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Evaluation of the effect of the addition of bioethanol to gas oil on coking diesel engine injector terminals

The article presents the results of empirical research and their analysis regarding the impact of diesel oil and diesel oil mixture with bioethanol on coking the test injector nozzles of the XUD9 engine from PSA. The research included three fuel deals: diesel fuel as the base fuel and diesel oil mix with ONE10 bioethanol (10% bioethanol plus diesel oil (V/V)), ONE20 (20% bioethanol plus diesel oil (V/V)). They were conducted on the basis of CEC PF-023 developed by CEC (Coordinating European Council). Each of the above-mentioned fuels was tested using a new set of injectors. The propensity of the fuel for coking the injector tips was expressed as a percentage reduction in the air flow through the nozzles of each injector for the given sheer increments. The test result was the average percentage of airflow reduction for all nozzles at 0.1 mm spike increments and was measured according to ISO 4010 "Diesel engines. Calibrating nozzle, delay pintle type". The test results for individual atomizers of the above-mentioned test engine in the area of sediment formation from flowing fuel shown a lower tendency to coke the injectors using diesel fuel-bioethanol in comparison to the use of pure diesel oil. Based on the CEC PF-023 test, it can be noticed that the level of contamination of the tested injectors for ONE10 fuel is about 3% lower, and for ONE20 fuel is about 4% lower than the level of pollution for diesel fuel.

Keywords: *injection coking, combustion, fuel plant, environmental protection, engine diagnostics*

1. Introduction

More and more stringent emission standards force the automotive industry to conduct research and seek technical solutions to ensure the least possible harmful effect of vehicles on the natural environment [6, 8, 17, 18].

For manufacturers of internal combustion engines, the main goal is to reduce noise, fuel consumption and emissions of toxic exhaust components – mainly from compression-ignition engines. One solution may be to supply combustion engines with fossil fuels with the addition of biofuel, which may be bioethanol [4]. The preparation of such a mixture and its application may reduce the emission of selected components of toxic fumes to the atmosphere [3, 16]. The great advantage of this type of fuels is also their availability. Mainly due to the fact that parts of such a fuel mixture are produced from renewable sources, which are subject of regeneration [2, 7, 14, 21]. One of the areas of research on bioethanol is its impact on the formation of the IDID (Internal Diesel Injector Deposit).

The internal injector deposition (IDID) phenomenon reduces the dynamics of internal injector working parts or their complete blocking. It may causes damage to important components of the engine's fuel supply system [5, 9, 11, 13].

Therefore, a test for coking injectors is very important in the preliminary processes of fuels intended for later commercial use. Thanks to it, we are able to determine the capping of nozzle tips that can cause problems with starting the engine, an uneven operation of the engine, uncontrolled changes in power and torque of the engine, and even its unexpected stop. As a consequence, it has an impact on the durability of the engine's fuel supply system and its operational parameters, such as the amount of fuel consumption or the level of emissions of selected toxic components of exhaust gases into the atmosphere [12, 15, 20].

2. Research purpose

The aim of the research is to analyze and evaluate the coking of the ends of injectors a self-ignition engine powered with liquid fuels of alternative vegetable origin. Empirical studies were carried out for diesel oil (ON) and a mixture of this fuel with bioethanol: ONE10 (10% bioethanol plus diesel) and ONE20 (20% bioethanol plus diesel). The tests were carried out on a test bench equipped with the XUD9A test engine used for this type of research by many research centres. The tests included assessing the degree of coking of atomizers in accordance with the CEC PF-023 procedure.

3. Physicochemical properties of fuels

For proper operation of the combustion engine, fuel with strictly defined physical and chemical properties is needed. Power systems have properties and constraints related to their construction and control, which are adapted to the appropriate physicochemical properties used in fuel engines [1, 10, 19].

For empirical studies, diesel oil (ON) and bioethanol (E) were used as a component of the mixture. Table 1 presents the physicochemical properties of the basic fuels used in the tests.

Table 1. Basic physicochemical properties of engine fuels used in tests

Parameter	Unit	Diesel fuel	Bioethanol
Cetane number	–	51.2	10
Heat value	MJ/kg	42.4	27.3
Density at 15°C	g/cm^3	0.836	0,795
Kinematic viscosity	mm^2/s	2.92	0.93
Surface tension	N/m	$3{,}63\cdot10^{-2}$	–
Flash-point	°C	13	–
Cloud point	°C	–16	–
The temperature of blocking the cold filter	°C	–34	–

Table 1cont.

Parameter	Unit	Diesel fuel	Bioethanol
Average elementary composition	%		
C		87.3	52.2
H		12.7	13.7
O		0	34.1
Sulfur content S	mg/kg	8	–
Water content	mg/kg	43.5	–
Solid impurities content	mg/kg	4	–
Coke residue in a 10% distillation residue	%(m/m)	0.02	–
Research on the corrosive effect on copper plates		1	–

In addition to diesel fuel, a test mix of this fuel with dehydrated bioethanol with the following composition was also used:

- ONE10 – 89% ON + 0.4% Rokanol O3 + 0.6% Rokok L3S + 10% Bioethanol (E-diesel),
- ONE20 – 78% ON + 1% Rokanol O3 + 1% Rokanol L3S + 20% Bioethanol (E-diesel).

The examined physicochemical properties of the above-mentioned mixtures are presented in Table 2.

Table 2. Selected physicochemical properties of mixtures

Parameter	Unit	Value	
		ONE10	ONE20
Flash-point (open crucible)	°C	34	32
Cloud point	°C	< +23	< +23
Density at 15 °C	kg/m^3	832.5	828.2
Kinematic viscosity at 40 °C	mm^2/s	2.43	2.27

Blends of diesel oil with bioethanol: ONE10 (10% bioethanol plus diesel) and ONE20 (20% bio-ethanol plus diesel) can be, due to their physicochemical properties, substitute fuels for diesel.

4. Research stand and test method

The research stand included:

- XUD9A research engine,
- Schenck W400 electromagnetic brake with a controller enabling constant engine speed,
- Electronic servomotor for setting the injection pump,
- Air consumption measurement system consisting of a laminar flow meter type E 7035 and a pressure difference meter type MK1,
- Standard systems for measuring speed, torque, fuel consumption, oil and coolant temperature, and other devices that meet the requirements of PN-88/S-02005,
- Device for determining injector opening pressure from L. Hartridge Ltd,
- Device for measuring atomizer throughput in accordance with ISO 4010.

The empirical studies of coking of injectors were carried out on a test stand at the Vehicles Institute, Warsaw University of Technology, which is shown in Fig. 1. The sediment formation was evaluated on the basis of CEC PF-023 tests using a new set of injectors for each fuel tested.

The scope of the measurements included the assessment of the degree of coking of the nozzles in accordance with the CEC PF-023 procedure, based on the examination of the propensity to contaminate fuel atomizers. LUCAS RDNO 6887 D 03 CFR type sprayers were used for testing. The tests were carried out in accordance with the above-mentioned standard and in the following order:

- measurement of the throughput of brand new sprays in accordance with ISO 4010,
- setting the injector opening pressure in accordance with the requirements of the CEC PF-023 procedure and mounting them on the engine,
- performing a ten-hour test sample in accordance with the CEC PF-023 procedure,
- capacity measurement of disassembled and contaminated atomizers in accordance with ISO 4010.

Fig. 1. The test stand equipped with XUD9A engine [12]

The propensity of fuel for cooking the injector tips is expressed as a percentage reduction in the air flow through the nozzles of each of the 4 injectors for a given needle lift value.

The test result is the mean value of the percentage airflow reduction for all 4 nozzles at a needle lift of 0.1 mm.

5. Research results

The tendency of fuels to form sediments is determined by measuring the air flow through the nozzles before and after the test. The result is expressed as the average percentage decrease in air flow through the nozzles. The results of flow rate tests through nozzles are presented in Tables 3–11 and graphically in Figures 2–7.

Table 3. Results of spray flow rate measurements before the test – ON

uplift [mm]	nozzle 1 [cm^3/min]	nozzle 2 [cm^3/min]	nozzle 3 [cm^3/min]	nozzle 4 [cm^3/min]
0.05	201	200	217	225
0.1	250	248	248	258
0.2	255	283	267	283
0.3	303	367	312	317
0.4	417	500	443	432
0.5	800	850	817	867

Table 4. Results of spray flow rate measurements after the test – ON

uplift [mm]	nozzle 1 [cm³/min]	nozzle 2 [cm³/min]	nozzle 3 [cm³/min]	nozzle 4 [cm³/min]
0.05	93	90	120	110
0.1	133	125	128	130
0.2	147	142	175	173
0.3	183	200	212	223
0.4	283	282	287	375
0.5	567	647	533	763

Table 5. Calculation results – ON

uplift [mm]	R1 [cm³/min]	R2 [cm³/min]	R3 [cm³/min]	R4 [cm³/min]	average [%]
0.05	53.6%	55.2%	44.6%	51.1%	51.1%
0.1	46.7%	49.5%	48.3%	49.7%	**48.5%**
0.2	42.5%	50.0%	34.4%	38.8%	41.4%
0.3	39.6%	45.5%	32.1%	29.5%	36.6%
0.4	32.0%	43.7%	35.4%	13.1%	31.0%
0.5	29.2%	23.8%	34.7%	11.9%	24.9%

Table 6. Results of spray flow rate measurements before the test – ONE10

uplift [mm]	nozzle1 [cm³/min]	nozzle2 [cm³/min]	nozzle 3 [cm³/min]	nozzle 4 [cm³/min]
0.05	165	198	215	223
0.1	251	252	249	251
0.2	253	281	264	281
0.3	301	363	309	314
0.4	413	496	439	428
0.5	799	812	819	859

Table 7. Results of spray flow rate measurements after the test – ONE10

uplift [mm]	nozzle 1 [cm³/min]	nozzle 2 [cm³/min]	nozzle 3 [cm³/min]	nozzle 4 [cm³/min]
0.05	84	90	115	108
0.1	137	134	132	136
0.2	148	145	177	175
0.3	185	202	214	226
0.4	286	277	320	339
0.5	584	599	642	689

Table 8. Calculation results – ONE10

uplift [mm]	R1 [cm³/min]	R2 [cm³/min]	R3 [cm³/min]	R4 [cm³/min]	average [%]
0.05	49.1%	54.8%	46.4%	51.6%	50.5%
0.1	45.5%	46.8%	47.0%	45.7%	**46.3%**
0.2	41.4%	48.3%	33.1%	37.7%	40.1%
0.3	38.4%	44.4%	30.8%	28.1%	35.4%
0.4	30.7%	44.0%	27.2%	20.8%	30.7%
0.5	26.9%	26.2%	21.7%	19.8%	23.6%

Table 9. Results of spray flow rate measurements before the test – ONE20

uplift [mm]	nozzle 1 [cm³/min]	nozzle 2 [cm³/min]	nozzle 3 [cm³/min]	nozzle 4 [cm³/min]
0.05	201	200	217	225
0.1	250	248	248	258
0.2	255	283	267	283
0.3	303	367	312	317
0.4	417	500	443	432
0.5	800	850	817	867

Table 10. Results of spray flow rate measurements after the test – ONE20

uplift [mm]	nozzle 1 [cm³/min]	nozzle 2 [cm³/min]	nozzle 3 [cm³/min]	nozzle 4 [cm³/min]
0.05	100	92	120	110
0.1	140	135	135	143
0.2	156	150	175	173
0.3	198	205	212	223
0.4	293	301	287	375
0.5	645	647	634	663

Table 11. Calculation results – ONE20

uplift [mm]	R1 [cm³/min]	R2 [cm³/min]	R3 [cm³/min]	R4 [cm³/min]	average [%]
0.05	50.2%	54.0%	44.6%	51.1%	50.0%
0.1	44.0%	45.5%	45.6%	44.6%	**44.9%**
0.2	38.8%	47.1%	34.4%	38.8%	39.8%
0.3	34.7%	44.1%	32.1%	29.5%	35.1%
0.4	29.7%	39.8%	35.4%	13.1%	29.5%
0.5	19.4%	23.8%	22.4%	23.5%	22.3%

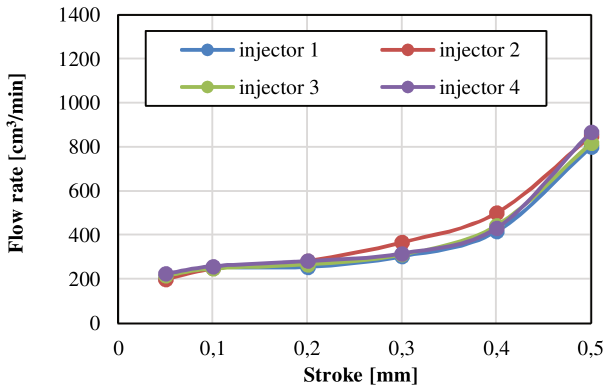

Fig. 2. The flow rate through nozzles before the test for ON fuel

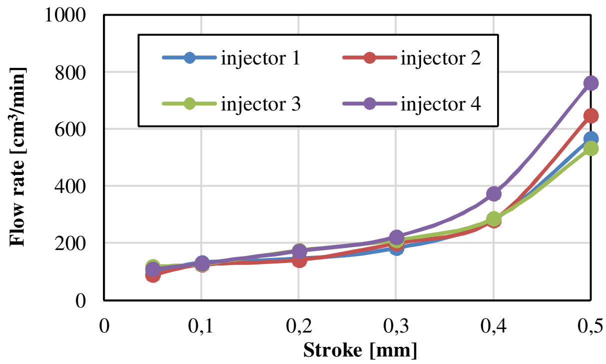

Fig. 3.The flow rate through nozzles after the test for ON fuel

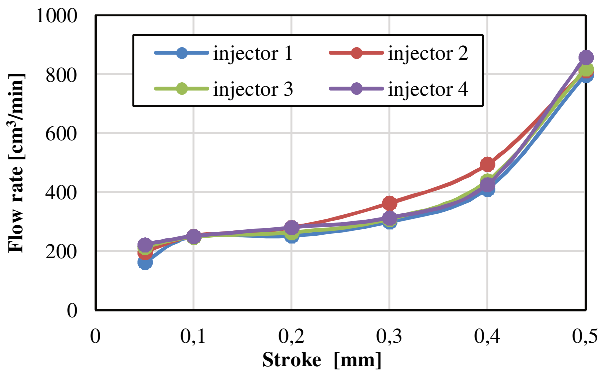

Fig. 4.The flow rate through nozzles before the test for ONE10 fuel

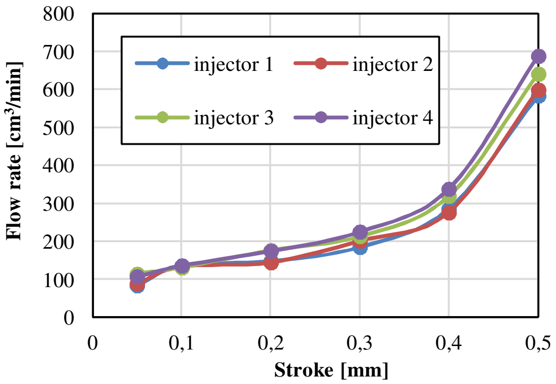

Fig. 5.The flow rate through nozzles after the test for ONE10 fuel

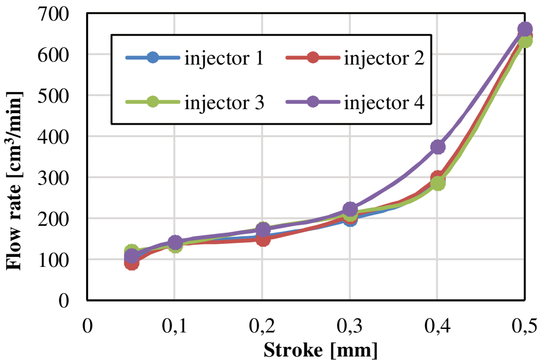

Fig. 7. The flow rate through nozzles after the test for ONE20 fuel

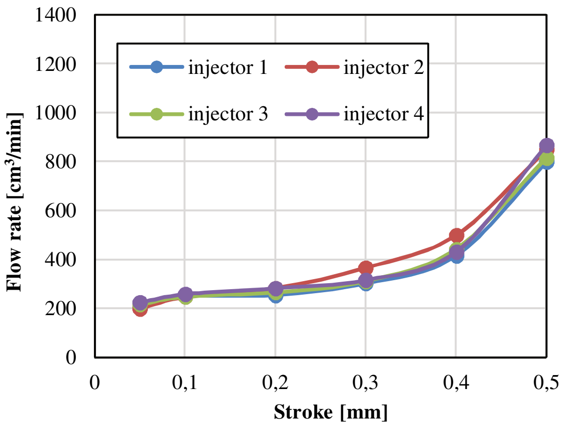

Fig. 6. The flow rate through nozzles before the test for ONE20 fuel

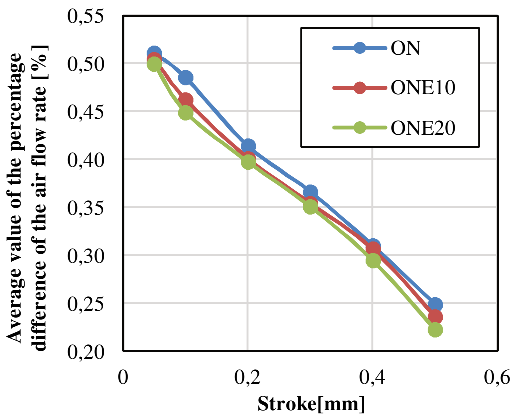

Fig. 8. The average value of the difference in the air flow rate through injectors obtained in the CEC test PF-023 while covering the test engine with three fuels

5. Conclusions

The tests showed a lower tendency to coke the injectors using diesel fuel-bioethanol in comparison to the use of pure diesel oil.

Based on the CEC PF-023 test, it can be noticed that the level of contamination of the tested injectors (at a heel of 0.1 mm) for ONE10 fuel is about 3% lower than the level of diesel injector contamination.

The level of injector coking for ONE20 fuel is about 4% lower than the level of pollution for diesel fuel.

Lower susceptibility to coking the injectors using a mixture of bioethanol and diesel oil compared to the diesel oil itself gives the possibility of reducing deposits at the ends of the injectors.

Surface coking at the tip of the needle tip - the sprayer and nozzle openings reduce or block the flow of fuel through the injector and change the spraying quality and microstructure of the sprayed stream. In addition, the contamination of the injector tip reduces the distance of the diffusion flame to the injector causing heat exchange between the deposits and deposits created in the sprayer, not with the spray of fuel creating a rich fuel-air mixture, which causes a slower combustion process and increased particulate matter emission.

In summary, sediments have a negative impact on the operation of injectors in CI engines. The problem is important from the point of view of their durability and reliability because their components have small dimensions, low mass and are manufactured with high accuracy using very advanced techniques. In contrast, the tolerance of performance of individual cooperating elements has a direct impact on the time and size of injection doses. All this indicates that the tendency to injectors coking is a considerable problem, which can be partially eliminated with the addition of bioethanol to diesel oil.

Nomenclature

ON	diesel oil
ONE10	10% bioethanol + diesel
ONE20	20% bioethanol + diesel
E	bioethanol
R1	injector 1
R2	injector 2
R3	injector 3
R4	injector 4
IDID	Internal Diesel Injector Deposit

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