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The influence of alcohol-gasoline blends and deposit control additives on fuel injector contamination in SI DI engines

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The intense and multidirectional development of internal combustion engines, forced by tightening environmental regulations, has necessitated the verification and definition of new requirements for engine fuels. The article presents an experimental analysis of the ethanol or butanol admixture effect on the SI DI engine injectors contamination process based on engine and fundamental research. Injectors were evaluated after Keep-Clean only and Dirty-Up (Keep-Clean) tests, along with the Clean-Up test in accordance with CEC F-113-KC and CEC F-113-CU test procedures. The positive effect of the detergent additive on the ability to wash out injector deposits was demonstrated. A reduction of more than 80 percent in the duration of injection compared to the contaminated system was achieved. It was proven that the use of the detergent additive in the Clean-Up procedure makes it possible to return the injectors to full efficiency, which confirms the thesis of the leaching of injector nozzle deposits of SI DI engines.

Key words: *SI DI engine, fuel injector deposits, ethanol, butanol, DCA*

1. Introduction

Over the past three decades, internal combustion engines have undergone rapid, multidirectional development. This development has been driven by the systematic tightening of regulations to limit emissions of pollutants and greenhouse gases (GHG) and the associated need to increase engine efficiency [12]. As a result, modern combustion systems were introduced, high-pressure fuel injection systems became widespread in both CI and SI engines, and advanced exhaust aftertreatment systems were implemented. Consequently, novel requirements for fuels for contemporary internal combustion engines have been established. The utilization of biocomponents as fuel additives, particularly alcohol and biofuels, has emerged as a pivotal aspect in this context [3, 4]. The following is a list of the elements in question: As a result, new requirements for motor fuels were introduced. Some of these requirements (in terms of physicochemical properties) are contained in the European standards EN590 for diesel fuel and EN228 for motor gasoline. Much broader requirements, including performance characteristics with a breakdown by category of diesel fuel and motor gasoline, were included and subsequently revised and supplemented in subsequent editions of the Worldwide Fuel Charter, the latest edition of which was released on October 28, 2019 [5]. The testing and evaluation of fuel performance properties has become of particular importance to both fuel manufacturers, the additive packages used for them, and engine manufacturers who have begun to demand the introduction of standardized, generally recognized testing methodologies and criteria for evaluating fuel performance. In response to such demands, American procedures for testing specific fuel properties by engine methods were developed in the US under ASTM, and in Europe, similar procedures were developed by the Coordinating European Council for the Development of Performance Tests for Fuel, Lubricants and Other Fluids (CEC). Both U.S. and European procedures for testing motor fuels have been identified in the Worldwide Fuel Charter as required tests for specific properties for both various categories of diesel fuel and motor gasoline. In addition, the Worldwide Fuel Charter also includes the limiting requirements that evaluations of tested fuel properties should meet.

Fuel plays a central role in engine design and performance optimization. This role encompasses the selection process of construction materials, including lubricating oils. The limits of engine control parameters, which determine its efficiency and the optimization of exhaust emissions, performance, and utility-operating characteristics, are determined by the properties of the fuel. Consequently, the fuel should guarantee the technical functionality and adequate, unchanging performance characteristics of the vehicle. It is imperative to consider the maintenance of requisite emission standards throughout the engine's life cycle. This consideration must be in accordance with the stipulated regulations and the vehicle manufacturer's warranty period. Any change of fuels on the market must be adapted to the existing fleet of motor vehicles and the technical requirements arising from engine design. As early as the 1980s, it was found that the formation of harmful deposits in internal combustion engines had a major negative impact on the quantitative and qualitative course of combustion mixture formation, as well as the process of cargo preparation and its combustion in the engine combustion chambers. At the same time, it was noted that in the case of engines with CI, the most dangerous deposits are formed on components of the fuel injection system [16]. In SI engines with indirect gasoline injection, the most deleterious deposits are those that form in the engine's combustion chambers, on the intake valves, and on their stems. In SI engines with direct fuel injection, the deposits that pose the greatest threat to engine operation are those formed in high-pressure fuel injection injectors.

The global policy to reduce pollution from road transport requires the introduction of diversified powertrains, which in turn requires the development of entirely new or significantly modified technologies and design solutions already in use. In the automotive sector, the fundamental direction of these endeavors is to subordinate the development of motor vehicles and the fuels or other energy sources used for them to the overriding goal of reducing emissions of harmful components, including greenhouse gases, into the atmosphere. Given these expectations, alcohol emerges as a compelling alternative for commercial use as a fuel, either as a standalone fuel or in blends with gasoline or diesel. The utilization of alcohol fuels has the potential to play a significant role in reducing the emissions of harmful components from exhaust gases. However, it is imperative to possess a thorough comprehension of the properties inherent to these fuels and to utilize them in a manner that corresponds with the requirements of contemporary engine designs. Ethanol and butanol are alcohols that are regarded as the most promising biocomponents for current conventional fuels. It is imperative to acknowledge that the prevailing criterion for assessing the viability of fuel alternatives for vehicles in operation is their environmental sustainability, a characteristic that is exemplified by alcohol fuels. A substantial body of research has been dedicated to the study of blends of conventional fuels with various alcohols. Among other things, the fuel's effects on the performance, efficiency, and various performance parameters of SI engines powered by it with indirect injection [2, 8, 10, 20] and direct injection [10] have been evaluated. The present study aims to elucidate the effects of alcohol/gasoline blends on the propensity to form or leach preformed various injector deposits of SI DI engines and their impact on the quantitatively and qualitatively assessed fuel atomization process in the combustion chambers.

The results of this study contribute to a more complete understanding of the subject and provide a basis for further research in this area. The motivation for the authors to undertake research aimed at deepening and expanding the knowledge of the effect of alcohol-doped fuels (ethanol or butanol) in keeping the fuel injectors of SI DI engines clean was provided by this study. The study also addressed the effect of deposits produced in the injectors on fuel atomization quality processes. The novelty of the work lies in the hybrid combination of two different research methodologies for evaluating the fuel injection process. The first part of the study evaluated changes in fuel dose due to the formation of fuel injector deposits and was conducted using an engine-wide standardized test methodology. In the second part of the study, changes in fuel spray quality were evaluated based on studies of macroscopic indicators of fuel spray in a constant volume chamber using laser illumination. The engine test procedure was developed by CEC and bears the designation CEC F-113 and the name: VW EA111 DISI Injector Deposit Test. It is currently the only standardized and recognized procedure in Europe to reliably evaluate fuels in terms of their tendency to keep SI DI engine injectors clean and their ability to leach deposits after they have been previously produced [17].

Engine analyses do not provide a complete research diagnosis of injector quality, including fuel atomization. Complementary to such analyses are optical evaluations of fuel atomization. Their uniqueness lies in the optical registration of fuel atomization images, and on the basis of these images, a diagnostic evaluation of the atomization is possible. Depending on the complexity of these optical analyses, macroscopic and microscopic evaluation of the fuel spray is possible. Injector tips located in combustion chambers are directly exposed to extreme conditions during the combustion process, including high pressure, temperature, and chemical interaction of fuel components. These conditions result in the intensive formation of deposits, which significantly affect the injector performance and thus the quality of the fuel-air mixture formed [9, 14]. External deposits, forming mainly around the exhaust ports, come primarily from the fuel being burned and, to a lesser extent, from engine oil. They cause deformation of the fuel jet and its excessive elongation, washing out the walls of the combustion chamber and the bottom of the piston. This results in increased fuel consumption and emissions of pollutants, particularly hydrocarbons (HC) and particulate matter (PM). Internal deposits, on the other hand, formed in the flow channels of injectors due to thermal oxidation and polymerization of fuel components (e.g., in the form of lacquers and resins), come exclusively from the fuel itself. Their presence leads to a reduction in the cross-sectional area of the outlet channels, reducing fuel flow and worsening its atomization. As a result, the average diameter of fuel droplets increases, the homogenization of the mixture deteriorates (lower excess air ratio, λ), and the evaporation time increases. All these factors contribute to a decrease in engine efficiency, lower engine performance, and increased fuel consumption [15, 21].

2. Properties of ethanol and butanol relevant to engine applications

Applying alcohol as a fuel admixture provides several benefits, such as reducing greenhouse gas (GHG) emissions, decreasing toxic exhaust emissions, improving energy security, and enhancing many fuel performance properties, including resistance to knock combustion [6, 7]. Table 1 compares the selected properties of gasoline, n-butanol, and ethanol.

Table 1. Comparison of selected fuel properties [11]

Properties	Gasoline	n-butanol	Ethanol
Chemical formula	Blend	C_4H_9OH	C_2H_5O
RON (Research Octane Number)	95	94–96	110
Density [kg/m^3]	753	810	790
Molecular weight [g/mol]	114	74	46
Gravimetric lower heating value [MJ/kg]	42.9	33.3	26.8
Volumetric lower heating value [MJ/dm^3]	32.3	27.0	21.2
Enthalpy of vaporization [kJ/kg]	380–500	716	904
Mass fraction of carbon [%]	86	65	52
Mass fraction of hydrogen „H" [%]	14	13.5	13
Mass fraction of oxygen „O" [%]	0	21.5	35
Viscosity [mPa · s]	0.4–0.8	2.57	1.08
Boiling point [°C]	199	118	78
Stoichiometric air-to-fuel ratio	14.7	11.2	9.0

In blends with gasoline, butanol exhibits several significant advantages over ethanol. Butanol is much less hygroscopic, better mixable with gasoline, and has a higher specific calorific value, which translates into lower specific fuel consumption (butanol versus ethanol blends). When butanol is blended with gasoline, the vapor pressure of butanol is lower than that of ethanol, making it easier to meet the requirements of EN 228. The biggest disadvantages of butanol relative to ethanol in blends with gasoline are a lower octane number and lower heat of vaporization, as well as higher density and viscosity, which can contribute to a higher tendency than ethanol to form deposits. Like conventional motor gasoline, ethanol fuels are prone to form deposits on engine components, particularly in intake manifolds, injector tips, intake valves, and combustion chambers [13, 19].

3. Aim and scope of the research

The purpose of the study was to investigate the effect of ethanol or butanol admixture to gasoline on the fouling process of SI DI engine fuel injectors. In addition, the effectiveness of ethanol or butanol admixture with Deposit Control Additives (DCAs) on the ability to leach previously formed fuel injector deposits was evaluated. The scope of the study included two phases of research:

- Engine tests to evaluate the change in operating conditions of injectors as a result of deposit contamination and flushing capabilities using prepared gasoline blends with alcohol and with/without DCA. The main objective of the tests was to maintain a constant engine operating point regardless of the change in the level of injector fouling.
- Research on optical evaluation of fuel atomization geometric indicators. Conducted on a model test bench, leading to a macroscopic assessment of the injected fuel spray based on injectors from various phases of engine tests. Different fuels were not evaluated during static optical tests; instead, injectors from prior engine testing phases were used. The goal was to analyze the differences in injectors during tests using the same fuel.

4. Research methodology

4.1. Engine test procedure and bench equipment

The tests were conducted in accordance with European engine test procedures CEC F-113 and used two variations of the procedure, i.e., CEC F-113-KC "Keep-Clean" Test Procedure and CEC F-113-CU "Clean-Up" Test Procedure (VW EA111 BLG) [18]. The tests were performed with a VW EA111 BLG engine, the selected technical parameters of which are included in Table 2. The engine was equipped with wall-guided direct fuel injection and a combined supercharging system (mechanical supercharging + turbocharging). The injection system featured 6-hole solenoid controlled injectors.

In the "Keep-Clean" version of the CEC F-113-KC procedure, the time allocated for conducting the one-step test is 48 hours. Throughout the duration of the test, the engine functions under steady-state conditions, characterized by two fundamental parameters: constant speed (2000 rpm) and constant load (56 Nm). The primary objective of the test is to assess the propensity of the fuel to form injector deposits, thereby determining the efficacy of maintaining clean injectors.

In the CEC F-113-CU "Clean-Up" variant of the procedure, the test is divided into two stages. In the first stage, which lasts 48 h, a base fuel is applied, without DCA additives. In this stage, the "Dirty-Up" injector fouling process is carried out. In the second stage of the test, 24 h, refined fuel is used. That part of the test allows assessment of the cleaning properties of the "Clean-Up" fuel, and therefore the effectiveness of flushing out the deposits formed in the first stage.

Table 2. Technical data of VW EA111 BLG engine

Type	–	4-cyl., in-line (wall-guided mixture formation system)
Displacement	cm^3	1390
Cylinder bore.	mm	76.5
Piston stroke	mm	75.6
No. of valve/cyl.	–	4
Compression ratio	–	10:1
Max power	kW	125 kW at 6000 rpm
Max torque	Nm	220 Nm at 1750–4500 rpm
Aftertreatment systems	–	Three-way catalysts, closed feedback loop
Emission norm	–	Euro 4

The change in the width of the injector control impulse was used as a criterion for evaluating the intensity and magnitude of changes in deposits formed or flushed out. The injection time is extended as the amount of deposits accumulating outside and inside the injector gradually increases, or reduced as deposits are flushed out of the injectors. The tendency of a fuel to form injector deposits is a key criterion for distinguishing fuels in terms of their functional and operational characteristics.

The fuel tests were carried out on an engine test stand in accordance with the CEC F-113-KC "Keep-Clean" Test Procedure and the CEC F-113-CU "Clean-Up" Test Procedure (VW EA111 BLG) – 2022 edition. Figure 1 presents a general view of the test stand.

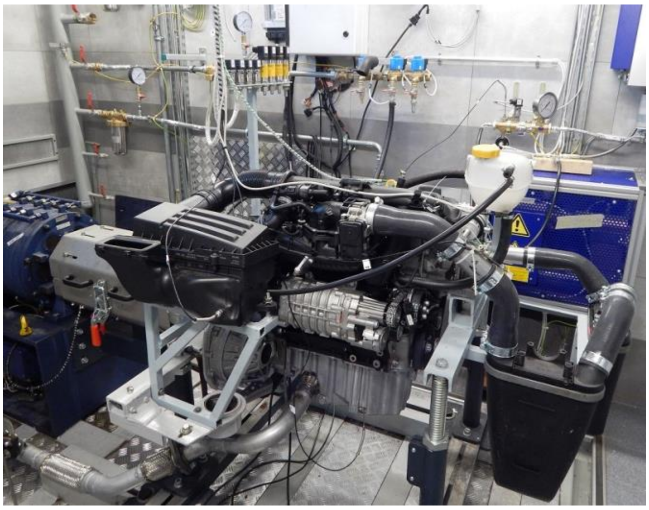

Fig. 1. View of the VW EA111 BLG engine test stand at INiG-PIB

4.2. DISI injector spray evaluation – optical test methodology

The second stage tests were carried out with a constant volume chamber (2.2 dm^3), which, along with the layout of the entire test stand, is shown in Fig. 2. Fuel was injected at a 10 MPa pressure with a 0.6 ms injector opening time. Spray pattern evaluation was performed as follows:

- a high-speed camera was used along with halogen illumination to evaluate geometric indicators of the spray
- a high-speed camera and NG:YAS 532 nm laser illumination system were used to evaluate the cross-sectional spray area of injected fuel.

The high-speed record process included:

- imaging frequency f = 10 kHz
- LaVision's HSS5 camera image size 512 × 512 px
- Nikkon AF Nikkor 24-85 mm 1:2.8-4 D lens
- image analysis was conducted using DaVis 10 software.

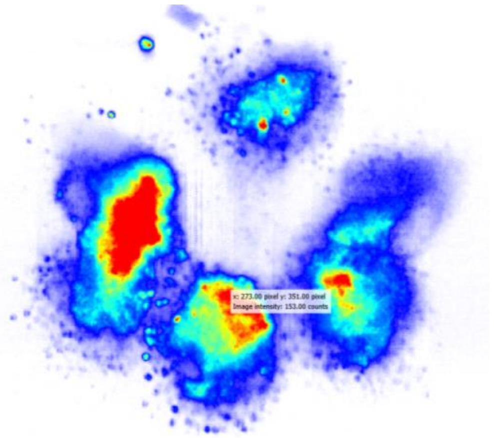

Fig. 3. View of raw images recorded with laser illumination

Data analysis was conducted using LaVision's DaVis 10 software. An example of a raw image is shown in Fig. 3. The program allowed the creation of macros for image analysis, including analysis of macroscopic indicators. The images were saved in a grayscale format that allowed individual assessment of each pixel's luminance (brightness). The choice of such an image processing form allowed the numerical representation of the results obtained.

The results were processed separately for halogen illumination and laser illumination. The first approach required the identification of macroscopic indicators of the spray (Fig. 4a), and the second – the area of the spray after it was cut with an optical cutter in a plane orthogonal to the fuel outflow (Fig. 4b).

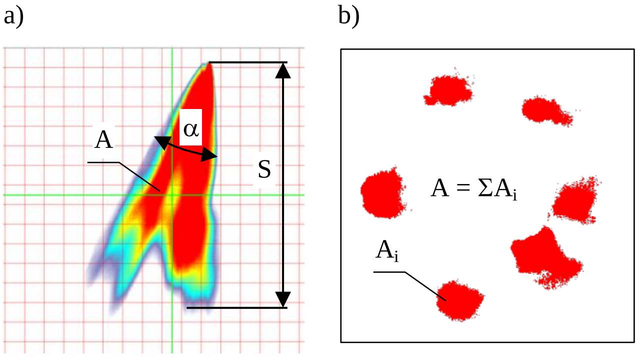

Fig. 4. Method of evaluating the fuel jet: a) with halogen lamps, b) with laser illumination

4.3. The fuel mixtures employed in the study

Five gasoline types with different physical and chemical properties were tested:

- RF-12-09 batch 11 used in CEC test procedures for checking, adjusting and calibrating test engines; it is often used for research or comparison purposes; this gasoline does not contain DCA and has a high tendency to form deposits on the intake valves of SI engines; in the tests it was the base fuel and at the same time (reference) fuel

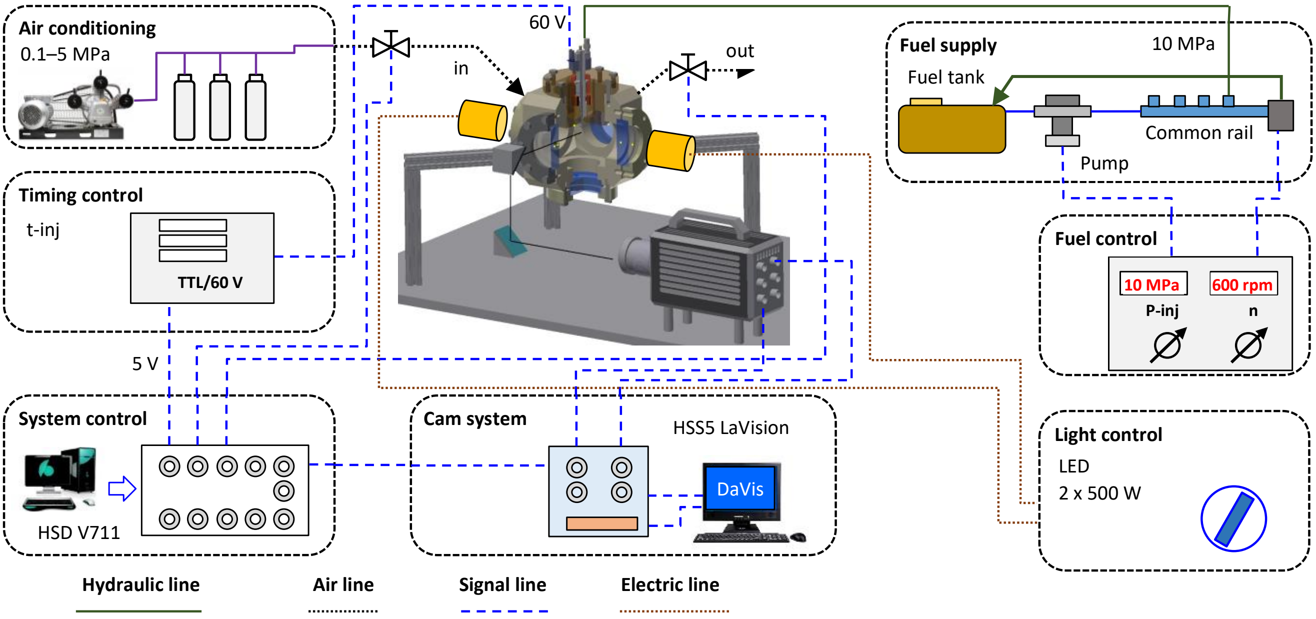

Fig. 2. Layout of fuel atomization studies under halogen illumination

– RF-12-09 batch 11 + 20% (v/v) ethanol
– RF-12-09 batch 11 + 20% (v/v) butanol
– RF-12-09 batch 11 + 20% (v/v) butanol refined with 500 ppm (m/m) DCA type additive
– gasoline RF-12-09 batch 11 doped with 20% (v/v) ethanol refined with 500 ppm (m/m) DCA-type additive.

The different fuel compositions (only 20%) resulted in similar (initial) fuel injection times – Table 3.

Table 3. Initial injection times of the tested fuels

Type of fuel	Initial injection time [ms]
RF-12-09 batch 11	1.577
RF-12-09 batch 11 + 20% (v/v) ethanol	1.575
RF-12-09 batch 11 + 20% (v/v) butanol	1.576
RF-12-09 batch 11 + 20% (v/v) butanol + 500 ppm (m/m) DCA	1.576
RF-12-09 batch 11 + 20% (v/v) ethanol + 500 ppm (m/m) DCA	1.577
The injection time values are average values	

The limitation of alcohol admixture to 20% (v/v) was due to the engine manufacturer's requirements for the maximum allowable alcohol content in gasoline. A DCA additive compatible with gasoline with alcohol content was used to refine the fuel blend. The amount of DCA additive was set at a level typical of fuels on the European market. The physicochemical properties of the fuel blends prepared for the tests are shown in Table 4.

All tests used the same set of injectors, which were subjected to a cleaning process strictly described in the CEC F-113 test procedure after each test. In addition, each injector was assigned to a specific engine cylinder and was therefore mounted to the same engine cylinder in each test.

5. Results

5.1. Assessing the tendency of fuels to generate injector deposits

Based on the engine tests carried out, the characteristics of the injection time variation in relation to the test duration were obtained. Figure 5 shows a comparison of the injection time changes of the tested fuels (base, base + 20E, base + 20B) obtained in tests conducted according to the CEC F-113-KC procedure. A test referred to as "Keep-Clean" (KC) in that case was equivalent to the "Dirty-Up" (DU) test due to the fact that the tested fuels cause the injectors to become more and more contaminated with deposits formed. The results (Fig. 5) represent the averaged difference in the electrical pulse width controlling the opening time of the injectors measured during engine operation in individual tests. As the measured pulse is unstable (it changes with a very high frequency and large amplitude over time), calculating the increase in pulse width (injection time) as the magnitude of its difference at the beginning and end of the test could be affected by a large error. Therefore, a methodology based on a trend function was used to calculate the change in pulse width that occurred during the test.

The averaged values calculated based on the trend are more representative than t based on the endpoints of the actual measurements. In this way, the average calculated width of the electrical pulse controlling the timing of a single injection during the test was obtained. The result is given in [%] of electric pulse width increase. The greater the difference, the greater the fuel's tendency to form deposits. Based on the CEC tests performed to date, based on the Student t-distribution, it was determined that a difference in the width of the electric control pulse of at least 1.8% is required to distinguish between the two results at the 90% confidence level.

Comparison of the test results for the three fuels tested (Fig. 5) divided the injection time increment up to 15 h and for the remainder of the test duration. The split is mainly due to the rapid increase in injection time, followed by its stabilization.

In relation to the reference RF-12-09 batch 11, the average calculated increase (during the first part of the test) in injection time was 3.06%, for the RF-12-09 batch 11 + 20% (v/v) ethanol – 3.94%, while for RF-12-09 batch 11 + 20% (v/v) butanol – 3.75%. The results so far have shown that the most important properties of unrefined fuel that have a major impact on injector deposit formation processes are T90, sulfur, olefins, and aromatics content, as well as vapor pressure, density, IBP, and octane number and upper distillation run [1, 21].

Table 4. Physicochemical properties of fuels used in engine tests

Property	Unit	RF-12-09 batch 11	RF-12-09 batch 11 +20% (v/v) ethanol	RF-12-09 batch 11 + 20% (v/v) ethanol + 500 ppm (m/m); DCA	RF-12-09 batch 11 + 20% (v/v) butanol	RF-12-09 batch 11 + 20% (v/v) butanol + 500 ppm (m/m); DCA	Test procedure
Notation	–	base	base + 20E	base + 20E + DCA	base + 20B	base + 20B + DCA	
Research octane number	–	96.3	98.3	98.2	98.8	98.8	EN ISO 5164
Motor octane number	–	87.1	87.7	87.6	88.7	88.7	EN ISO 5163
Sulfur content	mg/kg	5.0	3.7	3.3	3.5	3.4	EN ISO 20846
Content of hydrocarbon types:							
Olefinic	% (v/v)	5.5	< 4.0	< 4.0	< 4.0	< 4.0	EN 15553
Aromatic	% (v/v)	27.8	21.5	21.2	23.1	20.5	
Oxygen	% (m/m)	< 0.1	7.53	7.27	4.94	4.57	EN 1601
Organic compounds containing oxygen:							
Butanol	% (v/v)	< 0.80	< 0.17	< 0.17	20.2	20.1	EN 1601
Ethanol	% (v/v)	< 0.80	20.4	20.0	< 0.17	< 0.17	
Fractional composition:							
T10	°C	52.4	52.8	51.9	61.7	59.4	EN ISO 3405
T50	°C	106.8	72.7	72.0	102.6	101.9	
T90	°C	173.2	152.3	152.1	153.4	153.8	

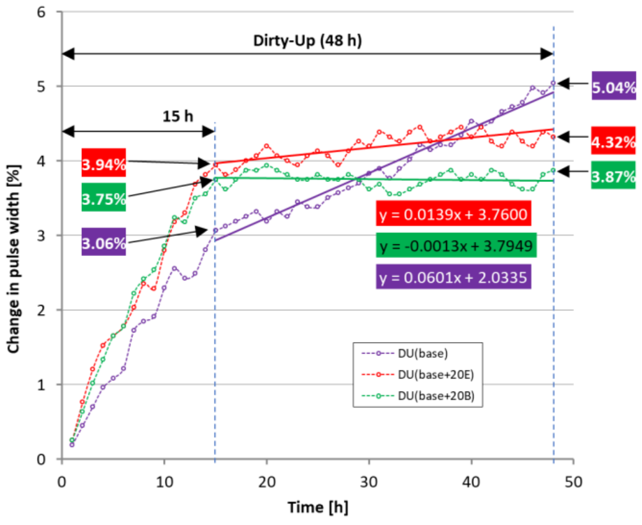

Fig. 5. Results comparison of the fuels ability to keep DISI engine injectors clean during the CEC F-113-KC (48 h) test

However, all the tested fuels were based on the same reference RF-12-09 Batch 11 fuel. Thus, the differences between their physicochemical properties were small and were mainly due to the admixture of ethanol or butanol – Table 2. In addition, the result is affected by the simultaneous interaction of different fuel properties, which can interact with each other. It is very difficult to determine the interactions that have different effects on the formation of injector deposits.

In the second part of the test, a continuous increase in injection time for the base fuel was observed. The final value of the injection time increment was 5.04%. The use of ethanol and butanol admixtures indicates that their share significantly reduces the fuel injection time. The use of butanol does not increase the injection time – a practically constant average value was obtained after 15 h of testing. The ethanol content increases the injection time, but the increment is only 0.5% of the base time.

The application of alcohol-enrichment fuels, after approximately 15 h of a test, caused deposit formation stabilization. The differences in the trends for different fuels are due to the intensity of the deposit precursor formation, the strength of their adhesion to the surface, and the simultaneous self-cleaning processes. Thus, the course of deposit formation is the result of their growth and flushing. It can be hypothesized that in that case, fuels that contain alcohol have a lower tendency to contaminate fuel injectors. As a result of the linear increase in injection time caused by non-alcohol-enrichment fuels, the level of contamination created will exceed that created by alcohol-containing fuels. The hypothesis put forward is confirmed by the trend lines in Fig. 5, which are plotted for each of the waveforms of changes in the size of the injection time control pulse width throughout the test. It can be seen that the trend lines have a flatter course for alcohol-doped fuel, including the flattest for fuel doped with 20% (v/v) butanol. In contrast, the course of the line showing the increase in injection time of a single dose of the base fuel during the test is much steeper.

5.2. Assessing the tendency of fuels to remove injector deposits

Figure 6 includes the results of the injection time changes of the tested fuels in a cycle including the "Dirty-Up" (DU) and "Clean-Up" (CU) phases. Each time, the DU phase was carried out with the reference fuel RF-12-09 Batch 11 fuel (base). Subsequently, four clean-up phases were carried out using alcohol-enriched fuels. Through this path, the effectiveness of flushing out injector deposits was evaluated by applying an admixture of alcohol without or with DCA to the reference fuel used in the "Dirty-Up" test.

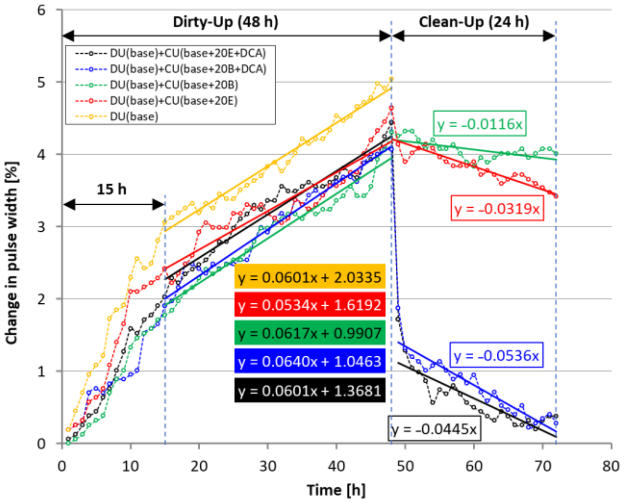

Fig. 6. Comparison of fuels' ability to remove DISI engine injector deposits according to CEC F-113-DU (48 h) and CEC F-113-CU (24 h) procedures

As in the previous test, the injection time increment period was divided into two groups: up to 15 h of the test and the rest of the 48 h of the test. This was due to a similar observation that the first part of the test generates a very large increase in injection time, and then a reduction in this phenomenon was observed. Mainly, the second part of the test was analyzed by linearizing the results obtained. The average slope of the curves is similar, which results from testing the same fuel (base).

The average increase in injection time extension was 0.6% for every 10 h of the test (this value is derived from the directional coefficient "a" in the equations in Fig. 6).

During the second part of the test – the "Clean-Up" – an addition of 20% (v/v) ethanol and the same concentration of butanol was applied to the base fuel. The use of the butanol additive resulted in a deposit washout rate of about 0.1% for every 10 h of the test. The use of the ethanol additive resulted in a higher rate of deposit washout, about 0.3% for every 10 h of test.

In the following part of the research, two more tests were carried out according to the F-113-CU procedure. In an effort to improve the efficiency of injector flushing, fuels with alcohol and DCA-type additive (performance additive) were used. When a reference fuel with a do-mix of 20% (v/v) ethanol + 500 ppm (m/m) DCA was used in the "Clean-Up" part of the test, a rapid reduction in injection time increment was achieved (within 1–2 h after the start of the test). A further phase of the test was able to achieve a 0.5% reduction in injection time increment for every 10 h.

By using a reference fuel admixed with 20% (v/v) butanol + 500 ppm (m/m) DCA in the "Clean-Up" part of the test, an average calculated reduction in injection time was also achieved by 0.5% for every 10 h of the test. In addition, it can be concluded that the efficiency of using the DCA additive is significantly higher than that of admixing ethanol or butanol.

5.3. Optical evaluation of spray indicators

Analysis of macroscopic indicators was carried out for all test cases. Fuel spray images under halogen illumination are shown in Fig. 7. The first three rows were dedicated to the effects of the DU phase, while the next four are a cycle covering the DU and CU phases.

Based on the camera images, analyses were made according to the data shown in Fig. 4a. The range of the spray, the flat area of the spray exposure, and the angle of the spray cone were taken for analysis (each jet was not analyzed separately). The results of this work are shown in Fig. 8, separately for contamination (DU) and leaching (CU) tests of injector orifices.

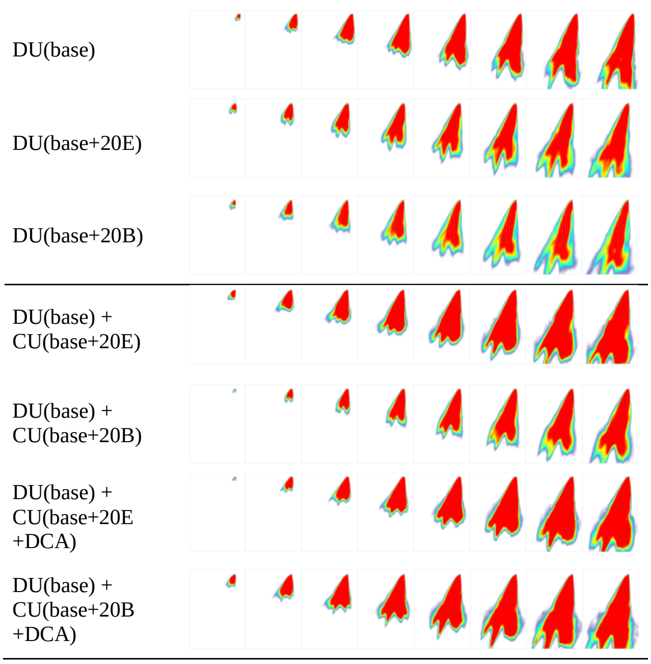

Fig. 7. Fuel spray images with halogen illumination (Δt = 100 µs; labels as shown in Table 2)

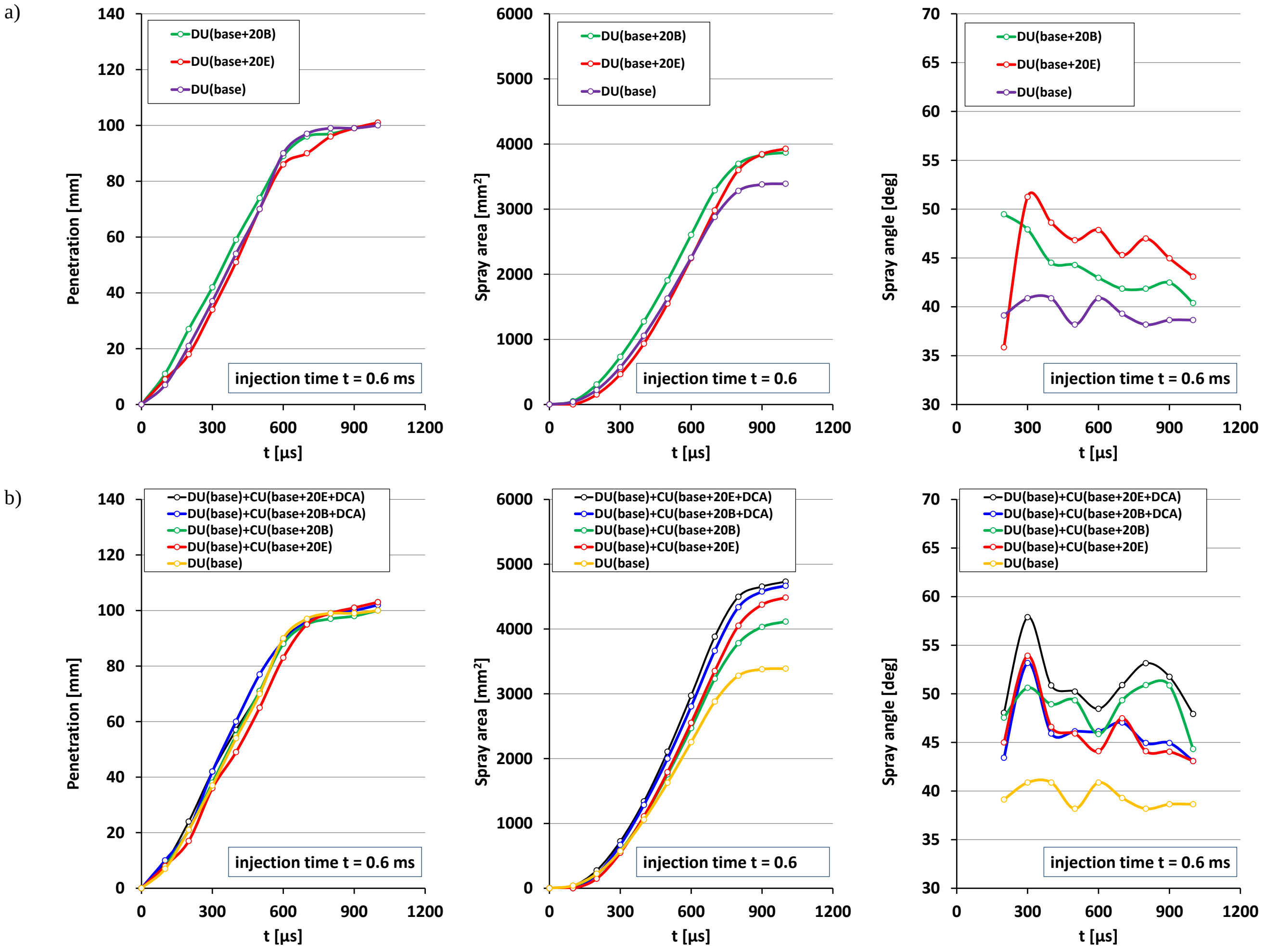

Fig. 8. Macroscopic indicators (penetration; spray area; spray angle) of the spray jet (t = 0.6 ms; p_{inj} = 10 MPa): a) after Dirty-Up test, b) after Dirty-Up and Clean-Up tests

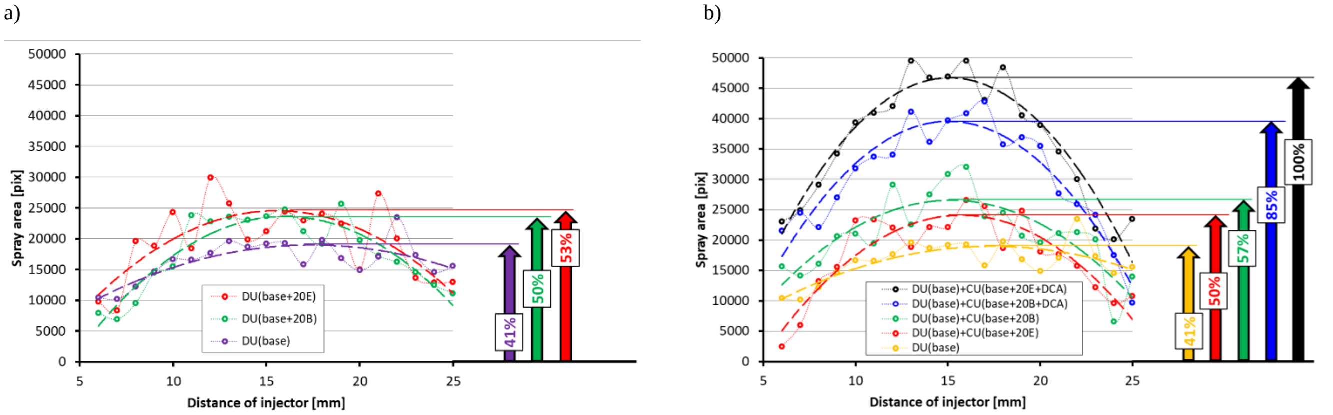

Fig. 9. Analysis of fuel atomization in the form of area fields under perpendicular laser light illumination of the jet: a) after Dirty-Up test, b) after Dirty-Up and Clean-Up tests

Analysis of fuel spray penetration indicates that there are no significant differences, regardless of the use of DU or DU + CU in the test. However, analysis of the fuel spray area already indicates some differences: significantly larger areas were obtained in the CU test. The application of ethanol and butanol increases the surface area in the DU test by approximately 15%. It means a reduction in injection time, which is also confirmed in Fig. 5. The shortest injection duration was recorded during the addition of butanol, which also confirms the area of the fuel jet from time 300 to approximately 800 μs after the start of injection. During the DU + CU test, the application of the DCA additive increases the jet area by 37% compared to the base fuel. It is difficult to identify a better system (butanol or ethanol additive), but the DCA additive is critical here.

The spray area is closely related to the angle of the spray cone. A small field correlates with a small spray angle (hole coking). Such correlations were noted during DU analysis, especially for the base fuel. Similarly, during DU + CU analysis, it can be clearly indicated that the use of DCA additives increases the spray cone angle. The use of DCA with ethanol allows for the largest spray cone angles. It follows that optical analyses are complementary to engine tests, but their results cannot determine the nature of the problem.

To further confirm the relationships obtained, cross-sections of fuel spray were analyzed according to Fig. 4b. On this basis, the individual areas of the plumes were summed, and their interpretation is included in Fig. 9.

In this part of the optical study, the area is presented as the number of pixels covering the spray. Basic research (DU) indicates that the maximum area occurs approximately 15 mm from the first measurement plane (which is half of the spray range – 50 mm). This means that the occurrence of the maximum area in the system containing the laser illumination takes place around 65 mm from the injector tip. It was confirmed that the sum of the cross-sectional area of the fuel plumes is the smallest at the base fuel (in the DU test) – Fig. 9a. Subsequent areas are larger and close to each other (also in the DU test with the addition of ethanol or butanol).

The analysis of the next part of the study during the leaching test (DU + CU) indicates that the lack of DCA addition results in similar cross-sectional area magnitudes. Such results are also confirmed by the data in Fig. 6. There, too, the lack of DCA addition does not result in large changes in injection time. The largest areas were obtained with the addition of DCA with both butanol – an increase of more than 40% over CU(base) and ethanol – an increase of as much as 60% – Fig. 9b. Although the individual areas do not represent exact relationships, the use of a trend line captures the trend of field changes very well.

Engine and non-engine fuel atomization tests were supported by photo material of the injector tips. The first test series (sample images of the injector tip) are shown in Fig. 10. Significant contamination of the injector nozzles, reducing the flow diameter, can be seen (after the Dirty-Up test). Such fouling is evident both for the reference fuel (base) and with the application of ethanol and butanol additives. The fouling indicates limitations in fuel atomization and, at the same time, the need to increase the percentage injection time during the test.


DU (base) DU (base + 20E) DU (base + 20B)

Fig. 10. View of unclean injector holes after Dirty-Up test

Figure 11 includes a view of the injector holes after the Clean-Up test. A view of the injector tip after the Dirty-Up test (first photo) is also included for comparison purposes. Significant differences in nozzle contamination were noted. The Clean-Up phases result in significant leaching of fouling.

6. Summary and conclusions

The combination of engine and non-engine tests, including optical studies, allows a wide-ranging (multi-directional) assessment of injector contamination and its effects during the application of varying base fuel additives (in the form of ethanol, butanol, and DCA additive).

Engine results analysis indicates an increase in injection time during Dirty-Up tests:

– by 5% in total for base fuel

- by approximately 4% with the application of fuels with 20% ethanol and butanol content, with a significant reduction in this increment observed after approximately 15 h of testing.

DU (base)

DU (base)
+ CU (base + 20E)

DU (base)
+ CU (base + 20B)

DU (base)
+ CU (base + 20^{E} + DCA)

DU (base)
+ CU (base + 20B + DCA)

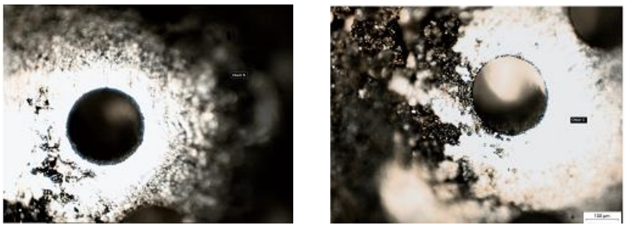

Fig. 11. Images of the spray holes after Dirty-Up and Clean-Up tests

An investigation of the Clean-Up test (using various additives) after the Dirty-Up test (base fuel) resulted in:

- similar injection extension during the Dirty-Up test (absolute increase of about 4%)
- a minor reduction in relative injection time (0.5% in the test) during the use of ethanol additive and a slight reduction in this time during the use of butanol admixture
- significant reduction in injection time increase with DCA addition: after 1–2 h of test, absolute injection time was reduced by about 3%; after that, injection time reduction was significantly reduced
- the ability to achieve the original (baseline) injection time with the use of DCA additive; it follows that the contaminants formed during the 48 h Dirty-Up test are leveled in the 24 h Clean-Up test after the use of 20% ethanol or butanol additive with DCA additive; the leaching of contaminants occurs rapidly (1–2 h) after the start of the test, and then take on a linear, slow leaching character.

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.

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Nomenclature

20D	admixture of 20% (v/v) ethanol	DU	Dirty-Up
20E	admixture of 20% (v/v) buthanol	KC	Keep-Clean
CU	Clean-Up	SIDI	spark ignition direct injection
DCA	500 ppm (m/m) Deposit Control Additives		

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