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THE PROCESS OF DEPOSIT FORMATION ON PIEZOELECTRIC INJECTOR OF *COMMON RAIL* FUEL INJECTION SYSTEM

Summary

The complexity of the deposit formation process on the components of compression ignition engine, including high-pressure injection Common Rail systems, is gaining global significance. Knowledge related to the mechanisms of their formation and chemical composition is still insufficient and requires further studies. The studies allowed, hypothetically, assuming several mechanisms of their formation, but each of them requires further research in order to be verified and finally confirmed. This is due to high complexity of the factors and conditions that may affect the initiation of the deposit formation, of which the most important are: fuel and additive composition and type of contaminants from fuel production and transport. Deposit physical nature may vary, as it may be soaps, salts of metals or ashless materials like imide or amide of organic polymers. This article contains the results of the research on the assessment of Common Rail injector components contamination and their technical condition, after 80 thousand km operational run, with the use of diesel and biofuel B10.
Key words*: engine, fuel injection, injector, fuel*

PROCES TWORZENIA OSADÓW NA ELEMENTACH WTRYSKIWACZY PIEZOELEKTRYCZNYCH UKŁADU WTRYSKU PALIWA TYPU *COMMON RAIL*

Streszczenie

Złożoność procesu tworzenia się osadów na elementach silnika o zapłonie samoczynnym, zwłaszcza w układzie zasilania Common Rail o wysokim ciśnieniu wtrysku, zyskuje istotne znaczenie. Wiedza związana z mechanizmami ich powstawania a także ich składem chemicznym jest wciąż niewystarczająca i dlatego procesy te wymagają dalszych badań. W badaniach zakłada się hipotetycznie kilka mechanizmów ich powstawania, ale każdy wymaga dalszych analiz w celu weryfikacji dokonanych założeń. Wynika to z dużej złożoności czynników i warunków, które mogą mieć wpływ na zapoczątkowania tworzenia się osadów, z których najważniejszymi są: skład paliwa, pakiety dodatków uszlachetniających oraz rodzaj zanieczyszczeń pochodzących z produkcji paliwa i transportu. Skład fizyko-chemiczny może się różnić, ponieważ mogą one stanowić mydła, sole metali lub materiałów bezpopiołowych oraz polimerów organicznych. W artykule zamieszczono wyniki badań autorów dotyczące oceny zanieczyszczenia i stanu technicznego wtryskiwaczy Common Rail zasilanych olejem napędowym i biopaliwem B10 po przebiegu eksploatacyjnym 80 tys. km.
Słowa kluczowe*: silnik, układ wtryskowy, wtryskiwacz, paliwo*

1. Introduction

Continuous advancement in development of combustion engine design and fuel process engineering bring major enhancement to performance characteristics, including limitation to the amount of deposits on engine components and emission of combustion gas toxic ingredients. Improvements to these solutions require various researches to be carried out both at the stage of formation & modernisation of engine structure and at the stage of implementation of technologically advanced fuels & new formula of engine oil. The contemporary feature of compression-ignition engines, including high-pressure Common Rail, is related to a growing complexity and, as a result, increased requirements concerning maintaining cleanness of components such as inlet system, combustion chamber, and injectors (frictional centre and injector taps).

Inevitable effect of fuel combustion in piston engine consists in formation of deposits on operating items that cause series of negative results in the course of their work, such as deterioration start-up abilities, power decrease, growth in fuel consumption, increase of fuel toxic ingredient emission [6, 7]. Solid deposits play significant role in modern engines that are equipped with elaborated, electronically controlled circuits. Contemporary compression-ignition engines require application of fuel that meet the criteria specified in the updated Worldwide Fuel Charter which includes standardised methods for engine testing along with detergent qualities of diesel oils and biofuels [13]. Operational and technical requirements towards diesel oils and biofuels should consider engine structural features, including high-pressure fuel injection system, multi-valve cylinder heads, multi-functional emission control, conditions of use, safety level and marketability [9, 11].

1.1. Factors shaping combustion process in compression-ignition engines

Following factors play crucial role for optimisation of combustion process in compression-ignition engines [4]:
- Fuel qualities (viscosity, density, fractional composition, cetane number, lubricity).

- Engine structural parameters (shape of combustion chamber, inlet system, compression ratio).
- Type and parameters of fuel injection (injection pressure, injection interval, stream range, vertical angle).

The phenomena that occur at the initial stage of combustion (ignition deceleration) determine its course, effectiveness, and emission of fuel toxic ingredients. Chemical ignition deceleration, which is one of major factors of the process, is conditioned mainly on fuel properties, such as fractional composition, heat of evaporation, continuous diffusion, pressure of saturated vapour, etc. These elements are crucial for the course of diffusion and heat exchange between air and fuel, forming fuel blend, and the value of self-ignition temperature. Considering optimal course of combustion, the duration of the initial stage (ignition deceleration) should be as short as possible and shortened along with the increase of engine rotational speed. The longer ignition deceleration causes the more fuel accumulation in combustion chamber and the more sudden combustion process (explosion stage) as well as the higher peak value of combustion pressure. The best self-ignition values, characterised by the least value of self-ignition deceleration, are attributed to diesel oils – normal chain, saturated hydrocarbons (paraffins). Fuel spraying is one of the most important factors related to combustion in compression-ignition engines. It is determined by the structural parameters of combustion chamber, the features of injection system and the parameters of injection.

Considering optimisation of combustion, sprayed fuel should be featured by possibly identical dimensions of all drops. The higher spray level (smaller diameter of drops) and spray homogeneity cause enhancement of vaporisation and combustion of fuel. The researches for new solutions related to injectors in Common Rail high-pressure injection system contributed to implementation of piezoelectric injectors. Injector tap diameter (from 0.123 mm do 0.117 mm) and length (to 0.85 mm) as well as increase in fuel injection dosage in the entire range of engine operation have been changed. Improved fuel spraying, increase in the range of stream and decrease in potential fuel coking on the surface of sprayer have been obtained [8]. Propagation of flame in conventional compression-ignition engine with direct injection during kinetic combustion, at 5.5^{o} crankshaft rotation upon fuel injection (right hand side) at the moment of forming heterogeneous diffusion flame with visible section of „separation” is shown in Fig. 1 [8].

The type and physicochemical properties of fuel (viscosity, density, fractional composition, cetane number, lubricity) and operational conditions of compression-ignition engine have material effect on the mechanism of deposit formation. The results of numerous researches [1, 2, 10] indicate the complexity of the process of deposit formation which may be diverse in respect of salts of metals' content in diesel oil, containing FAME or polymer ashless materials.

Necessity to limit deposit formation on Common Rail high-pressure fuel injection components has become an indicator for some researches. Diesel oils that have been commercially distributed may include various acidic components (non-saturated fatty acids) used as lubricating additives. That may support deposit formation due to the presence of acidic impurities and metal ions. As per [12], corrosion inhibitors that have been applied in the form of $NaNO_2$ in refinery pipelines (fuel flow), >0,1 mg·kg^{-1} content, may react with fatty acids forming sodium soaps of fatty acids.

Fig. 1. Propagation of flame in conventional self-ignition engine with direct fuel injection [8]
Rys. 1. Rozwój płomienia w konwencjonalnym silniku o zapłonie samoczynnym z bezpośrednim wtryskiem [8]

2. Experimental studies
2.1. Assessment of technical conditions of Common Rail fuel injection system in compression-ignition engine

The nature and specifics of experimental studies for engine fuels, including assessment of contamination level against durability of CR fuel injection system determines new trends for researches. In case of compression-ignition engines with fuel direct injection, its features determine quantity and duration of piezoelectric sprayer coking that is conditioned by fuel composition, fatty acid residue, package of additives and various solid impurities [5].

The range of studies included:
- generic analysis of deposits including chemical composition,
- technical condition assessment of piezoelectric injector (frictional centre),
- technical condition assessment of sprayer socket and taps (scanning microscope).

Technical condition of piezoelectric injectors in Common Rail compression-ignition engine (Fig. 2) including the type of deposits have been assessed through operational testing of vehicles powered by Ekodiesel Ultra and B10 biofuel as a mixture of 10% (V/V) FAME (Fatty Acid Methyl Esters) and 90% (V/V) ON – upon 80 thousand kilometre run.

Vehicle check-up procedures with OBDII diagnostics, for identification of reasons in case of periodical engine inefficiency, were carried out. Each time analysis of injector operational parameters, including identification of errors stored in the memory of ECU controller, was carried out. It was completed with application of external scanner only. Time analysis against variation run for selected operational parameters of CR system along with volumetric assessment for fuel flow rate on injector over-flow were carried out. Examples of selected operational parameters are shown in Table 1 that is related to correct *Smooth Running Control – SRC* including records for DPF regeneration state.

Source: own work / Źródło: opraccowanie własne

Fig. 2. General view on piezoelectric injector for compression-ignition engine powered by B10 biofuel upon 80 thousand kilometre operational run
Rys. 2. Widok ogólny wtryskiwacza piezoelektrycznego silnika o ZS zasilanego biopaliwem B10 po przebiegu eksploatacyjnym 80 tys. km

Table 1. Examples of engine selected operational parameters in the course of OBD II diagnostics
Tab. 1. Przykładowe zestawienie wybranych parametrów roboczych silnika w procesie diagnostyki OBD II

Control parameter	Measured value	Standardised value
Rotational speed	850 rev/min	Range of revolutions: up to 1500 rev/min
Dosage correction	95% 106% 109% 92%	Allowable value 20%
Cylinder injectors 1, 2, 3, 4		
Differential pressure for DPF Atmospheric pressure	46 hPa 980 hPa	230 hPa 600-1080 hPa
Mass air flow rate	290 mg/cycle	300 mg/cycle
Reload pressure	96 kPa	Basic value 100 kPa
Injection dosage	6.2 mg/cycle	6.8 mg/cycle

Source: own work / Źródło: opracowanie własne

ECU injection controller's role is to determine individual value of fuel unit dosage that is injected to each cylinder in order to meet the criteria for equality of crankshaft angular acceleration as a result of consecutive operational cycles within limits determined by the composition of toxic ingredients of exhaust gas. Variability of correction dosage against diagnostics assessment is assigned in many cases only to time characteristic for fuel injection excluding assessment of engine technical condition and diversified consumption of each cylinder. In order to eliminate this variable, a diagnostic assessment for static and dynamic leakproofness related to each cylinder in tested engines was carried out.

Setting about assessment of CR injector wear indicator, some decision simplifications related only to „overflow testing" determined through voluminal fuel outlay that is received from injector overflow tubes within selected time interval are taken. Obtained values occur not only from turning dosage received upon triggering internal control valve for injector pin rise and leakage of fuel along this pin but, as well, from alteration of outflow coefficient for particular sprayer injection taps. This type of diagnosis may not be carried out in case of some piezoelectric injectors as these are not equipped with overflow tube outlet.

For the purpose of this analysis, microscopic assessment for opening alterations, as a result of deposit formation and cavitation damages, was applied. Deposit formation within opening zone of fuel outlet on sprayer is shown in Fig. 3. Microscopic testing that demonstrates deposit formation in injector inlet of the sprayer supplied with B10 biofuel is shown in Fig. 4.

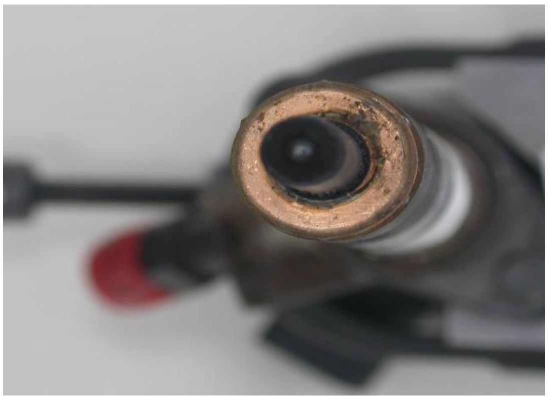

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Fig. 3. View on contaminated piezoelectric injector sprayer shown from the side of outlets upon 80 thousand kilometre operational run
Rys. 3. Widok zanieczyszczonego rozpylacza wtryskiwacza piezoelektrycznego od strony otworów wylotowych po przebiegu 80 tys. km

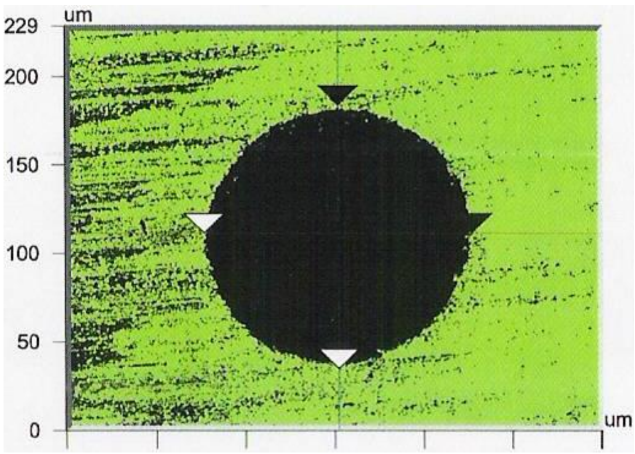

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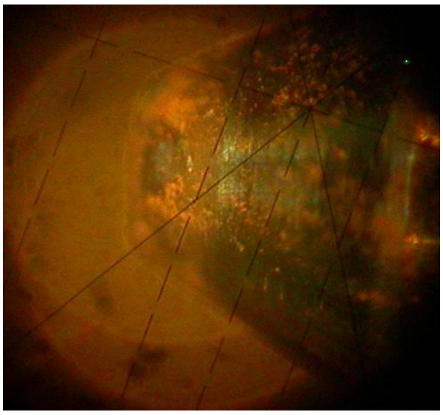
Fig. 4. Technical condition of a tap on injector sprayer that is supplied with B10 biofuel upon 80 thousand kilometre operational run recorded by camera
Rys. 4. Stan techniczny otworka rozpylacza wtryskiwacza zasilanego biopaliwem B10 po przebiegu eksploatacyjnym 80 tys. km, zarejestrowany kamerą

Basic geometric parameters that describe the nature of alterations on conical surface of sprayer section constitute cracks in the form of transverse and longitudinal scratches (typical pitting). Erosion of sprayer pin cone has been observed as well, within differentiated scale, in case of pins supplied with both diesel oil and B10 biofuel (Fig. 5) – testing by scanning microscope.

a) supplied with diesel oil



b) supplied with B10 biofuel

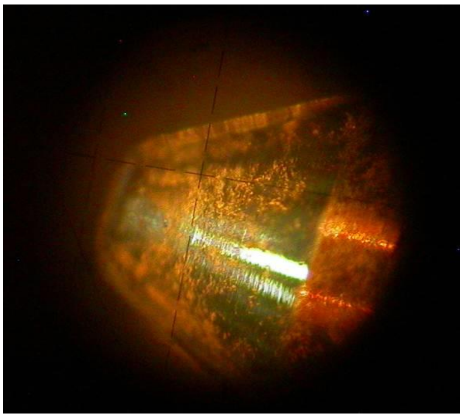


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Fig. 5. Erosion of injector sprayer pin cone upon 80 thousand kilometre operational run
Rys. 5. Proces erozji stożka iglicy rozpylacza wtryskiwaczy po przebiegu eksploatacyjnym 80 tys. km: a) zasilanie olejem napędowym b) zasilanie biopaliwem B10

2.2. Visualisation testing on fuel injection with piezoelectric injectors

Visualisation testings on fuel injection were carried out with Siemens piezoelectric injectors featured by 0 and 80 thousand kilometre operational run with the application of test stand for testing pump and injectors in Common Rail injection system that has been supplemented with high-pressure pump outlay module and volumetric efficiency (Fig. 6).

Assessment of the run of fuel injection in Common Rail system was carried out with application of Autotechnika tester that enabled simulation of injector or injector unit control, adjustment of injector opening time and frequency of switching on, including injector open impulse counting. The tester enabled injector opening time control within 200-2000 ms and each 10 ms step, injector opening frequency within 1-50 Hz and each 1Hz step, at the number of counted impulses within 1-10000 and each 1 step.

Geometry of fuel injection was recorded with High Speed Star 5 La Vision camera that was equipped with monochromatic CMOS converter (1024x1024 definition at 3000 frames per second) – Fig. 7.

The scope of testing included assessment of fuel stream range versus injection time at nominal pressure for injectors supplied (80 thousand kilometre) with diesel oil and B10 biofuel as well as at zero operational run injector supplied with B10 (Fig. 8).

Source: own work / Źródło: opracowanie własne

Fig. 6. Test stand for high-pressure pump and injectors in Common Rail fuel injection system
Rys. 6. Stanowisko do testowania pomp i wtryskiwaczy układu wtrysku paliwa typu Common Rail

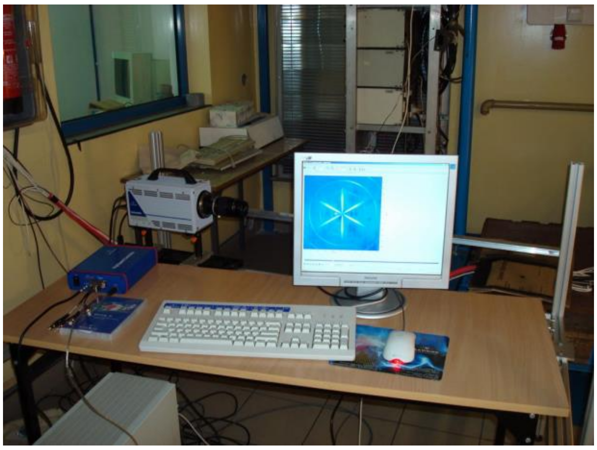

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Fig. 7. View on test stand including High Speed Star5 camera
Rys. 7. Widok osprzętu stanowiska badawczego wraz z kamerą

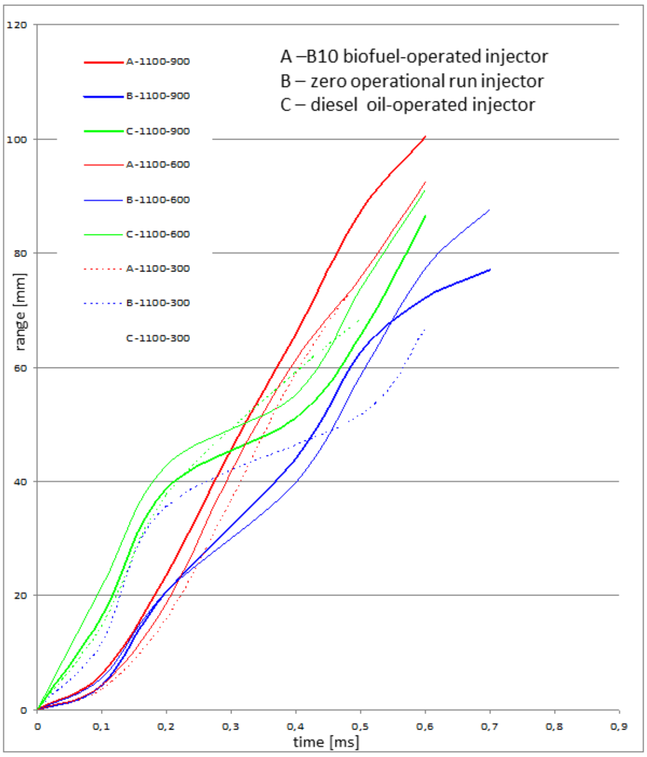

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Fig. 8. Fuel stream range versus injection time at 110 MPa pressure on injectors, in the course of operational run (80 thousand kilometre), supplied with diesel oil and B10 biofuel as well as for zero operational run supplied with B10 biofuel

Rys. 8. Zasięg strugi paliwa funkcji czasu wtrysku i ciśnienia 110 MPa wtryskiwaczy zasilanych w trakcie eksploatacji (80tys.km) olejem napędowym i biopaliwem B10 oraz dla zerowego przebiegu eksploatacyjnego przy zasilaniu paliwem B10

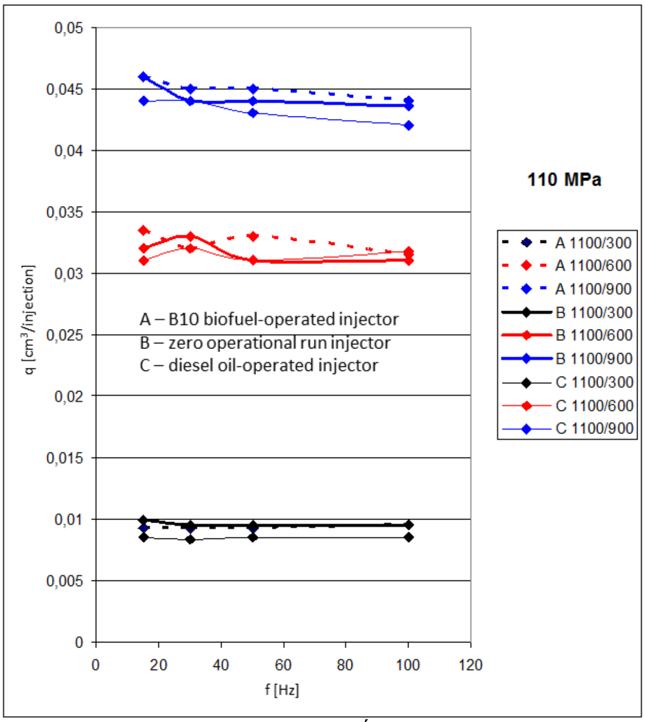

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Fig. 9. Unit outlay for fuel versus injector opening frequency at nominal pressure. Unit operated with diesel oil and B10 biofuel

Rys. 9. Wydatek jednostkowy paliwa w funkcji częstotliwości otwarcia wtryskiwacza przy ciśnieniu nominalnym przy zasilaniu ON i biopaliwo B10

The curves shown in Fig. 9 represent single outlay of fuel versus injector opening frequency at nominal pressure in case of supplying with diesel fuel and B10 biofuel B10. Zero operational run piezoelectric injectors supplied with diesel oil and B10 biofuel, which has been assessed, were featured with approximate stream range that indicated stability of operational conditions. This demonstrated insignificant sensitiveness to minor (20%) differential pressure of injected fuel obtaining comparable value of fuel unit dosage; however the quantity of injected diesel oil dosage was different from B10 biofuel dosage in case of application of nominal pressure for various opening times. It proves that the endings of injector were coked.

The analyses that have been carried out indicate that efficiency of high-pressure Common Rail fuel injection units deteriorates. Deposits (carbon deposits) that form on endings of sprayers constitute the reason for such deterioration which is a crucial factor for operated compression-ignition engines. As deposits form in various manners, there is a need to continue testing within determined range. Working conditions for injectors that follow cyclical pattern of altering loads at temperatures reaching up to approximately 300°C depend on physicochemical properties of fuels. Registered geometrical and structural alterations on precise pairs of injector frictional node upon 80 thousand kilometre operational run (especially B1- biofuel-operated) should be attributed to non-saturated fatty acids and metallic ions presence occurring from the occurrence of FAME. Fuel and biofuel additive chemical compositions largely determine tendency to deposit formation around injector outlets. The presence of linoleic and linolenic acids leads to biofuel oxidation and polymerisation.

2.3. Spectral analysis on deposits forming within fuel injector outlets

It has been determined that the need for *Smooth Running Control – SRC* through the application of ECU controller on engine supplied with B10 biofuel was mainly the result of fuel inappropriate spraying occurring from accumulation of carbon deposits within sprayer outlet zone. Spectral analyses were oriented to deposit chemical composition identification that served for determination of B10 biofuel application impact on deposit formation. The process of application included the assessment of precipitated non-oxidised organic ingredients content. Spectral analysis on deposits collected from the sprayers' surface within CR injector outlets was carried out. X-ray fluorescence spectra including XRF ED energy dispersion were recorded with ED 2000 Oxford Instruments whereas infrared spectra (FTIR) were recorded with FTS 175 BIO-RAD.

XRF curve record for deposits collected from sprayer placed on engine supplied with and B10 Ekodiesel Ultra biofuel are specified in Fig. 10-11. On the basis of alteration assessment on band intensity for identified elements, a quality assessment on deposits was carried out. Such elements as mainly iron, zinc, chromium, nickel, and copper were found in tested deposits. Except that, presence of calcium, phosphorus, and sulphur was confirmed. Iron is a derivative of corrosion process, whereas chromium, nickel, and copper occurrence is a prove for the existence of frictional wear in CR high-pressure pump unit. The presence of zinc, calcium, and phosphorus is resulting from engine oil degradation, including degradation of additives that contact FAME. Except that, depressants as components of biofuel additives contain iron ions [3].

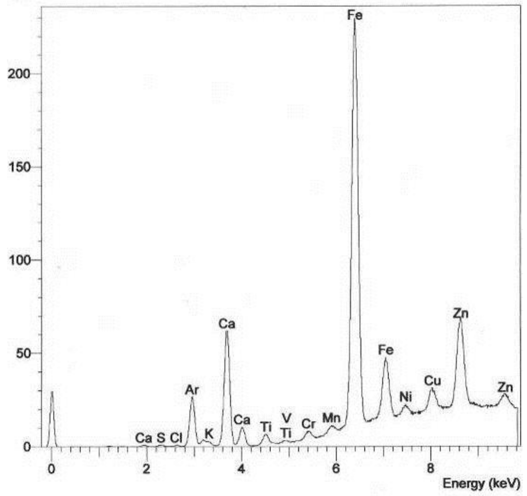

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Fig. 10. XRF spectrum for deposits collected from the zone of B10-operated engine injector openings

Rys. 10. Widmo XRF dla osadów ze pobranych ze strefy otworów wtryskiwacza silnika zasilanego paliwem B 10

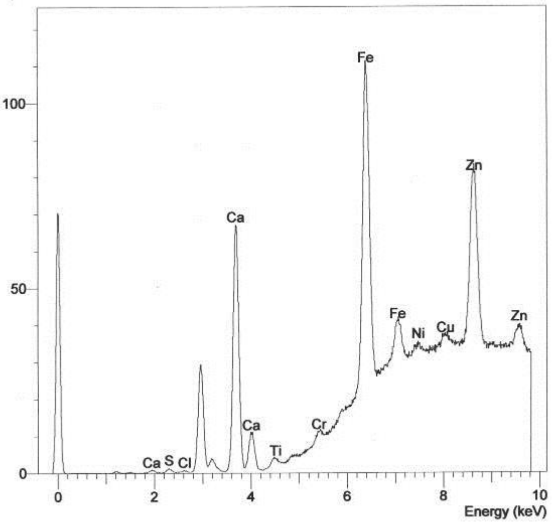

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Fig. 11. XRF spectrum for deposits collected from the zone of Ekodiesel Ultra-operated engine injector openings

Rys. 11. Widmo XRF dla osadów ze pobranych ze strefy otworów wtryskiwacza silnika zasilanego paliwem Ekodiesel Ultra

In XRF deposit spectrum for B10-operated engine, a higher intensity of iron band was observed. Relatively high intensity of calcium and zinc band intensity was recorded. It indicates presence of pollutions in engine oil and occurrence of band that indicates presence of nickel. The effect that disturbs spectral analysis is the presence of fraction derived from engine breather oil emulsion.

Upon washing out diesel oil and B10 biofuel deposits (originating from engine fuel unit injectors) with chloroform, infrared spectrum was obtained, Fig. 12, in which remaining from fuel and greasing oil degradation were observed.

The spectrum approx. 1655 cm^{-1} is the most intensive within 2000 cm^{-1}–1600 cm^{-1} diagnostic area. It confirms occurrence of organic compound oxidation to carbonyl and carboxyl structures. The influence of these compounds on nitrogen oxides is most likely related to the presence of hydrate salts of carboxyl acids. These substances may, as well, originate from oxidation and degradation of additive bases that are present in engine oil.

Approx. 1630 cm^{-1} band is derived from other compounds that contain C-O-NO_2 bonds. These originate from nitro-oxidation of engine oil components and fuel by nitrogen oxides. In case of a substance emitted from deposit for B10-operated engine, IR spectrum is richer. Intensive band 1747 cm^{-1} related to presence of esters was observed, but it may not be confirmed unambiguously whether there are FAME non-degraded esters or the products of their degradation or di- or trimerisation. For identification of ester group deposits, relations between carbonyl groups C=O (aliphatic) and their corresponding band within wave number 1750-1735 cm^{-1} zone are representative. The presence of ester structures is confirmed by bands within „finger print" (approx. 1240 cm^{-1} and 1160 cm^{-1}) range. The band approx. 1720 cm^{-1} originates from other carbonyl or carboxyl compounds, whereas the band approx. 1633 cm^{-1} indicates the presence of products that are the result of interaction between nitrogen oxides and products of fuel oxidation. Weak band approx. 1735 cm^{-1} originates from other compounds containing C=O bonds that form as a result of diesel oil and fuel ingredient oxidation.

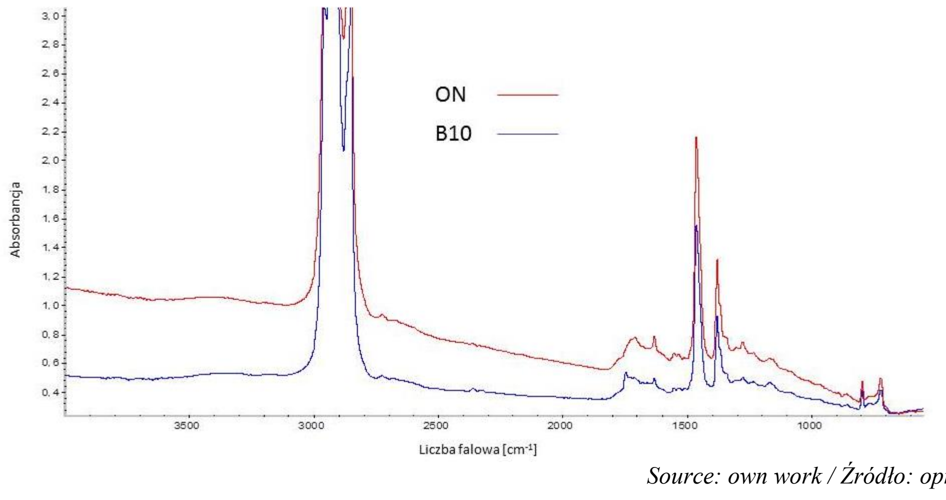

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Fig. 12. Infrared spectrum (4000-900 cm^{-1}) for soluble part of deposit coming from outlet of injector placed on engines that are supplied with tested diesel oil (red curve) and B10 (blue curve)

Rys. 12. Widmo w podczerwieni (zakres 4000-900 cm^{-1}) części rozpuszczalnej osadu ze strefy wylotu otworów wtryskiwacza silników zasilanych badanymi paliwami ON (czerwony) i B10 (niebieski)

3. Conclusions

1. Limitation of deposit formation on operational elements of piezoelectric injectors in Common Rail high-pressure fuel injection system supplied with mercantile diesel oil and B10 biofuel requires application of more efficient detergent-dispergate additive and, at the same time, guarantee demanded operational properties.
2. Fuel volume insignificant divergence in the course of piezoelectric injectors' operation in Common Rail high-pressure system operated by diesel oil and B10 biofuel result from different physicochemical properties of those products and increased deposit formation in B10 biofuel.
3. FAME, which is present in diesel oil, create favourable conditions for deposit formation in compression-ignition engine due to B10 biofuel acidic impurities found in the production of fatty acid methyl ester of rape oil, including those formed throughout auto catalytic division of fatty esters with participation of metallic ions.
4. Visual testing on fuel (diesel oil, B10) injection constitutes valuable source of information for the development of flow curves related to described fuels in the course of designing injectors for Common Rail high-pressure system.
5. Analysis of X-ray fluorescence spectrum with energy dispersion in the range of assessment of elements' presence in deposit structure within sprayer outlet zone, including spectrum record in infrared radiation upon its extraction confirmed the presence of organic compounds.
6. Major source of deposit that formed on Common Rail high-pressure fuel injection system is a group of rape oil fatty acid methyl ester polymers and destructive residue originating from enriching packs.

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