The impact of alcohol admixture with gasoline on carbon build-up and fuel injectors performance

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Highlights

- The effect of adding alcohol to fuels is an increase in the injection time.
- Alcohol admixtures in fuels affect the geometrical parameters of the fuel spray.
- The best indicator for assessing admixtures is the fuel spray surface area.
- The admixture of alcohol into gasoline changes the carbon build-up process on the injector.

Abstract

The operating conditions of injectors in spark ignition engines with direct fuel injection make them susceptible to coking, which leads to a reduced quality of fuel atomization. This can be observed by a drop in performance and an increase in exhaust emissions, especially particulate matter. One effective method of reducing injector coking is by using detergent-dispersing gasoline additives. The article describes the effect of using an admixture with a varied alcohol content on the quantitative and qualitative fuel atomization indicators. The research consisted of a 48-hour engine test, done in accordance with the CEC F-113-KC procedure (CEC-F-113 test). After each test cycle, the injectors underwent optical tests with the use of an isochoric chamber. The spray penetration and surface area were analyzed at a set of different fuel injection parameter values. The research performed resulted in determining the influence of each tested admixture on the change of injection time and on the geometric indicators of the fuel spray. The obtained characteristics of the engine in operation and conducted stationary tests enabled the operational evaluation of the impact an alcohol admixture with gasoline fuels had on key engine parameters.

Keywords

spark ignition combustion engine, direct injection, fuel injectors, injector coking, gasoline, alcohol, injector operating parameters.

1. Introduction

Alcohols are an attractive alternative to commercially used fuel, both as fuels themselves as well as in blends with gasoline or diesel fuel. The switch towards alcohol-based fuels may be one of the significant factors which could contribute to the reduction of exhaust emissions into the atmosphere (including greenhouse gases) – provided that the properties of these fuels are well known and their optimal use is understood in terms of adapting to the requirements of the current prevalent engine design. Ethanol and butanol are alcohols considered to be the most promising biocomponents and admixtures for the conventional fuels currently in use. The European directives RED (*Renewable Energy Directive*) and FQD (*Fuel Quality Directive* 2009/30/EC) [15] introduced in 2009 make it possible to increase the ethanol content in traditional petrol up to 10% (V/V), and also favor the construction of Flex Fuel Vehicle type cars (FFV) designed to run on fuel containing up to 85% (V/V) ethanol. The FQD [15] directive allows using an butanol added to the gasoline (up to 15% (V/V)). Given separately (tert-butanol and isobutanol) and other butanol isomers are included in the group "other oxygen compounds" [12]. The

lower content of oxygen in butanol (21.6% (m/m)), compared to other alcohols, means that in compliance with the requirements of EN 228, more than 10% (V/V) of butanol can be mixed with gasoline. This butanol content in gasoline will not exceed the density, vapor pressure, and oxidative stability values required by EN 228.

When considering the choice of alcohol to be blended with gasoline as a fuel for an SI engine, several critical properties of such fuel should be considered in terms of engine requirements. The chemical energy of the alcohol-gasoline mixture defined as the calorific value of the fuel relative to the volume has a significant impact on the process of controlling the injectors operation. The change in injection parameters caused by the change of the fuel calorific value translates into the quality of the fuel-air mixture formation. This is of particular importance in the currently used direct fuel injection systems, where an appropriate amount of fuel, depending on the engine operating conditions, is supplied to the combustion chambers mainly by controlling the injection duration and timing [32]. Table 1 provides a comparison of the important physical and chemical properties of gasoline, n-butanol, isobutanol, and ethanol.

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Table 1. Selected physico-chemical properties of gasoline, n-butanol, isobutanol and ethanol [9, 13, 31]

Property	gasoline	n-butanol	isobutanol	ethanol
Chemical formula	complex mixture of carbohydrates	C_4H_9OH	C_4H_9OH	C_2H_5OH
Research octane number	95	94–96	113	110
Fuel density [kg/m^3]	753	810	806	790
Heating value – mass [MJ/kg]	42.9	33.3	33.3	26.8
Heating value – volume [MJ/dm^3]	32.3	27.0	26.8	21.2
Latent heat of vaporization [kJ/kg]	380–500	716	579	904
Mass fraction – C [%]	86	65	65	52
H [%]	14	13.5	13.5	13
O [%]	0	21.5	21.5	35
Viscosity [mPa·s]	0.4–0.8	2.57	3.33	1.08
Boiling point [°C]	199	118	108	78
Excess air ratio	14.7	11.2	11.2	9.0

Butanol mixtures with gasoline presents several significant advantages over ethanol, when used as a fuel for SI engines [24]. Butanol is much less hygroscopic, more miscible with gasoline and has a higher calorific value, which translates into lower fuel consumption (for mixtures containing butanol compared to mixtures containing ethanol). When butanol is mixed with gasoline, its blending vapor pressure is lower than that of ethanol, which makes it easier to meet the requirements of EN 228.

The biggest disadvantages of butanol in relation to ethanol when applied to fuels blended with gasoline are lower octane number and lower heat of vaporization as well as higher density and viscosity, which may contribute to a greater – when compared to ethanol – tendency to form undesirable deposits. This applies to the fuel injection system as well as the engine (intake valves and ducts, and combustion chambers). In summary, butanol has a greater performance potential than ethanol when used in gasoline-alcohol fuel blends and to power diesel engines.

The fuel injectors of Direct Injection Spark Ignition (DISI) engines operate under much harsher environmental conditions compared to those of Indirect Fuel Injection (PFI) engines [5]. The injector tips located in the combustion chamber are exposed to the direct influence of high pressure and temperature of the burning fuel, which has an impact on the rapid formation of harmful deposits inside and outside the injector holes. The chemical effects of the combusted fuel are also important [8]. In [16] the authors noted the significant influence that aromatic compounds contained in the fuel have on the rate of injectors contamination with carbon deposits. As a result, the emission of particulate matter increased in relation to the contamination of the injectors, characterized as 6%–8% of the loss of uniform flow as compared to new clean injectors. In addition, there was an about 2.5% greater reduction of the maximum torque obtained at an engine speed of 2000 rpm and below. However, the use of appropriate fuel additives (DCA – *Deposit Control Additives*), reducing the temperature of the injector tip and increasing the injection pressure were presented as effective methods for limiting the gradual disruption of flow out of the injectors [6, 26]. Optical fuel atomization tests in ambient conditions conducted by Henkel et al. [18] indicate a change in the shape of the fuel spray as a result of the injectors becoming contaminated. As a result of this change in the spray indicators, in tests on a 4-cylinder engine, an increase in the emission of PM/PN particles was observed. Using Laser Doppler Anemometry to assess the fuel atomization, a 30% greater mean droplet velocity in the initial spray and a 5% increase in the mean diameter of the droplets from contaminated injectors compared to clean ones were found [23].

The described build-up of contamination is a big problem for the proper functioning of the engine, because the quality of the fuel-air mixture formed in the combustion chambers is almost entirely dependent on (controlled by) the functioning of the fuel injectors, which are significantly impacted by the formation of harmful deposits on them. External deposits around the exhaust ports are formed mainly from combusted fuel and to a lesser extent from engine oil. They cause distortions of the atomized fuel spray and its elongation. Internal injector deposits in the fuel discharge channels are purely sourced in the fuel itself. They limit the flow rates of fuel injected into the combustion chambers due to the reduction of the outflow cross-section of the injector. Whenever any deviations or disturbances occur in the optimized fuel spray process, e.g. changes in the fuel spray angle, disruptions of the expected spray jet symmetry, extension of the fuel spray penetration or increase in the average diameter of the fuel droplet, they result in increased engine emissions as well as reduced engine performance, and efficiency [1, 17, 20, 36]. One of the possibilities of reducing injector coking is by using detergent additives based on Mannich principles or polyisobutylene succinimides [3]. In a more extensive analysis of DCA for fuels, Mannich-based detergents proved to be more effective than polyetheramine-based detergents [2]. The reduction of the tendencies for injectors to coke based on the results of testing many fuels with different characteristics was observed when increasing the T90 from 160°C to 182°C and increasing the sulfur concentration in the fuel from 30 to 150 ppm [4]. However, increasing the olefins from 5% to 20% and increasing the sulfur content above 400 ppm slightly in-creased coking again. Analysis of the coking, or deposit formation mechanism in the DI injector holes by Kinoshita et al. [21] showed an increased tendency of deposits formation when the injector tip temperature is increased to over 150°C. In addition, keeping the injector tip temperature below 90% of the fuel distillation temperature allows the injected fuel to flush the soot precursors away.

Disruptions in the combustible mixture formation in the engine cylinders can be caused by many factors, the most important of which are: the quality and time of fuel atomization, the penetration speed and depth of the atomized fuel spray, properly controlled movement (swirling) of the mixture, the interaction of the atomized fuel with the walls of the combustion chamber and the piston head, physicochemical properties of the fuel, as well as the temperature and pressure in the combustion chamber. Disruptions in the fuel atomization process cause issues, such as: an increase in the amount of fuel deposited on the combustion chamber walls, increase of the time necessary for fuel evaporation as a result of larger diameter of the droplets, or the uncontrolled evaporation of the fuel absorbed by the deposits formed, including at the injector tips. Combustion of a mixture with an incorrect composition and mixture quality can result in premature, uncontrolled ignition, misfiring and prolonged combustion on the outlet stroke. Initially, this leads to an increase in the exhaust emission of

harmful components, and eventually to an increase in fuel consumption, reduced engine performance, uneven engine operation and difficulties in proper engine ignition [14, 27, 34].

The deposit formation mechanisms in the engine differ depending on the factors and where these deposits are formed. The size of the formed sediments is the result of the sediment formation and removal processes. The mechanisms of deposit formation are known, although the processes of their formation are not fully understood yet. In the case of fuel injectors, sediment precursors are formed as a result of oxidation, condensation and precipitation of unstable hydrocarbons (aromatics and olefins) from the fuel [2]. These precursors form deposits through two distinct chemical reaction pathways, i.e. self-oxidation at low temperatures and the formation of coke deposits by pyrolysis at high temperatures. So far, it has not been possible to establish the borderline temperature between the reactions taking place at low and high temperatures – especially since the reactions assigned to both temperature groups have been observed to take place simultaneously in some temperature ranges [35]. Generally, factors promoting deposit formation can be related to the fuel type, engine design, injector design, and engine operating conditions. The degree of wear also has a significant impact on the fuel flow characteristics, regardless of the injector type [19]. Additionally, changes in the fuel supply system design, such as the length or diameter of the fuel container, are important [22].

Alcohol additions, such as ethanol, to conventional fuels can have a beneficial effect on keeping 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. As a result, very little soot is produced when ethanol is burned. The soot and injector deposit mechanisms are different for PFI and DISI engines. Since the temperature of soot formation is much higher than the temperature of deposit formation, it can be expected that the amount of injector deposits in the combustion of ethanol will be much lower than in the combustion of gasoline. Moreover, ethanol has a lower phase transformation heat, which causes the temperature of the injector nozzles to be lower compared to the temperatures present when the engine runs on just gasoline [7, 11]. Comparative studies of the DI engine operation powered by gasoline and E100 ethanol confirmed the possibility of limiting the deposits formation by supplying the engine with ethanol. Additionally, good cleaning properties were emphasized, even with a low 20% (V/V) ethanol content in gasoline [30].

In addition to the many advantages of ethanol – in terms of managing the amount of injector deposits in DISI engines – ethanol also has the disadvantage of having a lower boiling point (T90) than gasoline. As a result, ethanol-gasoline blends have a lower T90 compared to gasoline alone. The results of many studies [7, 11] have shown the advantages of ethanol or gasoline-ethanol blends in terms of the lower tendency to form injector deposits. In the case of the intake system, the use of E85 fuel with a significant ethanol content has the opposite effect in the form of an increased tendency to cause precipitates formation on the intake valves when indirect injection is used [10]. Similar conclusions were obtained when using cellulosic ethanol as fuel [25].

Due to the problem of injectors contamination in modern direct injection systems, the Authors of the article proposed assessing the impact of alcohol (ethanol or butanol) admixture with selected gasolines (with different physico-chemical properties) on the tendency to form injector precipitates. The discussed problem is significant due to the proven deterioration of the ecological indicators of internal combustion engines as a result of the gradual loss of proper fuel flow out. The proposed assessment method of the impact, that alcohol admixtures have, was divided into two stages:
- The first, consisting of carrying out engine tests in accordance with CEC-F-113 test, where the injectors are fed with specific types of fuels.

- The second, where the same injectors were mounted in an isochoric chamber, where the process of fuel flow was recorded with a high speed camera.

During the tests on the model stand (isochoric chamber), the injection and backpressure parameters were selected in such a way as to best reproduce the conditions present in engines tested on an engine dynamometer.

2. Research objects and methods

2.1. Fuels

As part of the engine tests, three petrol types, with different physical and chemical properties, were tested, including two with different alcohol content (ethanol or butanol). The reference fuels used in the CEC engine tests were considered as regular petrol in this research. The RF-12-09 batch 10 gasoline is a fuel with a high tendency to form deposits on the intake valves of SI engines. RF-02-03 gasoline is a fuel with a low tendency to form deposits on the intake valves of SI engines. CAF W18-936, on the other hand, is a fuel with a low tendency to form coke deposits in the engine injectors. It is used to calibrate the VW EA111 BLG test engines. The properties of the fuel prepared for the tests were listed in Table 2.

2.2. Research method

The research on the tendency of fuels to result in the formation of deposits on injectors in an engine was carried out in CEC-F-113 test. A four-cylinder EA 111BLG (by Volkswagen) spark-ignited engine with a displacement of 1.4 dm^3 was used in the dynamometer tests.

The tested engine is fitted with direct fuel injection, with a combined charging system (supercharging and turbocharging) – Table 3. The fuel injection was performed by 6-hole electro-magnetically controlled injectors made by Magneti Marelli (designated 03C 906 036 E).

The CEC F-113-KC procedure specifies tests lasting 48 h. The engine (during the tests) is operated at constant parameters: n = 2000 rpm and Mo = 56 Nm. The above engine operating parameters are defined (and required) following the European standard CEC F-113 – VW EA111 DISI Injector Deposit Test.

This test allowed the fuel to be assessed in terms of its ability to keep the injectors clean. The test result is the length difference of the fuel injection time (required is single injection). Measurements are taken before and after the test. The measured injection time is unstable and changes with a very high frequency and relatively large amplitude. Thus, calculating the increasing injection time by simple comparison its size at the beginning and at the end of the test could be biased. With this in mind, a methodology based on the use of the trend function was used. It was assumed that the values calculated from the trend function would be more representative than those based on the final measurement points. This is how the calculation of the average injection time at the beginning and at the end of the test was carried out. The dissimilarities between these two values results from the performed test, and is usually given in [%] increase in the electric pulse length controlling the duration of a single fuel injection. A detailed measurement and analysis of current-voltage waveforms during the injector's operation was not performed due to the length of the test [33]. The next research stage concerns assessing the impact that the generated injector deposits had on the fuel atomization quality as well as the change in the observed shape and measured parameters of the fuel spray.

A high-pressure constant volume chamber was used to assess the qualitative indicators of fuel atomization of the injectors. In tests with the use of the chamber, it is assumed that the piston movement and thermal changes of the gas inside the chamber on the analyzed phenomenon are negligible. Such assumptions are also made for the optical tests of the fuel injection process in static conditions.

Table 2. Properties of the types of fuel (based on gasoline) prepared for tests

Parameter	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	CAF W18-936	RF-02-03	RF-02-03 +10% (V/V) ethanol	RF-02-03 +10% (V/V) butanol	Test procedure
Notation		RF-12-09	RF-12-09+10E	RF-12-09+20E	RF-12-09+10B	CAF W18-936	RF-02-03	RF-02-03+10E	RF-02-03+10B	
Density @15°C	kg/m³	746.3 ±0.4	758.2 ±0.4	751.7 ±0.4	753.9 ±0.4	746.9 ±0.4	751.4 ±0.4	759.8 ±0.4	758.4 ±0.4	PN-EN ISO 12185:2002
Research octane number (RON)	–	96.0	97.4	98.2	97.8	96.1	99.3	99.9	100.0	PN-EN ISO 5164
Research octane number (RON)	–	85.9	86.4	87.8	86.8	86.7	88.0	88.7	88.9	PN-EN ISO 5163
Sulphur content	mg/kg	9.0 ±1.5	7.8 ±1.7	5.3 ±1.7	7.3 ±1.6	1.3 ±0.5	1.4 ±1.0	<0.3	<0.3	PN-EN ISO 20846:2020
Induction duration	min.	>360	>360	>360	>360	>360	>360	>360	>360	PN-EN ISO 7536:2011
Resin content	mg/100 ml	0.9 ±1.5	1.1 ±1.5	1.0 ±1.8	1.3 ±1.9	0.8 ±1.5	0.5 ±1.5	<0.5	1.0 ±1.5	PN-EN ISO 6246:2017-05
Content of hydrocarbon types:										
olefinic	% (V/V)	7.4 ±1.4	<5.0	5.1 ±1.1	5.7 ±1.5	7.9 ±2.0	4.3 ±1.1	<4.0	<4.0	PN-EN 15553:2009
aromatic	% (V/V)	32.1 ±2.6	30.4 ±2.6	28.8 ±2.6	30.4 ±2.6	31.8 ±2.6	33.1 ±2.6	30.2 ±2.6	28.5 ±2.6	
Benzene	% (V/V)	0.5 ±0.1	0.4 ±0.1	0.3 ±0.1	0.4 ±0.1	<0.1	0.16 ±0.1	0.1 ±0.1	0.1 ±0.1	PN-EN 238:2000+A1:2008
Oxygen	% (m/m)	0.11	3.73 ±0.29	7.40	2.23 ±0.29	4.8 ±0.47	<0.1	3.51 ±0.29	2.61 ±0.29	PN-EN 1601:2017-09
Organic compounds containing oxygen:										
methanol	% (V/V)	<0.80	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	PN-EN 1601:2009
ethanol	% (V/V)	<0.80	10.2 ±0.57	20.1	<0.17	4.8 ±0.37	<0.17	9.7 ±0.57	<0.17	
isopropyl alcohol	% (V/V)	<0.80	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	
tert-butyl alcohol	% (V/V)	<0.80	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	
isobutyl alcohol	% (V/V)	<0.80	<0.17	<0.17	7.4 ±0.43	<0.17	<0.17	<0.17	11.3 ±0.64	
other oxygen compounds	% (V/V)	<0.80	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	<0.17	
Dry vapor pressure equivalent (DVPE)	kPa	60.8 ±1.1	58.0 ±1.1	63.1 ±1.1	55.2 ±1.1	57.3 ±1.1	59.5 ±1.1	59.8 ±1.1	55.3 ±1.1	PN-EN 13016-2018-05:2009
Fractional composition:										
IBP	°C	34.8 ±3.4	38.5 ±3.4	37.2 ±3.4	38.1 ±3.4	33.3 ±3.4	37.2 ±3.4	42.3 ±4.8	43.0 ±3.4	PN-EN ISO+3405:2019
end of distillation temperature	°C	205.5 ±5.1	202.3 ±5.1	199.5 ±5.1	20.5 ±5.1	200.4 ±5.1	196.4 ±5.1	194.4 ±5.1	194.0 ±5.1	
distills	% (V/V)	97.9	97.8	97.6	97.7	97.6	97.9	98.4	98.5	
residue	% (V/V)	0.7	1.2	1.2	1.2	1.2	0.4	1.2	1.1	
losses	% (V/V)	1.7	1.0	1.2	1.1	1.5	1.1	0.4	0.5	
T10	°C	52.3 ±2.6	53.0 ±2.6	51.4 ±2.6	55.4 ±2.6	52.6 ±2.6	53.1 ±2.6	51.2 ±2.6	55.3 ±2.6	
T50	°C	106.5 ±3.6	100.8 ±3.1	72.4 ±3.1	99.6 ±2.9	96.0 ±3.6	96.8 ±3.5	85.9 ±2.9	95.0 ±2.9	
T90	°C	172.9 ±4.0	171.9 ±4.0	163.4 ±4.0	170.8 ±4.1	176.6 ±4.0	152.2 ±4.1	154.0 ±4.0	152.7 ±4.0	
Volatility index	–	746 ±36	859 ±36	936 ±36	722 ±36	1018 ±36	910 ±36	757 ±36	741 ±36	PN-EN 228 + A1-2017-06

Table 3. Technical specifications of the VW EA111 BLG engine used for testing

Type	–	4-cyl., in-line (wall-guided mixture formation system)
Displacement	[cm³]	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 test chamber consisted of a cube-shaped body with clear quartz windows placed in the openings of each of these walls, a mounting system for attaching the engine head, valves supplying and discharging gas (air) to the chamber, and a system of sealing and assembly connections. The constant volume chamber in the test setup was shown in Fig. 1. The test setup included a light source (halogen lamp) and a recording camera (Fig. 1a). The fuel injection was registered through the transparent chamber window and one of the steering mirrors (Fig. 1b). The technical data of the constant volume chamber were given in Table 4.

Table 4. Technical data of the constant volume chamber used in the fuel atomization tests

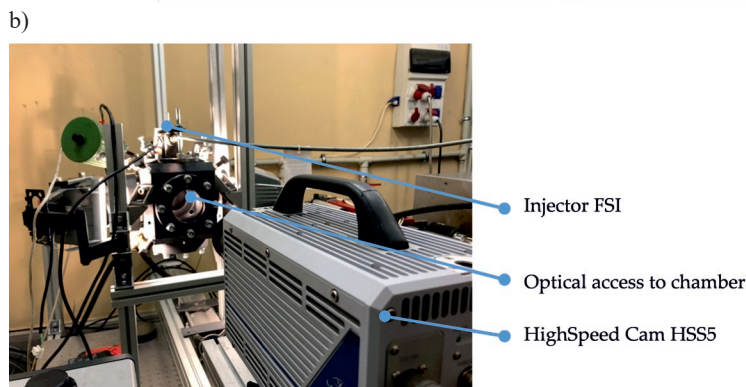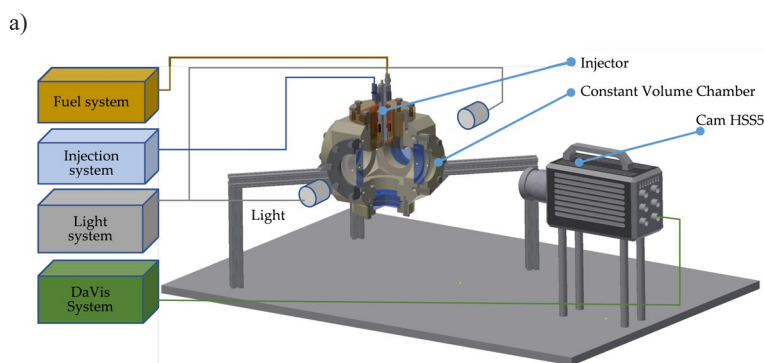| Element		Value	Characteristics	Dimensions
Element		outer diameter	material ϕ × h	steel 110 ×400 mm
		inner diameter	material ϕ × h	steel 90 × 350 mm
		volume	2200 cm³	
Optical access		material/thickness	quartz glass	30 mm
Light source		type	halogen lamp	230 V, 500 W

a)

b)

Fig. 1. Schematic (a) and picture (b) of the test stand for testing fuel atomization (6-hole injector, P_{inj} = 10 MPa; t_{inj} = 0.4 ms, camera: f = 10 kHz, lens: Nikon AF 24-85 mm f/2.8-4D IF, images 512 × 512 px)

Two injection pumps (high-pressure, up to 20 MPa) were used to perform injection of various fuels into the chamber. The modification of the original system allowed to use two different test fuels. A LaVision High Speed Star 5 recording camera was used to capture images of the fuel atomization. Image acquisition frequency was f = 10 kHz. The optical configuration of the camera for spray testing was shown in Fig. 1a. An AF Nikkor prime lens was used in the research. No optical filter was used in the tests, because the recording only concerned the light from the halogen lamp that was reflected from the injected fuel drops.

2.3. Scope of research

The test plan included testing each of the injectors at the injector opening time of t_{inj} = 0.4 ms and at three back pressure values: 0 MPa; 0.1 MPa; and 0.2 MPa. The fuel was supplied to the injector under constant pressure which equalled to 10 MPa. Each attempt was repeated twice.

The optical testing procedure was as follows (Fig. 2):
1. From each photo containing a spray of injected fuel, the first photo (considered as the background) was subtracted. In this way, only the difference in each photo was obtained, resulting from successive photos.
2. The mask, for which the calculations of the fuel spray geometrical indicators were made, was denoted.
3. Geometric indicators were determined using the following methods:
a. Spray penetration – S – determined based on the X coordinate (vertical change in the number of pixels) between the spray top and the maximum value in the vertical direction; the global penetration was determined, the analysis of individual spray of injected fuel was not conducted (due to their optical nature).
b. Spray surface area – A – determined based on the number of pixels in a given measurement area, the luminance of which is above a specified luminance value.
c. The angle of the spray cone – α – determined using four designated points on the bilateral envelope of the spray cone (these distances are 5 and 15 mm from the fuel outflow); based on four data points, the angle between them was calculated and the cone angle of the outgoing fuel spray was determined. Due to large changes in the illumination intensity of pixels in the vicinity of the fuel outflow, the specified angle was characterized by quite large measurement uncertainties.
d. Fuel spray velocity – v – determined based on the penetration related to individual recording times of subsequent images.

The analysis of the results was carried out with the use of LaVision's DaVis software.

3. Results

3.1. Engine test results for injector deposits

The comparison of changes in fuel injection time obtained using to CEC-F-113 test for the eight fuels selected for testing are shown in Figure 3. The data contained therein indicates the existence of different fuel injection times when using additives with high and low tendency to deposit formation. Admixtures with a high tendency for deposit formation significantly increase the fuel injection time, while those with a low tendency to form deposits corresponded with significantly shorter times. Analysis of these results resulted in obtaining different trends: in the first case (fuel with a high tendency to form deposits) an inertial (towards a fixed value) or linear trend was observed.
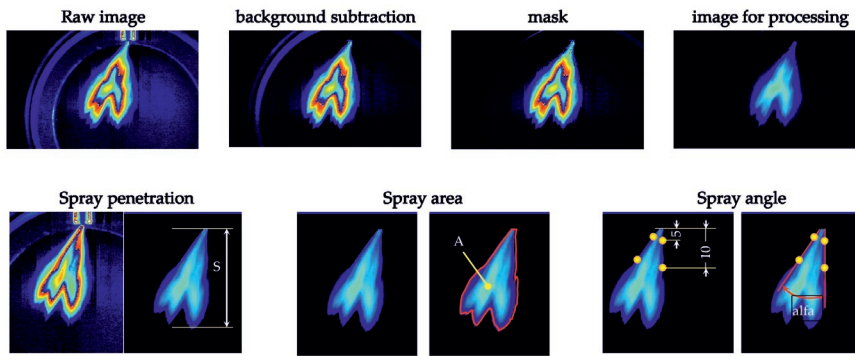
Fig. 2. *The image processing procedure and determining the geometric indicators of the injected fuel spray*
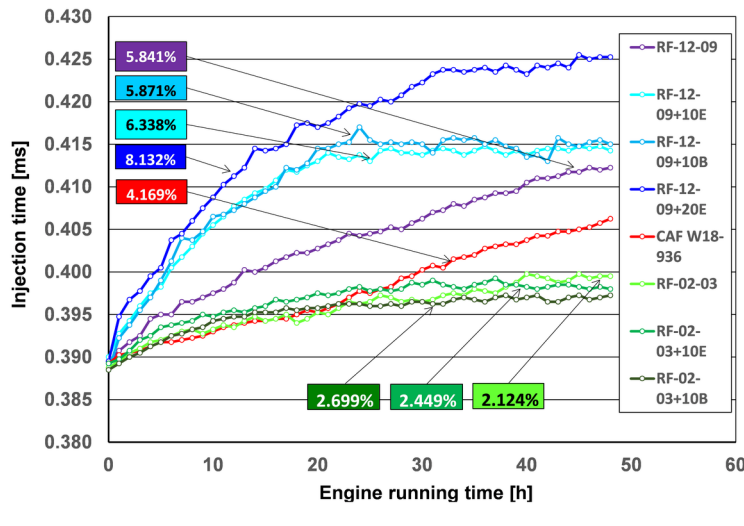

Fig. 3. *Evaluation of VW EA111 engine injector sedimentation tendency for tests done according to the CEC-F-113 test*

3.2. Results from tests carried out in a constant volume chamber

The test results of the injectors and fuels have been presented in the form of averaged surface area and spray penetration. An example of the surface area averaging process was shown in Fig. 4.

The following configuration was used for this research (new injectors were also taken into account):

a) tests including RF-12-09 fuel: fuel prone to high coking of the injector holes:
  ◦ test 1: RF-12-09 – no additives
  ◦ test 2: RF-12-09+10E: with 10% ethanol
  ◦ test 3: RF-12-09+10B: with 10% butanol

◦ test 4: RF-12-09+20E: with 20% ethanol
b) tests including RF-02-03: fuel: fuel that limits coking of the injector holes:
  ◦ test 5: RF-02-03: no additives
  ◦ test 6: RF-02-03+10E: with 10% ethanol
  ◦ test 7: RF-02-03+10B: with 10% butanol

The activities presented in Fig. 4 were applied to all performed test series. The mean surface area and spray penetration values (Fig. 5) indicate flow characteristics changes for the tested injectors when using the RF-12-09 fuel.

The backpressure increase in each analyzed case reduced both the surface area and spray penetration. Specific changes in the characteristics from alcohol admixtures to the RF-12-09 fuel were as follows:

• the addition of 10% ethanol (RF-12-09+10E) caused the greatest decrease in surface area and penetration for tests without any backpressure present (decrease in the maximum surface area by 15% compared to the tests of new injectors – NEW),

• the addition of 20% ethanol (RF-12-09+20E) reverses this relationship, increasing the surface area in all tests by 8%–17% depending on the backpressure value,

• the test determining the effect of the RF-12-09 fuel alone, without any admixtures in the form of ethanol or butanol, was characterized by a significant reduction in the surface area during tests with backpressure – a reduction of 33% at a backpressure of 0.1 and 0.2 MPa.

• the test without additives (RF-12-09) and with 10% addition of butanol (RF-12-09+10B) resulted in a similar change to the tests of new injectors in the absence of backpressure in the chamber, thus having little to no effect on the measured parameters.

With no backpressure present the fuel spray achieved a maximum surface area at about 2 ms after starting the injection. Increasing the back pressure increased this time.

The spray penetration analysis was carried out only up to 2 ms time into the injection, because in the later period the range did not increase any more (or the technical limitations of filming are reached).

Geometric indicators of the fuel spray from the injectors tested with RF-02-03 fuel with alcohol admixtures were presented in the averaged comparison (mean values from the analyzed tests) in Fig. 6. Similarly to the analyzes carried out earlier, the impact of fuel on the process of mixture formation and the surface area and spray penetration were determined. When analyzing the data from Figure 6, it was found that:
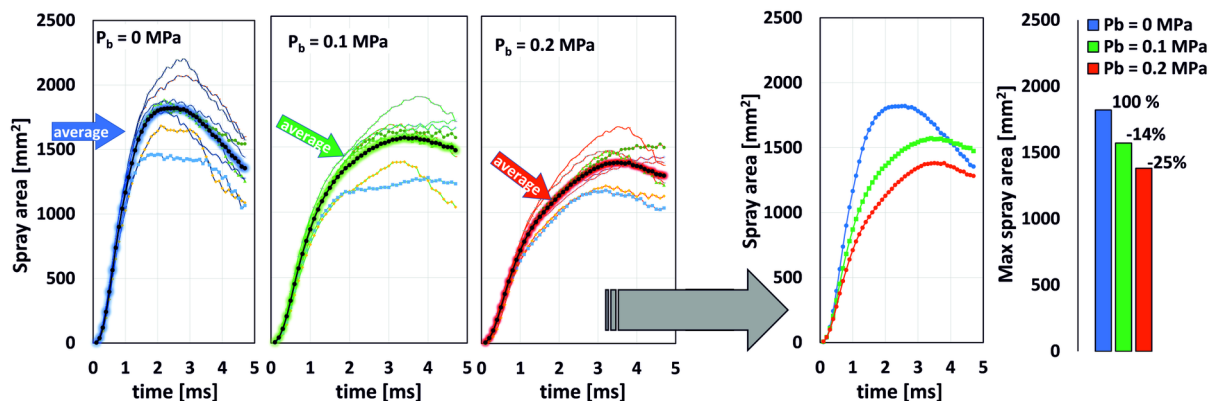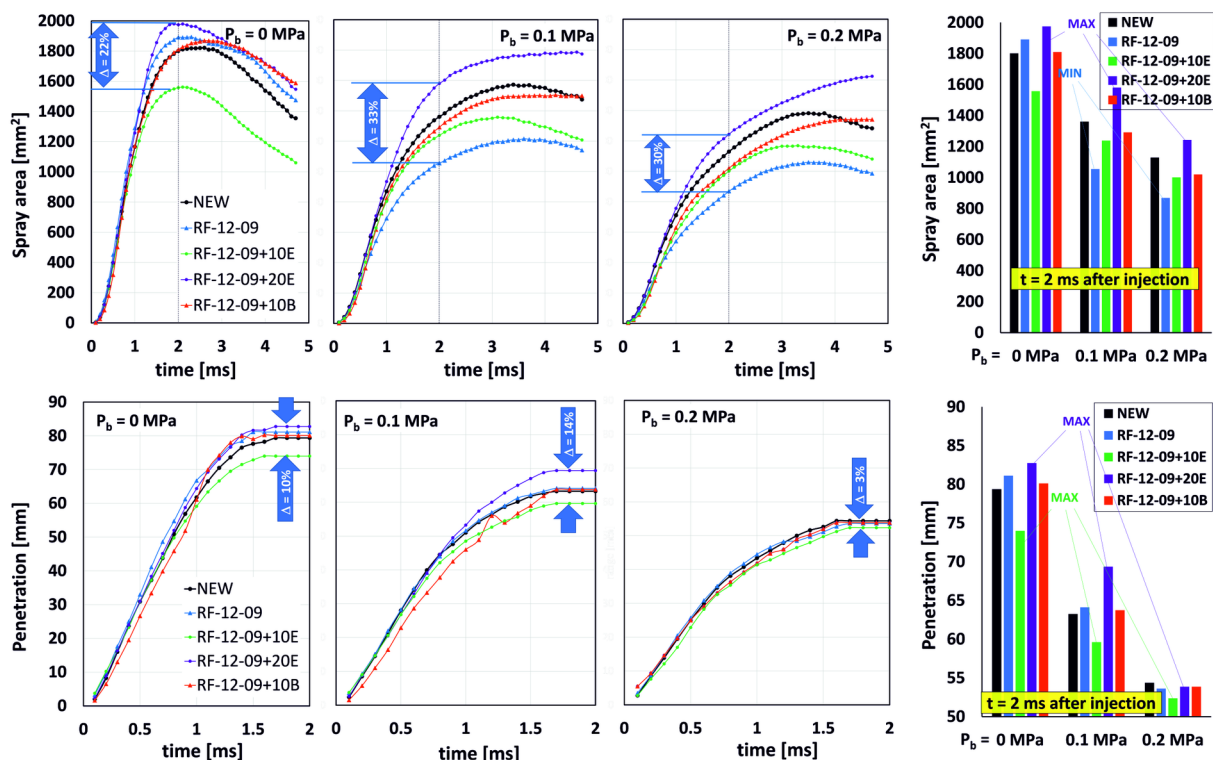

Fig. 4. *Results of the spray surface area tests for the RF-12-09 fuel (P_{inj} = 10 MPa and P_b = 0; 0.1; 0.2 MPa; the results show the process of determining the mean values)*

- the surface area of the RF-02-03 fuel without additives was reduced by 10%–24% at the end of the test compared to the initial values,
- the addition of 10% butanol (RF-02-03+10B) did not increase the surface area both in the absence of backpressure and with its increase to 0.1 MPa when compared to the fuel without the additive,

- the addition of 10% ethanol (RF-02-03+10E) increased, in the entire scope of the analysis, the spray penetration and the surface area for the tests carried out at backpressure of 0.1 and 0.2 MPa (in the absence of backpressure, this regularity was not observed, however).

Fig. 5. Results of the spray penetration and surface area tests for the RF-12-09 fuel (P_{inj} = 10 MPa and P_b = 0; 0.1; 0.2 MPa; the results show the mean values from the tests of 4 injectors according to Table 2)
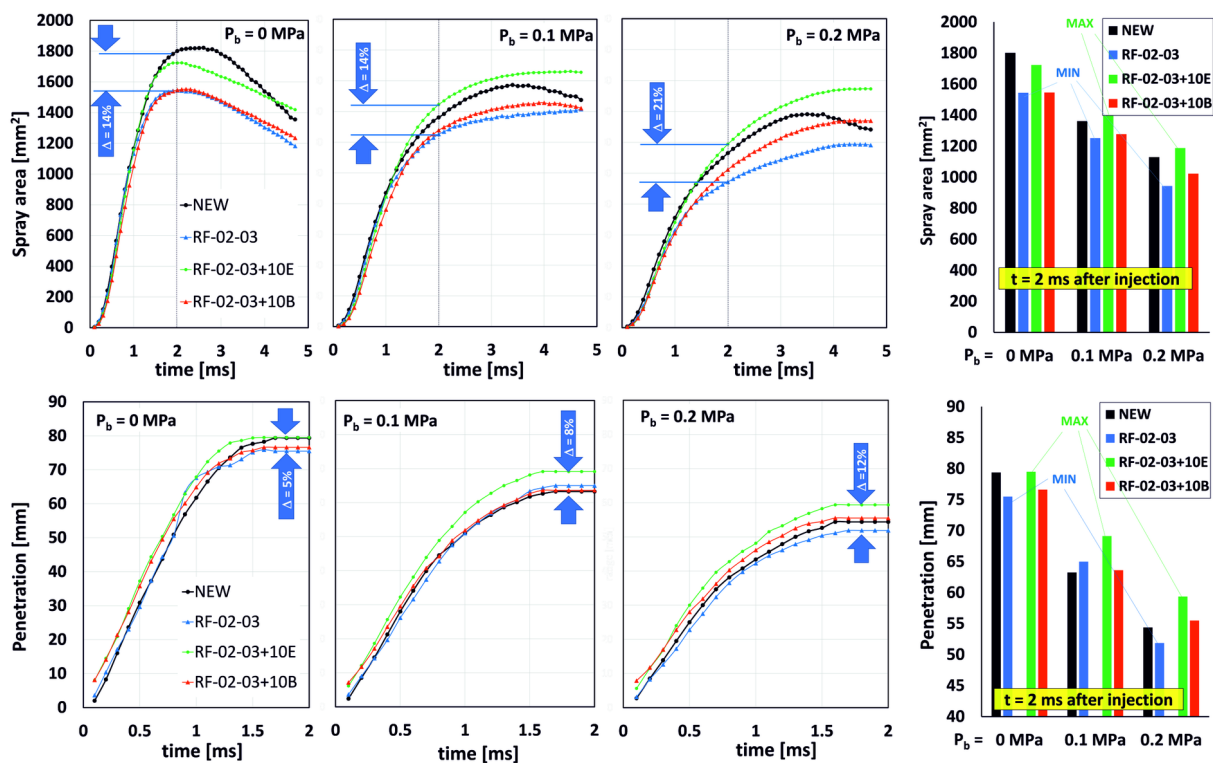

Fig. 6. Results of the spray penetration and surface area test for the RF-02-03 fuel (P_{inj} = 10 MPa and P_b = 0; 0.1; 0.2 MPa; the results show the mean values from the tests of 4 injectors according to Table 2)

4. Results discussion

When considering the results, it should be emphasized that each engine design, combustion process control strategy and injector design have a very significant impact on the process and intensity of the injector coking phenomenon. Thus, the final result of the evaluation of fuel choice depends on the deposit formation progression and the amount of deposits formed over time. In this case, the assessment was based on the VW EA111 BLG engine tested in accordance with the CEC-F-113 test.

The fuel assessments carried out previously in accordance with the above-mentioned procedure allowed – as part of the work of the CEC TDG F-113 Work Group – to determine the repeatability of the results gathered from this method based on Student's t-distribution. According to the calculations in order for two results to be distinguishable with a 95% confidence interval, their absolute difference must be about 3.0% of the change in the electric pulse length which controls the injection time. However, taking into account that in practice it is a large change in the signal pulse length, it was established that when evaluating the results, a smaller confidence interval (90%) would be used, for which an absolute dissimilarities between the results of the change in the electric pulse length of 1.8% for the injectors opening time in a single fuel injection. This allowed for a sufficient differentiation and results comparison for the tested fuels. The results of evaluation for the eight fuels presented in Fig. 3 was divided into four groups. The first group included only one fuel (CAF W18-936). As it is the reference fuel dedicated to the tuning and control of the VW EA111 BLG engine operation, this fuel was used for the first of the conducted tests. The obtained result (4.169% of the averaged increase in the width of the injector opening electric impulse in a single fuel injection) confirmed that the engine was well prepared for tests, as per the requirements of the CEC-F-113 test. The requirements of this procedure state that the result for this fuel should have the value of 5 ±2%. Taking into account the obtained test results, the second group included the following fuels: RF-12-09 (result: 5.841%), RF-12-09+10E (result: 5.871%) and RF-12-09+10B (result: 6.338%). These results should be considered as being statistically the same value result. On the other hand, the result for the fuel RF-12-09+20E (8.132%) could not be statistically included in the same group and had to be treated as separate (third group). The fourth group included the results of the following fuels: RF-02-03 (2.699%), RF-02-03+10E (2.249%) and RF-02-03+10B (2.124%). In the case of fuels from the second and third groups, an unfavorable effect of alcohol admixture on counteracting the formation of injector deposits was observed – RF-12-09 (5.841%), RF-12-09+10E (5.871%), RF-12-09+10B (6.338%), and RF-12-09+20E (8.132%). In the case of fuels from the fourth group, the resulting change was below the reference value – RF-02-03 (2.699%), RF-02-03+10E (2.249%) and RF-02-03+10B (2.124%). These results are not consistent with those described in [5, 7, 30], but instead more aligned with the results described in [25]. Perhaps the reasons for the discrepancy in these results of the alcohol impact on the injector deposits formation tendency should be sought in the interactions of the properties of RF-12-09 and RF-02-03 fuels with alcohols, which are difficult to determine – Table 2. It should be noted, however, that both in the case of the fuels in the second and fourth groups, the addition of one of the alcohols to gasoline RF-12-09 and RF-02-03, respectively, caused such a small variation in the result that – from a statistical point of view – these results can be considered the same. Therefore, one can only indicate trends in the scope of changes in the results caused by the addition of alcohols. The only deviation was noted in the case of adding 20% (V/V) ethanol to gasoline RF-12-09, which resulted in a significant, even from a statistical point of view, increase in the length of the injector opening electric pulse in a single fuel injection, i.e. 8.132% for fuel RF-12-09+20E relative to 5.841% for RF-12-09 fuel. The differentiated trends that occur in the case of fuels with and without alcohol content presented in Fig. 7 and 8.
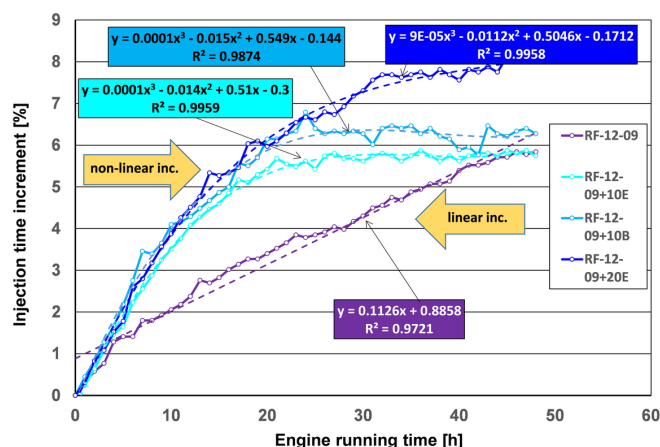

Fig. 7. The changes of fuel injection time for the tested fuel from the second fuel group
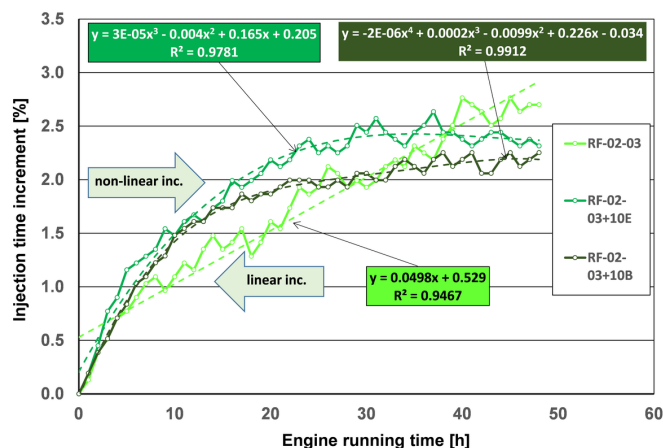

Fig. 8. The changes of fuel injection time for the tested fuel from the fourth fuel group

All the fuel injection pulse duration results presented in Fig. 7 and 8 were characterized by a gradual, but un-stable, increase over time. Considerable, often rapid fluctuations in changes in fuel injection time could be observed during the test. Such fluctuations in values could be most reasonably explained by the simultaneous and opposed processes of contamination of the injectors and their cleaning, i.e. removal of already produced deposits by the following fuel dose (for example, during the formation of deposits on the inlet valves of the engine [28, 29]). In order to better evaluate the trend of injection time changes of the tested fuel samples, their trend lines are drawn in Fig. 7 and 8. Using these trend lines, it can be noted that in the case of fuels with no alcohol admixtures (RF-12-09 and RF-02-03), there was a gradual, linear increase in fuel injection time throughout the duration of the test. It can be assumed that if the test time was extended, the fuel injection time would further increase, and hence coke deposits on the nozzles and in the injector outlet holes to continue gathering. Another trend of changes in the fuel injection time observed in the conducted tests was in the case of fuels containing alcohols. For these fuels, the trend lines indicated a logarithmic increase in the fuel injection time increase. As a result, after a period of progressive increase in fuel injection time, the duration stabilizes over many cycles at a certain level. In the case of the RF-12-09 fuel containing alcohol, this stabilization takes place 25–30 hours from the start of the test – Fig. 7, and in the case of the fuel RF-02-03 in approximately 22 to 25 hours – Fig. 8. Therefore, it would be expected that the fuels containing alcohol (for the tests described in this work, using ethanol or butanol) are less prone to facilitating deposit formation on the fuel injectors. This is because due to the linear increase in fuel injection time observed for fuels without alcohol admixtures, the level of injector contamination

will over time exceed that of injectors using fuels with alcohol admixtures, since alcohol helps stabilize the increasing injection time over a certain number of engine work cycles. The dissimilarities in the trends of the size and formation of the injector deposits for the tested fuels resulted mostly from the intensity of the initial deposit precursor formation processes, the force of their adhesion to the surface on which they were formed and the simultaneous processes of self-cleaning of the injectors. The logarithmic curve shows that deposit precursors are formed more intensively at the beginning of the test cycle, adhere more strongly to the surface and/or are removed less intensively. In the case of a linear relationship, the sediment formation and removal processes take place with a constant intensity in a certain proportion, with the deposit formation processed being dominant. After the formation and stabilization of sediment precursors on the surface of the injectors, further contamination of the injectors is the result of the sediment build-up and removal processes.

The fuel spraying indicators analysis for high-pressure injectors in a constant volume chamber, while averaging the obtained results, was presented in the further part of the work. The results of the fuel spray surface area were presented for two analytical points in the form of the spray surface area within 2 ms after the start of fuel injection (SOI) and the maximum surface area during the optical analysis. The results presented in Figures 9 and 10 contain the maximum spray surface area, where the reference value (100%) was defined as the area obtained using new clean injectors, and the percentage changes of the analyzed parameter based on the fuels used.

The analysis of the results obtained for the RF-12-09 fuel (Fig. 9) leads to the following conclusions:

a) The RF-12-09 fuel has shown a reduction of the spray surface area in relation to the reference value with $P_b = 0.1$ and 0.2 MPa; tests without backpressure did not show this trend.

b) 10% addition of butanol to the RF-12-09 fuel increased the surface area of the fuel spray at each backpressure value in relation to the fuel with 10% ethanol. However, a 20% addition of ethanol significantly increased this indicator, regardless of the air backpressure. This may suggest a better performance of the admixture of high ethanol content in gasoline. Increasing the fuel spray area suggests an increase in its flow cross-section. The addition of 20% ethanol resulted in the highest spray surface area at each backpressure setting to be achieved.

c) Significant differences in the surface area growth time were observed for fuels containing significant amounts of ethanol and butanol admixture, as it resulted in changes in the fuel outflow characteristics.

d) Having no backpressure in the chamber resulted in a slight difference between the maximum surface area and that achieved at $t = 2$ ms after SOI. Further increase in the backpressure resulted in even greater differences between the two analytical points, in the measurements carried out at $P_b = 0.1$ MPa, the maximum surface area was on average approximately 14% greater than that achieved at the 2 ms point. While in the tests carried out at $P_b = 0.2$ MPa, this difference was about 25%.

The analysis of the results obtained for the RF-02-03 fuel (Fig. 10) leads to the following conclusions:

a) The use of RF-02-03 fuel resulted in a reduction of the surface area by 10%–15% in each of the test point ($P_b = 0$–0.2 MPa).

b) The addition of butanol caused a slight increase in the obtained surface area at each test point for the fuel RF-02-03.

c) The addition of ethanol (10%) increased the surface area compared to both the base fuel as well as fuel with the butanol admixture.

d) Admixtures showed favorable effect compared to the base fuels, but still indicated a smaller spray surface area achieved than those obtained in tests of new clean injectors.

e) For both the RF-12-09 fuel and the RF-02-03 fuel a slight difference was obtained in tests between the maximum surface area and that achieved at the time $t = 2$ ms after SOI, at $P_b = 0$ MPa; increasing the back pressure increased the differences between the two measured points.
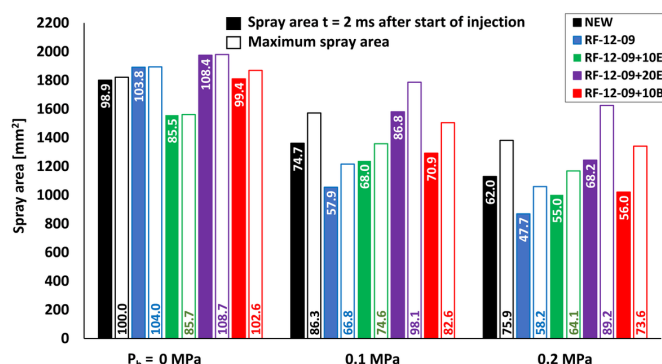

Fig. 9. *Summary of the averaged maximum surface area and the area covered at 2 ms after injection start for the RF-12-09 fuel and its additives*
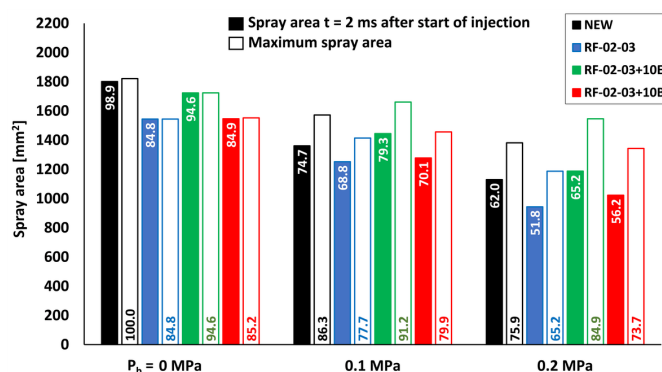

Fig. 10. *Summary of the averaged maximum surface area and the area covered at 2 ms after injection start for the RF-02-03 fuel and its additives*

5. Conclusions

Analysis of alcohol admixtures with gasoline impact on the formation of precipitates and performance parameters of fuel injectors resulted in a set of conclusions.

- The results of engine tests conducted in accordance with the CEC-F-113 test and the results of optical analyzes of fuel atomization in the direct injection system were correlated.
- The effect of the choice of fuel type and the alcohol admixture was verified by using the change in the duration of the injector control pulse as the measured indicator. It has been shown that the fuel with a higher content of sulfur, resins, olefin-type hydrocarbons and with a lower volatility index (RF-12-09) increased the injection time in relation to the RF-02-03 and CAF W18 fuels at the same operating point of the engine.
- The addition of alcohols (ethanol, butanol) to the fuel RF-12-09 and RF-02-03 had a measurable effect on the sediment formation, varying from linear for basic fuels to non-linear, for fuels with admixtures of alcohols as measured throughout the 48-hour test period.
- Optical tests showed that a 10% ethanol admixture to a fuel with a lower tendency for deposit formation (RF-02-03) resulted in the greatest values of surface area and spray coverage. Additionally, with the back pressure $P_b = 0.1$ MPa and 0.2 MPa, these indicators were still higher than for new clean injectors.
- For the fuel with a higher tendency to form deposits (RF-12-09), the best atomization rates were obtained with the addition of 20% ethanol. With such an admixture, the obtained indicators were greater than those for the new clean injectors. The spray surface area and the penetration increased with the addition of ethanol.

In the case of a lower content of additives (10% ethanol or 10% butanol) the atomization indicators were lower than those reached using clean injectors.

- The greatest impact of using alcohol admixtures on changing the fuel flow characteristics out of the injectors was achieved for the fuel with a higher tendency to deposit formation (RF-12-09).

- During the tests of fuels, only the addition of ethanol increased the atomization indicators to values greater than those obtained for new clean injectors.

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