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OPERATIONAL EVALUATION OF ATOMIZATION INDICATORS FOR GASOLINE WITH ADMIXTURES OF ETHANOL AND BUTANOL DURING KEEP-CLEAN TESTS

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Abstract:

The global policy of reducing road transport sector pollution requires the introduction of significantly modified already in use technologies and construction solutions. Currently, direct fuel injection technology is the best solution in terms of reducing fuel consumption and exhaust emissions of standard pollutants into the atmosphere, as well as further improving the engine performance. In terms of exhaust emissions, direct injection spark ignition engines are characterized by significantly higher exhaust emissions of particulate matter (approximately 10 times higher) compared to indirect fuel injection SI engines, they show a greater tendency to knocking combustion and are prone to the formation of harmful deposits on engine parts, including in the fuel injectors. The injector tips located in the combustion chamber are exposed to the direct influence of the very high pressure and temperature caused by the combusting fuel-air mixture, which contributes to the rapid formation of harmful deposits.

Operation-based injectors contamination in spark ignition engines results in a reduction of the cross-sectional flow diameter of the injector, which then necessitates the extension of the injection time in order to maintain the fuel dose and the expected engine operating parameters. The tests were carried out on an engine dynamometer and an optical test stand for fuel atomization process. The presented research analyzes indicate the possibility of using admixtures that effectively reduce the likelihood of contamination. The paper presents a results analysis of engine tests performed in accordance with the CEC F-113-KC procedure. Additionally, the injectors were tested to conduct an analysis of the injected fuel stream's geometric indicators. The range, surface area and speed of the injected fuel stream as well as the fuel distribution in the stream were determined based on an equivalent indicator. The obtained results indicated that ethanol and butanol admixtures of 10% (V/V) to gasoline did not significantly extend the fuel injection time as compared to the reference fuel. A further increase in the proportion of ethanol caused a significant deterioration of the fuel flow and the geometric indicators of the fuel spray.

Keywords: *fuel injection, fuel additives, Keep-Clean tests, fuel atomization, fuel injector deposits*

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1. Introduction

The global policy of reducing road transport sector pollution requires the introduction of completely new or significantly modified already in use technologies and construction solutions. This requires conducting research in new fields of study or to extend and deepen the research done in already explored fields. In the automotive industry, the most common approach taken by these projects seems to be making the development of motor vehicles and the fuels powering them, or other energy sources, focused on the goal of reducing the emissions of harmful exhaust components, including greenhouse gases (GHG) to the atmosphere (Czerwinski et al., 2006). In the case of the design of internal combustion engines with SI (spark ignition), the use of direct fuel injection technology – DISI (Direct Injection Spark Ignition) has become commonplace. Currently, this technology is the best solution in terms of reducing fuel consumption and exhaust emissions of standard pollutants into the atmosphere, as well as further improving the engine performance (Andrych-Zalewska et al., 2022). The technology that cooperates with and at the same time supports DISI in achieving its goals is boosting the engines (usually turbocharging as the most efficient boosting system). The aforementioned technologies and solutions made it possible to pursue and popularize the process of so-called "downsizing" of engines, which improves the overall efficiency of the engines, and therefore reduces their fuel consumption, while significantly increasing their specific power. Apart from the indisputable advantages of these technologies, some disadvantages also exist. They also require very specific operational conditions and create problems that are inherently different from those encountered in indirect fuel injection systems. In terms of exhaust emissions, DISI engines are characterized by significantly higher exhaust emissions of particulate matter (approximately 10 times higher) compared to indirect fuel injection SI engines, they show a greater tendency to knocking combustion and are prone to the formation of harmful deposits on engine parts, including in the fuel injectors. Such deposits significantly deteriorate both the performance and operational parameters of the engines. This is a challenge and defines new research areas for engine designers, but also for fuel producers, in particular for the production of fuel additives, especially DCA (Deposit Control Additives) (Stępień et al., 2021).

2. The problem of injectors contamination

Compared to Port Fuel Injection (PFI) engines, the fuel injectors of DISI engines operate in a much more harmful environment. The injector tips located in the combustion chamber are exposed to the direct influence of the very high pressure and temperature caused by the combusting fuel-air mixture, which contributes to the rapid formation of harmful deposits. The chemical effects of the products of the combusted fuel are also significant (Awad et al., 2021; Gueit, Arondel & China, 2015; Henkel et al., 2017; Shuai et al., 2018; Stępień et al., 2011). This can become a big problem for the proper engine operation, because the quality of the air-fuel mixture formed in the combustion chambers is almost entirely dependent (controlled) on the operation of the fuel injectors, which are largely influenced by the formation of deposits in them. External deposits around the fuel outlet ports are formed primarily from burned fuel as well as from lubricating engine oil to a lesser extent. These deposits disrupt the fuel stream flow, which disrupts stream atomization. Thus fuel ends up reaching the combustion chamber walls and the piston crown, which leads to an increase in fuel consumption and harmful components exhaust emissions (in particular HC and PM). Internal injector deposits, on the other hand, are formed exclusively from fuel. They limit the flow rates of the fuel injected into the combustion chambers due to the reduction of the cross-section area of the injector fuel flow channels. This can lead to an increase of the mean diameter of the atomized fuel drop, the quantitative proportion of fuel-air mixing (excess air coefficient – λ) as well as extending the fuel evaporation time (Altin & Eser, 2004; Huang et al., 2020; Lindgren et al., 2003; Xu et al., 2015). In general, even a small amount of deposits formed in the channels and around the fuel injector outlet ports of DISI engines affect the fuel injection process, both quantitatively and qualitatively in an uncontrollable manner. It can be observed in the form of limiting the fuel flow rate from the injector (China & Rivere, 2003; DuMont et al., 2009; Huang et al., 2020; Dhanji & Zhao, 2022), distortion of the spray pattern of fuel streams (Lindgren et al., 2003; Wang et al., 2017), deterioration of the fuel atomization quality (Altin & Eser, 2004; Lindgren et al., 2003), disruptive interaction of fuel streams with the turbulent air supplied to the combustion chambers (Altin & Eser, 2004; Lindgren et al., 2003). The above-mentioned changes in the injectors operation reduce the efficiency and performance of the engine in connection with an increase in the harmful exhaust components emission, an increase in fuel consumption, difficulties with starting the engine and its irregular operation, especially when idling.

The fuel composition has a significant impact on the formation of injector deposits. The evaporation temperature of 90% of the fuel (T90) is particularly important. Two hypotheses regarding the role of T90 in deposit formation are known. One of them assumes that the higher the T90 temperature a fuel has, the less likely it is to form injector deposits (Altin & Eser, 2004; Dhanji & Zhao, 2022). The second assumes that if the nozzle tip temperature is below the T90 value, some fuels will have a lower tendency to form deposits, and if the injector tip temperature is higher than T90, the tendency to form deposits will be higher (Altin & Eser, 2004; Dhanji & Zhao, 2022).

The effect of gasoline sulfur content on the formation of injector deposits has been the subject of many studies (China & Rivere, 2003; Donghwan & Sungwook, 2021; Edney et al., 2021). These studies showed the negative effect that sulfur contained in the fuel has on the engine and exhaust system, but in regards to the impact of the amount of sulfur contained in the fuel on the increase or decrease of the tendency to form deposits, the results of various tests were found to be divergent, and in many cases simply contradictory.

Performed research on the influence of the fuel olefin content on the deposits formation tendency in the injectors showed that increasing the olefin content caused an increase in the deposits formation (Dhanji & Zhao, 2022). Other studies have shown that an increase in the molecular weight of olefins leads to more deposits being formed (Hongliang et al., 2020).

The amount of information available in the literature on the effect that aromatic compounds have on the formation of injector deposits is very limited. It is only known, generally, that the aromatics contained in the fuel in general favor the formation of injector deposits (Edney et al., 2021).

The alcohol content in the fuel, more specifically ethanol, helps maintain the injectors clean. Unlike gasoline, alcohol is a single component fuel, with no double bonds, which makes it more thermally stable. The ethanol molecule contains only two carbon atoms, and most importantly one oxygen atom, which makes it 35% oxygen. The result is that ethanol produces very little soot when burning. Although the mechanisms of soot formation and deposits in the injectors are different for DISI engines, primarily because the soot temperature is much higher than the deposit formation temperature, it can be expected that the amount of injector deposits when burning ethanol will be lower than for gasoline. Moreover, ethanol has a lower phase change heat, which causes the temperature of the injector nozzles to be lower compared to the temperature obtained by using gasoline (Song et al., 2016; Taniguchi, Yoshida & Tsukasaki, 2007). In addition to the many advantages of ethanol in terms of controlling the amount of injector deposits in a DISI engine, it also has a disadvantage in the form of a lower boiling point compared to gasoline. As a result, ethanol blends with gasoline have a lower T90 compared to pure gasoline. But in general, the results of many published studies have indicated overall advantages of ethanol or gasoline-ethanol blends in terms of a lower tendency to form injector deposits, especially after a longer period of engine operation (Altin & Eser, 2004; DuMont et al., 2007; Morlan, Smocha & Lorenz, 2020).

For studies on deposits formed in SI engines, the Worldwide Fuel Charter (2013 edition) indicates the following American methods: ASTM D 5500, ASTM D 6201, ASTM D 5598 and ASTM D 6241 and European CEC F-05-93 (M102E), CEC F-16-96 (VW Boxer) and CEC F-20-98 (M111). All the American methods assume conducting tests in cars or engines from the 1980s, and these are only indirect fuel injection engines. The tests include assessing any deposits found on the intake valves or fuel injectors. The European methods assume that all the above-mentioned tests are to be carried out in PFI engines from the 1990s with indirect fuel injection. The assessments are made for deposits on the intake valves and in the combustion chambers. Thus, none of the methods mentioned are representative of the current, most common both in the USA and in Europe, Direct Injection Spark Ignition (DISI) engines. Only in 2016, as part of the CEC (Coordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants and Other Fluids), the development of a research procedure that meets the above expectations has began. The first "Draft" of the procedure was released in December 2017. The procedure was given the designation CEC F-113-KC and the name: VW EA111 DISI Injector Deposit Test. This procedure was included as one of the requirements for the assessment of category 6 gasoline in the sixth edition of the Worldwide Fuel Charter of October 28, 2019. The CEC F-113-KC procedure is currently the only approved, standardized, pan-European test procedure used to assess the quality of gasoline testing for a deposit formation tendency in the injectors of direct fuel injection SI engines.

The motivation for conducting this research was the use of the pan-European, standardized test procedure CEC F-113-KC to assess the effect of alcohol (ethanol or butanol) admixture with gasoline on the deposit formation tendency on fuel injectors. In the further part of the research, an extension to the assessment of the injector deposits effects was prepared based on an analysis of the fuel stream geometric parameters carried out in stationary tests with a constant volume chamber.

3. Research method

3.1. Engine tests

The fuel tests were carried out on an engine test bench according to the CEC F-113-KC "Keep-Clean" Test Procedure. It is a 48-hour test in which the engine (VW EA111 BLG) is operated under constant engine speed (2000 rpm) and at constant load (56 Nm). The test allows to assess the base or admixture fuel in terms of its ability to keep the injectors clean, and thus to prevent the formation of undesirable deposits.

The fuel evaluation criterion in the tests is the change of the electric impulse width which controls the injection opening time and thus the fuel dose. This time changes (lengthens) as the amount of deposits accumulating inside and outside of the injector gradually increases. The waveform of the measured pulse is unstable and changes with a very high frequency and amplitude over time. Therefore, calculating the increase in pulse width (injection duration) by comparing its size at the beginning and end of the test would also contain a large error. In order to avoid this, a methodology based on trend function was used, which made it possible to obtain the computational mean width of the electric pulse controlling the injection time at the beginning and at the end of the test. The difference between the average injection time control pulse width at the beginning and the end of the test, usually given in [%], was the test result.

3.2. Scope of research

The research included the evaluation of the influence that an admixture of alcohols (ethanol and butanol) with gasoline have on the tendency of deposits formation a DISI engine injectors. The engine part of the tests was carried out in accordance with the CEC F-113-KC procedure, and therefore within the scope of the "Keep-Clean" tests. Taking into account the construction materials of the VW EA111 BLG test engine, especially in the direct fuel injection system, and the engine manufacturer's limitations regarding the permissible alcohol content for fuels to be used in it, this procedure assumes testing gasoline fuels with a maximum alcohol content of up to 20% (V/V).

The bench tests include geometrical analyzes of injectors powered by different fuels in the test engine, but currently powered by the same fuel – gasoline. Such studies do not analyze the geometry of various fuel streams. The tests are instead aimed at determining the differences in the flow characteristics change of the injectors as well as the conditions of deposit formation in engine tests.

3.3. Test object and equipment

3.3.1. Fuel tests

As part of the research, four gasolines differing in physicochemical properties and an admixture of alcohol (ethanol or butanol) were used as fuel in engine tests. In order to better distinguish the influence of the various physicochemical properties on the deposit formation, the fuel used for the tests did not contain additives from the DCA group. The tests used an RF-12-09 batch 10 gasoline with a high tendency to form deposits on the intake valves of SI engines used as a reference fuel in CEC engine tests. The physicochemical properties of the fuel samples prepared for engine tests were presented in Table 1.

Table 1. Physiochemical properties of gasoline blend samples produced for the engine tests

Property	Unit	RF-12-09 Batch 10	RF-12-09 Batch 10 +10% (V/V) ethanol	RF-12-09 +20% (V/V) ethanol	RF-12-09 Batch 10 +10% (V/V) butanol	Test procedure
Notation	–	RF	RF+10E	RF+20E	RF+10B	
Research octane number	–	96.0	97.4	98.2	97.8	PN-EN ISO 5164
Motor octane number	–	85.9	86.4	87.8	86.8	PN-EN ISO 5163
Sulfur content	mg/kg	9.0 ±1.5	7.8 ±1.7	5.3 ±1.7	7.3 ±1.6	PN-EN ISO 20846:2020
Content of hydrocarbon types:						PN-EN 15553:2009
Olefinic	% (V/V)	7.4 ±1.4	5.7 ±1.4	5.1 ±1.1	5.7 ±1.5	
Aromatic	% (V/V)	32.1 ±2.6	30.4 ±2.6	28.8 ±2.6	30.4 ±2.6	
Oxygen	% (m/m)	0.11	3.73 ±0.29	7.40	2.23 ±0.29	PN-EN 1601:2017-09
Organic compounds containing oxygen:						PN-EN 1601:2009
Methanol	% (V/V)	< 0.80	< 0.17	< 0.17	< 0.17	
Ethanol	% (V/V)	< 0.80	10.2 ±0.57	20.1	< 0.17	
Fractional composition:						PN-EN ISO + 3405:2019
T10	°C	52.3 ±2.6	53.0 ±2.6	51.4 ±2.6	55.4 ±2.6	
T50	°C	106.5 ±3.6	100.8 ±3.1	72.4 ±3.1	99.6 ±2.9	
T90	°C	172.9 ±4.0	171.9 ±4.0	163.4 ±4.0	170.8 ±4.1	

3.3.2. Measuring equipment

The engine tests were carried out in accordance with the CEC F-113-KC test procedure. The VW EA111 BLG engine, widely known and used in many series of VW vehicles, was used as the test engine for research. It is a direct injection engine with a combined boost system (mechanical boost + turbo boost) built in a downsizing convention. The engine used air-guided fuel injection. The fuel was injected during the test at 77 bar of pressure. The main technical parameters of the VW EA111 BLG engine were included in Table 2. The engine test bench was shown on Fig. 1.

Table 2. Main technical parameters of the VW EA111 BLG engine

Engine code	EA111 BLG
Type	4-cyl., in-line
Displacement	1390 ccm
Bore	76.5 mm
Stroke	75.6 mm
Valves per cylinder	4
Compression ratio	10:1
Maximum output	125 kW @ 6000 rpm
Maximum torque	220 Nm @ 1750-4500 rpm
Standard Fuel	Super Plus at RON 98
Emission standard	Euro 4

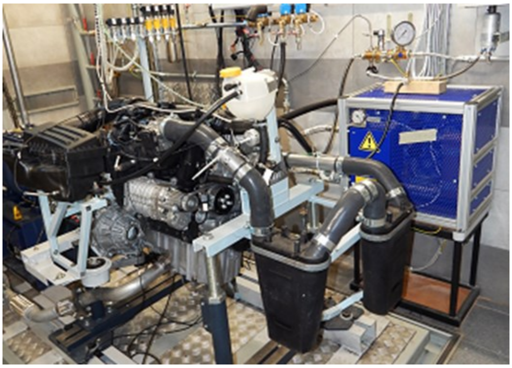

Fig. 1. Engine stand for operational tests at the Oil and Gas Institute – National Research Institute

3.4. Research plan

The research was divided into two sections: engine and bench tests. The engine tests concerned the analysis of changes in the fuel injection time, while the bench tests focused on the analyzes of the fuel stream geometry. The tests were carried out according to the procedure shown in Table 3.

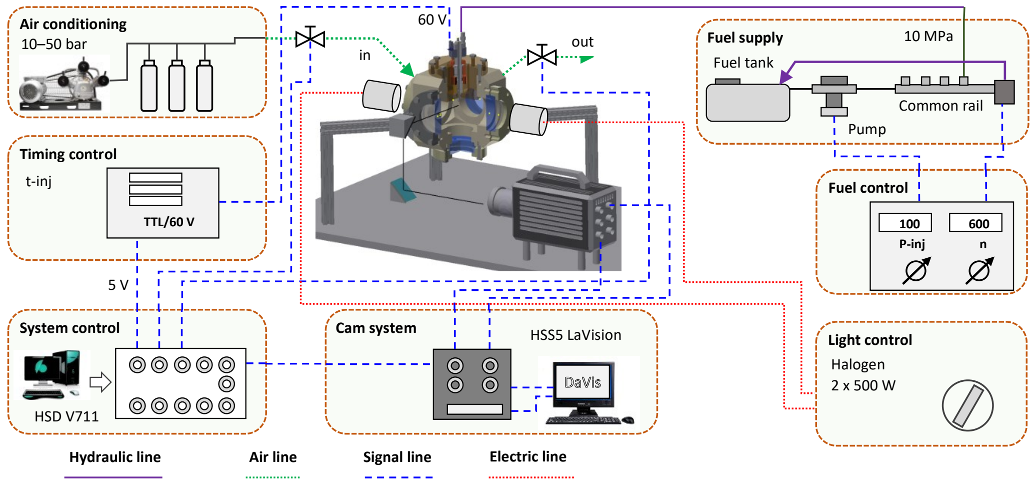

Fig. 2. Schematic of the test stand for fuel atomization analysis

Table 3. Test plan for engine and bench tests

Engine tests – dynamometer test bench		
n	rpm	2000
Mo	Nm	56
Time	h	48
Fuels	RF; RF+10E; RF+10B; RF+20E	
Analysis	fuel injection time change	
Stationary tests – constant volume chamber		
t_{inj}	ms	0.4
P_{inj}	MPa	10 MPa
P_b	MPa	0; 0.1; 0.2
Repetitions	3x	

3.5. Results processing and analysis methods

Results analysis was conducted in two aspects:

a) engine tests: changes in fuel injection time throughout a span of 48 hours in a test were determined; deposits are formed on the injectors as part of the test, which translates into increased fuel injection time in order to maintain the engine operating parameters (constant rotational speed and constant fuel dose value throughout the test);

b) bench tests concerning geometric analyzes of fuel streams: these tests were carried out on a dynamometer using injectors powered by various fuels; Gasoline was used in the bench tests to analyze the effects of the injectors operation with various fuels, and not to analyze the fuel spray properties of various fuels.

The research on the fuel stream cross-sections (Fig. 3) was carried out for the time t = 0.6 ms after the start of the injection:

a) for the cross-section – at a distance of 5 mm from the tip of the fuel atomizer

b) for the longitudinal section – along the stream axis

4. Engine test results

Figure 4 compares changes in the fuel injection time obtained according to the CEC F-113-KC procedure for the four tested fuels with the properties as given in Table 1. Figure 4a shows the changes (increase) in the duration of each separate fuel injection during 48 hours of the test, while Figure 4b shows changes in the injection time as a percentage increase. All the fuel injection time measurements presented in Fig. 4 were characterized by a gradual, but unstable, increase over time. Significant, often rapid fluctuations in the fuel injection time changes were observed during the test.

The likely cause of such fluctuations in the duration of fuel injections was the simultaneous competition between the processes of injector contamination as well as the injectors being cleared, i.e. the produced deposits being dislodged and removed. Typically, with non-alcoholic fuels, there is a gradual, linear increase in fuel injection time throughout the test duration. In this case, the processes of deposits formation and removal had a constant intensity and

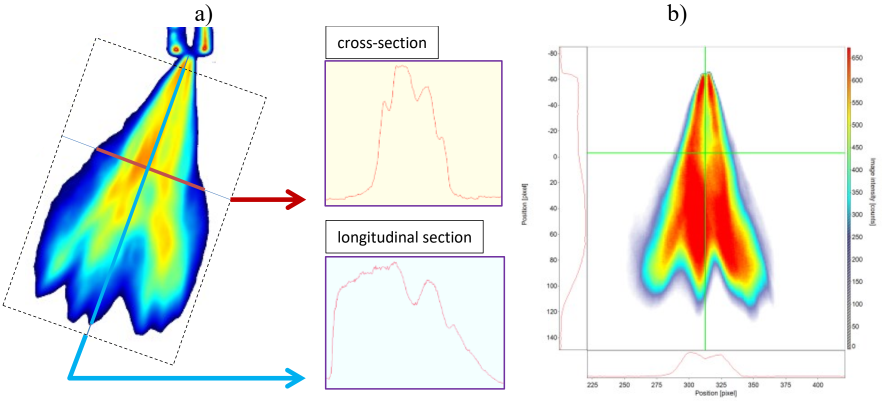

Fig. 3. Research methodology of the fuel distribution in longitudinal and crosssectional images of fuel spray: a) theoretical analysis of the cross-sections, b) practical implementation with the use of graphic software

while having a certain proportionality where the deposit formation processes were overall more intensive. After the deposit precursors have formed and stabilized on the injectors surface, further deposit formation on the injectors was the result of the opposing processes of deposit build-up and removal. Interpretation of the test result is very difficult because the end result is the resultant of all the effects associated by various fuel properties, some of which may have interactions that are very difficult to determine, with varying effects on the formation of injector deposits – Table 1. It can be hypothesized that if the test duration was extended, the fuel injection time would further increase, resulting from the growing deposits on the injector nozzles and in the fuel outlet holes, especially in the case of fuels without alcohol admixture. Such a thesis could be confirmed by the results obtained for the fuel labelled RF in Fig. 4 in the framework of the tests presented in the article.

It should be assumed that if this test duration was extended, then after some time which is difficult to estimate, the intensity of the deposit growth and removal processes would eventually have evened out.

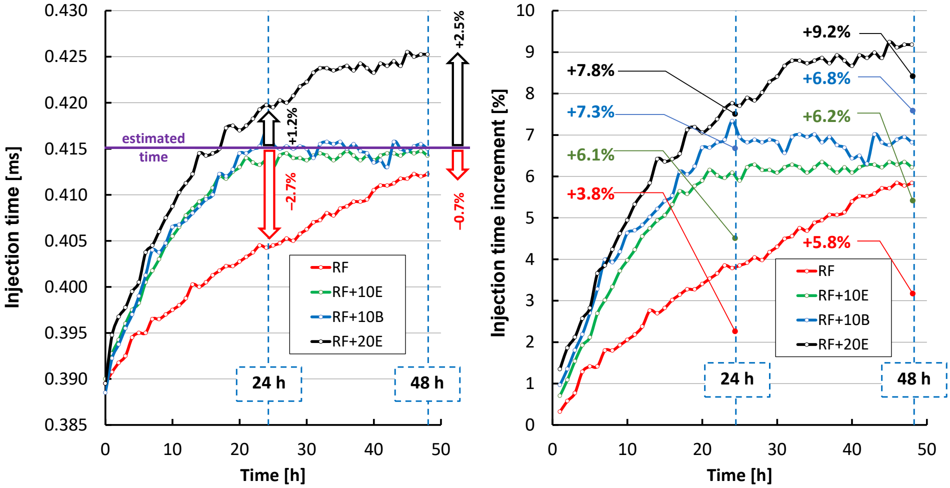

Fig. 4. The results of the injection time tests and their changes from the fuels used

Then the size of the sediment present in and on the injectors would stabilize at an approximately constant level. Another trend of changes in the fuel injection time observed in the conducted tests was found for fuels containing alcohols. In this case, changes in fuel injection time were approximately logarithmic. As a consequence, for fuels containing 10% (V/V) of alcohol (ethanol or butanol), labelled as RF+10E and RF+10B, after a period of approximately 24 hours of progressive increase in fuel injection time the duration of each injection eventually stabilized at a certain level (Fig. 4a). The fuel containing 20% (V/V) ethanol, labelled as RF+20E, was able to stabilize the rate of injector deposition process, and thus the width of the electric pulse controlling the time of a single fuel injection, after about 30–35 hours into the test duration.

By analyzing the properties of the tested fuels, Table 1, it can be inferred that the high injector deposits growth tendency for the RF fuel was related, among other things, to an increased content of sulfur and olefins in relation to the other tested fuels (China & Rivere, 2003; Donghwan & Sungwook, 2021; Edney et al., 2021; Dhanji & Zhao, 2022). On the other hand, a faster, initial increase in the size of deposits in the case of the RF+20E fuel could have also been caused by the lower T90 value (Altin & Eser, 2004; Edney et al., 2021; Gueit, Arondel & China, 2015; Von Bacho et al., 2009). The reference level of the stabilized single injection time of the fuel dose was adopted after completing the 48-hour fuel test. It was based on the results obtained for the RF+10E and RF+10B fuels, and shown in Fig. 4a. The stabilized single injection duration of the fuel dose for the RF+20E was higher than the reference level by 2.5%, while the corresponding value for the RF fuel was lower by 0.7%. However, it should be emphasized that in the case of the RF fuel, a steady linear increase in the injection time of a single dose was observed up to until the very end of the test, for which injection time failed to properly stabilize. Thus, it can be hypothesized that alcohol containing fuels have a lower tendency to lead to deposits formation in the fuel injectors. This is due to the fact that the amount of formed injector deposits in the case of alcohol-free fuels did exceed the level of deposit formation created by fuels containing alcohol, however, after a time longer than 48 hours, which was the total test duration for the CEC F-113-KC procedure. As a consequence, the injection time stabilization of the fuels ended up being greater for fuels not containing alcohol in their composition. The described trends could probably have been found after a shorter period of time, if the tests were carried out on fuels with a higher alcohol content.

5. Fuel atomization test results

The fuel atomization tests were carried out at three different values of backpressure in order to reproduce the variable pressure in the engine cylinder. The values were determined based on analyzes of the internal combustion engine operation: at low rotational speeds, there was no effect of the compressor boost, at higher speeds the effect was noticeable. Hence why the tests were carried out with three backpressure settings: 0; 0.1 and 0.2 MPa. An example of the base fuel injection sequence was shown in Fig. 5.

The analysis of the stream geometric indicators started with the assessment of the fuel stream range. Due to the specific geometry of the test system – the size of the quartz window with a diameter of $\varphi = 84$ mm at the backpressure $P_b = 0$ bar, the maximum possible stream range value was obtained (Fig. 6). The stabilization time was about 1.5 ms. With the backpressure $P_b = 1$ bar, this time increased to $t = 1.6$ ms and did not cover the entire measuring window. At $P_b = 2$ bar, the fuel stream range stabilization time was 1.7 ms.

Due to slight differences (about 11–12 percent) in the fuel atomization conditions (up to about 1.5 ms), the surface of the fuel stream was also analyzed. Due to the fuel stream illumination in the vertical plane and the same registration of the stream image (when rotated around the vertical axis by 90 degrees), it was not possible to separate each stream for analysis. All five fuel streams were assessed and treated together as a complete surface area (Fig. 7).

The analysis of the fuel stream surface area shows the smallest area was obtained in the test engine when using injectors fed with fuel with the highest 20% ethanol admixture (RF+20E). It follows that a high proportion of ethanol increased the deposit formation on the injectors. Similar results concerning the injection time were observed in the engine tests (at least during 48 hours of the engine test), as shown by the data in Fig. 4. There the injection times for fuel with high ethanol admixture were also increased.

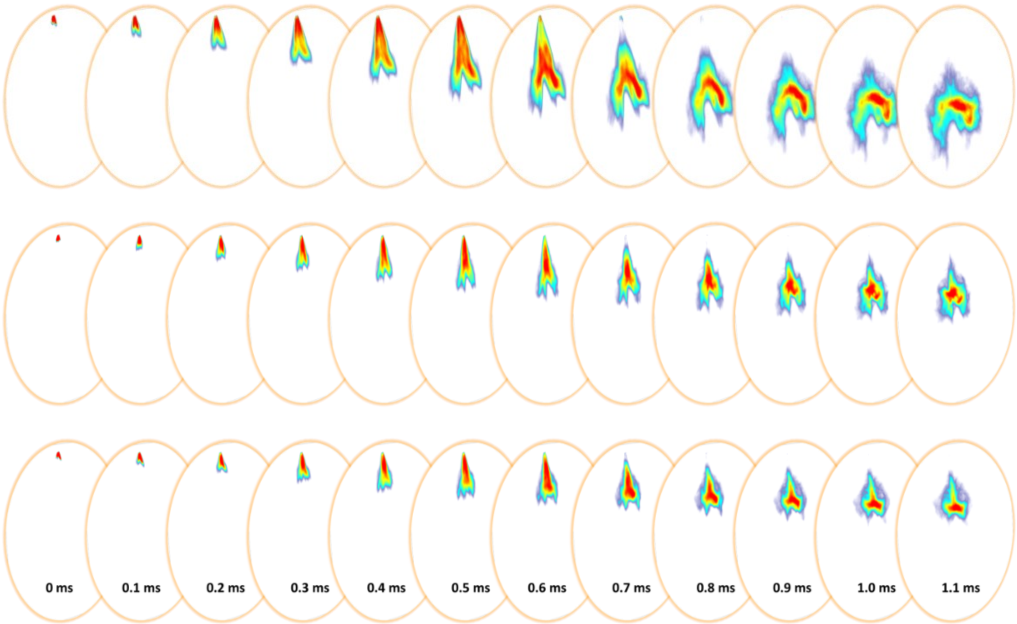

Fig. 5. An example of a base fuel injection sequence at different backpressure values (P_{inj} = 10 MPa; t_{inj} = 0.4 ms; P_b = 0; 0.1 and 0.2 MPa)

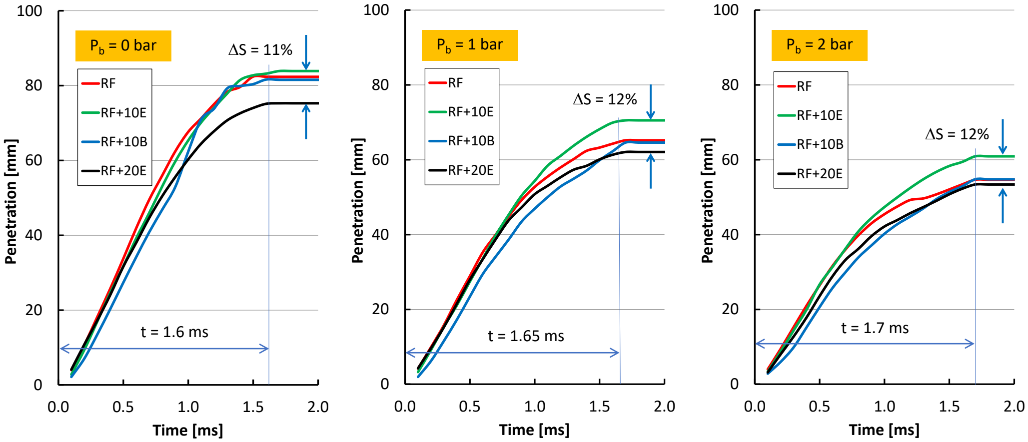

Fig. 6. Fuel stream range analysis for the tested fuels (P_{inj} = 10 MPa, P_b – variable, t_{inj} = 0.4 ms)

Partial admixtures of ethanol and butanol seemed to result in similar of fuel stream areas – this can be seen in particular in analyzes performed without any backpressure. It seems that the analyzes related to deposit formation should be conducted in such conditions, as their results are more closely aligned with the results obtained in the engine tests. The existence of air backpressure distorts these analyzes somewhat. Nevertheless, the greatest admixture of ethanol, even with a non-zero backpressure, indicated an increased deposits formation on the injectors (Fig. 7).

The fuel atomization speed analysis is a derivative of the stream range and the injector opening duration. The analysis of the data in Fig. 6 did not indicate any unequivocal changes in the fuel stream range, and the same was true for the outflow speed. It was found that the high admixture of ethanol caused deposits to form on the holes, which resulted in a reduced fuel flow rate. When testing injectors fed with 20% ethanol, the fuel flow velocity was reduced by about 5 m/s (with slight variations between other fuels). Such differences were not obtained in tests where backpressure was present. This is another element indicating the impact of air backpressure on limiting this test method.

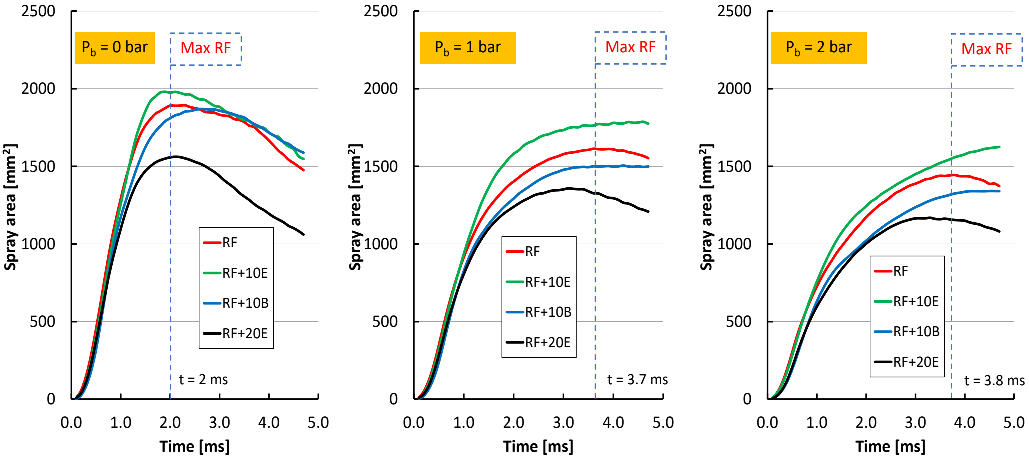

Fig. 7. Fuel stream surface area analysis for the tested fuels (P_{inj} = 10 MPa, P_b – variable, t_{inj} = 0.4 ms)

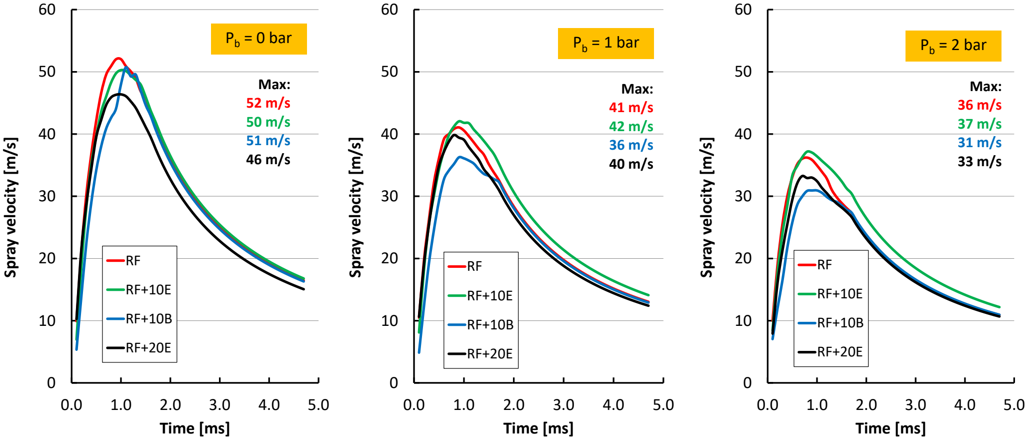

Fig. 8. Fuel stream spray velocity analysis for the tested admixtures (P_{inj} = 10 MPa, P_b – variable, t_{inj} = 0.4 ms)

6. Results and discussion

Analyzes of typical geometric indicators of fuel streams do not indicate the existence of clear or obvious differences for injectors operating with different fuels. Therefore, a decision was made to perform additional analyzes, which enabled the analysis of the injector deposit buildup.

Attempts were made to evaluate the differences in the obtained fuel stream areas for different injectors (Fig. 9). Results of these tests were related to the reference fuel surface area. Analyzing the data in Fig. 9 indicated slight changes in the fuel stream surface area for the injectors fed with fuels with slight admixtures of ethanol and butanol. Relative to the reference fuel, which reached the maximum stream range, these differences were about 3–4% (in the absence of backpressure). Increasing the backpressure increased these differences to between 7–9%. The biggest variation from the reference fuel values were found for a high admixture of ethanol, irrespective of the backpressure value – reaching about 20%. This value was concluded to not be an error in measurement. Therefore, high ethanol admixtures increase the fuel tendency to form deposits on the injector holes of gasoline direct injection engines, at least during the 48-hour test period (in accordance with the CEC F-113 KC procedure).

The above analyzes were supported by studies of the fuel (gasoline) stream cross-sections at its outflow from the injectors as they were initially supplied with different fuels. Their flow changes could be noted in the form of increased illumination intensity of the light reflected from the stream. Such studies indicate a possible presence of high fuel concentration in certain areas of the stream, which may confirm the theory of a change (decrease) of the flow cross-section in the injector holes.

Analysis of the stream's cross-section (as shown in Fig. 3) indicated an increased intensity of illumination when supplied with base fuel RF+20E (Fig. 10). This increased glow intensity indicated that there was an increased fuel concentration in the core of the image. Another research method confirmed the thesis that high ethanol admixture increased the formation of deposits on the injectors.

Analyzing the above assumptions in the presence of backpressure did not clearly indicate the existence of similar relationships. With the backpressure present, a large admixture of ethanol still indicated an increased illumination intensity, but the most increased intensity was instead found for injectors using a butanol admixture. A recurring feature is the fact that the base fuel and a fuel with a small admixture of ethanol indicated a low lighting intensity of the fuel stream core. In the case of these two fuels, the analyzes are repeatable regardless of the backpressure value.

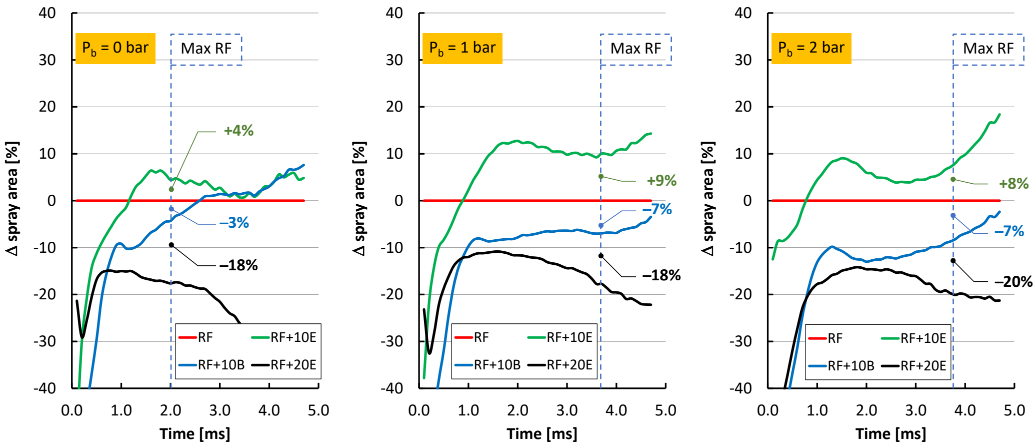

Fig. 9. Differences in the injector stream surface area at different backpressure values

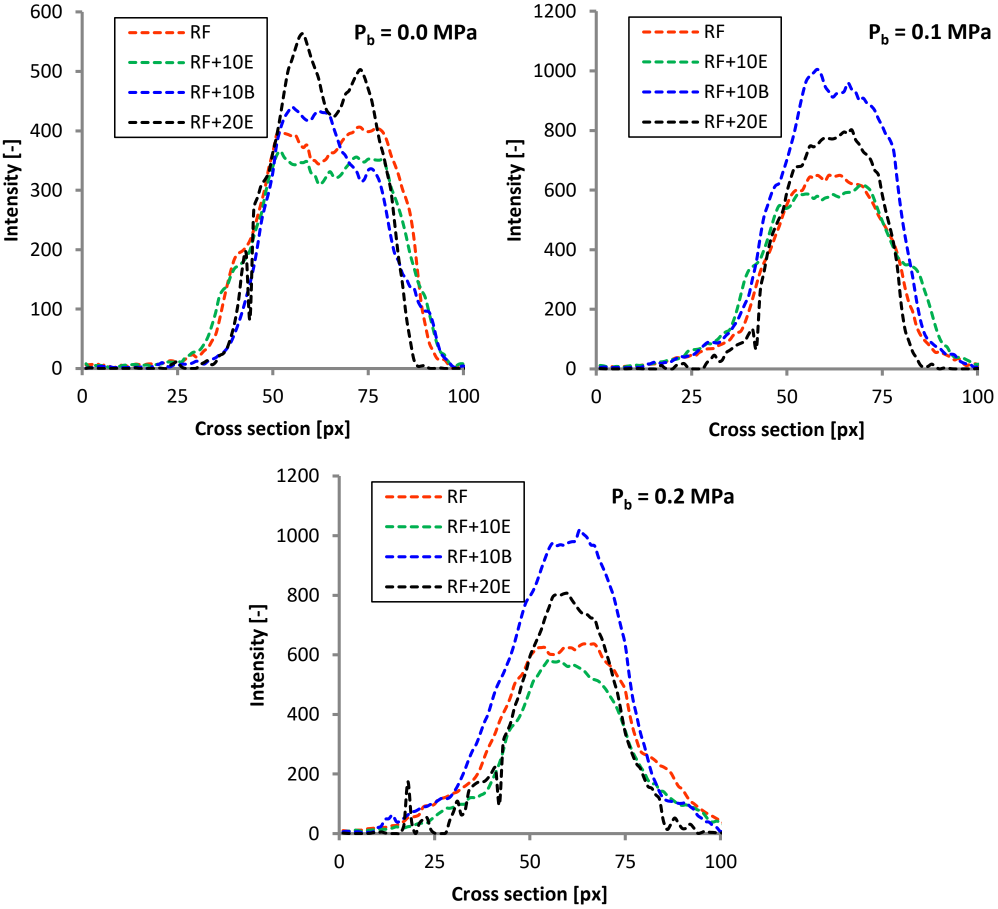

Fig. 10. Cross-sectional analysis of the fuel stream illumination intensity

Similar analyzes were carried out in the longitudinal cross-section of the fuel stream. Where the injectors supplied with fuels with admixtures of ethanol also resulted in a high stream illumination intensity. Such results were confirmed by low backpressure values. Increasing the backpressure reduced the differences between the results, which was the result of reduced surface area of the stream as well as its greater concentration around the stream core. With an increased backpressure value, the highest illumination intensity was observed for injectors that used a butanol admixture (similar results as those obtained for previous cross-sectional analyzes).

7. Conclusions

Engine and bench tests enable the quantitative assessment of deposits formation on injectors fed with fuels with ethanol and butanol admixtures. The most important conclusions derived from the presented research were listed below.

1. Fuel with high ethanol admixture leads to significant changes in the injectors flow cross-section in engines with direct gasoline injection. Tests performed in accordance with the CEC F-113-KC procedure have shown the importance of such test results. The deposits forming in the injector holes, measured by the increase in fuel injection time, was about 10% after the 48-hour test.

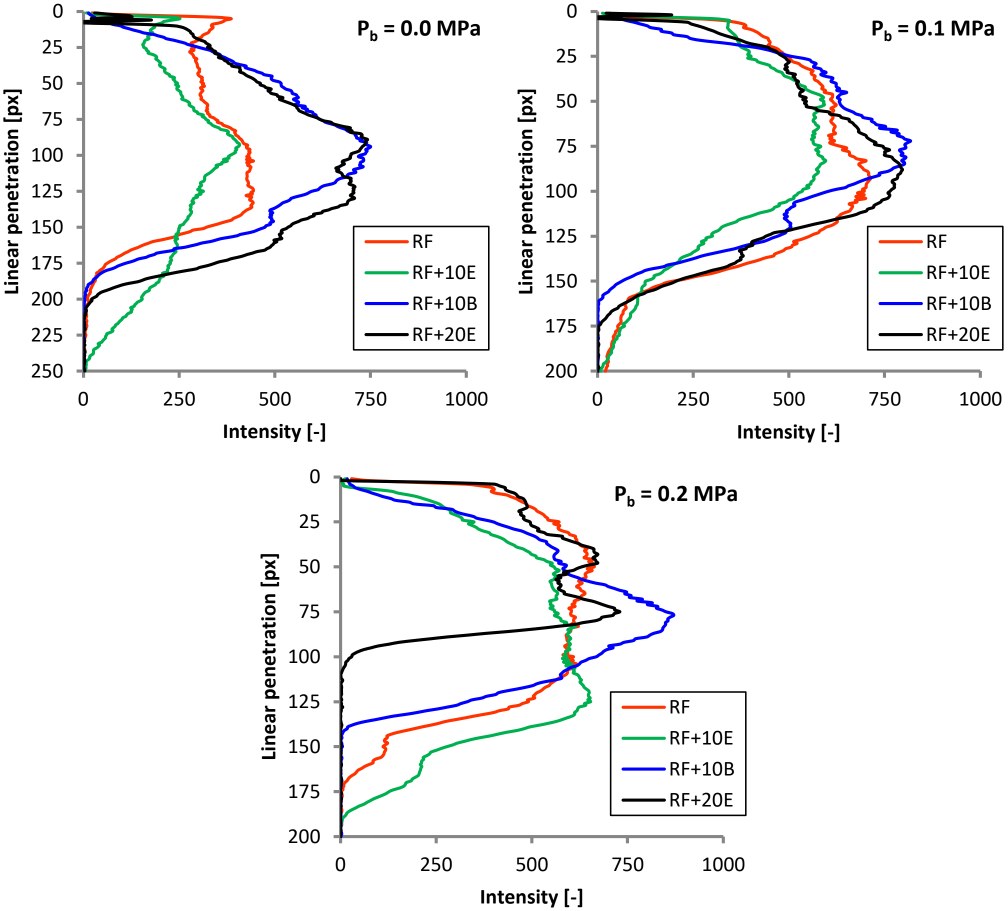

Fig. 11. Longitudinal cross-sectional analysis of the fuel stream illumination intensity

2. Halfway through the test, it was found that the standard fuel supply required an injection time increase of about 4% in order to maintain constant engine operating conditions. Whereas using fuels admixed with 10% ethanol and butanol increased the injection time by 6%. For fuel with a high admixture of ethanol, the injection time had increased by 8% in order to maintain constant engine operating parameters.
3. Small admixtures of ethanol and butanol indicated that formation of deposits in the injector holes after 24 hours remained at a constant level. The increase in injector deposits when using a large ethanol admixture was not declining.
4. Due to the lack of clear differences in typical geometrical analyzes of the fuel stream, the stream surface analysis and stream cross-section analysis were proposed; the proposed research methodology indicated the possibility of non-engine evaluation of changes in the formation of injector deposits during engine tests.
5. The most effective method of evaluating the injector deposits formation without measuring inside the engine was the stream surface area analysis along with its cross-section; the obtained results of the engine tests were most coherent for analyzes conducted in the absence of backpressure in the cylinder.

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