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Potential of ethanol and butanol in reducing deposits of SIDI engine injectors

ARTICLE INFO

The operation of conventional (hydrocarbon) fuels causes certain effects in the internal combustion engine. Despite the satisfactory efficiency of internal combustion engines, their fuel systems, particularly the injectors, are subject to constant fouling. The article analyzes the possibility of reducing the deposit of high-pressure gasoline injectors using the alcohol addition of ethanol and butanol. The study was conducted under the engine and non-engine conditions. Fuel injection timing was analyzed when fueling with different mixtures, and non-engine analyses were conducted to determine changes affecting the injectors. The results indicate the possibility of reducing injector hole coking using ethanol and butanol as a 20% additive to the base fuel.

1. Introduction

The global policy for reducing pollutants from the road transport sector currently concerns regulated harmful components of exhaust gases such as NO_x, CO, CO oxide, HC unburned hydrocarbons, particulate matter PM, and CO_2 carbon dioxide emissions as a component of GHG (greenhouse gases).

On April 17, 2019, Regulation (EU) No. 2019/631 of the European Parliament and of the Council defining CO_2 emission standards for new passenger cars and for new light commercial vehicles repealing Regulations (EC) No. 443/2009 and (EU) No. 510/2011 [16] was introduced. On 8 June 2022, the European Parliament adopted a Regulation of the European Parliament and of the Council (EU) that amends Regulation (EU) No 2019/631 concerning more stringent CO2 emission standards for new passenger cars and light commercial vehicles, aligning with the EU's ambitious climate targets. The European Parliament advocated for a 20% reduction in average CO2 emissions by 2025, a 55% reduction by 2030, and a 100% reduction by 2035, compared to the levels recorded in 2021.

Alcohols are interesting alternative to commercially utilized fuels, independently or blended with gasoline or diesel. Incorporating alcohol fuels can be a viable solution towards reducing the emission of harmful exhaust constituents, including greenhouse gases, into the atmosphere. However, to make the most of this solution, a comprehensive understanding of alcohol fuel properties and their compatibility with modern engine designs is crucial. Among the alcohols, ethanol and butanol are considered the most promising bio-components for existing conventional fuels. Since 2009, the European RED (Renewable Energy Directive) and FQD (Fuel Quality Directive) have acknowledged the potential of ethanol by permitting a maximum content of 10% (V/V) in motor gasoline while also encouraging the development of Flex Fuel Vehicles (FFVs) capable of running on fuel containing up to 85% (V/V) ethanol.

In 2011, a consortium consisting of the European Commission's Joint Research Centre, the European Council for Automotive R&D (EUCAR) and CONCAWE presented possible future scenarios for meeting the requirements of the Renewable Energy Directives and Fuel Quality Directive, among which some assumed the introduction of fuels with higher ethanol content such as E20 [4]. In June 2013, CEN/TC19/WG38 published a report (CEN/TR 16514) on "E10+" fuels, particularly concerning E20/25. These are fuels for SI engines containing between 20% (V/V) and 25% (V/V) ethanol in their composition. As a result, the European Commission proposed conducting further studies on the feasibility of introducing E20/E25 fuels to the market, considering that previous studies have already shown their great potential for reducing emissions of GHG and other harmful components emitted by internal combustion engines into the atmosphere. Furthermore, augmenting the ethanol content in the fuel would yield several favorable outcomes, such as reducing vapor pressure and elevating the octane number of the fuel. As part of a new agreement between the European Commission and CEN, the Commission agreed to fund a project on expanded research on E20/E25 fuels, together with ePURE (European Renewable Ethanol). This research aimed to understand better and comprehensively assess the environmental impact of E20/25 fuel, improve the energy efficiency of engines, and identify obstacles that need to be overcome before this type of fuel can be marketed [16]. On 11 December 2018, the European Parliament and the Council issued Directive 2018/2001, commonly called the RED II Directive or the Biofuels Directive. This directive outlines various measures aimed at supporting the utilization of energy derived from renewable sources and supporting the advancement of renewable energy sources as a whole. The directive sets renewable energy consumption targets for 2021-2030 and strongly promotes biofuel production from waste. The RED II Directive recasts and repeals previous legislation (Directive 2009/28/EC, Directive (EU) 2015/1513 and Council Directive 2013/18/EU) establishing a mutual system for all European Union countries to promote energy from renewable sources in various sectors of the economy. This means increasing the share of renewable

energy in the energy mix by 2030 in sectors such as electricity, heating and cooling, and transport [5].

To date, much research has been carried out on blends of conventional fuels with various alcohols for evaluating the performance of internal combustion engines. Nevertheless, there has been a notable lack of recognition and comprehensive explanation regarding the impact of certain properties of the tested alcohols on engine performance and operational characteristics. The progression of the mixture formation process holds significant importance in a DISI (Direct Injection Spark Ignition) engine, considering that the fuel is injected directly into the engine cylinder. Direct fuel injection generally allows for better mixture formation than indirect injection engines. The significance of the fuel injection process in a DISI-type engine arises from several factors, including the higher fuel injection pressure, precise control over injection pressure variations, and the timing and quantity of fuel delivery [3, 23]. The formation of the fuel-air mixture is contingent upon various aspects, such as the internal structure of the liquid stream, the atomization process, and fuel evaporation characteristics [21–23]. Notably, the internal structure of the jet stream during injection plays a pivotal role as it directly influences the jet atomization process and vaporization properties [13, 14, 21]. Generating any deviation or disturbance in the optimized atomized fuel spray pattern, such as: changing the jet angle, disturbing the assumed atomization symmetry of the spray pattern, increasing the penetration, or increasing the average diameter of atomized fuel droplets, has a deteriorating effect on engine emissions and performance [20, 23]. The formation process of the combustible mixture in the engine cylinders is prone to interference, influenced by several critical factors. Among these factors, the key determinants include the special quality and timing of fuel atomization, the velocity and penetration depth of atomized fuel droplets, the effective control of mixture movement (swirl), the interaction between atomized fuel droplets and the chamber walls/piston bottom, the inherent physical and chemical properties of the fuel, as well as the prevailing temperature and pressure conditions within the chamber. Disruptions to the fuel atomization process can lead to undesirable outcomes, including an augmented accumulation of fuel on the walls of the combustion chamber, prolonged fuel evaporation time caused by larger droplet sizes, and unregulated evaporation of fuel absorbed by deposits formed on the injector tips. Igniting a poorly mixed and improperly composed mixture can result in untimely, uncontrolled ignition timing and combustion failure during the exhaust stroke. Consequently, this gives rise to elevated emissions of harmful exhaust constituents, accompanied by heightened fuel consumption, diminished engine performance, erratic operation, and challenges initiating the engine [3]. Even a small amount of deposits formed in the channels and around the outlet ports of the fuel injectors of DISI engines uncontrollably changes both quantitatively and qualitatively the injection process by limiting the magnitude of the fuel outflow rate from the injector [14, 25], distorting the spray pattern of the jets [14], deteriorating the quality of the spray [25], and adversely interacting the fuel jets with the turbulence of the air supplied to the combustion chambers [3,

23]. In the latest designs of reciprocating internal combustion engines, including the DISI type, preventing the formation of injector deposits has a decisive impact on the engine's maintenance of the manufacturer's declared performance characteristics as well as performance and emissions. Therefore, an issue of particular interest is the propensity of various fuels to form injector deposits in DISI engines and their effect on the emission of standardized and non-standardized exhaust components into the atmosphere. Deposits forming in the injector outlet channels affect the flow rate, jet penetration depth and spray cone angle and the start and end of injection. They can change the injectors' spray characteristics, which, in turn, can affect the engine cylinder's charge formation and combustion processes [3, 11, 21–23, 26]. External coke deposits around the injector outlet ports are mainly formed from burnt fuel and, to a lesser extent, from lubricating engine oil. They cause distortions in the spray pattern of the fuel, flushing the combustion chamber walls and piston crown with fuel and consequently increasing fuel consumption and emissions (especially HC and PM) [3, 22, 23]. Internal injector deposits are formed exclusively from fuel. They diminish the fuel injection flow rate into the combustion chambers by restricting the cross-sectional area of the injector openings. This has the effect of increasing the average droplet diameter of the atomized fuel, the quantitative ratio of fuel-air mixing (air excess ratio "λ") and increasing the fuel evaporation time [3, 22, 23]. As a result, this leads to decreased engine efficiency and performance and increased fuel consumption.

Including alcohol, such as ethanol, in the fuel has a favorable impact on maintaining clean injectors. Unlike gasoline, alcohol is a single-component fuel without double bonds, granting it greater thermal stability. Ethanol, for instance, comprises merely two carbon atoms and, notably, one oxygen atom, resulting in an oxygen content of 35%. Consequently, the combustion of ethanol yields minimal amounts of soot. While the mechanisms behind soot formation and injector deposits differ in DISI engines, primarily due to the substantially higher temperature required for soot formation compared to deposit formation, it can be anticipated that the presence of ethanol in the fuel would lead to significantly reduced injector deposits compared to gasoline. In addition, ethanol has a lower heat of phase transition, resulting in a lower injector nozzle temperature than when the engine is fueled with gasoline [24]. Apart from the numerous benefits of ethanol in mitigating deposit formation on DISI engine injectors, it does have one drawback: its lower boiling point in comparison to gasoline. Consequently, including ethanol in gasoline blends leads to a reduced T90 temperature compared to pure gasoline, potentially fostering the formation of injector deposits. However, numerous studies have demonstrated the advantages of ethanol or gasoline-ethanol blends regarding their diminished propensity for injector deposit formation [1, 6, 7, 10, 18].

The motivation for the project presented in the article was to study the effect of the admixture of alcohol (ethanol or butanol) to gasoline on the formation of deposits of DISI engine fuel injectors. Quantitative and qualitative changes

in the injected fuel dose were used as criteria for evaluating deposit formation. The novelty of the work lies in combining the study of changes in the size of the injection time of a single dose of fuel, due to the formation of injector deposits, carried out using a standardised, pan-European engine test methodology, with the evaluation of changes in fuel atomization quality based on the study of the macroscopic atomization indices of a fuel jet in a constant-volume chamber using laser illumination.

2. Ethanol and butanol as fuel additives

When evaluating the selection of alcohol-gasoline blends as a fuel for spark-ignition internal combustion engines, various crucial fuel properties must be taken into account, considering the engine's requirements. While the energy content per unit mass, indicated by the calorific value, is vital in assessing the fuel's overall energy characteristics, the calorific value relative to the fuel's volume plays a significant role in determining fuel injection timing and, consequently, the formation of a high-quality fuel-air mixture over time, potentially influencing engine performance. This aspect holds particular significance in the fuel injection system used in modern engines, namely direct fuel injection. In this system, the precise amount of fuel required for optimal engine operation is delivered to the combustion chambers by adjusting the injection duration, which is contingent upon the engine's operating conditions [26].

Ethanol and butanol are the most promising alcohol-based biocomponents for current conventional fuels. These alcohols possess advantageous functional, operational, and environmentally friendly properties, enabling a reduction in the reliance on hydrocarbon fuels for powering engines [15]. Thus far, ethanol has garnered more extensive usage, blended in varying ratios with gasoline and widely adopted as fuel for spark-ignition engines in numerous countries. This is likely attributed to the abundance of research focused on ethanol, both in terms of understanding its properties and practical application, facilitating its earlier and broader implementation as a fuel either in its pure form or as an additive. The comparatively lower production cost of ethanol than butanol is also a significant factor. However, given the manifold advantages of butanol over ethanol and its properties, which closely resemble those of gasoline, it is believed to possess greater potential for future green fuel applications.

Table 1 contains a comparative analysis of selected properties of gasoline, n-butanol and ethanol.

Both butanol and ethanol have a higher density than gasoline. Butanol, on the other hand, has a higher density than ethanol, so its maximum allowable proportion in blends with gasoline is less than that of ethanol, given the requirements in EN 228 for gasoline (blend) density. As the content of n-butanol and ethanol in a mixture with gasoline increases, the heating value of the mixture decreases in an approximately linear fashion. However, due to the higher calorific value of n-butanol relative to ethanol on both a unit weight and volume basis, the calorific value of a mixture containing n-butanol decreases less as the n-butanol content increases compared to a corresponding increase in ethanol. Therefore, gasoline blends containing a certain amount of n-butanol will lower engine fuel con-

sumption compared to gasoline blends with the same ethanol content [2, 8, 9].

Table 1. Physical and chemical properties of gasoline, n-butanol and ethanol

Properties	gasoline	n-butanol	ethanol
Chemical formula	Complex mixture of compounds	C_4H_9OH	C_2H_5O
LOB [–]	95	94–96	110
Density [kg/m³]	753	810	790
Mass calorific value [MJ/kg]	42.9	33.3	26.8
Volumetric calorific value [MJ/dm³]	32.3	27.0	21.2
Latent heat of vaporization [kJ/kg]	380–500	716	904
Mass participation „C" [%]	86	65	52
Mass participation „H" [%]	14	13.5	13
Mass participation „O" [%]	0	21.5	35
Viscosity [mPa·s]	0.4–0.8	2.57	1.08
Boiling point [°C]	199	118	78
Excess air ratio [–]	14.7	11.2	9.0

An increase in ethanol content in the gasoline mixture will result in a rise in octane number. This is highly advantageous due to the possibility of using such fuel in engines with a higher compression ratio and, therefore, higher efficiency. This offers the possibility of avoiding using octane-raising additives in such fuels. Unlike ethanol, n-butanol has an octane number close to gasoline, and therefore increasing its share in the mixture with gasoline will not change the octane number. Thus, considering this utility parameter, butanol is more easily convertible with gasoline than ethanol.

When used as a fuel in blends with gasoline for spark-ignition (SI) engines, butanol offers several advantages over ethanol. Notably, butanol exhibits lower hygroscopicity, superior miscibility with gasoline, and a higher heating value, resulting in lower fuel consumption compared to blends containing ethanol. Furthermore, when blended with gasoline, butanol has a lower blending vapor pressure than ethanol, facilitating compliance with the requirements of EN 228. However, it is important to acknowledge certain drawbacks of butanol compared to ethanol when blended with gasoline. These include a lower octane number, reduced heat of vaporization, and higher density and viscosity, which may contribute to an increased tendency to form harmful deposits in the fuel injection system, as well as in engine components such as valves, intake ports, and combustion chambers. In summary, when utilized in gasoline-alcohol fuel blends for SI engines, butanol exhibits greater potential in terms of performance characteristics compared to ethanol.

The various thermophysical properties of alcohols can cause significant differences in both their atomization and spray structure and evaporation characteristics [17].

The application of alcohol as a fuel admixture is very important because it provides several benefits, such as reducing greenhouse gas emissions, reducing emissions of toxic exhaust components, increasing energy safety, and improving many fuel performance properties, including knock combustion resistance [19]. Knock combustion is a major barrier to achieving higher thermal efficiency in

reciprocating internal combustion engines [12, 17, 19]. The fuel atomization process heavily influences the performance of a spark-ignition (SI) engine, particularly a direct-injection engine fueled by a gasoline-alcohol blend. Consequently, numerous researchers are devoting their efforts to conducting further studies and enhancing this process, specifically mitigating the adverse effects of injector deposits [12].

3. Methodology

3.1. Methodology of engine testing

The rapid development and widespread use of gasoline direct injection (GDI) systems have made it necessary to develop test methodologies and evaluate the tendency of gasoline of different compositions to form destructive fuel injector deposits. Initially, the available, European-wide test methodologies developed by the CEC (Coordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants and Other Fluids) only included evaluations of deposits formed on various engine components, but only with indirect injection. Therefore, the automotive industry demanded the development of a generally applicable, recognized test procedure to evaluate and distinguish between fuels that meet and do not meet the requirements of engine and fuel injection system manufacturers for keeping the fuel injection system clean during engine operation. In 2016, the CEC formed a new TDG-F-113 DISI Working Group and began developing a test procedure to meet the above expectations. Finally, in December 2017, a procedure was published that received the CEC designation F-113-KC and the name: VW EA111 DISI Injector Deposit Test. The widely known and used VW EA111 BLG type engine (Table 2) was used as the test tool.

Table 2. Technical specifications of the VW EA111 BLG engine used for testing

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	–	Tree-way catalysts, closed feedback loop
Emission norm	–	EU4

The engine under consideration is a direct-injection configuration incorporating a combined boost system that combines mechanical supercharging and turbocharging, following the "downsizing" approach. The fuel injection system employed in this engine is of the wall-guided type, and it utilizes electromagnetically controlled injectors featuring six injection holes. The procedure allows conducting fuel evaluation, including DCA (Deposit Control Additive), according to two tests, i.e.:

- CEC F-113-KC "Keep-Clean" Test Procedure: This is a 48 h test during which the engine is operated under constant speed (2000 rpm) and constant load (56 Nm) conditions. It allows evaluation of the base or refined fuel in terms of its ability to keep the injectors clean.

- CEC F-113-CU "Clean-Up" Test Procedure: Includes a 48 h part of the "Dirty-Up" test performed according to the "Keep-Clean" test and a 24 h part of the "Clean-Up" test in which the engine operates under the same conditions as in the "Dirty-Up" or "Keep-Clean" test. The test allows evaluating the cleaning properties of the fuel used in the "Clean-Up" part of the test.

The evaluation criterion for assessing the propensity of the fuel to generate injector deposits during the test is the variation in the width of the electrical pulse governing the fuel injection duration. As the deposits gradually accumulate both externally and internally within the injector, this duration progressively lengthens. Figure 1 illustrates a visual representation of the fuel injector, highlighting the presence of external deposits near the fuel outlet apertures.

Fig. 1. View of the fuel injector and external deposits in the area of the fuel outlet holes – VW EA111 BLG test engine
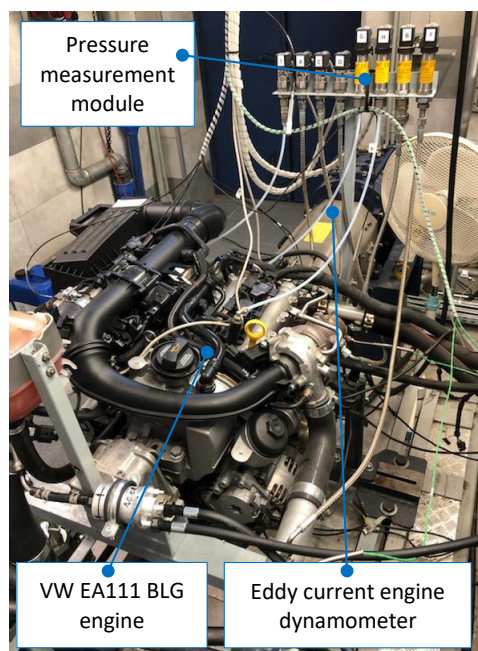

Fig. 2. Engine test stand (INIG-PIB)

Figure 2 shows a general view of the test bench for testing according to test procedure CEC F-113, on which tests were carried out at INiG-PIB. The project's tests were conducted per the CEC F-113-KC procedure (VW EA111 BLG) – 2022 edition.

3.2. Methodology of model testing

The static tests were conducted using a constant volume chamber (2.2 dm^3) into which fuel was injected at 10 MPa from a high-pressure injector without air back pressure

(Fig. 3). During the analyzes in the constant volume chamber, the same injector was used on which the engine tests were carried out. The same base fuel was used in the tests. The atomized fuel jet was evaluated using two systems: a) a camera together with a halogen light source – for the evaluation of spray geometric indexes; b) a camera and laser illumination system for the evaluation of the cross-section of the injected fuel jet. Laser illumination was generated using NG:YAG 532 mm pulsed laser light. The circular laser beam was converted into a so-called "light knife" in the collimator.
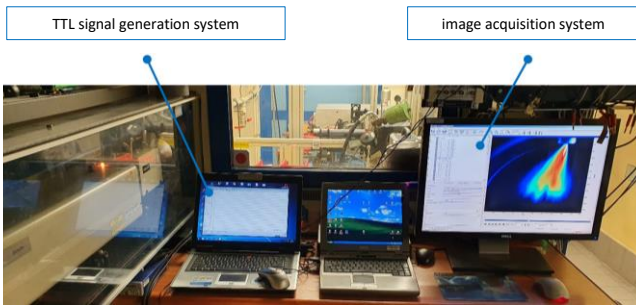
Fig. 4. View of the control panel for the operation of a test stand equipped with an isochoric chamber

The injection time was 0.5 ms, and the signal was generated from a Sequencer device (Fig. 4). Recording of images at 10 kHz was performed using an HSS 5 LaVision camera (with a resolution of 512 × 512 pixels). A Nikkon AF Nikkor 24-85 mm 1:2.8-4 D lens was used. Image analysis was carried out using DaVis 10 software.

3.3. Method of processing optical test results
Analysis of the images was conducted for:
- fuel spray, analyzing the range, area and cone angle of the jet (Fig. 5a); this research was based on measuring the side spray of fuel with halogen lighting;
- cross-sectional area of the fuel jet with detailed analysis of each jet cross-sectional area (Fig. 5b).

4. Fuels used in the study
The project's engine tests used three motor gasolines varying in composition including:
- CEC RF-12-09 batch 11 – base (reference fuel)
- CEC RF-12-09 batch 11 + 20% (V/V) ethanol
- CEC RF-12-09 batch 11 + 20% (V/V) butanol

The choice of reference gasoline was based on its popularity for research applications and availability across Europe. RF-12-09 batch 11 gasoline is a fuel with a high tendency to form deposits on intake valves used to calibrate Mercedes M102E and Mercedes M111 research engines.

The restriction of the alcohol admixture to 20% (V/V) was due to the engine manufacturer's requirements for the maximum allowable alcohol content in petrol. The physicochemical properties of the fuel samples prepared for testing are shown in Table 3.
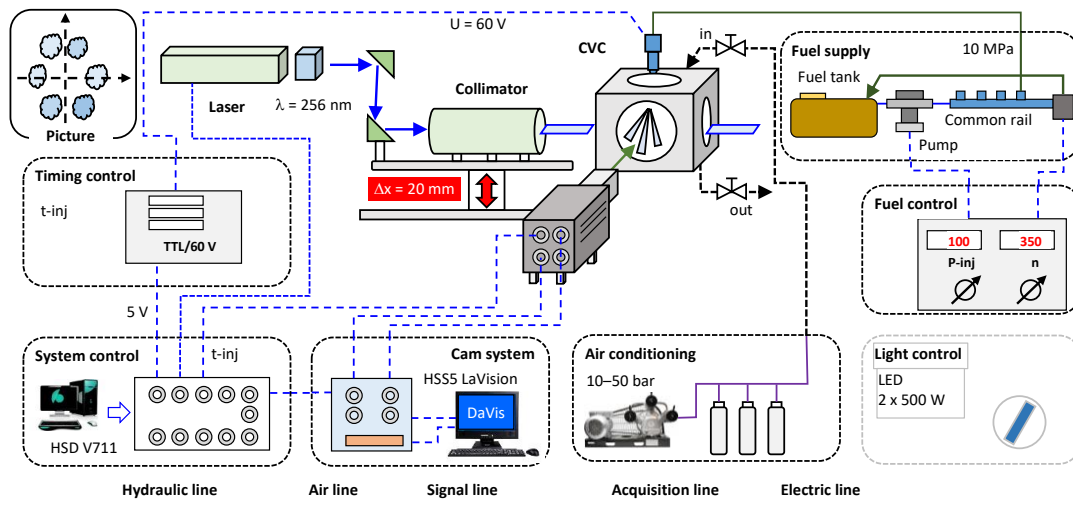

Fig. 3. Schematic of fuel atomization tests using laser illumination – cross-section of all fuel jets
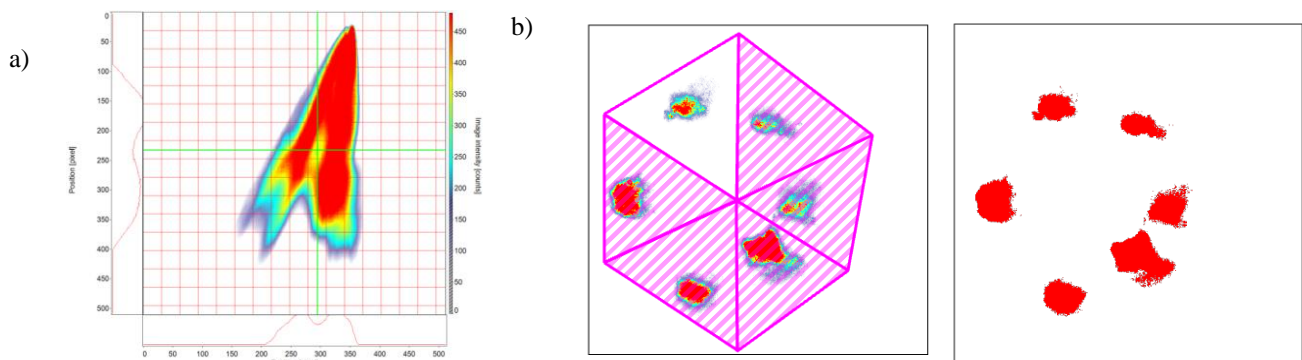

Fig. 5. Davis 7 software panel for analysis of individual areas of fuel injection: a) macroscopic analysis; b) stream cross-section analysis

5. Results discussion

5.1. Analysis of engine tests

Figure 6 shows a comparison of the changes in fuel injection times obtained during tests conducted according to the CEC F-113-KC procedure for the three fuels tested. The first test (base fuel) evaluated the ability of the raw fuel without alcohol admixture to keep the injectors clean.
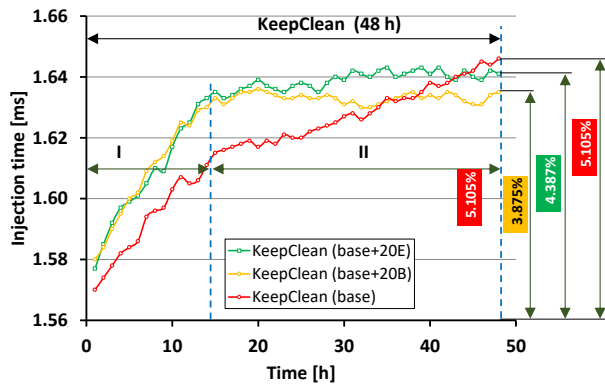

Fig. 6. Results comparison of the fuel's ability without and with alcohol admixture to maintain the cleanliness of DISI engine injectors according to the CEC F-113-KC procedure

Test two (base fuel + 20E) evaluated the same raw fuel admixed with 20% (V/V) ethanol according to the same procedure, and test three (base fuel + 20B) evaluated fuel admixed with 20% (V/V) butanol. The test result is the averaged difference in the electrical pulse width controlling

the fuel injectors' opening time in a single fuel injection, measured before and after the test.

Due to the highly fluctuating and rapidly changing nature of the measured pulse, characterized by both high frequency and significant amplitude variations over time, determining the total pulse width or injection time solely by comparing its magnitudes at the beginning and end of the test could result in substantial errors. To mitigate this, a methodology based on a trend function is employed, as it provides more reliable and representative values compared to those based solely on the endpoints of the measurement. By utilizing this approach, average calculations of the electrical pulse widths controlling the injection time are obtained at the start and conclusion of the test. The test result is determined by calculating the difference between the average widths of the electrical pulse controlling the time of a single fuel injection at the beginning and end of the test. This difference is expressed as a percentage [%], indicating the increase in width. A larger difference indicates a greater tendency of the fuel to form injector deposits.

It is important to consider that the characteristics of each engine design, the combustion process strategy, injector design, and operating conditions significantly influence the development and severity of injector deposition phenomena. Therefore, the final evaluation of a fuel is based on the progression of deposit formation and the size of injector deposits observed over a specific period. Thus far, evaluations of fuels using the procedure above have been conducted in various European laboratories affiliated with the CEC (Coordinating European Council), specifically

Table 3. Physical and chemical properties of gasoline samples prepared for engine testing

Parameter	Unit	RF-12-09 batch 11	RF-12-09 batch 11 + 20% (V/V) ethanol	RF-12-09 batch 11 + 20% (V/V) butanol	Test method
		1	2	3	
Density at temperature 15°C	kg/m^3	734.4	747.2	753,9	PN-EN ISO 12185
Research octane number (LOB)	-	96.3	98.3	98,8	PN-EN ISO 5164
Motor octane number (LOM)	-	87.1	87.7	88,7	PN-EN ISO 5163
Sulfur content	mg/kg	5.0	3.7	3,5	PN-EN ISO 20846
Induction period	minutes	> 360	> 360	> 360	PN-EN ISO 7536
Resin content present	mg/100ml	0.5	1.0	2,5	PN-EN ISO 6246
Hydrocarbon content of type: – olefin – aromatic	 % (V/V) % (V/V)	 5.5 27.8	 < 4.0 21.5	 < 4.0 23.1	PN-EN 15553
Benzene content	% (V/V)	0.36	0.3	0.3	PN-EN 238:2000 +A1
Oxygen content	% (m/m)	< 0.1	7.53	4.94	PN-EN 1601
The content of oxygen-containing organic compounds:					
– methanol	% (V/V)	< 0.80	< 0.17	< 0.17	PN-EN 1601
– ethanol	% (V/V)	< 0.80	20.4	< 0.17	
n-butanol	% (V/V)	< 0.80	< 0.17	20.2	
– isopropyl alcohol	% (V/V)	< 0.80	< 0.17	< 0.17	
– tert-butyl alcohol	% (V/V)	< 0.80	< 0.17	< 0.17	
– isobutyl alcohol	% (V/V)	< 0.80	< 0.17	< 0.17	
– other oxygen-containing organic compounds	% (V/V)	< 0.80	< 0.17	< 0.17	
Fractional composition: – IBP – end of distillation temperature – distills – residue – losses – evaporation temp. 10%, T10 – evaporation temp. 50%, T50 – evaporation temp. 90%, T90	 °C °C % (V/V) % (V/V) % (V/V) °C °C °C	 32.9 196.9 97.9 1.1 1.4 52.4 106.8 173.2	 36.7 196.5 98.2 1.0 0.8 52.8 72.7 152.3	 36.7 198.0 98.5 1.0 0.5 61.7 102.6 153.4	PN-EN ISO 3405

through the efforts of the CEC TDG F-113 Working Group. These evaluations have allowed for determining result repeatability using statistical analysis based on the Student's t-distribution.

It has been determined that a minimum absolute difference of 1.8% in the magnitude of the electrical pulse width is required to distinguish between the two results with a 90% confidence interval. Comparing the results of the CEC F-113-KC tests for the three tested fuels (as shown in Figure 3), the average increase in calculated injection time for the reference fuel was 5.105%, for the reference fuel with 20% (V/V) ethanol admixture was 4.387%, and for the reference fuel with 20% (V/V) butanol admixture was 3.875%. Previous research has identified several key properties of unrefined fuel that significantly affect the formation of injector deposits, including T90 temperature, fuel sulfur, olefin and aromatics content, as well as vapour pressure, density, IBP, and octane number [22, 23]. However, all the tested fuels were based on the same reference fuel (RF-12-09 batch 11), resulting in small differences in their physicochemical properties, primarily attributed to adding ethanol or butanol. Additionally, the final result is influenced by the complex interaction of various fuel properties, which can have intricate and difficult-to-determine effects on deposit formation. Analyzing the final results obtained for the three fuels, it can be observed that, from a perspective of repeatability, these results should be considered comparable and statistically evaluated. Notably, the pattern of deposit formation during the 48-hour test period is of interest. In the case of the reference fuel, a nearly linear increase in deposits formed throughout the test can be observed (as shown in Figure 3).

Consequently, after a 15-hour test run, the calculated increase in injection time of a single fuel dose is 2.936% (Area I). Subsequently, between 15 hours and 48 hours, the increase in injection time of a single fuel dose changes from 2.936% to 5.105% (Area II). The situation differs for the reference fuel with a 20% (V/V) ethanol admixture, where the increase in injection time of a single fuel dose follows a logarithmic trend. After approximately 15 hours of the test run, a clear deviation in the trend of deposit formation can be observed at an increase in injection time of a single fuel dose of 3.942% (Area I). Then, between 15 and 48 hours of the test, the increase in injection time of a single fuel dose changes from 3.942% to 4.387% (Area II). A similar trend is observed for the reference fuel with a 20% (V/V) butanol admixture, where a distinct break in sediment formation occurs at an increase in injection time of a single fuel dose of 3.748% after about 15 hours (Area I). Subsequently, between 15 and 48 hours of the test, the increase in injection time of a single fuel dose changes from 3.748% to 3.875% (Area II). Hence, in the case of fuels blended with alcohol, the formation of deposits stabilizes after approximately 15 hours of testing. The differences in the trend and rate of injector deposit formation for different fuels can be attributed to the intensity of deposit precursor formation processes, the strength of adhesion to the surface, and the simultaneous self-cleaning processes of injectors [22, 23]. After the formation and stabilization of deposit precursors on the injector surface,

their growth and removal processes determine the subsequent course of deposit formation. A linear pattern occurs when deposit formation and removal processes occur concurrently, with a constant predominance of fouling. Thus, it can be hypothesized that fuels containing alcohol (in the case of the tests described here, ethanol or butanol) have a lower tendency to foul the fuel injectors. This is because, due to the linear increase in fuel injection time caused by non-alcohol-containing fuels, the level of injector fouling created will exceed that of alcohol-containing fuels due to their stabilization after a certain period.

5.2. Analysis of optical tests

An optical analysis of the fuel spray is shown in Fig. 7. As can be seen from the images, there is some variation in the geometry of the recorded areas. Very similar extents of the jet can be seen. The variation relates to changes in the fuel concentration in the jet, as the degree of exposure of the images is slightly different. Analysis of the ethanol base fuel spray indicates a higher fuel concentration in the jet's core than in the other spray cases.

A detailed macroscopic analysis is shown in Fig. 8. Very similar values of the spray area can be seen, which is differentiated only in the range t = 750–1000 us to the beginning of fuel outflow (Fig. 8a). Identical values of penetration indicate (Fig. 8b) that it is necessary to analyze further quantities, which will adequately enable the evaluation of changes in the fuel spray, using different additives to the base fuel. For this reason, the jet cone angle was determined (Fig. 8c), which already indicates clear differences in fuel atomization. For the base fuel, this angle obtains almost constant values (about 40 deg). With butanol addition, this angle is greater: at the beginning of the atomization, about 50 deg and then decreases to about 40 deg. The atomization of the fuel from the injector running on fuel with ethanol addition shows a higher value of this angle from 55 deg at the beginning of atomization to about 43 deg after about 1 ms.

The results of the tests using laser illumination are shown in Fig. 9. Image analyses were performed in multiple cross-sections (from about 5 to 25 mm) from the maximum penetration. The spray areas shown indicate differences in the spray created by the three differently contaminated injectors. The use of the base fuel indicates a reduction in the cross-sectional area of the orifices, resulting in limited areas of some outflow orifices. The ethanol additive reduces fuel outflow to the least extent, as indicated by the large cross-sectional areas of the plumes. The use of butanol as an additive reduces the cross-sectional flow areas somewhat, but the reduction is not as significant as when only the base fuel is used.

A detailed assessment of the number of pixels in each isolated injected fuel jet is shown in Fig. 10. The data included are for the cross sections shown in Fig. 9. These analyses confirm that ethanol as an additive obtains the largest spray area. However, these changes are not very large. It should be noted that optical tests were conducted on the same base fuel, and the changes obtained are due to measurements of the injector, which was fed with different fuels.
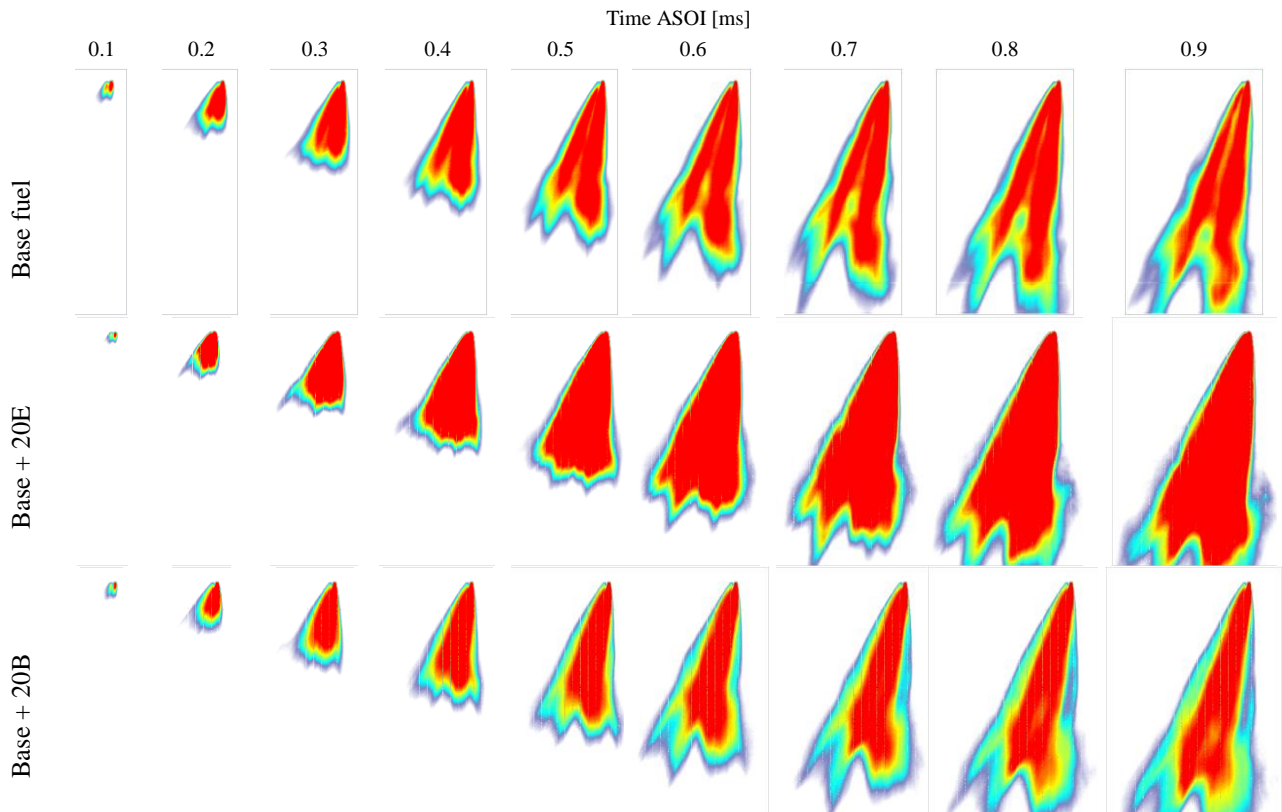
Fig. 7. Sequence of fuel spray images from the tested injectors
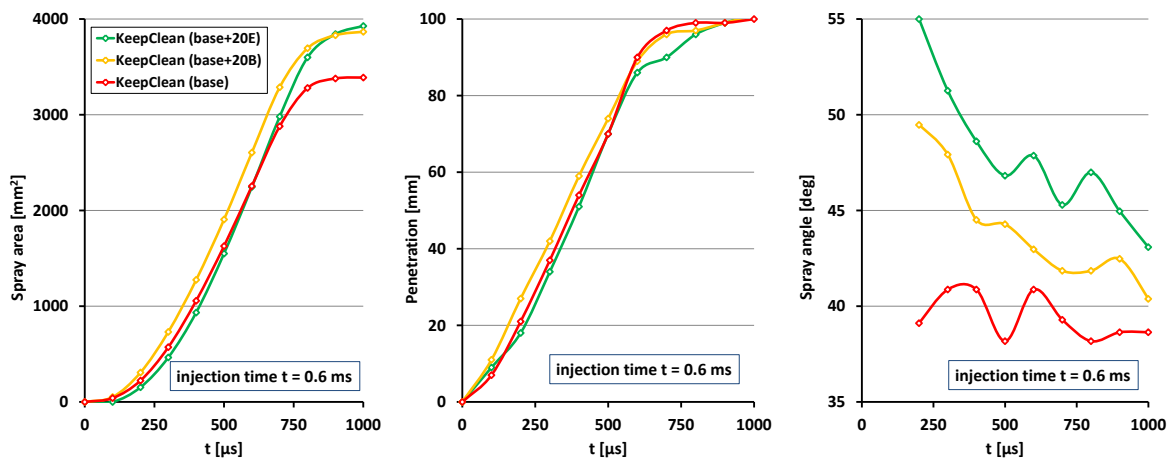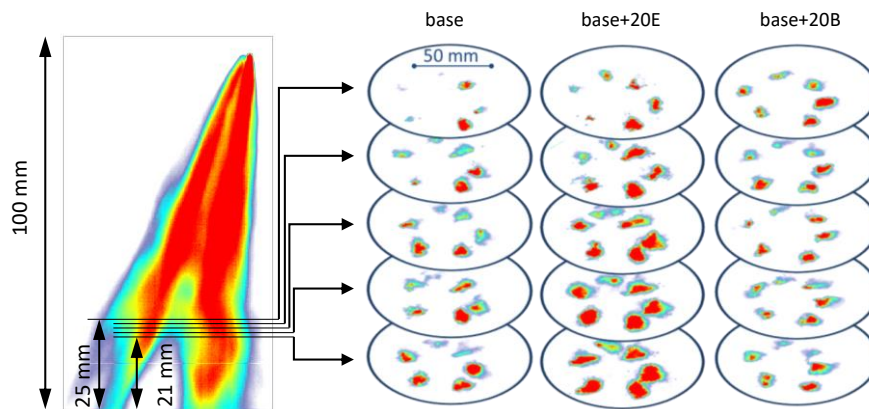

Fig. 8. Macroscopic indicators of fuel sprays

Fig. 9. Representation of the stream cross-section location with results (the results refer to successive tests of fuel atomization; t_{inj} = 0.6 ms; t = 1 ms)
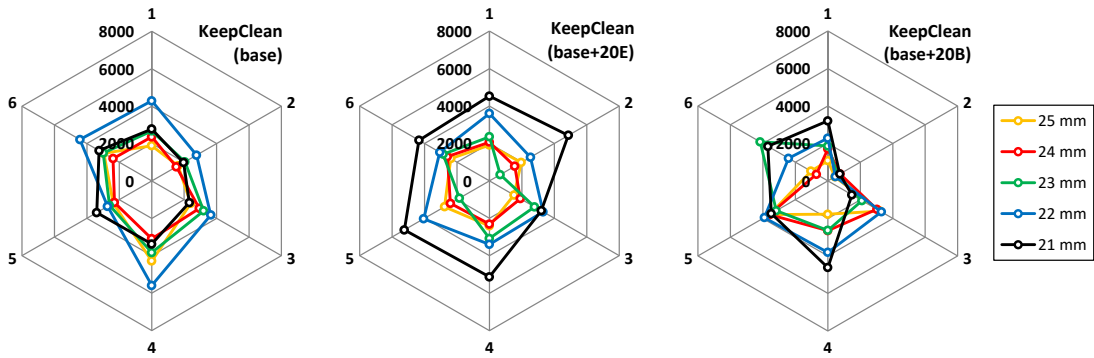
Fig. 10. Areas of the fuel stream from Fig. 9, including the isolation of each fuel stream

Figure 11 shows the total pixels from the fields of all injector orifices in a given unit of time to the beginning of fuel atomization. Instantaneous injection area values are included in Fig. 11a, while Fig. 11b shows trend lines for the three summed injection areas. The analysis results presented here show that the flow diameters of the injectors increase when base fuel additives are used. The use of fuel additives significantly increases the fuel flow area. The increase in area is more than 20% compared to the base fuel.
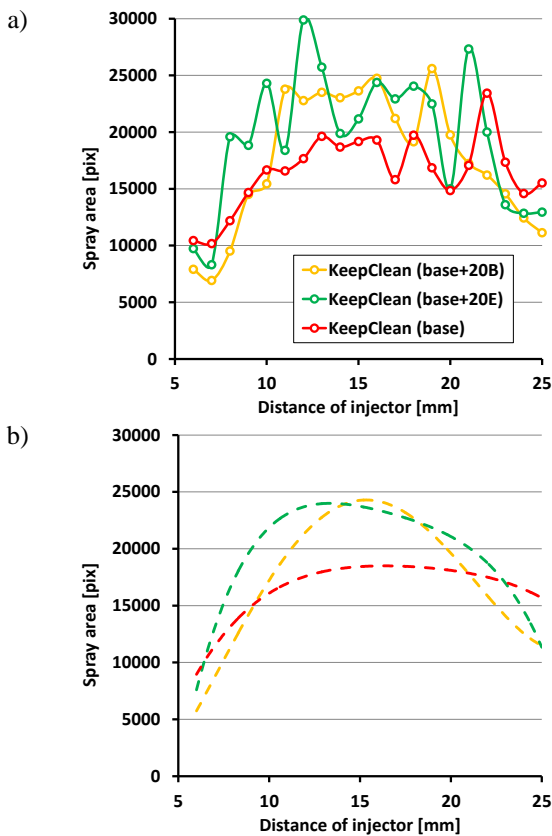

Fig. 11. Total area value of fuel jets over the full range of analysis (a) and averaged area values determined by a polynomial (n = 4) trend line

In addition, an analysis of the structure of the outflow holes was performed using a microscope. One of the elements of such tests was the determination of the different diameters of the actual bore of the working injector (Fig.

12). The results indicate that the pinhole is partially coked, as its diameters are different. The differences obtained are up to 30%.
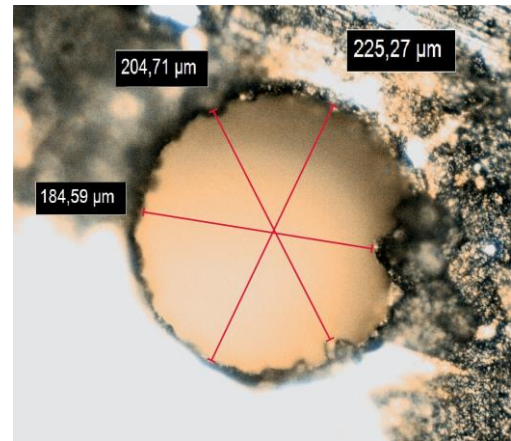

Fig. 12. Example values defining injector hole diameter

In the next stage of the work, an optical analysis of all the holes of the working injector was carried out (Fig. 13). These studies indicate varying deposition of the holes. The analyzed images do not clearly indicate large changes in injector orifice contamination. Thus, a full contamination analysis requires both engine and bench tests with their support by optical data.

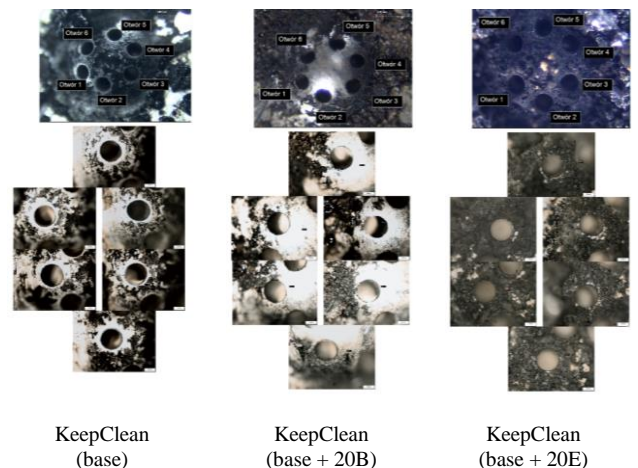KeepClean (base)   KeepClean (base + 20B)   KeepClean (base + 20E)

Fig. 13. Images of the injector tip and holes after testing

6. Conclusion

The experimental work evaluated the effect of adding alcohols (ethanol, butanol) to the fuel on forming deposits in the injector holes. A direct injection system with multi-hole injectors was analyzed. A comprehensive evaluation was made by combining tests on a multi-cylinder engine, optical tests using laser illumination and magnification photography.

By analyzing the change in fuel injection time during a 48-hour test on an engine dynamometer, it was proven:

1. The addition of 20% V/V alcohol increases the injection time relative to the reference fuel RF-12-09 batch 11.
2. After 15 hours of the test, the relative increase in injection time was 2.936%, 3.942% and 3.748% respectively for the use of reference fuel, ethanol admixture and butanol admixture.
3. After 48 hours of testing, the relative increase in injection time was 5.105%, 4.387% and 3.875% for the use of reference fuel, ethanol admixture and butanol admixture, respectively.
4. In the case of fuel containing an admixture of alcohol, there is a balancing of the processes of formation and removal of deposits after only a few hours of testing.
5. Alcohol-containing fuels have a lower tendency to contaminate fuel injectors.

Based on optical studies of the development of the fuel jet from the injectors used during the engine tests, it was noted:

1. As a result of recording the jet outflow parallel to the axis, a change in the jet shape was noticed without an increase in jet penetration.
2. The use of an alcohol admixture in the fuel after 48 hours of injector operation results in an increase in the spray area and cone angle (parallel view) relative to the use of the reference fuel.
3. The type of alcohol used has no significant effect on the resulting surface area of the sprayed fuel (parallel view; perpendicular view).
4. The largest cross-sectional area of the jet occurs at a distance of about 15 mm from the tip of the injector.

Photographing the injector holes with 1,000 times magnification allowed to:

1. Determine the location of deposit accumulation depending on the fuel used.
2. Indication of the base + 20E mixture as the one where the highest amount of deposits occurs on the outer part of the atomizer. The smallest deposit on the outer part was obtained using base + 20B.

Nomenclature

20B	the addition of 20% V/V butanol
20E	the addition of 20% V/V ethanol
ASOI	after start of injection
CEC	Coordinating European Council
CNG	compressed natural gas
DCA	deposit control additive
DISI	direct injection spark ignition
ePURE	European Renewable Ethanol
EUCAR	European Commission's Joint Research Centre, the European Council for Automotive R&D
FFVs	flex fuel vehicles
FQD	fuel quality directive
GDI	gasoline direct injection
GHG	greenhouse gases
ISC-FCM	in-service conformity – fuel consumption monitoring
LPG	liquefied petroleum gas
RED	Renewable Energy Directive
λ	air excess ratio

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