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The influence of particulate contamination in diesel fuel on the damage to fuel injection systems

The impact of various size particulate contamination on the process of accelerated wear followed by damage to the fuel injection system has been studied in long-term tests on an engine test stand. Also processes of tribological wear of working components of fuel injectors and of high pressure pumps material has been characterised. Measurement results of particulate contamination in diesel fuels available on the Polish market have been presented, referred to requirements of the PN-EN590 standard and of the Worldwide Fuel Charter. In the summary attention has been drawn to the growing problem of particulate contamination in fuels available on the market, and in particular their threat to durability and proper operation of increasingly complex and precisely manufactured HPCR type fuel injection systems.

Key words: *HPCR type fuel injection systems, particulate contamination in diesel oil, tribological wear of HPCR components, tests on engine test stand*

1. Introduction

Operational fluids must fulfil many functions, among which the following are most important:

– supply of energy,
– lubrication of mating surfaces of working components,
– heat removal,
– power transfer in hydraulic systems,
– corrosion protection.

To fulfil their functions such fluids must feature appropriate practical properties and quality parameters specified in appropriate standards, regulations, or ordinances. Durability of automotive vehicle driving units and reliability of their operation depends to a large extent on the quality of operational fluids used in them, including the contained particulate contamination. The existence of particulate contamination in operational fluids causes accelerated wear of mechanically mating components, makes their operation difficult, and finally results in failures, repair shut-downs, and financial losses.

Permanent pursuit of obtaining better and better parameters in the field of unit power and fuel consumption forces significant technical progress in terms of improving the energy performance of engines, at the same time frequently revealing delays in parallel development of manufacturing technology and materials science, and in particular physical metallurgy and accompanying metallographic investigations [1–3]. This leads to reduced durability of crucial components of engine fuel injection systems, resulting both from design and operational reasons. The amount of information proving the occurrence of mechanical failures of actuator components of modern HPCR fuel injection systems, more and more widely used to fuel diesel engines, has been growing for some time. Subassemblies and component of aforementioned systems during the operation are subject to various types of dynamically changing thermal and mechanical cyclical loads, at a complex stress state. This is caused, among other things, by pumping the fuel by the injection pump under a pressure of approx. 250 to 300 MPa, and its quick changes in the high-pressure part of the fuelling system due feeding the fuel via injectors to the engine combustion chambers. The obtaining of so high pressures is inseparably related to the necessity of precise manufacture and matching of the moving, mating parts (frequently with accuracy of approx. 1 μm) [1–5]. Such a high manufacture precisions makes that the aforementioned key actuator components of high-pressure injection systems are very sensitive to any particulate contamination or substances inconsistent with standard PN-EN 590, which can occur in the fuel, causing damage resulting in dysfunction of injection systems and the necessity to carry out usually very costly repairs. The design and way of operation of crucial subassemblies of the fuel injection systems suggest the occurrence of material's tribological wear processes, including attrition, scuffing, fatigue, fretting, diffusive, pitting, and erosive wear, which gives an opinion about the complexity of both damage origination mechanisms, as well as factors that affect them. In practice, in fuel existing in the commercial trade, one can encounter various pollutants, like hard abrasive particulate matter, soft resinous (organic) substances, microbiological structures, water, etc. [4–8].

Hard abrasive particles are the dominating reason for premature damage (wear) to working surfaces of pairs of precise injection pumps (pumping) and injectors (dosing). In this case processes of tribological material wear prevail, including attrition, scuffing, fretting, diffusive, pitting, and erosive wear. As it has been experimentally found, particles 1–5 μm in size are most dangerous, as they can get between moving parts of precise pairs, gradually increasing the existing clearance between them, which has a crucial impact on deterioration of parameters of injection pumps and injectors operation. The erosive wear is caused by hard particles of particulate contamination carried by the fuel hitting with high speed the working surfaces of precise working elements [8–12]. The risk of accelerated wear and damage to components of HPCR type injection systems is affected more by the size distribution of particulate contamination than by its total weight. On average, one litre of diesel fuel contains more than 5×10^4 of hard pollutants bigger than 15 μm (coarse-grained fraction) and more than 5×10^5 hard pollutants bigger than 5 μm (fine-grained fraction) [4].

The main sources of particulate contamination in diesel fuel comprise:
- production – from refinery plants and from ester producing plants
- transport – when pollutants get to diesel fuel
- storage – when pollutants get to diesel fuel
- filling – pollutants get to the fuel from outside
- leaks in the engine fuel system, causing pollutants penetration into diesel oil
- attrition of mating surfaces of working elements
- corrosive destruction of design surfaces of working elements.

Particulate contaminations can substantially differ between each other, and they may be broken down according to the following criteria:
- particle size
- chemical nature (inorganic, organic)
- hardness
- chemical reactivity
- shape
- electrical character.

Standard PN-EN 590 in the requirements for diesel oil defines a permissible amount of pollutants, determined in weight terms (24 mg/kg).

The Worldwide Fuel Charter in the third edition of 2006 [13] for cat. 2, 3, and 4 diesel oil introduced additional requirements related to the particulate matter size distribution in classes: > 4 µm, > 6 µm, and > 14 µm determined pursuant to the ISO 4406 procedure. In the case of category 2, 3, 4, and 5 the Worldwide Fuel Charter (fifth edition) limits the particulate matter content, including:

Mass up to: 10 mg/kg

Distribution of particulate contamination size: 18/16/13 (acc. to ISO code) in accordance with standard ISO 4406.

The particulate contamination content by weight is determined in accordance with the procedure of EN 12662 (mg/kg).

The Worldwide Fuel Charter recommends the standard ISO 4406:2005 as the method to determine the level of pollutants, and to determine the amount of pollutants - the standard ISO 4407 or standards, in which the grain size composition is determined by the method of automatic particle counter, e.g. ISO 11500.

2. Methodology

The HPCR fuel injection system is a separate functional system working directly with a diesel engine. In this system there exist motional matchings, which are tribological systems, where these are systems operating at both sliding and rolling friction.

The HCPR type fuel injection system performs the process and fuel feeding and spraying in diesel engine cylinders and consists of such basic subassemblies as [4]:
- fuel feeding pump
- fuel filters
- high-pressure injection fuel pump
- high-pressure fuel accumulator with high-pressure piping
- fuel injectors
- integrated module controlling the engine operation.

The subassemblies selected for further analysis in the project, such as a high-pressure injection fuel pump and fuel injectors are at the same time subsystems with the following tribological systems:
- high-pressure injection fuel pump: roller–cam, roller–follower, pump piston–follower, eccentric cam–follower, dosing valve
- injector: nozzle needle–guide in the body, nozzle needle –seat, electromagnetic valve plunger–guide.

2.1. Tests on the engine test stand

The engine simulation tests of HPCR system premature wear caused by particulate contamination contained in the Diesel fuel were performed on a multi-purpose test stand equipped with a modern, widely used HSDI (High Speed Direct Injection) FORD 2.0i 16V Duratorq TDCi diesel engine coupled with an Alpha 160 AF eddy current brake from AVL, with a control module allowing the programming of the engine operation parameters (rpm, load, phase time and ramp time between phases). The basic technical parameters of the FORD 2.0i 16V Duratorq TDCi are given in Table 1 [4].

Table 1. Selected technical parameters of the FORD 2.0i 16V Duratorq TDCi engine

Engine type	four-stroke, compression ignition
Fuel injection type	Direct fuel injection, common rail (Delphi) electronically controlled, cooperating with the Levanta engine control system
Cylinders arrangement	In-line, vertical
No. of cylinders	4
Injection sequence	1-3-4-2
Type of timing gear	DOHC/4 VPC
Cylinder diameter	86.0 mm
Piston stroke	86.0 mm
Displacement	1998 cm^3
Maximum power	130 KM (96 kW) at 3800 rpm
Max. torque	330 Nm at 1800 rpm
Max. instantaneous speed	4800 rpm
Idle speed	750±20 rpm
Compression ratio	18.2
Filling	turbocharged with intercooler and “over-boost” function
Valve clearance	Hydraulic adjustment
Capacity of lubrication system with filter	6.0 dm^3
Complies with emission standard	Euro IV

The engine tests were performed in a 4-phase, repeatable cycle which reflected the average engine operating conditions in a low-intensity city traffic. The parameters of the 4-phase cycle are given in Table 2.

Table 2. Parameters of the 4-phase engine cycle

Phase	Time [s]	Engine speed [rpm]	Engine load [Nm]
1	30	800	~0
2	300	1850	100
3	120	3000	70
4	120	1500	50

The test duration time was set as 200 hours. Two engine tests were carried out under the project:. In the first test to fuel the engine a commercial diesel fuel was used, meeting requirements of the standard PN-EN 590 + A1: 2017, containing 4.8 mg/kg of particulate contamination. In the second test a fuel with the maximum permitted amount of particulate contamination, acc. to PN-EN 590 + A1: 2017 equal to 24 mg/kg of fuel, was used to feed the engine, however, it did not meet the limit specified for this parameter acc. to the Worldwide Fuel Charter (max. 10 mg/kg of fuel). An assumption was also made that the size distribution of contaminants contained in the fuel for tests will not be consistent with the recommendations of the Worldwide Fuel Charter in that respect (18/16/13 acc. to ISO 4406). The fuel was prepared based on the same commercial diesel fuel as used in test one. Additional particulate contamination was introduced to this fuel, in the form of Standardized Arizona Test Dust Contaminant ISO 12103-1 Fine Grade (A2) (SAE J726/ISO5011 Fine Grade) at such an amount as to obtain the permitted, described above, amount of contaminants, i.e. 24 mg/kg. In addition, the fuel was prepared so as to guarantee the contaminant size distribution corresponding to code 18/17/15 per ISO 4406. New sets of fuel injectors were used in tests.

Also tests of particulate contamination content in random sampled, on various petrol stations, samples of commercial diesel fuels of various producers were performed.

The particulate contamination content by weight was determined in accordance with the procedure of PN-EN 12662 (mg/kg). Distribution of particulate contamination size: 18/16/13 (acc. to ISO code) was determined in accordance with standard ISO 4406.

3. Results

3.1. Results of HPCR system components evaluation after the test of diesel oil consistent with PN-EN 590 + A1: 2017 with a low particulate contamination content

After the test completion the high-pressure pump and fuel injectors of HPCR system were disassembled to perform visual inspection of working surfaces of element's mating pairs. No damage of working surfaces of the assessed elements was found visible to the naked eye. To continue the evaluation, the components of fuel injectors were cut on a diamond saw to prepare specimens reflecting forms of wear in those parts of the system. Surface examinations on a HITACHI S-2600 N scanning electron microscope were performed to identify the forms of wear existing on selected injector components. No major forms of wear were found inside the nozzle tips (only material oxidation along the line of machining is visible and few shallow attrition places in a direction skew to the machining line) – Fig. 1.

Also needles, apart from small oxidation and clear traces of machining on majority of their length, have not shown traces of major surface wear. Visible small traces of needles attrition (asymmetric in nature) were found only on surfaces of their cylindrical guiding parts - Fig. 2.

No traces of wear (attrition) whatsoever were found on the working elements of the high-pressure pump.

In addition, tests of surface roughness and development were conducted, limited (due to a pretty complicated and costly procedure) to elements of selected nozzle needles. Tests were carried out in 3 random selected micro-areas (of approx. 1 mm^2 area each) of each needle representing a set originating from the performed test, at a distance of 5 to 15 mm from the place, where the needle cone passes into its guiding, working cylindrical part.

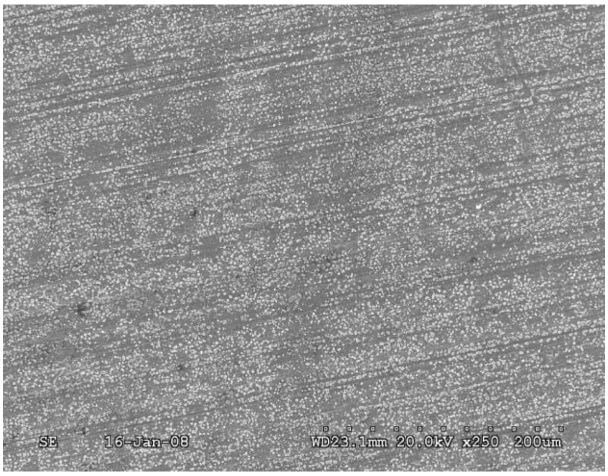

Fig. 1. Image of inside working surface of the nozzle tip body. Visible lines of machining shaping the surface of mating with the nozzle needle. Oxide bands arranged in accordance with the machining lines draw attention

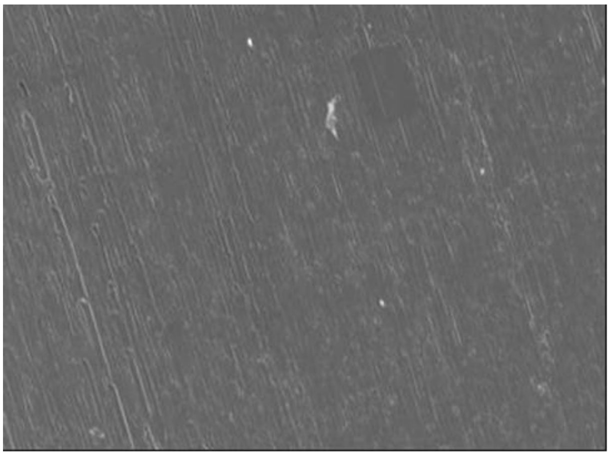

Fig. 2. Image of nozzle needle surface structure in its bottom, cylindrical (guiding) part. Characteristic places of attrition passing perpendicular to the needle axis draw attention in the image. No traces of surface oxidation. The surface of greater smoothness (worn) than in the central part of the element

For each place of test a height map was determined, 3D visualisation showing the surface topography and representative roughness profiles in the direction aligned with the needle axis (red line), and also in the direction perpendicular to the needle axis.

At the same time, for each place of test basic parameters describing the surface roughness were determined, i.e.: Ra – average roughness, Rq – mean square deviation of roughness, and Rt – maximum roughness height and selected parameters describing the profile line. Fig. 3 presents evaluation results of the first from the three tested micro-areas.

a)

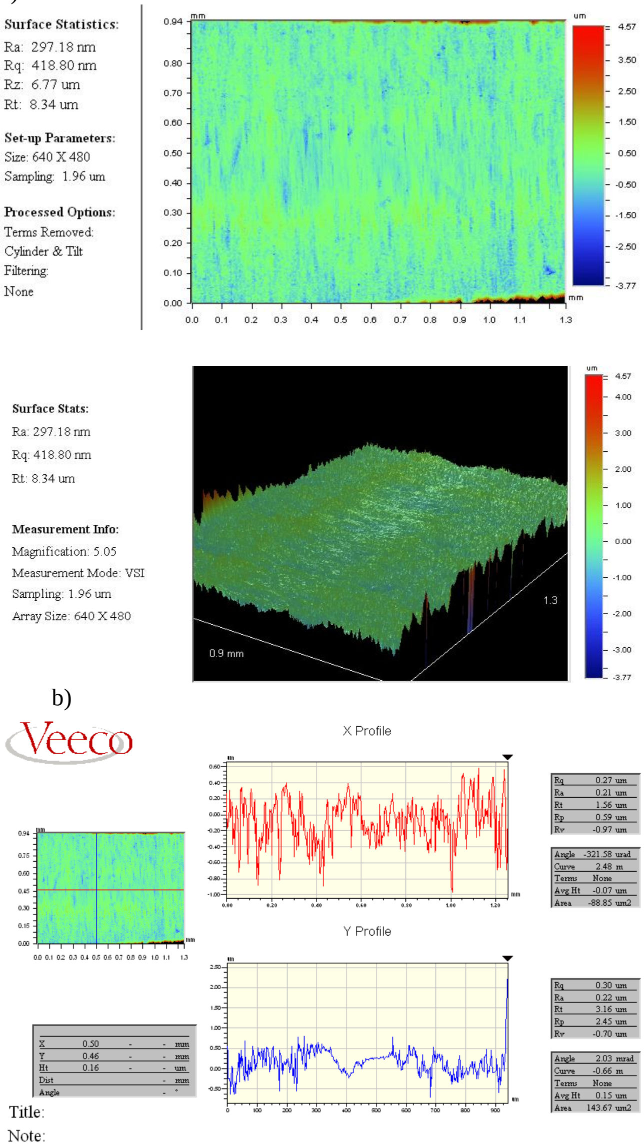

Fig. 3. Graphical results of testing the development (a) and roughness (b) of nozzle needle surface after the first test, for the first evaluated microarea [4]

3.2. Results of HPCR system components evaluation after the test of diesel oil consistent with PN-EN 590 + A1: 2017 with an increased amount of particulate contamination

After working during 178 hours difficulties occurred related to the maintaining the engine operation parameters in the test and at its starting. After starting, attempts to load it resulted in uneven operation and in effect, the engine stopped. The basic inspection of injectors in terms of flow, hence comparison of fuel dosage evenness via the measurement of overflow from individual injectors gave a clearly negative outcome. Differences in the amount of fuel dosed by individual injectors exceeded 30%.

Like in the case of the first test, after the second test completion the high-pressure pump and fuel injectors of HPCR system were disassembled to perform visual inspection of working surfaces of element's mating pairs. Visible damage traces (mainly in the form of attritions) were found on working surfaces of needles and plungers of valves controlling the fuel flow – Fig. 4.

a)

b)

Fig. 4. Traces of mechanical damage originated from the impact of hard particulate contaminations acting on the working parts of a) injector needle, and b) piston of valve controlling the fuel flow

Figure 5 presents selected components of the injection pump subject to macroscopic examination. This examination revealed clear traces of abrasive damage (microcutting, scratching, ploughing, adhesive wear) formed on side guiding walls of follower seats in the body of high-pressure part of the considered pump – Fig. 5a. Also characteristic, of this pump design, wear of the raceway of internal cam ring was found in the form of circumferential abrasive scratches and microgrooves (grooves) and thermal changes of colour – Fig. 5b. On side walls of followers damage of fretting nature was visible – Fig. 5c. Damage of similar type was observed on front surfaces of pistons in the high-pressure part of the pump – Fig. 5d.

a) b) c) d)

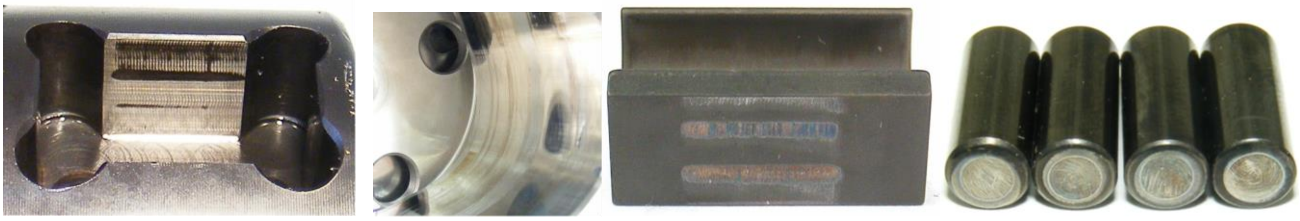

Fig. 5. Traces of abrasive or fretting damage observed on the working surface of high-pressure pump components: a) side guiding walls of follower seats in the pump body, b) raceway of internal cam ring, c) side follower walls, d) front piston surfaces

Before further evaluation, the nozzles of fuel injectors were cut on a diamond saw to prepare specimens reflecting forms of wear in those parts of the system. To identify the wear forms existing in selected injector elements the surface was examined on a HITACHI S-2600 N scanning electron microscope. Traces of damage (mainly in the form of attritions) found in internal working surfaces of nozzle bodies have clearly indicated the existence of an abrasive agent in the area between needles and nozzle bodies mating with them – Fig. 6.

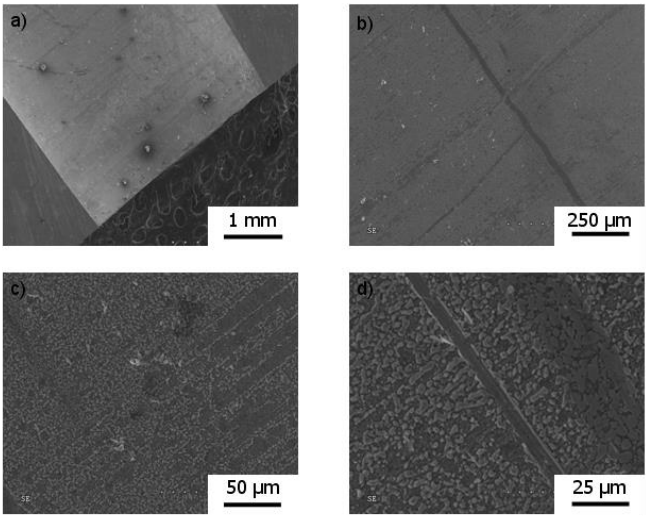

Fig. 6. View of internal working surfaces of injector nozzles, including a) single particulate contaminations of significant size, strongly embedded in the surface, b) an example of material wear, passing parallel to the nozzle axis, c) blooms of oxide nature, which arrange perpendicularly to the nozzle axis, d) local bloom attritions, proven by a line parallel to the nozzle axis not covered by a layer of considered bloom.

Figure 7 presents results of tests of surface roughness and development of selected nozzle needles elements after the second test completion. Test results apply to the first of three studied areas of nozzle needle elements, like in the case of the first test.

Table 3 presents a comparison of selected parameters of surface roughness evaluation results in three studied microareas of needle elements originating from the first and the second test.

Table 3. Comparison of roughness results of evaluated needles surfaces

Roughness Microarea	**Ra [nm]**	**Rq [nm]**	**Rt [µm]**
Nozzle needle after the first engine test			
first	210	281	8.84
second	216	288	8.13
third	229	338	14.46
Nozzle needle after the second engine test			
first	418	536	9.74
second	424	537	10.05
third	431	599	23.98

When comparing roughness results of evaluated nozzle needles after both tests it is possible to state that in the case of nozzle needles originating from the CR system working with diesel fuel containing an increased amount of particulate contamination (second test) – Fig. 7, Table 3, the surface roughness in each of studied areas is much higher as against similar ones, related to needles after the first test – Fig. 3, Table 3.

a)

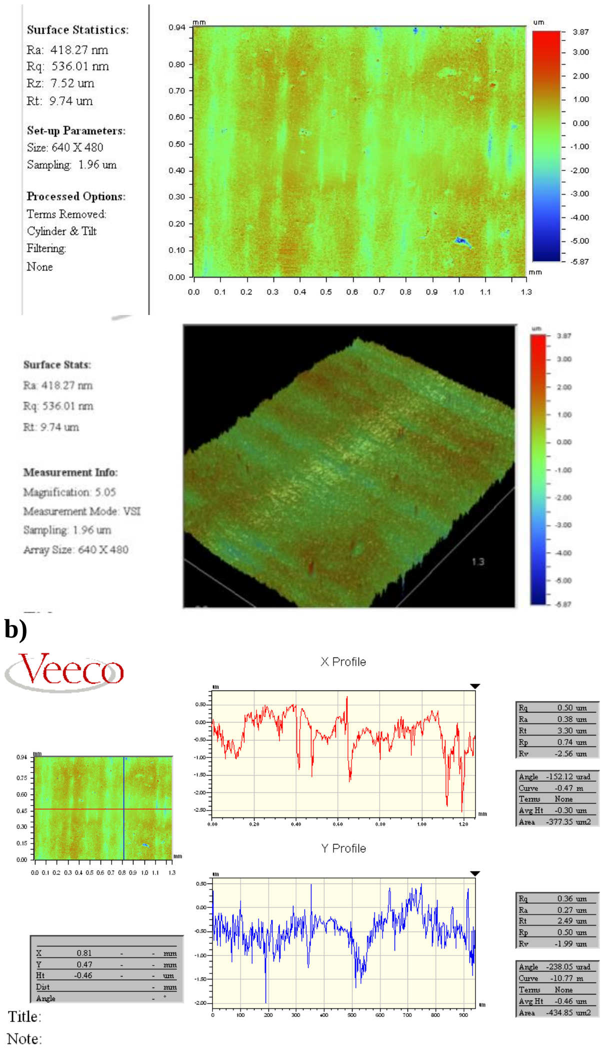

Fig. 7. Graphical results of testing the development (a) and roughness (b) of nozzle needle surface after the second test, for the first evaluated microarea [4]

Moreover, in the case of needles from the second test, apart from a higher surface roughness, grooves passing in the direction aligned with the needle axes are observed and also local extractions of the material and particles of particulate contamination locally embedded in the surface.

The needle surfaces after the first test feature roughness resulting from the applied preliminary mechanical treatment of the surface.

3.3. Results of particulate contamination measurements in commercial diesel fuels

Figures 8, 9, and 10 present results of particulate contamination weight content in random selected, in 2018, samples of commercial diesel fuels. In each of figures the orange line marks the maximum permissible amount of particulate contamination in accordance with requirements of PN-EN 590 + A1. These figures present consecutively the measured number of particles, in diesel fuel samples, broken down into sizes, i.e.: > 4 μm (code ISO 18): 1300–2500 particles – Fig. 8, > 6 μm (code ISO 16): 320–640 particles – Fig. 9, and > 14 μm (code ISO 13): 40–80 particles – Fig. 10. In each of figures the red line marks the maximum permissible amount of particulate contamination in accordance with requirements of the Worldwide Fuel Charter.

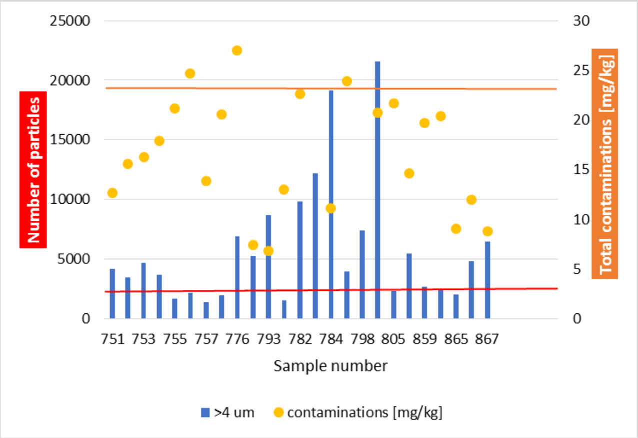

Fig. 8. Weight and quantity content of particulate matter (for particle size > 4 μm) in studied samples of diesel fuels

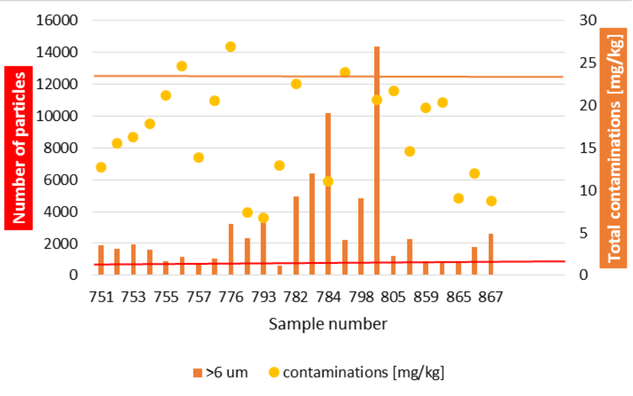

Fig. 9. Weight and quantity content of particulate matter (for particle size > 6 μm) in studied samples of diesel fuels

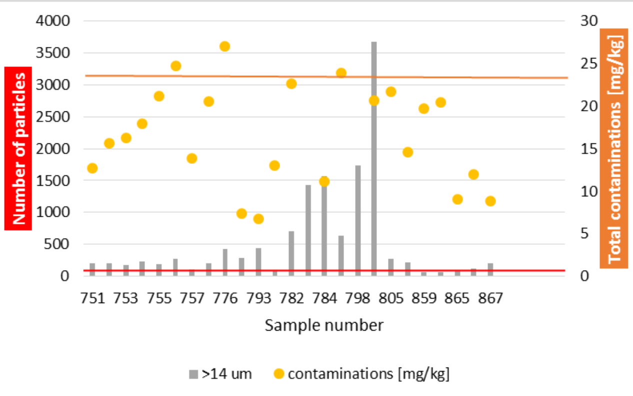

Fig. 10. Weight and quantity content of particulate matter (for particle size > 14 μm) in studied samples of diesel fuels

The obtained results have shown that in the case of weight content measurements for particulate contamination in random taken fuel samples it was found that in approx. 10% of cases the maximum value permitted by the standard PN-EN 590 +A1 was exceeded – Figs. 8, 9, and 10. Much more frequent and higher cases of exceeding were found in the case of particulate matter number measured in the same samples. In the case of particle size > 4 μm (code ISO 18), the cases of exceeding were registered in more than 60% of samples, including cases of exceeding the permissible value twice in approx. 40% of samples – Fig. 8. In the case of particle size > 6 μm (code ISO 16), the cases of exceeding were registered in more than 75% of samples, including more cases of exceeding more than twice in approx. 60% of samples – Fig. 9. While in the case of particle size > 14 μm (code ISO 13), the cases of exceeding were registered in more than 75% of samples, including cases of exceeding the permissible value twice in more than 50% of samples – Fig. 10.

4. Conclusions

The project comprised performance of tests, on an engine test stand, on the impact of particulate contamination quantity and size in diesel fuel on a possibility of accelerated wear and deterioration of operation of modern HPCR fuel injection systems. Also tests of particulate contamination content (total weight content and distribution of contamination size) in random sampled, on various petrol stations, samples of commercial diesel fuels of various producers were performed. The obtained results and observations allowed formulating the following conclusions and hypotheses:

- Particulate contamination in diesel fuel is an increasingly big threat to proper operation and durability of components of modern HPCR type fuel injection system, even if its amount does not exceed the permissible weight determined by the PN-EN 590 standard.
- The rate, size, and form of damage (wear) of working elements of HPCR fuel injection systems is affected not only by the amount (measured by weight) of particulate contamination, but primarily by its size distribution.
- Current studies on fuels available on the market in Poland prove frequent cases of exceeding the amount of particulate contamination in diesel fuel in terms of weight, and in particular in terms of particulate contamination size distribution.
- Further design and technological development of HPCR systems can force introduction of changes in the field of requirements related to particulate contamination of fuels determined by standard PN-EN 590, and even their broadening by parameters so far not subject to limitation (particulate matter size distribution), like it is the case of the Worldwide Fuel Charter.
- Manufacturers of HPCR type fuel injection systems seek lowering the permissible content of particulate matter in fuels, taking into account that further development of those systems will be heading towards obtaining higher and higher pressure of fuel injection, and hence related more and more precise machining and mating of working elements assemblies.

Nomenclature

HSDI Speed Direct Injection

HPCR High Pressure Common Rail

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