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Assessment of the Impact of the Addition of Biomethanol to Diesel Fuel on the Coking Process of Diesel Engine Injectors

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Abstract: The paper presents unique research results on the effect of coking of diesel engine injector nozzles powered by mixtures of 10%, 20% and 30% biomethanol and diesel fuel compared to the engine being supplied with pure diesel fuel. The test results, obtained from an experiment conducted in accordance with the ISO 15550-1 standard, show the legitimacy of using biomethanol as an additive to diesel fuel due to the lower coking effect of the injector nozzles, which has a positive impact on the reduction of pollutant emissions during engine operation. Regarding the CEC PF-023 test, the tendency to reduce the coking tendency increases the percentage of biomethanol additive to diesel fuel. With a 10% share of biomethnol, the average coking effect of the injectors is over 1% lower, but with a share of 30% of bio-methanol, the coking effect is nearly 2% lower.

Keywords: injection coking; combustion; biomethanol; environmental protection; engine performance; diesel engine

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1. Introduction

Transport is a significant contributor to air pollution and greenhouse gas emissions, which are constantly increasing. The environmental requirements regarding the limits for emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), sulphur dioxide (SO_2), particulate matter (PM_{10}, $PM_{2.5}$) and particle number (PN), polycyclic aromatic hydrocarbons, benzene and heavy metals emitted by vehicles equipped with internal combustion engines are driving engine design changes and improving fuel quality parameters. Reducing pollutant emissions from the transport sector and establishing a market for clean vehicles is particularly important for agglomeration zones facing difficulties in meeting the requirements of the new Directive on air quality and cleanliness for Europe [1]. In addition, the requirements of the Directive (EU) 2018/2001(REDII directive) of the European Parliament and of the Council (sets targets for the consumption of renewable energy sources in 2021–2030 and strongly promoted the production of biofuels) [2] and meeting the goal of climate neutrality (by 2050 zero greenhouse gas emissions) contribute to the need to search for new alternative fuels.

European Union legislation regulates emissions from motor vehicles using the Euro emission standards. Council Directive 91/441/EEC of 26 December 1991 introduced quantitative restrictions on the content of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) in exhaust gas. The necessity to reduce the emissions of harmful exhaust components from a compression ignition engine has forced the modification of the engine structure, as well as the expansion of exhaust gas treatment systems. Fuel injection is one of the basic factors determining the quality of load preparation in the cylinder of a compression ignition engine. The quality of the fuel atomization affects the macrostructure and microstructure of the atomized fuel stream and the preparation of the fuel-air mixture in the cylinder [3].

Contaminants appearing inside the injector and at its tips, near the outlet of the nozzles of the sprayer nozzle, are defined in the literature by Pundir [4] and Quigley [5] as injector coking. The phenomenon of injector coking is related to the course of many subsequent chemical reactions of the fuel, and the products of decomposition of hydrocarbons in the injector nozzle and on its external surface has been described by Stanik [3] and Watkinson [6]. The coking of nozzles is not a new phenomenon, and it appeared with compression ignition engines with indirect injection in passenger cars [5]. Publications by Quigley [5], Caprotti [7], Leedham [8] and Tang [9] have pointed out that the excessive coking of pintle injectors is caused by the incompatibility of diesel fuel and engine oils lubricating pistons and radial high-pressure fuel pumps, as well as two-section in-line pumps in vans and trucks, which have an impact on the exhaust emissions and driving characteristics of cars. Stanik [3], Quigley [5] and Leedham [8] found that even minimal engine oil leakage was critical contamination increasing coking of pintle injectors. Stanik [3] and Tang [9] observed that the introduction of compression-ignition engines equipped with a High-Pressure Common Rail System (HPCRS) to the automotive market increased the tendency to coke multi-hole, high-pressure injectors due to the diameter of the nozzle holes (below 150 μm) and high tip temperatures of the injector located in the combustion chamber. Caprotti [10,11] observed that the introduction of HPCRS increased the power and torque of the engine, improved the driving characteristics of the vehicle and lowered fuel consumption by up to 30%, and the level of exhaust emissions was reduced by 95% compared to engines with indirect diesel fuel injection.

The need to solve the presented problems led to the development and implementation) of a test procedure to assess the quality of diesel fuels, without additives and with a package of such additives, in terms of their tendency to coke the nozzles of diesel injectors with indirect injection, by the CEC (Coordinating European Council.

A new procedure (CEC F-98-08 Direct Injection Common Rail Diesel Engine Nozzle Coking Test) is currently used for the coking and fouling of modern multi-bore injectors as a standard test to assess the quality of fuels and the effectiveness of detergent additives. In this procedure, a Peugeot DW-10 diesel engine with direct injection meeting the Euro 4 emission standards, equipped with injectors meeting the requirements of Euro 5 emission standards was used. Research conducted by Hawthorne [12] and Quigley [5] showed that the procedure CEC F-98-08 is not very cost-effective, longer than the previous one and that the procedure cycle is designed for high loads and does not reflect the real life of the engine. In addition, this procedure requires the use of zinc neodecanoate to accelerate the fouling of the injectors.

Due to the type of diesel fuel additive used (biomethanol) and the results of comparative studies by Stanik [3], Birgel in [13,14] and Struś [15], the authors decided to use the older CEC PF-023 method on the XUD9 A/L engine.

Several publications have described the use of alcohol (bioethanol and biomethanol) as a fuel additive in marine fuels [16] or the use of alternative fuels in road transport [17]. Although several studies have considered methanol and ethanol as an additives to diesel fuel [18,19], biomethanol (polish name: wood alcohol its dehydrated biomethanol) has not been tested in this role so far. The research used wood alcohol, which is dehydrated methanol, treated as 99.9% biomethanol. Biomethanol is a flammable liquid. It burns in the air with a blue, barely noticeable flame. Due to the production process, it is easy to maintain the purity of this fuel. Therefore, there are no sulfur compounds in the exhaust gas. With a well-conducted alcohol combustion process, the exhaust gas contains water vapor, CO and relatively a low content of nitrogen oxides. After burning the fuel, no additional waste, e.g., ash, is left, and there are no particles matters in the exhaust gas. According to the research [20], the addition of methanol to the fuel reduces the emissions of CO, HC and NO_x. Similar results were obtained by the authors of [21] using the bio-additive with diesel fuel. According to the authors of [21], the bio-additive reduced the emissions of CO, CO_2, HC and PM in the exhaust gas in comparison to the engine powered diesel fuel.

In the research, methanol produced from biomass was treated as a second-generation fuel. This type of fuel is promoted in the EU for the use of energy from renewable sources in accordance with the RED II Directive (2018) [2].

The research on a new generation of fuel mixtures of the biomethanol-diesel oil type is a scientific novelty. This type of subject cannot be found in other publications, but biomethanol-diesel blends have been widely described. Alcohols (e.g., as methanol) are an attractive alternative as a commercially used fuel, both as intrinsic fuels and in blends with gasoline or diesel fuel. The use of alcoholic fuels may be one of the significant factors contributing to the reduction of the emission of harmful exhaust components into the atmosphere (including greenhouse gases)—provided that the properties of these fuels are well known and their optimal use in terms of adapting to the requirements of the current engines. A possible way to improve the fuel economy and engine emissions could also be with alternative fuels combined with an innovative combustion system. The industry and research by Sequino [22] and Beatrice [23] regardingconventional diesel combustion has led to the development of innovative combustion systems able to improve the CO_2 and NOx-Soot tradeoffs, such as specific bowl design, innovative fuel injection systems, injection strategy and EGR systems.

2. Materials and Methods

The article evaluates the degree of coking of nozzles according to the procedure CEC PF-023 test, which consists of making the propensity to contaminate the fuel nozzles for the fuel (biomethanol).

2.1. Test Method

The measurements aimed to assess the degree of coking of the nozzles by the CEC PF-023 procedure. The procedure for the Diesel Engine Injector Nozzle Coking Test (PSA XUD9 A/L) involves testing the propensity to contaminate fuel atomizers.

The research stand consisted of an aslow-aspirating, four-stroke engine PSA XUD9 A/L with indirect injection, produced by Peugeot Citroen (Peugeot Societe Anonyme—PSA) and intended for use in passenger cars.

The PSA XUD9 A/L engine used for testing based on the CEC F-23-01 procedure was the engine (with the parameters shown in Table 1), with indirect injection equipped with a Ricardo swirl chamber, with Lucas RDNO SDC 6850 pintle injectors (non-flattened), equipped with Lucas Roto Diesel DCP R8443B910A centrifugal fuel pump and a nozzle opening pressure of 11.5 MPa [24,25].

Table 1. Basic engine parameters.

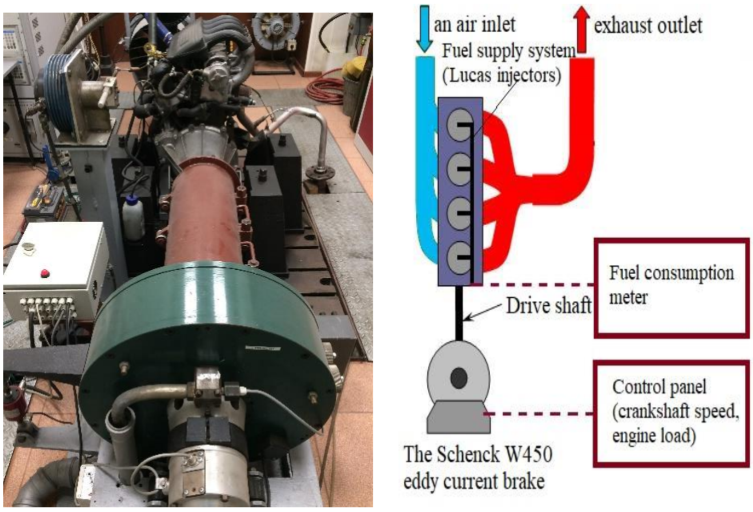
Name of Parameter		Engine Parameter
No. of Cyls. & Arrangement		4-cylinder
Valve Mechanism		two-valve per cylinder engine
Displacement	[cm^3]	1905
Max. Output	[kW @ rpm]	47 @ 4600
Max. Torque	[N·m @ rpm]	118 @ 2000

The empirical research of coking of injectors was conducted on a test stand at the Vehicles Institute, Warsaw University of Technology, as shown in Figure 1.

In addition, the research stand included [3]:

- The Schenck W450 eddy current brake with a controller allowing to obtain a constant rotational speed of the engine,
- “The servomotor for controlling the injection pump,
- The air consumption measurement system consists of a laminar flow meter type E7035 and a differential pressure meter type MK1,

- The standard measurement systems for engine crankshaft rotational speed, torque, fuel consumption, oil and coolant temperature, and other devices that meet the requirements of PN-88/S-02005,
- A device for determining the injector opening pressure, produced by L. Hartridge Ltd.,
- A device for measuring the throughput of nozzles according to ISO 4010" [25].



(**a**) (**b**)

Figure 1. The research stand: XUD9A engine (**a**) and scheme of research stand (**b**).

The torque measurement error on our dynamometer controlled by the Schenck system was ±3 Nm, with a rotational speed of ±5 rpm. The Laminar flow meter-measuring accuracy was ±1%, and the differential pressure gauge when the measuring element temperature differed from the reference temperature (+20 °C), with a max. ±0.8%.

The research was conducted in the following order according to the CEC PF-023 procedure:

- Measurement throughput of brand-new nozzles by ISO 4010,
- "Setting the injector opening pressure by the requirements of the CEC PF-023 procedure and mounting them on the engine" [25],
- Conducting a 10 h test trial by the CEC PF-023 procedure,
- Measurement throughput of dismantled and contaminated nozzles by ISO 4010.

The test simulated city driving and lasted 10 h and 3 min. The engine tests were conducted at various engine speeds and loads, and included 134 periodically recurring cycles consisting of four phases with the following parameters [15]:

- First phase: 1200 ± 30 rpm with an engine load of 10 ± 2 Nm for 30 s;
- Second phase: 3000 ± 30 revolutions per minute with an engine load of 50 ± 2 Nm for 60 s;
- Third phase: 1300 ± 30 rpm with an engine load of 35 ± 2 Nm for 60 s;
- Fourth phase: 1850 ± 30 rpm with an engine load of 50 ± 2 Nm for 120 s.

The degree of coking of pintle injectors after a 10 h engine test is defined as a percentage reduction in the patency of the nozzles. This parameter is a calculation of the airflow limitation through the atomizer (at 0.1 mm injector needle lift), measured according to "ISO 4010. Diesel engines", the delay pintle type and the calibrating nozzle [15].

2.2. Physicochemical Parameters of Fuels

For empirical studies, diesel fuel by the EN 590 (diesel fuel (EN590)) and biomethanol were used as a mixture component. Table 2 shows the physicochemical parameters of the fuels used in the tests.

Table 2. Elementary physicochemical parameters of engine fuels used in the research.

Parameter	Unit	Diesel Fuel [1]	Biomethanol
Cetane number	-	51.4	6
Net calorific value	MJ/kg	42.5	19.9
Density at 15 °C	g/cm^3	0.838	0.792
Viscosity at. 40 °C	mm^2/s	2.91	0.74
Surface tension (20 °C)	N/m	3.64×10^{-2}	-
Flash point	°C	102	-
Cloud point	°C	−17	-
Cold filter plugging point (CFPP)	°C	−35	-
Sulfur content	mg/kg	9	-
Water content	mg/kg	43.8	-
Total solid contamination	mg/kg	5	-
Carbon residue (on 10% distillation residue)	%(m/m)	0.01	-
Copper strip corrosion	class	1	-

[1] Diesel fuel in accordance with the EN 590.

The following fuel was used for empirical research: diesel fuel (EN590) and diesel fuel (EN590) mixture with dehydrated biomethanol with the following volumetric composition (*v/v*):

- SD1—90% diesel fuel + 10% biomethanol (M-diesel),
- SD2—80% diesel fuel + 20% biomethanol (M-diesel),
- SD3—70% diesel fuel + 30% biomethanol (M-diesel).

The tested physicochemical parameters of the above compositions (mixtures) are presented in Table 3.

Table 3. Basic physicochemical parameters of mixtures (compositions).

Parameter	Unit	Result		
		SD1	SD2	SD3
Flash point (open crucible)	°C	33	32	23
Cloud point	°C	<+22	<+23	<+27
Density at 15 °C	kg/m^3	833.5	829.2	823.9
Viscosity at. 40 °C	mm^2/s	2.66	2.41	2.12

3. Results

Tables 3 and 4 and Figures 1–15 show the results of the research on the coking tendency of pintle injectors by the CEC F-23-01 procedure for the diesel fuel (EN590) and diesel fuel (EN590) mixture with biomethanol.

The results of the tests performed by the CEC PF-023 procedure showed (Figure 15) that the injectors were less prone to coking when fueling the engine with a mixture of diesel fuel with biomethanol compared to the engine with pure diesel fuel. Research has shown that the addition of alcohol to diesel fuel (any alcohol) reduces coking. The fuel tendency to coke the injector tips is shown as the percentage reduction of airflow through the nozzles of each of the four injectors for the given needle lift values. The result of the whole test is the mean percentage airflow reduction for all four nozzles of 0.1 mm needle lift (per CEC) (Figures 2–14 and Table 4). Figure 15 shows that the injectors were less prone to coking when the engine was fed with a mixture of diesel fuel with biomethanol compared to pure diesel fuel.

A tendency to reduce the coking tendency can be observed when increasing the percentage of biomethanol additive to diesel fuel. With a 10% share of alcohol, the average coking effect of the injectors was over 1% lower, but with a share of 30% of alcohol, the coking effect was nearly 2% lower.

Tables 2 and 3 show, with the addition of more biomethanol, the density and viscosity of this mixture further decreased. Of course, the different physicochemical properties of these fuel mixtures have an important influence on the change of the parameters of the fuel injection process and the course of its combustion. The experiments conducted using this engine showed that the use of lower viscosity fuels reduced the coking of the atomizers. It can be assumed that both this and the significant differences in fuel densities also have a substantial impact on shaping other engine operating characteristics.

Table 4. Results of the research on the coking tendency of pintle injectors by the CEC F-23-01 procedure for the diesel fuel (EN590) and diesel fuel (EN590) mixture with biomethanol.

Nozzle Lift [mm]	Nozzle No. 1		Nozzle No. 2		Nozzle No. 3		Nozzle No. 4	
	Before Test	After Test	Before Test	After Test	Before Test	After Test	Before Test	After Test
				Diesel fuel				
0.05	199	90.4	199	88.8	214.5	118.8	221.8	111.9
0.1	246.5	130	245.1	123.4	245.8	127.1	256.6	131.1
0.2	251.5	145.2	281.5	140.1	262.9	173.3	281.5	171.6
0.3	301.3	181.5	361	198.2	310.4	209.7	312.5	221.1
0.4	410.5	280.5	498	278.8	435.9	283.6	429.2	371.3
0.5	793	561	840.5	640.8	808.5	528	856.1	755.7
				SD1				
0.05	196.3	102	196.2	101.5	212.6	108.9	221.7	115.7
0.1	245.3	133.1	245	124.9	244.6	128.2	245.4	129.9
0.2	250.2	146.6	278.9	161.3	261.7	174.9	277.9	173.1
0.3	319.3	193	349.8	196.8	305.8	211.4	310.7	242.8
0.4	428.9	283	489.6	271.3	435	289.7	423.5	375.6
0.5	798.8	624.1	824	571.7	849.7	612.8	885.9	693.4
				SD2				
0.05	184.7	83.8	177.6	89.3	204.1	114.8	192.3	107.7
0.1	247.1	134.2	249.8	125.9	248.4	129.2	248.2	135.9
0.2	251.9	147.8	260	144.7	260.5	176.3	263	174.5
0.3	299.7	194.5	342.3	201.4	308	213.2	312.9	224.8
0.4	411.7	285.2	444	276.5	438	302.1	426.5	337.8
0.5	796.4	572.4	810	597.6	816.8	639.7	856.3	667
				SD3				
0.05	163.9	85	196.6	88.4	201.2	112.2	201.2	112
0.1	248.9	137	248.8	128.5	249.1	134.9	253.9	132.6
0.2	250.7	149.6	268.5	144.5	262.2	178.5	258.5	176.8
0.3	298.1	197	360.5	204	306.4	215.9	311.3	227.8
0.4	409.6	289	490.5	279.9	435.8	306	424.4	352.5
0.5	786.4	578	815.6	536	802.8	646	852	711

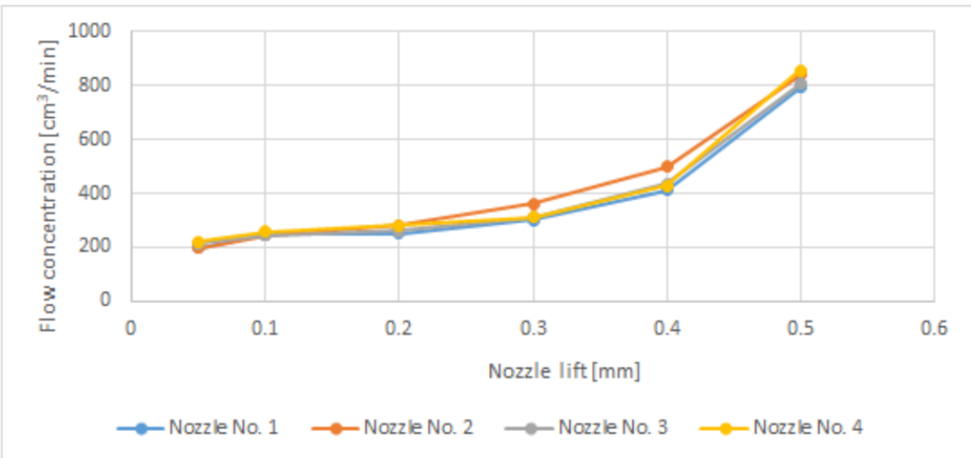


Figure 2. The flow before the test for diesel fuel.

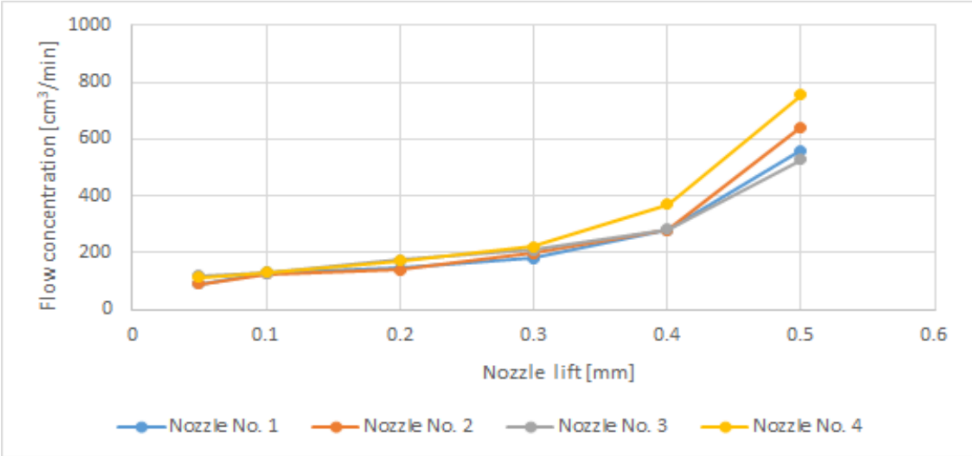


Figure 3. The flow after the test for diesel fuel.

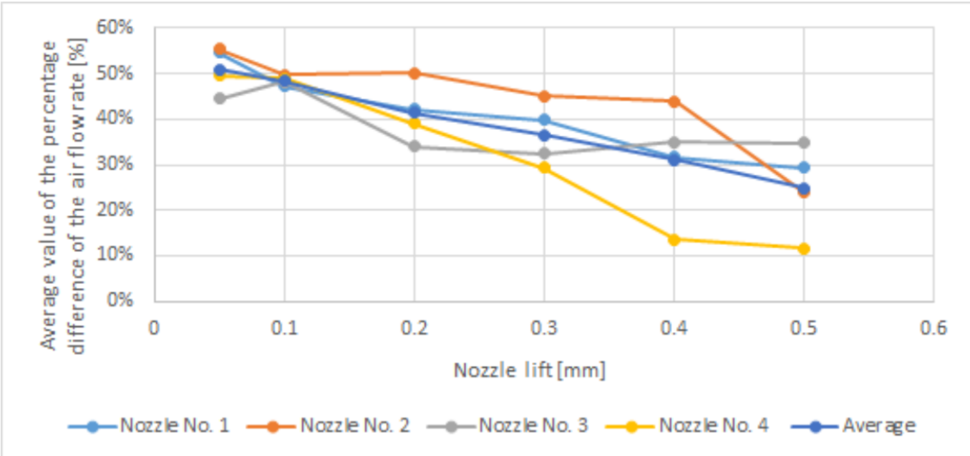


Figure 4. The mean value of the airflow rate for diesel fuel.

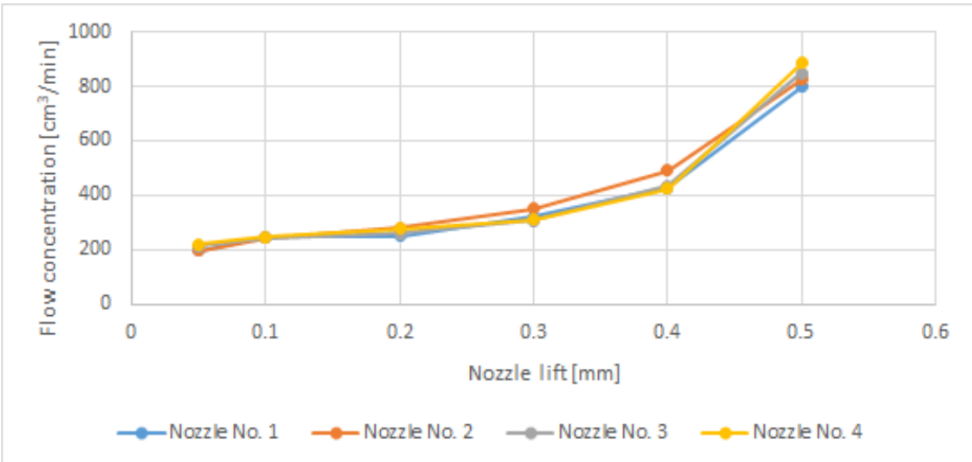


Figure 5. The flow before the test for SD1.

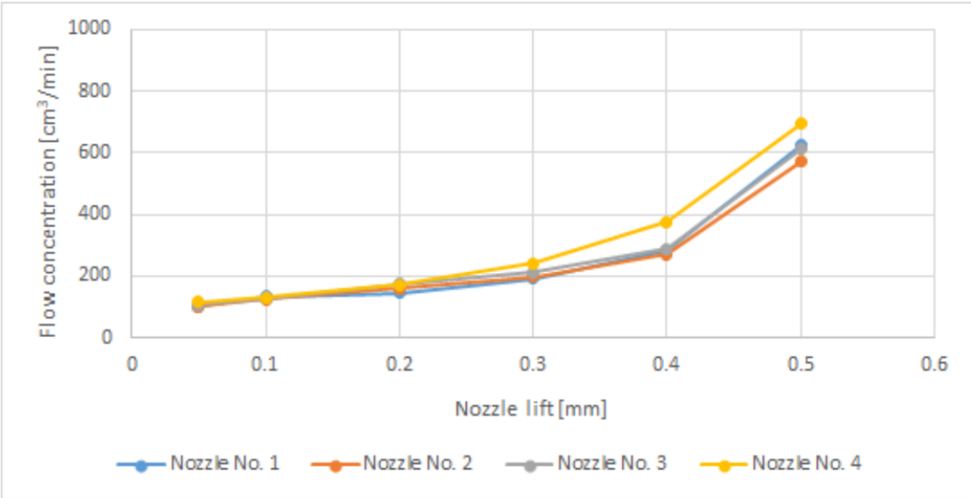


Figure 6. The flow after the test for SD1.

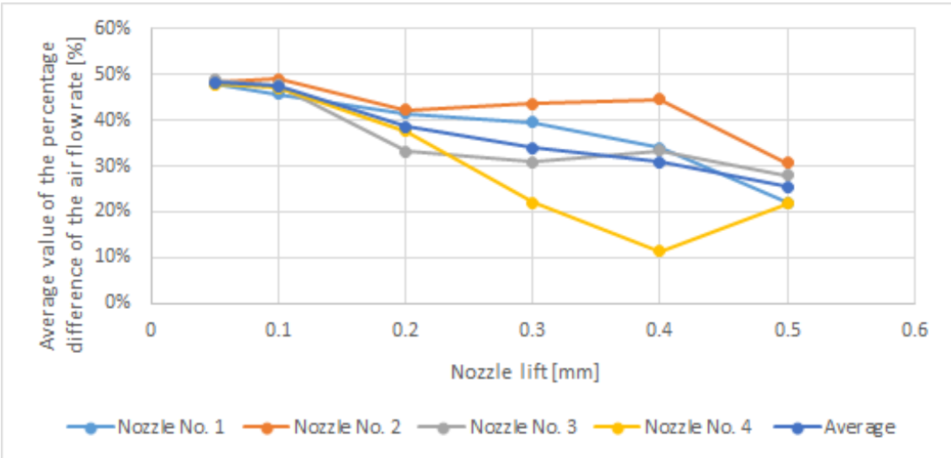


Figure 7. The mean value of the airflow rate for SD1.

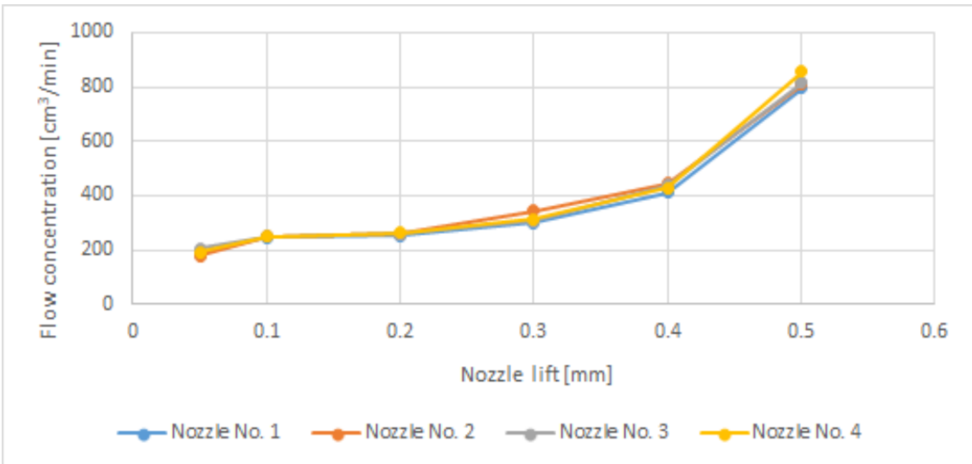


Figure 8. The flow before the test for SD2.

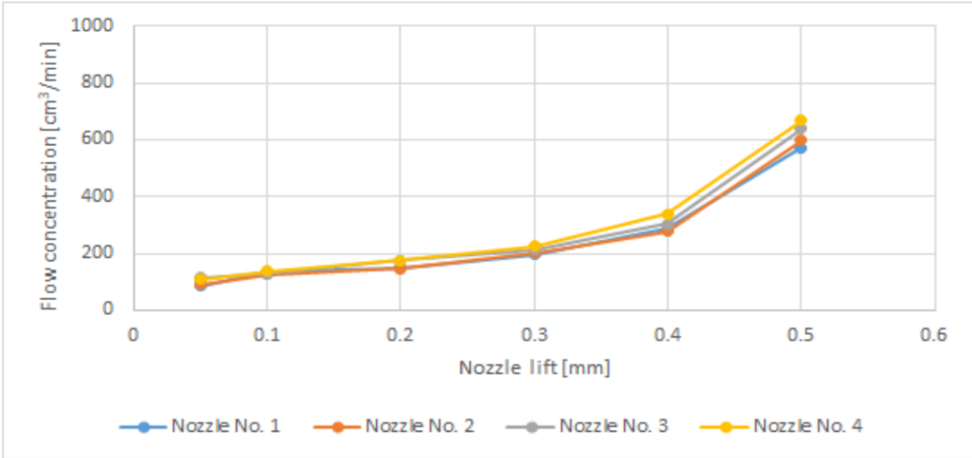


Figure 9. The flow after the test for SD2.

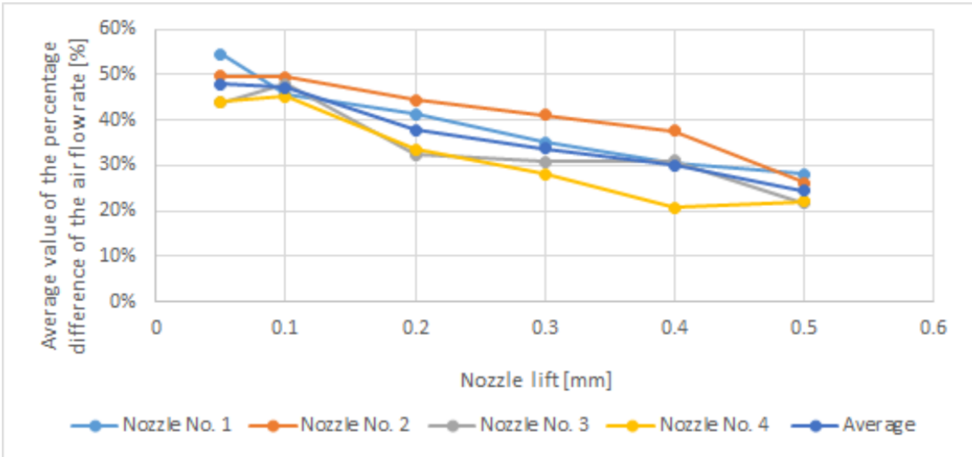


Figure 10. The mean value of the airflow rate for SD2.

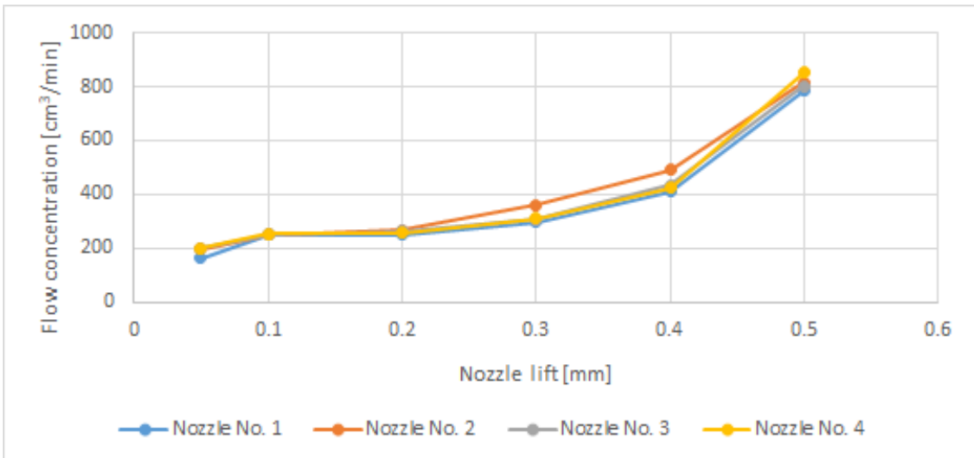


Figure 11. The flow before the test for SD3.

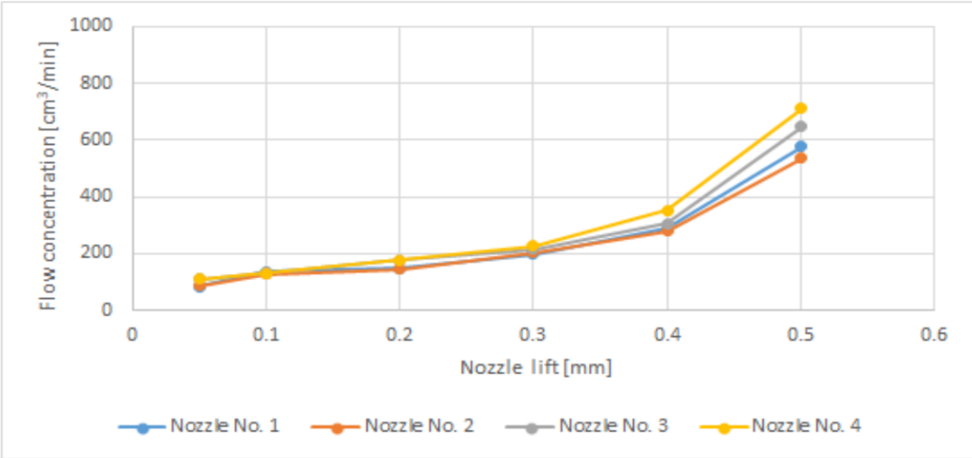


Figure 12. The flow after the test for SD3.

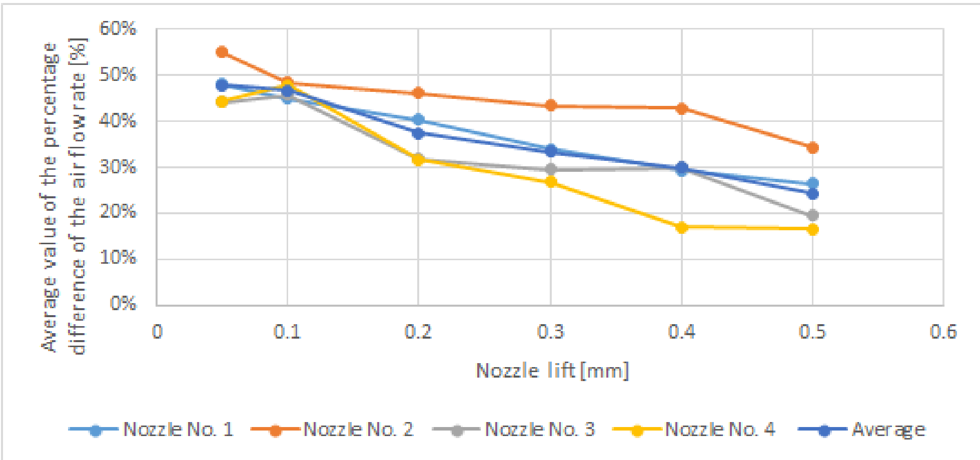


Figure 13. The mean value of the airflow rate for SD3.

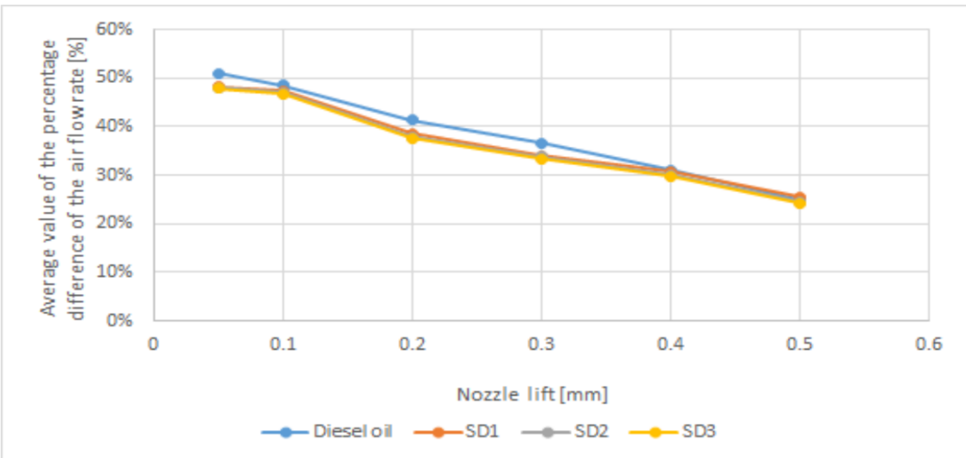


Figure 14. The mean value of the difference in the airflow rate through the injectors obtained from the CEC test PF-023.

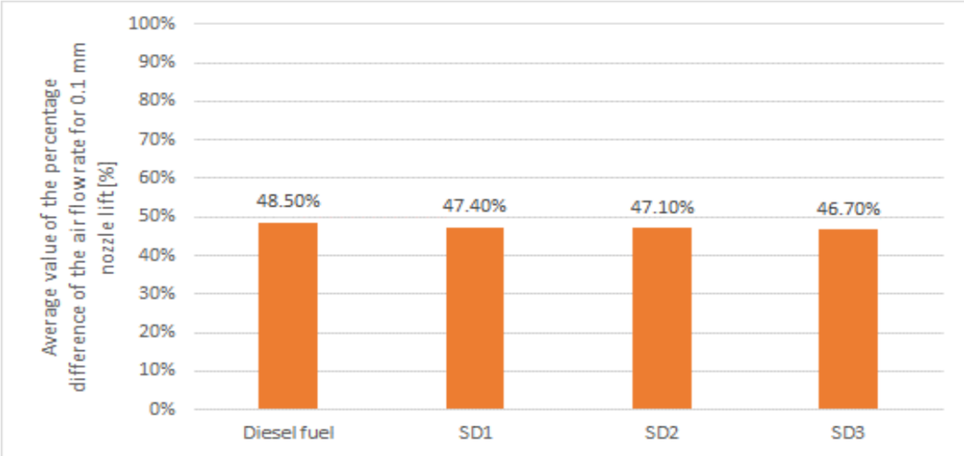


Figure 15. The mean value of the airflow rate difference (expressed as a percentage) for a 0.1 mm nozzle lift in the CEC test PF-023.

4. Discussion

The deposit formation mechanisms in the engine differ depending on several factors and where they 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 their formation processes are not fully understood. In the case of fuel injectors, sludge precursors are formed as a result of the condensation, oxidation and precipitation of unstable hydrocarbons (olefins and aromatics) from the fuel [26].

The authors conducted an experiment involving the addition of 30% biomethanol to diesel fuel despite the fact that the authors were aware that commercial fuel of this type would not be applicable in diesel engines due to its physicochemical properties (LC, calorific value, etc.).

Deposits have a negative effect on the operation of injectors in diesel engines. The components of injectors are small in size, lightweight and are manufactured with high accuracy using very advanced techniques. The problem is significant in terms of their reliability and durability. In addition, the tolerance of the performance of individual cooperating elements has a direct impact on the time and size of the injection doses. The test results show that the tendency to coke the injectors is a serious problem that can be partially overcome by adding biomethanol to diesel fuel.

The coking of injector nozzles has a negative effect on the shape and size of the fuel sprayed dose. This disrupts the combustion process in a diesel engine. It contributes to the increased emission of hydrocarbons and solid particles in the exhaust gas, hindering the operation of catalytic converters and DPF filters and polluting the atmospheric air.

The phenomenon of coking of the injectors is undesirable and affects the dynamic parameters of the engine, increasing the emission of pollutants and the service life of the engine. Arpaia et al. [27] explained the physical origin of injector coking in diesel engines and identified the most important construction parameters and operating variables for the occurrence of this phenomenon. It has been shown that contamination of the injector is influenced by many factors, such as the nozzle configuration, injector temperature, fuel composition, bore diameter and conicity. A similar situation was described by the authors of [28], discussing, inter alia, the disturbing situations caused by carbon deposits and coked injector tips. Similarly, the authors of [29] described the disturbing situations caused by the coking of diesel injectors in the engine.

Bio-additives to diesel fuel may have different effects on the coking phenomenon [30]. After analyzing many studies, it can be concluded that coking is a potentially serious problem when using unmodified vegetable biodiesel. However, degummed, chemically processed and refined vegetable oil mixed with diesel fuel can be used for the longer operation of a compression-ignition engine. It has been reported that there was a slight decrease in braking force and a slight increase in fuel consumption with the use of vegetable oil. However, the lubricating properties of biodiesel are better than those of diesel, which can extend the engine's life. Moreover, the biodiesel fuel is environmentally friendly, produces much less HC and NOx, and produces no SOx. In addition, there is no CO_2 increase at the global level.

The authors believe that using a biomethanol supplement should eliminate the problems mentioned above. The authors believe that using our fuel blends (ON-biomethanol), we can rule out most of these problems or postpone a potential failure of the power supply system, which will result in an extension of the engine's uptime.

5. Conclusions

The tests were performed based on the CEC PF-023 procedure, in which the test apparatus was a Peugeot XUD9 engine (only such engine complies with this procedure). All injectors were replaced with new ones before the test procedures, and we measured the airflows before and after the test procedures.

The test results show a more minor tendency to coke the injectors using diesel mix-compared to pure diesel fuel. This allows for the conclusion that further increasing the proportion of biomethanol in the mixture will have a positive effect on reducing the effect of coking of the injectors, which has an important impact on the improvement of the internal combustion engine operating conditions and the emission of toxic exhaust components.

The use of a mixture of biomethanol and diesel fuel, compared to pure diesel fuel, allows for the reduction of deposits at the ends of the injectors and is less susceptible to the coking of the injectors.

The subject of atomizer coking has been widely discussed in articles regarding the mixture of diesel fuel with ethanol. However, there is no information about coking in the case of diesel fuel with biomethanol. The article presents a pioneering study of the addition of biomethanol to diesel fuel in terms of injector coking.

The experiment with mixtures of 20% and 30% was deliberate but purely scientific. We aimed to determine what would happen with coking when we increased the amount of biomethanol in the fuel. Because studies have shown that reducing coking by 1% extends the life of the injector, we will thus gain several thousand kilometres of additional mileage on such fuel without engine failure.

In addition, biomethanol as a second-generation biofuel meets the requirements of the REDII directive. Therefore, the authors believe that the use of an abundance of biomethanol for diesel fuel may contribute to the reduction of fossil CO_2 emissions, which will have a beneficial effect on the environment.

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