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Zinc as a catalyst supports processes of Diesel injector deposit formation

The article presents a comparative analysis of engine tests results concerning assessment of reference Diesel fuel RF-79-07 Batch 9 with the addition of two various zinc catalyst toward formation of fuel injector deposits of HSDI (High Speed Diesel Injection) Diesel engine. Engine dynamometer, comparative tests were done in compliance with requirements of standardized test according to pan-European research procedure CEC F-98-08, at which as a criterion for the fuel injectors deposit formation assessment has been assumed loss of engine rated power between the beginning and the end of the test. For engine calibration used in the above mentioned procedure the fuel used shall be the reference fuel CEC RF-79-07 with a low tendency to injectors fouling and the same fuel with artificially, intentionally introduced 1 ppm Zn as a metallic catalyst to support the process of injector deposits formation. When starting to reference fuel developing with admixture of Zn, it has been established that, Zn may be present in fuel in the form of zinc salts, colloidal and in the form of micro-particulates, constitutes traces fuel contaminations. Given that the colloidal form of zinc is difficult to produce, and zinc micro-particulates are filtered in the engine fuel system, it has been established that, Zn will be artificially introduced into the fuel in the form of the easily soluble synthetic Zn salt that is Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$), that is the same as recommended by test procedure CEC F-98-08 or will come from galvanized drums introduced as a result of fuel conditioning in a galvanized drums. Tests covered assessments of reference Diesel fuel without and with the addition of zinc catalyst of varying chemical structures and with different zinc contents. The conducted research has demonstrated that:

- Diesel fuel doped even with traces of zinc increases its tendency to fuel injector deposit formation;
- Contained in the Diesel fuel zinc compound influence on the rate and amount of fuel injector coking deposits of the Peugeot DW10B test engine generated in the test at a CEC F-98-08 procedure;
- The increase of the zinc volume contained in the Diesel fuel beyond the indicated in CEC F-98-08 test procedure level of 1 ppm, causes the rapid loss of the fuel detergent performance which is proven by rapid loss of engine rated power.

Key words: Diesel fuel, fuel injector deposit, zinc catalyst, engine dynamometer tests.

Cynk jako katalizator wspomagający procesy tworzenia osadów wtryskiwaczy silników z zapłonem samoczynnym

W artykule przedstawiono porównawczą analizę wyników testów silnikowych dotyczących oceny tendencji do tworzenia osadów wtryskiwaczy silnika ZS typu HSDI (*High Speed Direct Injection*) dla wzorcowego oleju napędowego RF-79-07 Batch 9 z dwoma różnymi katalizatorami cynkowymi. Porównawcze testy silnikowe wykonywano zgodnie z wymaganiami znormalizowanego testu według ogólnoeuropejskiej procedury badawczej CEC F-98-08, w której jako kryterium oceny wielkości utworzonych osadów na końcówkach wtryskiwaczy przyjęto wielkości spadku mocy silnika. Do wzorcowania silnika wykorzystywanego w wyżej wymienionej procedurze badawczej stosuje się paliwo wzorcowe CEC RF-79-07 o niskiej tendencji do zanieczyszczania wtryskiwaczy i to samo paliwo ze sztucznie, celowo wprowadzonym 1 ppm Zn jako katalizatorem metalicznym wspomagającym proces tworzenia osadów wtryskiwaczy. Przystępując do opracowanie paliwa wzorcowego z domieszką Zn, ustalono, że Zn może występować w paliwach w postaci soli cynku, koloidalnej i w postaci mikrocząstek stałych, stanowiących śladowe zanieczyszczenia paliwa. Biorąc pod uwagę, że koloidalna postać cynku jest trudna do wyprodukowania, a mikrocząsteczki cynku podlegają procesowi filtracji w układzie paliwowym silnika, ustalono, że do paliwa będzie sztucznie wprowadzany Zn w postaci łatwo rozpuszczalnej syntetycznej soli cynku, tj.: neodekanianu Zn ($Zn(C_{10}H_{19}O_2)_2$), a zatem takiej jak zaleca procedura badawcza CEC F-98-08, lub będzie pochodził z ocynkowanych beczek, w których paliwo było przetrzymywane. Testy obejmowały oceny wzorcowego oleju napędowego bez i z katalizatorem cynkowym o różnych strukturach chemicznych oraz z różną zawartością cynku. W wyniku przeprowadzonych badań stwierdzono między innymi, że:

- wprowadzenie do oleju napędowego nawet śladowych ilości cynku zwiększa jego skłonność do tworzenia osadów na końcówkach rozpylaczy paliwa,

- zawarty w paliwie związek cynku ma wpływ na szybkość tworzenia i wielkość osadów koksowych tworzonych w teście według procedury CEC F-98-08, na końcówkach wtryskiwaczy silnika Peugeot DW10B,
- zwiększenie ilości zawartego w paliwie cynku ponad wskazany w procedurze badawczej CEC F-98-08 poziom 1 ppm powoduje gwałtowną utratę właściwości detergentowych paliwa – na co wskazuje szybki spadek mocy maksymalnej silnika.

Słowa kluczowe: olej napędowy, osady wtryskiwaczy paliwa, katalizator cynkowy, testy silnikowe.

Introduction

The gradual evolution of CI engine design, starting from engines with indirect low-pressure fuel injection using in-line, multi-sections and then distribution (rotary) fuel pumps and pintle injectors, led to the introduction of High Speed Direct Injection (HSDI) engines with High Pressure Common Rail (HPCR) injection systems. The use of HPCR fuel injection systems has had a great impact on improving the timing control of the processes of fuel injection and its fragmentation, which has contributed to shortening the time of development and improvement of the quality of the air-fuel mixture in the engine cylinders, the optimisation of combustion processes and consequently the considerable reduction of the emission of harmful components and fuel consumption. This was possible thanks to significant design changes in the fuel injection system, its operation and working conditions of some components [20, 21]. At the same time, the problem of the so-called coking of injector nozzle outlet ducts was observed in CI engines with indirect fuel injection system as early as in the 1980s. Over time, the increasingly complex and precisely constructed components of the high-pressure fuel injection systems became more and more susceptible to failures caused by various types of deposits produced on the work surfaces of components of these systems. From the point of view of the risks to the correct operation of the fuel injection system posed by the formation of deposits, the most sensitive element are injectors, especially their nozzles. In the case of HPCR systems, these are usually multi-hole injectors [17, 19].

The technical solutions used in HPCR systems which bring them their advantages include the maximum reduction of the diameter of the ducts ending with atomized fuel outlet holes, giving the fuel outlet ducts the appropriate shape and the high fuel injection pressure. The geometry of the fuel outlet duct has a major influence on the flow current field lines and, consequently, on the fragmentation of the fuel into droplets and their dispersion in the air charge and then evaporation. For a more precise and stable fuel injection, the inlet edges of the ducts are rounded off by application of flow grinding using a special liquid, i.e. by means of electrical discharge machining [17, 19, 23].

Rounding off the edges at the inlet of the conical fuel duct leads to an increase in fuel flow velocity and efficiency as well as an increase in the range of the out-flowing fuel stream and thus an improvement in the flow conditions. At the same time, the geometry of the fuel outlet influences the processes of turbulence, cavitation and spatial distribution of the fuel stream velocities inside the nozzle [2–5, 9]. In the actual operating conditions, the use of conical outlet ducts in nozzles brings measurable effects, allowing to increase the velocity of the out-flowing fuel stream and thus its momentum. This significantly improves the quality of atomization, resulting in the better mixing of fuel and air in the combustion chamber. However, all the design and engineering solutions described above may not have the expected effect due to the formation of deposits, among other things, on nozzle tips and inside nozzle ducts. In engines with indirect fuel injection system, the fouling of pintle injector nozzles with coke deposits includes both the fuel outlet duct and the area around the edge of the fuel outlet ring hole and the cylindrical part of the pintle working with the fuel injection hole – Figure 1. In case of this type of injectors, the size and rate of coking of injector nozzles are more influenced by the type (design) of the used nozzle than by the fuel. The opposite is true for external deposits at the nozzle tips of HPCR fuel injection systems, where the deposits form around and at the edges of the fuel outlet holes but also on the walls inside the fuel ducts of injector nozzles – Figure 1. They are usually a mixture of organic and inorganic deposits. Given that the internal diameter of the fuel duct is often less than 0.1 mm, the produced deposits cause deformation of the stream of the atomized fuel and a change in its range, which adversely affects the processes of fuel fragmentation and mixing with air in the engine combustion chambers [6, 7, 10, 13, 14, 19, 21]. This results in reduced engine performance, uneven engine operation, increased emissions of harmful components of exhaust gases and increased fuel consumption. In extreme cases, the deposits forming inside the fuel ducts can lead to a complete blockage of the hole, especially when the engine is often stopped and cooled down during operation, which allows the deposits to stabilize.

The popularisation of low-sulphur diesel oils and the share of the biocomponents contained within them led to the intensification of deposit formation on the internal surfaces of the components of both pumps, injectors and nozzles, which cause

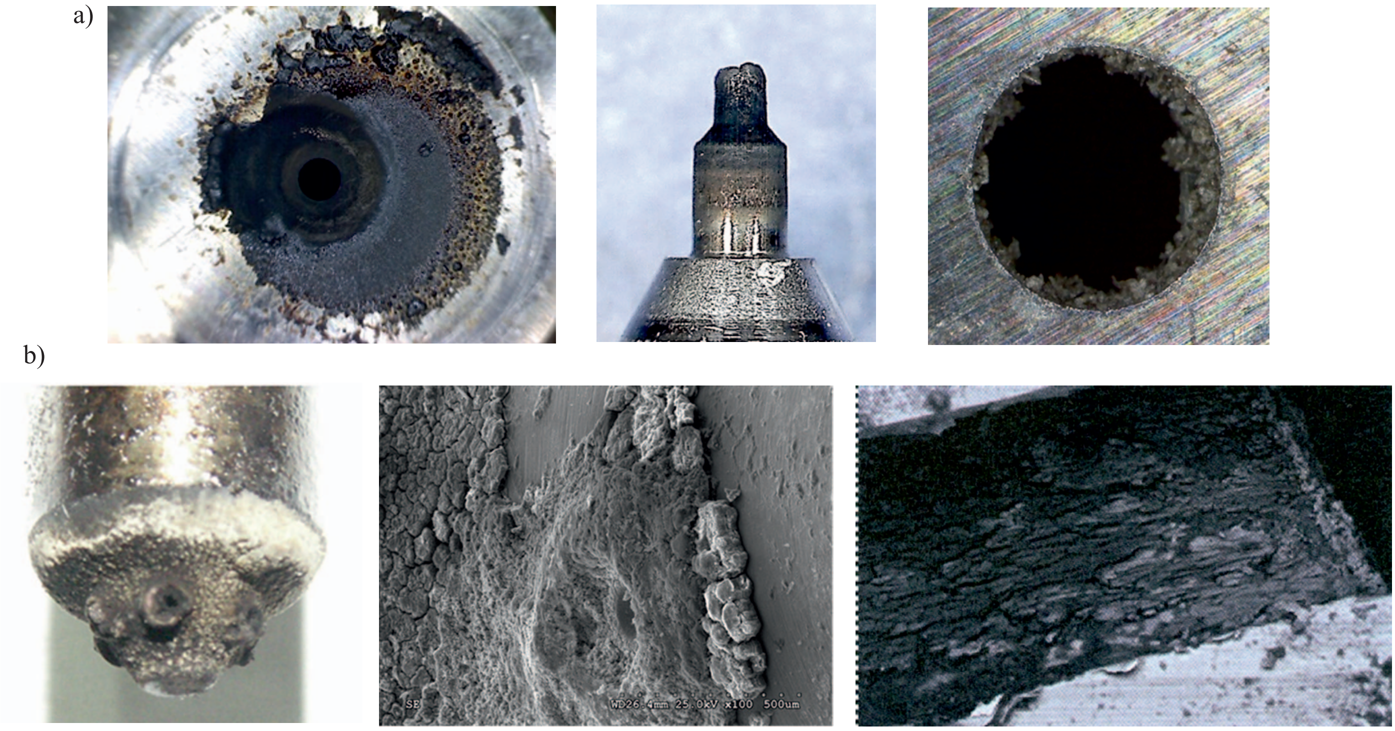

Fig. 1. Various forms of external coke deposits (INiG – PIB);
a) on pintle injector nozzles, b) on multi-hole injector nozzles (Common Rail)

the coking of fuel dispensing holes, which – especially in the case of precise HPCR multi-hole injectors – began to pose risk to their proper and stable operation.

An additional factor that poses a potential threat to this type of injectors is their operation on fuels containing biocomponents. Apart from many indisputable and generally known advantages, this type of fuel is characterized by a number of unfavourable properties from the point of view of the operation with a traditional combustion engine, including low stability and the tendency to produce acids with low molecular weight which significantly accelerate the formation of coke deposits in the area of injector nozzles of the engine fuel supply system [8, 11, 16, 25, 26]. Other factors contributing to the formation of injector deposits include the direct impact of the environment of combustion processes and the very high temperature the nozzle tips can heat up to (about 350°C). In addition, the high precision of their construction required to obtain a very high fuel injection pressure (250÷300 MPa), causes a significant fuel temperature increase during a sudden drop of its pressure after its passage (leakage) through the leaks of working pair of the injector firing pin and the cylinder in the injector nozzle housing [3, 22, 24]. In combination with the impurities entering the fuel in the processes of its production, distribution and storage (especially the contamination with metallic elements with catalytic properties), this intensifies the process of the formation and growth of the internal deposit.

These problems, which occur globally, have led to the need to develop a pan-European, universal engine procedure for testing and assessment of the formation of external deposits at the nozzle tips of HPCR fuel injectors.

As a result, under the CEC (Co-ordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants and Other Fluids), a Working Group CEC TDG-F-098 was established in 2006 to develop the required test procedure. The development of this procedure was started on the assumption that it must allow for a reliable differentiation between diesel oils with high and low tendency to produce external fuel injector deposits in the tested engine. The size of the decrease in the maximum engine power measured at the beginning and after the end of the test was used as a criterion for assessing the size of the deposits produced during the test. The power decrease is caused by quantitative and qualitative disturbances in the fuel injection into the engine combustion chambers due to the formation of deposits in the ducts and around the fuel outlets of the injector nozzles. It was established that the maximum acceptable power decrease for a fuel that does not pose a risk to the proper operation of an HPCR fuel injection system should not exceed 2%.

An HSDI engine, specifically Peugeot DW10B from the HDi family, which meets the Euro 4 emission requirements for harmful exhaust gas components was used as the test apparatus. It is a turbocharged 4-cylinder unit with a 2.0 dm^3 displacement, 4-VPC, OHC valve train and the maximum power of 100 kW and equipped with an HPCR fuel injection system with the maximum injection pressure of 1.600 bar. The injection system uses Euro 5 injectors with six outlets with a diameter of 0.11 mm.

They are characterized by particularly precise finishing of the internal conical outlet ducts with a low CD (cone factor). The edges at the inlet of the ducts are rounded with hydro-erosion machining to minimize the cavitation processes.

Ultimately, June 2008 saw the adoption of the pan-European testing methodology described in the procedure entitled: Development of Peugeot DW10 Direct Injection Diesel Nozzle Fouling Test and designated as CEC F-98-08 [15, 17]. This procedure describes the only currently standardized method to assess the detergent properties of refined and non-refined diesel oils in HSDI (High Speed Direct Injection) compression ignition engine powered by HPCR (High Pressure Common Rail) technology.

The engine calibration process uses reference fuel CEC RF-79-07 with a low tendency to foul the injectors and the same fuel with artificially introduced 1 ppm of Zn as a metallic catalyst supporting the process of injector fouling. When starting to develop a reference fuel with an admixture of Zn, it was established that Zn might be present in the fuels as zinc salts, in a colloidal form and in the form of solid micro-particles, which form trace fuel impurities. Given the fact that the colloidal form of zinc is difficult to manufacture and that zinc micro-particles are subject to the process of filtration in the engine fuel system, it was decided that Zn would be artificially introduced into the fuel in the form of an easily soluble synthetic zinc salt, i.e. Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$).

In accordance with literature data, trace amounts of metallic elements contained in diesel oils affect engine deposit formation processes in fuel injectors [1, 4, 11, 12, 19, 21].

One such element is the above-mentioned zinc used in the CEC F-98-08 test, which contributes most to the external fuel injector fouling in HPCR fuel injection systems [4, 5, 9, 11, 17, 21].

The results of the tests described in the literature and the fact that one of the zinc salts (neodecanoate) is used in a standardised engine test (CEC F-98-08) to assess the process of fuel injector fouling encouraged the author to carry out a study of the influence of the amount of zinc contained in the fuel and the chemical structure of zinc compounds on the external CI engine fuel injector fouling.

Contemporary diesel oils do not usually contain zinc and it is not present in any of the components or additives. Therefore, this metal is a type of diesel fuel pollutant. Most often it can be introduced into the fuel during transport and distribution as a result of a contact with zinc-containing tanks (e.g. galvanized drums) or elements of the low-pressure part of the fuel injection system (e.g. fuel filter housing coated with zinc). Therefore, a zinc compound introduced into fuel in this natural way was used for comparison tests with artificially introduced zinc in the form of zinc salt, i.e. Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$) in accordance with the procedure CEC F-98-08.

Subject matter of the study

The tests assessed diesel oil CEC RF-79-07 Batch 9 with the physicochemical properties specified in Table 1 for use as a reference fuel in accordance with the requirements of test procedure CEC F-98-08.

Zinc was introduced into the diesel fuel CEC RF-79-07 Batch 9 in two forms:

- zinc neodecanoate ($Zn(C_{10}H_{19}O_2)_2$) – a representative of aliphatic acid salts used in the test procedure CEC F-98-08,
- zinc in the form of ZnO, $ZnO.H_2O$ oxide/hydroxygenate was introduced as a result of fuel conditioning in a galvanized drum. It was decided to conduct dispersion under the influence of detergent-dispersing additives and FAME of oxides/hydroxygenates from the passivated inner drum surface.

The tests also included an assessment of the impact of a higher-than-1 ppm zinc content in the fuel on the fuel tendency to foul the injector nozzle tips. Table 2 presents a list of all the fuels with zinc whose results are presented in the article.

Table 1. Selected physicochemical properties of the reference diesel fuel CEC RF-79-07 Batch 9 [Haltermann]

Tested parameter	Unit	ON-CEC RF-79-07 Batch 9	Determination method
Cetane number	–	52.7	EN ISO 5165
Density at 15°C	kg/m^3	835.3	EN ISO 12185
Fractional composition – 95% (*v*/*v*) distils to temperature	°C	348.8	EN ISO 3405
Fractional composition – 50% (*v*/*v*) distils to temperature	°C	247.0	EN ISO 3405
Kinematic viscosity at 40°C	mm^2/s	2.85	EN ISO 3104
Cold filter blocking temp.	°C	–5	EN 116
Ignition temp.	°C	65	EN ISO 2719

ect. Table 1

Tested parameter	Unit	ON-CEC RF-79-07 Batch 9	Determination method
Carbon residue from 10% dist. res.	% (*m/m*)	0.015	EN SO 10370
Ash content	% (*m/m*)	< 0.002	EN ISO 6245
Sulphur content	mg/kg	7.6	ASTM D 5453
Water content	mg/kg	65	EN ISO 12937
Total contamination	mg/kg	6	EN 12662
FAME content of medium distillates	% (*v/v*)	0.0	ASTM D 7371
Oxidation stability	mg/ml	0.022	EN ISO 12205
Lubrication, wear scar diameter (WSD) at temp. 60°C	µm	380	EN ISO 12156-1
Zn content	mg/kg	< 0.1	ASTM D 7111
Cu content	mg/kg	< 0.1	ASTM D 7111

Table 2. List of fuels assessed in the engine test according to the test procedures CEC F-98-08

Item	Fuel	Content Zn [ppm]	Origin Zn	Comments
1.	CEC RF-79-07 Batch 9	~0	–	Reference fuel to DW10
2.	CEC RF-79-07 Batch 9	~1	Artificially introduced in the form of a zinc salt Zn neo-decanoate ($Zn(C_{10}H_{19}O_2)_2$)	Zn compound and the method of introduction in accordance with CEC F-98-08
3.	CEC RF-79-07 Batch 9	~1	Zinc from galvanised drums in which the fuel had been kept for a period of 5 weeks	The fuel was a mixture of "fresh" CEC RF-79-07 Batch 9 with the same fuel previously stored in a galvanized drum
4.	CEC RF-79-07 Batch 9	4	Zinc from galvanised drums in which the fuel had been kept for a period of 5 weeks	The fuel was a mixture of "fresh" CEC RF-79-07 Batch 9 with the same fuel previously stored in a galvanized drum

Test methodology

All the tests were carried out on a test stand equipped with a Peugeot DW10B engine – Figure 2. The tests were conducted according to the current version of test procedure CEC F-98-08.

The only exceptions that were made from this procedure in some of the tests described below concerned the use of a different Zn chemical compound and/or its content other than 1 ppm in the test fuel.

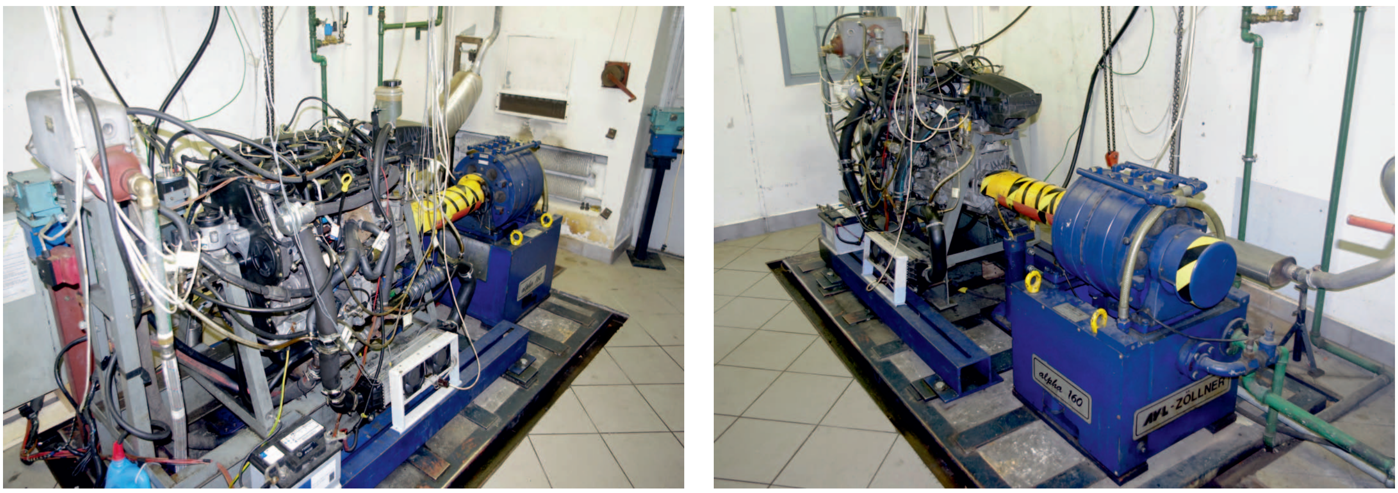

Fig. 2. A test stand with Peugeot DW10 engine according to the procedure CEC F-98-08 (INiG – PIB)

Test results

Both before and after each test, ASTM D 7111 method was used to check and confirm the content of Zn introduced into the fuel CEC RF-79-07 Batch 9 and that the content of Cu, Pb, Sn, Ca, K, Na metallic impurities did not exceed 0.2 ppm for any of the elements.

The first test assessed the tendency of the reference fuel RF-79-07 Batch 9 without the introduction of zinc to produce injector deposits (Table 2/Item 1). The results of the changes in the maximum power of the Peugeot DW10B engine, which was a criterion for assessing the size of injector nozzle coking as a result of the combustion of the tested fuel in the engine are presented graphically in Figure 3. The final test result for the change in the maximum design power was –0.05%. Therefore, the detergent properties of the fuel effectively prevented the formation of fuel injector fouling, which allowed for the maintenance of the engine's maximum power at the same level during the entire test.

The second test assessed the fuel RF-79-07 Batch 9 into which 1 ppm of Zn was introduced in the form of a zinc salt, i.e. Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$), in the manner strictly described in the test procedure CEC F-98-08 (Table 2/Item 2). Figure 3 show the changes in the maximum engine power during the test. The final test result for the change in design power is –5.58%. This is a much higher decrease in power than the limit value of 2%.

The third test (Table 2/Item 3) assessed the fuel RF-79-07 Batch 9 into which 1 ppm of Zn had been introduced in a natural manner (through storage in galvanised drums). Figure 3 illustrates graphically the changes in the maximum power of the Peugeot DW10B engine during the test. This time, the final result of the maximum power decrease was 7.16%.

The last, fourth test (Table 2/Item 4) introduced 4 ppm of Zn into the fuel RF-79-07 Batch 9 in a natural way (through storage in galvanised drums). This was intended to check how the increase in Zn contained in the fuel would affect the size of the formation of injector coke deposits in the Peugeot DW10B engine, and thus the decrease in the maximum power obtained in the standard test according to the test procedure CEC F-98-08. Figure 3 illustrates graphically how the maximum engine power changed during each test. As can be seen, in the case of supplying the engine with the fuel CEC RF-79-07 Batch 9 containing 4 ppm of Zn, the test was interrupted after 25 hours of engine operation due to the impossibility to maintain the required operating parameters due to incorrect functioning of fouled fuel injectors.

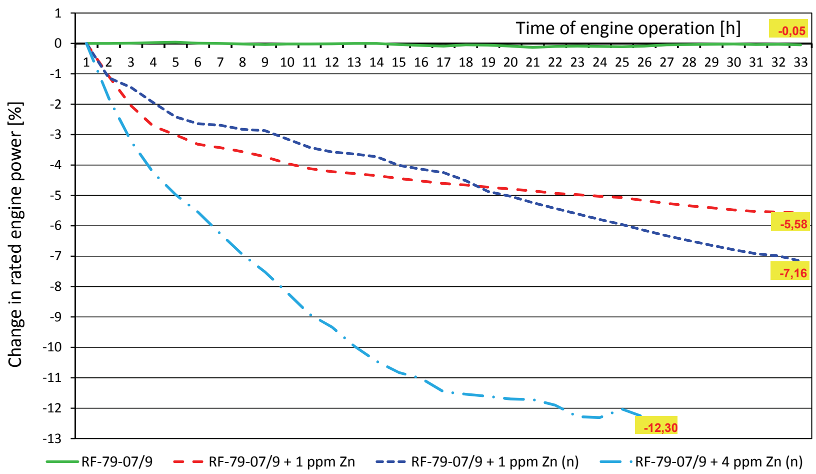

Fig. 3. Comparison of the changes of the decrease in the power of the engine supplied with RF-79-07/9 fuel not containing Zn or containing Zn of different origins and its different content

Discussion of study results – conclusions

Table 3 shows results of all the engine tests carried out according to test procedure CEC F-98-08.

Due to the very high cost of the engine test according to the above-mentioned test procedure, all the fuels were assessed once. Therefore, when comparing the obtained results, it was necessary to assume that the repeatability of the results was within the same range for each of the tests performed.

Figure 3 shows the comparison of the changes of the decrease in the power of the engine supplied with RF-79-07/9 fuel not containing Zn or containing Zn of different origins, taking into account the influence of the quantity of the contained zinc on the test result (Table 3/Item 1–4). It was determined that with 1 ppm of zinc in the fuel, the zinc in the form of ZnO, $ZnO.H_2O$ oxide/hydroxytoxide introduced as a result of fuel conditioning in a drum causes a maximum power decrease which is approx. 30% higher (7.16%) in the test compared to the zinc introduced in the form of Zn neodecanoate (5.58%) – Figure 3. The course of the maximum power decrease curves in the test indicates that in the first part of the test (up to about 18 hours), the value of the decrease in the maximum power is lower in the case of the fuel containing zinc ZnO, $ZnO.H_2O$ oxide/hydroxytoxide than in the case of fuel containing zinc in the form of Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$). In the second part of the test,

Table 3. The influence of different zinc catalysts and their contents in the fuel on the engine power decrease and the deposits produced at the fuel nozzle tips

Item	Fuel	Content Zn [ppm]	Origin Zn	The decrease in the engine's maximum power after the test CEC F-98-08 [%]	External coke deposits on fuel injectors
1.	CEC RF-79-07 Batch 9	~0	–	**0.05**	
2.	CEC RF-79-07 Batch 9	~1	Artificially introduced in the form of a zinc salt Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$)	**5.58**	
3.	CEC RF-79-07 Batch 9	~1	Zinc from galvanised drums used for fuel storage	**7.16**	
4.	CEC RF-79-07 Batch 9	4	Zinc from galvanised drums used for fuel storage	**12.30**	

the trend changes and consequently the final decrease in the maximum power is greater for the fuel containing zinc introduced through fuel conditioning in a galvanized drum. On the other hand, the increase in the zinc content of the fuel to 4 ppm as a result of its conditioning in a galvanized drum resulted in a decrease of the maximum engine power in the test by 12.30%, i.e. approx. 70% more than for the fuel containing 1 ppm of zinc of the same origin – Figure 3.

After each test, thin layers of coke deposits were found on the outer surfaces of the injector tips. The fuel not containing Zn and containing 1 ppm of artificially introduced Zn in the form of Zn neodecanoate caused the formation of deposits with a darker, brown-grey colour. In the case of the fuel containing naturally introduced Zn from fuel conditioning in a galvanized drum, a clear thickening of deposit around the fuel outlets was found, especially when using the fuel containing 4 ppm of Zn (Table 3), which testified to a faster process of deposit formation, probably also inside the fuel outlet ducts. This led to a significant decrease in the maximum engine power (12.30%) and an interruption of the test after 25 hours due to the engine's sudden stopping during the test, a difficulty starting the engine and its unstable operation.

In conclusion, the tests showed that:

- The introduction of even trace amounts of zinc into diesel fuel increases its tendency to build up deposits at the tips of fuel injectors compared to a similar evaluation carried out for the same zinc-free fuel,
- Even a trace content of zinc, which is a fuel pollutant, affects the rate and amount of coke deposits produced at the injector tips of the Peugeot DW10B engine in the test according to the procedure CEC F-98-08. The effects can be observed in the form of more or less smooth decreases in the maximum engine power during the test,
- The zinc in the form of ZnO, $ZnO.H_2O$ oxide/hydroxytoxide introduced into the fuel as a result of its conditioning in a galvanized drum causes a greater decrease in the maximum engine power in a test according to CEC F-98-08 than artificially introduced zinc in the form of Zn neodecanoate ($Zn(C_{10}H_{19}O_2)_2$),
- The increase in zinc content of the fuel above the 1 ppm level indicated in the CEC F-98-08 test procedure results in a rapid loss of fuel detergent properties, as evidenced by the rapid increment in the engine power decrease due to a higher deposit formation rate at the fuel nozzle tips.

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Literature

[1] Baker J., Cook S.: *Sodium Contamination of Diesel Fuel, its Interaction with Fuel Additives and the Resultant Effects on Filter Plugging and Injector Fouling*. SAE Technical Paper no. 2013-01-2687, 2013.
[2] Balfour G., Bhatti N., Caprotti R.: *Deposits Control in Modern Diesel Fuel Injection Systems*. SAE Technical Paper no. 2001-01-2250, 2001.
[3] Barker J., Richards P., Goodwin M., Wooler J.: *Influence of High Injection Pressure on Diesel Fuel Stability: A Study of Resultant Deposits*. SAE Technical Paper no. 2009-01-1877, 2009.
[4] Birgel A., Ladommatos N., Aleiferis P., Milovanovic N., Lacy P., Richards P.: *Investigations on Deposit Formation in the Holes of Diesel Injector Nozzles*. SAE Technical Paper no. 2011-01-1924, 2011.
[5] Brigel A., Ladommatos N., Aleiferis P., Zülch S., et al.: *Deposit Formation in the Holes of Diesel Injector Nozzles: A Critical Review*. SAE Technical Paper no. 2008-01-2383, 2008.
[6] Caprotti R., Bhatti N., Balfour G.: *Deposit Control in Modern Diesel Fuel Injection Systems*. SAE Technical Paper no. 2010-01-2250, 2010.
[7] Caprotti R., Breakspear A., Graupner O., Klaua T.: *Diesel Injector Deposits Potential on Future Fuelling Systems*. SAE Technical Paper no. 2006-01-3359, 2006.
[8] Fang H.L., McCormick R.L.: *Spectroscopic Study of Biodiesel Degradation Pathways*. SAE Technical Paper no. 2006-01-3300, 2006.
[9] Ikemoto M., Omae K., Nakai K., Ueda R., Kakehashi N., Sunami K.: *Injector Nozzle Coking Mechanism in Common-rail Diesel Engine*. SAE Technical Paper no. 2011-01-1818, 2011.
[10] Kumagi S., Takahashi A., Nagato H., Stradling R.: *Development of an Injector Deposit Formation Test Method for a Medium-duty Diesel Engine*. JSAE 201590029 SAE 2015-01-1914, 2015.
[11] Lacey P., Gail S., Kientz J., Benoist G., et al.: *Fuel Quality and Diesel Injector Deposits*. SAE Int. J. Fuels Lubr. 2012, vol. 5(3), pp. 1187-1198, DOI: 10.4271/2012-01-0693.
[12] Lacey P., Gail S., Kientz J.M., Milanovic N., Gris C.: *Internal Injector Deposits*. SAE Technical Paper no. 2011-01-1925, 2011.
[13] Orhan A., Semith E.: *Carbon Deposit Formation From Thermal Stressing of Petroleum Fuels*. Prepr. Pap.-Am. Chem. Soc., Div. Fuel Chem. 2004, vol. 49(2), pp. 764–766.
[14] Parsinejad F., Biggs W.: *Direct Injection Spark Ignition Engine Deposit Analysis: Combustion Chamber and Intake Valve Deposits*. SAE Paper no. 2011-01-2110, 2011.
[15] Prabakaran B., Udhoji A.: *Experimental investigation into effects of addition of zinc oxide on performance, combustion and emission characteristics of diesel-biodiesel-ethanol blends in CI engine*. Alexandria Engineering Journal 2016, vol. 55, pp. 3355–3362.
[16] Shiotani H., Goto S.: *Studies of Fuel Properties and Oxidation Stability of Biodiesel Fuel*. SAE Technical Paper no. 2007-01-0073, 2007.
[17] Stępień Z.: *Ewolucja metodyki oceny zanieczyszczenia rozpylaczy silników o zapłonie samoczynnym*. Nafta-Gaz 2014, no. 10, pp. 707–716.
[18] Stępień Z.: *Intake valve and combustion chamber deposits formation – the engine and fuel related factors that impacts their growth*. Nafta-Gaz 2014, no. 4, pp. 28–34.
[19] Stępień Z.: *Investigations of injector deposits in modern diesel engines*. Combustion Engines 2016, vol. 165(2), pp. 9–20.
[20] Stępień Z.: *Przyczyny i skutki tworzenia wewnętrznych osadów we wtryskiwaczach silnikowych układów wysokociśnieniowego wtrysku paliwa*. Nafta-Gaz 2013, no. 3, pp. 256–262.
[21] Stępień Z.: *The reasons and adverse effect of internal diesel injector deposits formation*. Combustion Engines 2014, vol. 156(1), pp. 20–29.
[22] Tanaka A., Yamada K., Omori T., Bunne S., Hosokawa K.: *Inner Diesel Injector Deposit Formation Mechanism*. SAE Technical Paper no. 2013-01-2661, 2013.
[23] Tang J., Pischinger S., Lamping M., Korfer T., Tatur M., Tomazic D.: *Coking Performance in Nozzle Orifices of DI-Diesel Engines*. SAE Technical Paper no. 2009-01-0837, 2009.
[24] Ullmann J., Geduldig M., Stutzenberger H., Caprotti R., Balfour G.: *Investigation into the Formation and Prevention of Internal Diesel Injector Deposits*. SAE Technical Paper no. 2008-01-0926, 2008.
[25] Urzędowska W., Stępień Z.: *Prediction of threats caused by high FAME diesel fuel blend stability for engine injector operation*. Fuel Processing Technology 2016, vol. 142, pp. 403–410.
[26] Żak G., Ziemiański L., Stępień Z., Wojtasik M.: *Problemy związane z tworzeniem się osadów na elementach układów wtryskowych nowoczesnych silników Diesla – przyczyny, metody badań, przeciwdziałanie*. Nafta-Gaz 2013, no. 9, pp. 702–708.

Legal and normative acts

[27] CEC F-98-08 *Development of Peugeot DW10 Direct Injection Diesel Nozzle FoulingTest*.

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