.2
13.09–20.12.2021	170,831	177,598	6767	0.1	–0.2	0.2	–0.1

Measurements progress is described in Table 2. Each nozzle performance measurement took place after a certain time ramp-up with an unloaded engine (idling 782–784 revolutions per minute). The car worked in daily operation, mainly on medium-long routes in Central European climatic conditions. The regularly serviced vehicle burned standard fuel – B7 diesel.

3.3. Measurement results

Figure 7 shows on the display of the Guttman Mega Macs PC the condition of the nozzles before chemical decarbonisation from 9. June 2021, with an odometer reading of 164,882 km. The numerical and graphic record shows that the nozzles have a significantly uneven fuel supply due to carbon pollution.

The deviation between nozzle performance ranges from –0.8 to +1.0, which is a large variance (1.8 in absolute value). The ideal variance is 0.0, i.e. no deviation. The accepted maximum deviation in vehicle operation is from +1 to –1. From the above, it follows that the engine has significantly contaminated injectors. According to general recommendations, its operation is within the permitted limit values. The engine is at risk of damage and a reduction in service life.

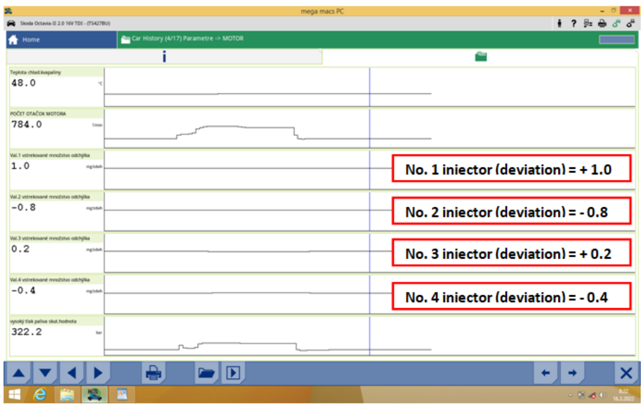

Fig. 7. EOBD diagnostic device – condition of nozzles before chemical decarbonisation

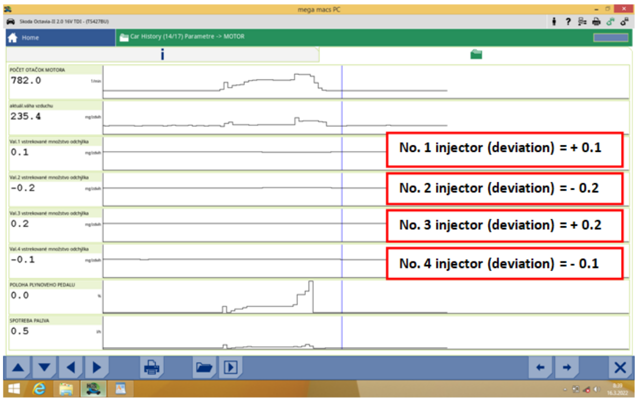

Fig. 8. EOBD diagnostic device – condition of nozzles after chemical decarbonisation

The results of the measurements after the decarbonisation procedure are shown in Fig. 8, which is dated 20 December 2021 with an odometer reading of 177,598 km. It follows from the numerical and graphic record that the nozzles have a much more even supply of fuel after the cleaning of carbon deposits than before decarbonisation. The deviation between nozzle performance ranges from –0.2 to +0.2, which is an acceptable variance (0.4 in absolute value).

Graphical interpretation of long-term engine decarbonisation is shown in Fig. 9–11. The change in fuel supply deviation (y) is a function of the mileage (x), i.e. y = f(x). The smoothing techniques used in chemical applications are based, for example, on moving averages or the Savitzky-Golay method [25]. Here, standard tools of mathematical functions and trend curves were used to interpret the results.

Figure 9 graphically shows the reduction of deviation (unevenness) of fuel supply between injector no. 1 and no. 2 depending on the mileage. From a mathematical point of view, this process can be expressed with high accuracy using a simple polynomial regression (eq. (9) and (10)), where the coefficient of determination R^2 reaches high values (0.94 to 0.97). From a practical point of view, injector No. 1 with increased fuel supply compensates for the work of the weaker injector No. 2, which, due to the contamination of the nozzle, delivers a smaller supply of fuel to the combustion chamber of the engine.

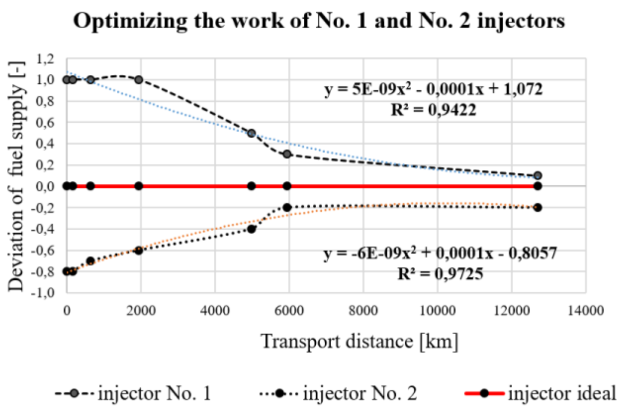

Fig. 9. Ballance of the decarbonisation process of the No.1 and No.2 injectors

For injector No. 1 is the supply of fuel deviation:

$$deviaton = 5\cdot 10^{-0.9}\cdot l^2 - 0.0001\cdot l + 1.072 \quad (R^2 = 0.9422) \tag{9}$$

For injector No. 2 is the supply of fuel deviation:

$$deviation = -6\cdot 10^{-0.9}\cdot l^2 + 0.0001\cdot l - 0.8057 \quad (R^2 = 0.9725) \tag{10}$$

The control unit (EDC – Electronic Diesel Control) can provide this process of optimization and compensation to a certain small extent. With enormously dirty nozzles, even EDC cannot compensate for the uneven work of the injectors.

Differences may also apply to the correction of fuel dosage, as the manufacturer assumes top-down adjustment by means of coding or by earlier disassembly of the nozzle and changing the thickness of the needle wash [22].

The engine is uncultivated, especially at idling speed, and has high mechanical and noise vibrations. Its effectiveness and service life are significantly reduced. The risk of engine damage increases (Fig. 2).

For injector No. 3 is the supply of fuel deviation:

$$deviation = 4\cdot 10^{-0.9}\cdot l^2 - 5\cdot 10^{-0.5}\cdot l + 0.1903 \quad (R^2 = 0.6404) \tag{11}$$

For injector No. 4 is the supply of fuel deviation:

$$deviation = -3\cdot 10^{-0.9}\cdot l^2 + 7\cdot 10^{-0.5}\cdot l - 0.4566 \quad (R^2 = 0.8302) \tag{12}$$

Analogously, similar to Fig. 9, Fig. 10 graphically shows the reduction of deviation (unevenness) of fuel supply between injector no. 3 and no. 4, depending on the mileage. From a mathematical point of view, this process can be expressed with relatively high accuracy using a simple polynomial regression (equations (11), (12)), where the coefficient of determination R^2 reaches acceptable values (0.64 to 0.83).

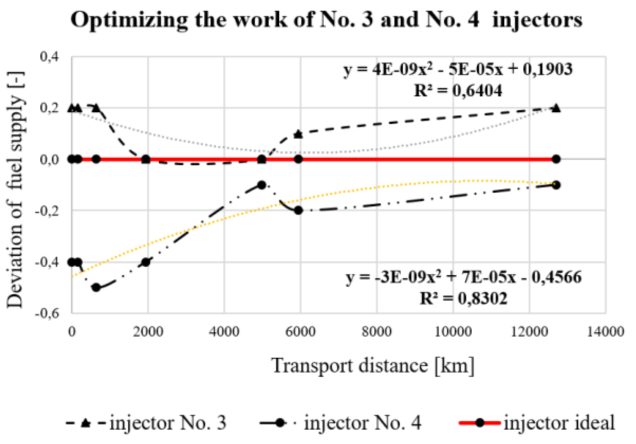

Fig. 10. Balance of the decarbonisation process of the No. 3 and No. 4 injectors

Since the decarbonisation procedure is a complicated process (unevenness of the graphs), defining the decarbonisation process using a simple polynomial regression proved to be the most advantageous. With the help of the regression function (also expressed by the graph connector Fig. 9, Fig. 10), a relatively accurate approximation of the real state was achieved.

Figure 11 records the overall balance of the decarbonisation process of all four injection nozzles in accordance with Table 1. The change in fuel supply deviation (y) is a function of the mileage (x), i.e. y = f(x). The graphic display shows that the decarbonisation process was most pronounced in the interval from 200 km to 6000 km. At 6000 km, the values stabilized, and later there were no significant changes. The fuel supply deviation of individual nozzles continuously decreased during the entire process, converged to zero and stabilized in the interval (–0.2, +0.2).

From similar studies carried out in the past, it follows that both added additives and the type of fuel used affect the parameters of the injection nozzles.

Among the optical metrics evaluated, only selected macroscopic parameters (spray area and angle) showed sensitivity to fuel composition. Although the spray penetration does not indicate differences, the other indicators in the form of spray area and spray angle significantly indicate changes due to the use of additives [23].

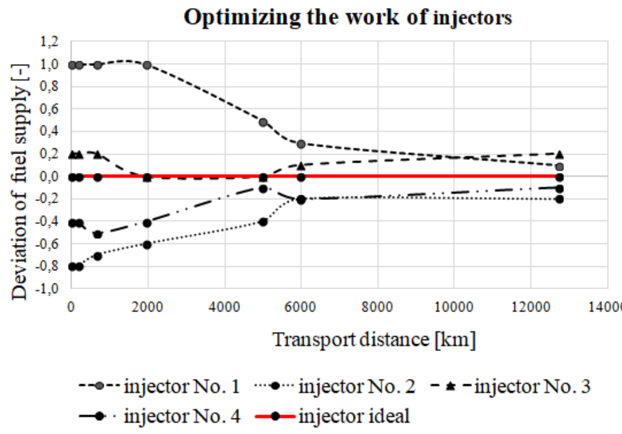

Fig. 11. Balance of the decarbonisation process of the all (four) injectors

3.4. Diagnostics of the oil filling

In the area of the fuel system, chemical decarbonisation has brought positive results.

However, it is questionable how this procedure was reflected in the physical and chemical picture of the oil filling. The situation was also complicated by the decarbonizing oil additive BG 112 DOC, which is being discussed due to the possible disruption of the chemical composition of the engine oil. The use of the intensive fuel additive BG 245 and its possible impact on oil degradation were also questionable.

Tables 3 and 4 record the course of oil charge measurements from new condition to exceeding its service life. (The tables are directly related to each other, and Table 4 is a continuation of Table 3).

These tables provide an overview of the basic physical and chemical parameters of the oil that we monitored and that are most often dealt with in practical tribology. In the gray column (Table 3) are the values of the new oil filling (reference sample), which is compared with the worn sample. Green colored cells in the tables mean satisfactory results. The red colored cells of Table 4 mean unsatisfactory results. In the table of measurements (Table 4), the unsatisfactory parameter kinematic viscosity at 40°C appears. Since this parameter is unimportant for the operation of an internal combustion engine (it is especially important in industrial machines), we did not pay more attention to it in the research.

Engine oil manufacturers warn customers not to mix various cleaning additives into the oils. It is generally known that it is not recommended to mix oils of other types and brands.

3.5. Measurement results

Similar to the vast majority of cases, this long-term monitoring showed that the most fragile parameter of engine oil was the TBN parameter. But during our monitoring, we also found an abnormal premature drop in kinematic viscosity (Table 5 – red colored cells).

These two most fragile parameters were subjected to deeper analysis. On the basis of correlation analysis (equations 7, 8), the interdependencies between TBN, kinematic viscosity at 100°C and the traveled route were investigated.

Table 3. Engine oil measurement – one life cycle of the oil filling

	8/6/2021 reference sample	9/6/2021	17/6/2021	25/6/2021	allowed values	results for vehicle operation
	mileage of the car: 0 km	mileage of the car: 151 km	mileage of the car: 492 km	mileage of the car: 1285 km		
	total mileage of the car: 164,882 km	total mileage of the car: 165,033 km	total mileage of the car: 165,525 km	total mileage of the car: 166,810 km		
Glycol [%]	0	0	0	0	max. 0	passes
Oxidation [abs/0.1]	12.4	15.1	15.4	17.7	max. 40	passes
Soot [% wt]	0	0.02	0.05	0.07	max. 3	passes
Sulfation [abs/0.1]	17.3	17.7	18.0	19.7	max. 45	passes
Nitration [abs/0.1]	3.9	4.2	5.0	5.7	max. 30	passes
TBN parameter [mg KOH/g]	6.8	6.6	5.8	4.8	min. 3.5	passes
Water content [ppm]	254	132	158	137	max. 5000	passes
Kinematic viscosity at 40°C [mm^2/s]	72.5	69. (–4.1%)	66.6 (–8.1%)	65.9 (–9.1%)	max. difference ±20% compared to the new sample	passes
Kinematic viscosity at 100°C [mm^2/s]	12.6	12.2 (–3.2%)	11.9 (–5.6%)	11.7 (–6.7%)	max. difference ±20% compared to the new sample	passes

Table 4. Engine oil measurement – one life cycle of the oil filling

	8/8/2021	13/9/2021	12/20/2021	allowed values	results for vehicle operation
	mileage of the car: 3053 km	mileage of the car: 968 km	mileage of the car: 6.767 km		
	total mileage of the car: 169,863 km	total mileage of the car: 170,831 km	total mileage of the car: 177,598 km		
Glycol [%]	0	0	0	max. 0	**passes**
Oxidation [abs/0.1]	18.2	18.3	20.3	max. 40	**passes**
Soot [% wt]	0.34	0.37	0.48	max. 3	**passes**
Sulfation [abs/0.1]	22.9	23.0	26.3	max. 45	**passes**
Nitration [abs/0.1]	10.8	11.5	20.1	max. 30	**passes**
TBN parameter [mg KOH/g]	3.6	3.5	**0.0**	min. 3.5	**missed**
Water content [ppm]	217	119	343	max. 5000	**passes**
Kinematic viscosity at 40°C [mm^2/s]	61.2 (–15.6%)	59.8 (–17.5%)	**44.3 (–38.9%)**	max. difference ±20% compared to the new sample	**missed**
Kinematic viscosity at 100°C [mm^2/s]	11.0 (–12.7%)	10.8 (–14.3%)	**8.4 (–33.1%)**	max. difference ±20% compared to the new sample	**missed**

Table 5. Monitoring of the most fragile of the oil filling parameters

Time interval	Vehicle operation: initial state [km]	Vehicle operation: end state [km]	Vehicle operation: total sum [km]	The most fragile parameters on the oil: TBN [mg KOH/g]	The most fragile parameters on the oil: Kinematic viscosity at 100°C [mm^2/s]
08.06.2021	164,882	164,882	0	6.8	12.6
08.06–09.06.2021	164,882	165,033	151	6.6	12.2
09.06–17.06.2021	165,033	165,525	492	5.8	11.9
17.06–25.06.2021	165,525	166,810	1285	4.8	11.7
25.06–08.08.2021	166,810	169,863	3053	3.6	11.0
08.08–13.09.2021	169,863	170,831	968	3.5	10.8
13.09–20.12.2021	170,831	177,598	6767	0.0	8.4

Table 6 shows a very strong (according to Cohen, perfect: r = 0.9 to 1) positive correlation of the TBN parameter and kinematic viscosity υ (r = 0.99). At the same time, both of these parameters express a very strong inverse correlation with the increase in kilometers (r = –0.99).

Table 6. Correlation matrix of the investigated parameters of the engine oil

	Transport distance [km]	TBN [mg KOH/g]	υ at 100°C [mm^2/s]
transport distance [km]	1		
TBN [mg KOH/g]	–0.988381921	1	
υ at 100°C [mm^2/s]	–0.989799344	0.986871717	1

For total base number (TBN):

$$TBN = -0.0005 \cdot l + 6.3576 \quad (R^2 = 0.9769) \tag{13}$$

For the kinematic viscosity (υ) at 100°C:

$$\upsilon = -0.0003 \cdot l + 12.363 \quad (R^2 = 0.9797) \tag{14}$$

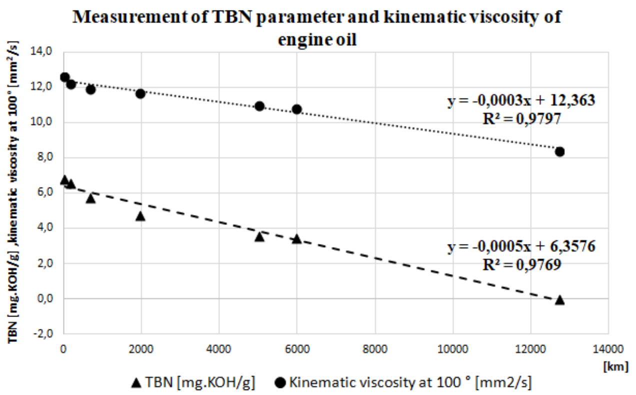

Fig. 13. Course of TBN parameter and kinematic viscosity at 100°C during the life cycle of the oil filling

The course of the most fragile parameters depending on the mileage of the vehicle can be expressed using a simple linear regression. Both parameters are defined by straight line equations and have a linearly decreasing trend (9) (10), where the coefficient of determination R^2 reaches a value of up to 0.98. Their graphic interpretation is in Fig. 13.

The study of the problem shows that the observed parameters (TBN and υ) have an almost ideal linear slope and an almost perfect mutual correlation, which is quite unusual in this respect.

From the theoretical point of view of tribology, this is a significant result. From the practical point of view of tribology, it follows that the oil filling has exceeded its lifetime of the TBN parameter and the kinematic viscosity at 100°C approximately after running for 7000 to 8000 km. Under standard operating conditions (without decarbonisation preparations), the engine used to have an oil life of 12,000 to 15,000 km in the past. The results of the experiment show that the decarbonisation procedure resulted in a very rapid degradation of the engine oil.

3.6. Discussion

It's still true that the most reliable and precise method of diagnosing Common Rail fuel injectors are bench tests. They are carried out on special test benches [10, 21]. In our case, we used a non-disassembly diagnostic method using a portable PC and an EOBD interface. This alternative produced interesting results.

Any flow restriction caused by carbon deposits has, except for defective fuel dispersion, an impact on the lowered fuel supply of the injector into the combustion chamber. In this case the insufficient fuel supply of the injector must be compensated by the other injectors. Such as forced fuel compensation by the engine control unit is undesirable in the long run in terms of uneven engine load, as well as in terms of its durability. The uneven fuel supply between injectors should not exceed 15% while the engine is operating [16].

In general, decarbonisation sets are effective in contaminating injection nozzles. They are highly beneficial and harmless to the fuel system.

After 12,716 km of vehicle operation with applied chemical preparations in the lubrication and fuel system, it is possible to state that the cleaning effect on the injection nozzles is striking and very important for engine operation.

	transport distance [km]	Injector No. 1	Injector No. 2	Injector No. 3	Injector No. 4
transport distance [km]	1,00				
Injector No. 1	-0,94	1,00			
Injector No. 2	0,89	-0,96	1,00		
Injector No. 3	-0,04	0,09	-0,30	1,00	
Injector No. 4	0,84	-0,91	0,85	-0,32	1,00

Fig. 12. Correlation matrix of the investigated injectors

In this experiment, in addition to monitoring the long-term chemical decarbonisation of the engine, we also verified the compensation process of the EDC injectors on the Skoda II 2.0 TDi CFFB engine. The fact that the injectors compensate for fuel delivery in pairs, as interpreted in the graphs, cannot be generalized. EDC works on all injectors simultaneously. It should be taken into account that after exceeding the idling speed of the unloaded engine to 1200–1500/minute, all injectors equalize (the sum of fuel supply deviations of all injectors = 0). The correlation analysis in Fig. 12 shows that the weakest injector, No. 1, is most supported by injectors No. 2 and No. 4. There are many strong correlations in the comparison. This method of compensation process depends on the EDC software and may differ from the engine manufacturer

In the case of an oil filling, we cannot talk about the harmlessness of decarbonisation sets.

Although the research results show that the chemical and cleaning effect of decarbonisation preparations accelerates the degradation process of the oil, it should be borne in mind that the engine had worked almost 165,000 km at the beginning of the measurements and engine management often required the regeneration of the DPF filter. These factors also significantly contributed to the observed oil degradation. Therefore, one must be careful when making hasty conclusions about the significant harmfulness of chemical decarbonisation on the oil filling.

It is still true that it is necessary to strictly follow the recommendations of the manufacturer of the decarbonisation preparation and the manufacturer of the engine oil. It is necessary to be more careful when recommending some manufacturers of cleaning products, as “overdosing the product is not a mistake” (Fig. 14).

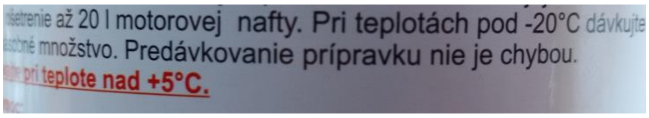

Fig. 14. Cleaning product manufacturer's recommendation: "Overdosing the product is not a mistake"

The vehicle user, in order to quickly clean the engine, often tends to exceed the recommended doses of the chemical product. This often happens with older engines with high mileage, which are heavily clogged with deposits. It is in these engines that the compression space has reduced tightness and there is a significant leakage of fuel with cleaning additives into the engine oil. Cleaning fuel additives in engine oil have a significant anti-detergent effect and damage the lubricating film. Frequent regeneration of the DPF filter and frequent cold starts of the engine significantly contribute to the undesirable process.

4. Conclusion

The effect of chemical decarbonisation brought very positive results on fuel injectors. An accompanying phenomenon was the undesirable effects of this procedure on engine oil. The results of the experiment show that after the decarbonisation procedure, the injectors had a much more even fuel delivery than before decarbonisation, but decarbonisation resulted in very rapid degradation of engine oil.

In the vehicle's service manual, the Skoda Octavia II car manufacturer recommends changing the oil after two years of operation or after 30,000 km of run-in. From the point of view of the operation of diesel cars, it is recommended to shorten the oil change interval to 7000–10,000 km after chemical decarbonisation of the engine. These recommendations are general and may change depending on the nature and circumstances of the problem.

Reducing the oil change interval in this case indicates potential benefits to the condition of the engine and its components, which in turn can reduce maintenance costs as well as reduce downtime and repairs [5].

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Nomenclature

DPF	diesel particulate filter
ECU	electric central unit
EDC	electronic diesel control
EOBD	European on-board diagnostic
OBDII	on board diagnostic
TBN	total base number
c	fuel output speed
dD	diameter of injector holes
k	statistical covariance
l	transport distance
p_k	compression pressure in the cylinder
p_v	injection pressure
Q_m	weight per unit of time
r	correlation coefficient
R^2	coefficient of determination
S, S_{Tr}	the size of the flow area of the inj. Holes
VVpa1	fuel injection dose
ww_{Tr}	fuel velocity at the injector hole
z_o	the number of injector exit holes
ρ_p	fuel density
τ_d	duration of injection
υ	kinematic viscosity

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