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Study of the Technical and Operational Parameters of Injectors Using Biogas Fuel

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Abstract: Using biogas fuel in a modern internal combustion engine equipped with gas equipment of the fourth and fifth generations can create several difficulties. This is due to the low heat of combustion of untreated biogas, the presence of moisture, and the specifics of the injectors. The main problem of the studies we considered is that there are no data on the operating parameters of biogas fuel injectors. Studies on the parameters of the Matrix, Barracuda, Valtek, Hana, and Keihin injectors in relation to biogas fuel were carried out according to performance indicators, the linearity of operation, the resistance of the injectors, the ability to maintain factory parameters, and service life. According to the indicators of performance and linearity of work, Valtek injectors have the highest deviation in productivity and linearity of work, with an average of 38.8%, and the lowest deviation of Barracuda injectors is 7.5%. Keihin (15.3%) and Hana injectors (19.1%) also showed good performance indicators, and therefore can be used effectively for biogas fuel systems. As a result of research on the response time of the injectors, it was established that the best indicators were found for Hana (1.75 ms) and Keihin (1.99 ms) injectors. Valtek injectors showed good response rates (2.07 ms), as did Barracuda injectors (2.19 ms), but the highest response time was found in Matrix injectors, with 2.44 ms. Keihin injectors had the lowest average resistance value of 1.25 ohms, and Valtek injectors had the highest resistance value of 3 ohms. According to the research results, Keihin, Matrix, and Barracuda injectors provide the best ability to maintain factory performance when using biogas fuel at 2 to 5%, and Valtek had the worst performance up to 20%. Keihin, Barracuda, and Hana experimental injectors had the highest service life, which is from 200 to 250 thousand km of car mileage. The lowest indicators were found for Valtek and Matrix injectors, the service life of which varies from 70 to 100 thousand km of mileage.

Keywords: engine; alternative fuels; biogas; economy; injectors; spraying; linearity of work; consumption; power; reliability

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1. Introduction

The vast majority of gasoline internal combustion engines (ICEs) and some diesel engines are converted to run on gaseous fuel to reduce fuel costs. This, in turn, can create several difficulties related to the low heat of combustion of untreated biogas, the presence of moisture, and the specifics of the injectors. The problem of low heat of combustion can be solved by purifying biogas from unwanted components and moisture. To solve the issues of optimal and accurate fuel dosing, mixing quality, and further combustion in the internal combustion engine cylinder, there is a need to study the main operational indicators. Based on the results of the conducted research, it will be possible to provide recommendations on the optimal parameters for the use of injectors for biogas fuel. So,

the question of researching the performance indicators of the injectors and justifying their choice in the process of using biogas as fuel is quite relevant, and its solution will ensure the most effective combustion of biogas in internal combustion engines.

Biogas is considered as one of the potential types of gaseous fuel that can be used in both gasoline and dual-fuel diesel internal combustion engines. As a rule, biogas is produced in an oxygen-free environment by anaerobic fermentation [1]. The obtained gas consists mainly of methane, carbon dioxide, and small concentrations of hydrogen sulfide. The methane present in biogas is the only useful gas that has a lower calorific value of approximately 50.4 MJ/kg [2,3]. The high number of octanes in biogases ensures the operation of an internal combustion engine with high resistance to detonation, making biogas suitable for engines with a high compression ratio (diesel engines). This, in turn, increases thermal efficiency [1,4]. However, biogas has a low cetane number, which makes it practically unsuitable for use in compression ignition combustion engines [4]. Since the self-ignition temperature of biogas is quite high, the use of biogas in a compression ignition engine requires an ignition source [3]. A high-cetane-number fuel can be used as the ignition source, which is directly injected into the engine cylinder at the end of the compression stroke, while biogas or high-octane fuel (base fuel) is admitted with air into the intake manifold during the engine intake stroke. This is called dual-fuel mode (DFM) [5–8].

Gaseous fuels such as compressed natural gas (CNG), methane, industrial gas, furnace gas, pyrolysis gas, and biogas are potential alternative fuels and can be used in a diesel engine in dual-fuel mode. The use of CNG in diesel and gasoline engines is widespread in the current decade [9]. However, over the past few years, CNG reserves have declined dramatically, which may lead to a CNG availability crisis in the future by 2030 [10,11]. Among gaseous fuels, using biogas in diesel engines provides a certain advantage in terms of waste to energy, waste minimization, and waste to biofertilizers. Biogas is environmentally friendly and can be obtained from readily available waste, biomass by-products, agricultural by-products, the food industry, solid household waste, and sewage [12–15].

The presence of CO_2 in biogas worsens its combustion quality when used in engines [16,17]. CO_2 from biogas can be separated by cleaning the biogas in a scrubber. The properties of purified biogas are almost the same as those of CNG, and it can be used in CNG-powered vehicles without any engine modifications. Purified biogas can also be used for decentralized electricity production. Biogas is a very suitable fuel for SI engines, but it can be effectively used in CI engines in dual-fuel mode due to its very high anti-knock properties compared to diesel [18,19].

Ignition delay in a diesel engine running on biogas can be minimized by using a fuel with a high cetane number. For this purpose, diethyl ether (DEE) is a promising choice because DEE is renewable in nature and can be easily produced from ethanol at a reasonable cost [20–23]. Studies are available on the use of DEE in dual-fuel diesel engines with biodiesel or diesel as the pilot fuel and CNG, liquefied petroleum gas (LPG), or biogas as the main fuel [20–23]. The injection of DEE in a dual-fuel engine results in shorter ignition delays and shorter combustion durations [21,22,24].

So, as we can see from studies [1–24], the composition and properties of biogas allow it to be used in power systems for SI engines and CI engines in the dual-fuel mode of operation. The scientists in works [25–39] studied the efficiency of diesel engines powered by DFM with biogas fuel. For example, in works [25–31], research was conducted on the DFM engine to assess productivity, emissions, and combustion parameters, and under certain operating conditions of gas injectors, NO_x and CO_2 emissions were reduced, but engine power was also reduced due to the lower calorific value of biogas compared to hydrocarbon fuel. The authors of [32–39] conducted studies on the environmental parameters of DFM engines in load mode and found that NO_x and CO_2 emissions increase as the load increases. The authors of [40–47] found that DFM diesel engines can effectively operate on various gaseous fuels, including traditional fuels such as LPG, CNG, and grey hydrogen, as well as renewable fuels such as Bio-CNG, green hydrogen, industrial gas, and

synthetic gas in combination with diesel fuel, without significantly impairing the technical, operational, or environmental performance of the internal combustion engine. The study of the energy indicators of biogas and its efficiency of use in engines with spark ignition was carried out by scientists in [48–50]. The results of the studies indicate that during the operation of diesel engines using biogas, there is a decrease in hydrocarbon and CO_2 emissions compared to operations using gasoline. It was also found that when working on biogas, the peak output power of the engine decreases, but with the help of the electronic control unit, it can be adjusted to increase.

So, from the above, it can be seen how promising the use of biogas fuel is in engines with gasoline and dual-fuel diesel power systems. However, as confirmed by research, the economic and environmental friendliness of these engines largely depends on the operating parameters of the gas injectors, and therefore, the study of the operating parameters of gas injectors in the process of using biogas fuel is quite relevant. The relevance of this research is especially increasing due to the low heat of combustion of biogas; as a result of this, it is necessary to supply a larger amount of fuel, which not all injectors can provide.

2. Materials and Methods

To carry out the study of operating parameters, we chose LPG/CNG gas injectors from the most common manufacturers, namely, Matrix HD.344.51, manufacturer Matrix Mechatronics (Ivrea, Italy); Barracuda Single 120NL, manufacturer Alex (Kleosin, Poland); Valtek Type 30, manufacturer Valtek SPA Unipersonale (Cuneo, Italy); Hana Type C, manufactured by Hana Engineering Co., Ltd. (Hwaseong-si, Republic of Korea); and Keihin KN9 73cc, manufacturer Keihin (Yokohama-shi, Japan)

The research was carried out experimentally on an installation containing an Audi A6 2.4 V6 (Neckarsulm, Germany) as the base car, the brief technical characteristics of which are given in Table 1. This car is equipped with a gas power system of the 4th generation, STAG QMAX 6 Plus (Białystok, Poland), a brief technical characteristic of which is given in Table 2.

Table 1. Brief technical characteristics of the Audi A6 2.4 V6 car.

Parameter Name	Value
Engine	V6
Type of main fuel	Gasoline
Main fuel system	MPI
Engine volume	2.4 L
Cylinder diameter/piston stroke	81/77.4 mm
Compression ratio	10.3
Power	130 kW
A turning point	230 N·m
Fuel consumption for the combined cycle	9.7 L/100 km
Turbocharging	-

Table 2. Brief technical characteristics of the STAG QMAX 6 Plus HBO.

Parameter Name	Value
Installation model	STAG QMAX 6 Plus
Gas reducer	KME Gold
Communication with automotive OBD and EOBD systems	none
Injectors with which HBO can work	Valtek, AEB, Barracuda, Hana, Matrix, Keihin
Number of cylinders	6
Country of manufacture	Poland

The biogas used in the research was produced by Goodvalley Ukraine (Ivano-Frankivsk, Ukraine). The plant for the production of biogas from organic waste is located near a farm

in the village of Kopanky, Ivano-Frankivsk (Ukraine). The composition and properties of the biogas fuel according to the Goodvalley Ukraine company are given in Table 3.

Table 3. Composition and properties of biogas fuel according to the Goodvalley Ukraine company.

Parameter Name	Units of Measurement	Parameter Value
Components:		
CH_4	%, vol.	55
CO_2		35
N_2		10
Fuel density at temperature T = 323 K	kg/m^3	1.211
Molecular weight	kg/kmol	27.03
Heat capacity of fuel at injector temperature T = 333.15 K	J/(kg·K)	1484
Lower heat of combustion	MJ/kg	24.63

The internal resistance of the coil of the test injectors was measured using a digital multimeter of the UT30C model, manufactured by UNI-T (Dongguan City, Guangdong Province, China), the brief technical characteristics of which are given in Table 4.

Table 4. Brief technical characteristics of the UT30C digital multimeter.

Parameter Name	Value
Alternating voltage (AC)	200 V/500 V; ±(1.2% + 10)
Direct voltage (DC)	200 mV/2000 mV/20 V/200 V/500 V; ±(0.5% + 2)
Direct current (DC)	200 mA/2000 mA/20 mA/200 mA/20 A; ±(1% + 2)
Resistance	200 ohm/2000 ohm/20 kohm/200 kohm/20 Mohm; ±(0.8% + 2).
Temperature	−40 °C~1000 °C; ±(1% + 3)

The study of the dependence of the maximum conditional productivity of the injectors depending on the type of fuel and the oscillogram of the injector response time was carried out using a stand for diagnosing gas injectors (AC Stag (Białystok, Poland)) and a GBO injector tester (Kyiv, Ukraine), which had a built-in oscilloscope. The brief technical characteristics of the AC Stag v. 1.81 software complex are given in Table 5.

Table 5. Brief technical characteristics of the AC Stag software complex.

Parameter Name	Value
Engine type	Direct fuel injection
Maximum number of cylinders	8
Power system type	LPG, CNG
Standards and approvals	E8 67R-01 5753, E8 10R-05 8913, E8 110R-00 5754
Feeding	On-board network of the car

Experiments on the study of productivity and the response time of injectors were conducted in the educational and scientific production vehicle laboratory of the National Technical University of Oil and Gas (Ivano-Frankivsk, Ukraine).

Environmental parameters in the laboratory were monitored using a weather station: Sencor SWS 9700 (Japan). The brief technical characteristics of the station are given in Table 6.

Table 6. Brief technical characteristics of the Sencor SWS 9700 weather station.

Parameter Name	Value
Measuring range of external temperature	from −40 °C to +80 °C, +/−1 °C
Indoor temperature measurement range	from −40 °C to +70 °C, +/−1 °C
Humidity measurement range	from 20% to 90% (1% resolution)
Range of measurement of air flow speed	0–180 km/h

The study of the service life of gas injectors was carried out at the base of the "PROFI-GAS" service station in the city of Ivano-Frankivsk (Ukraine). We used the service station database in the period from 1 January 2019 to 31 December 2023. When researching the resources for this work, we took into account the following data: brand of injectors; the volume of the engine on which they were operated; engine operating conditions; mileage of injectors before repair.

3. Results and Discussion

Structurally, gas injectors are very similar to gasoline ones, with the exception of only a few models. But even gas injectors that are similar in design differ significantly from their gasoline counterparts in terms of their parameters. The volume of gas evaporated in the gearbox and supplied to the cylinders is 250 times greater than the equivalent dose of gasoline, and the throughput in the gas injector is ten times greater.

In addition, gas injectors have low electrical resistance—1–3 ohms—while their gasoline counterparts have 16–17 ohms. This is because gas injectors need to pass through much more fuel by volume. Accordingly, they should have a different control strategy.

The gasoline injector opens with a simple 12 V pulse, but if the same pulse is applied to the gas one, it will simply burn out due to the low resistance of the winding. Therefore, gas injectors are opened using pulse-width modulation; that is, an initial pulse is applied to the injector, which opens it, and then the pulse disappears and reappears. This happens so quickly that the injector does not have time to close and the winding does not overheat.

Since the gas is in a vaporized state, unlike gasoline, there is no need to use a high-precision atomizer, a fairly common fitting that is installed in the intake manifold near the gasoline injector.

In gas injectors, as well as in gasoline ones, several important parameters depend on the stability and uniformity of engine operation, fuel consumption, reliability, etc.

One of the most important parameters is the contingent productivity and linearity of gas injectors. So, for example, the injector opens for 3 ms and emits a certain portion of gas; then, when it opens for 6 ms, the portion of gas should be twice as much. And although this parameter has been comprehensively studied with commercial gas fuel, the study of the performance and linearity of gas injectors using biogas fuel has not been conducted.

For this research, six injectors of the fourth generation of the most common manufacturers were chosen, namely, Matrix, Barracuda, Valtek, Hana, and Keihin.

Before starting the research, the injectors were heated to a temperature of 60 °C at an ambient temperature of 19 °C and a humidity of 45%.

For clarity and convenience of analysis in the processing of the research results and the construction of graphical dependencies in Figures 1–5, we use the minimum (blue line) and maximum (red line) values of the productivity and linearity of the injectors with biogas fuel.

Based on the obtained results, the dependences of the conditional productivity of the injectors (L/min) on the impulse/opening times (ms) are constructed (Figures 1–5).

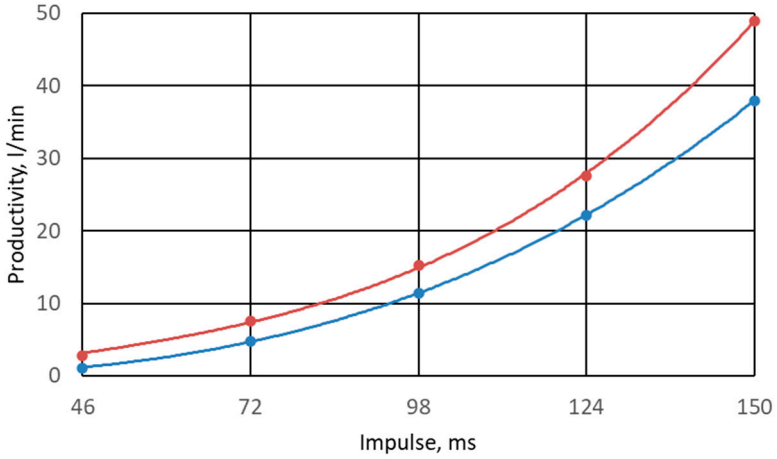


Figure 1. Study of contingent productivity and linearity of Matrix gas injectors.

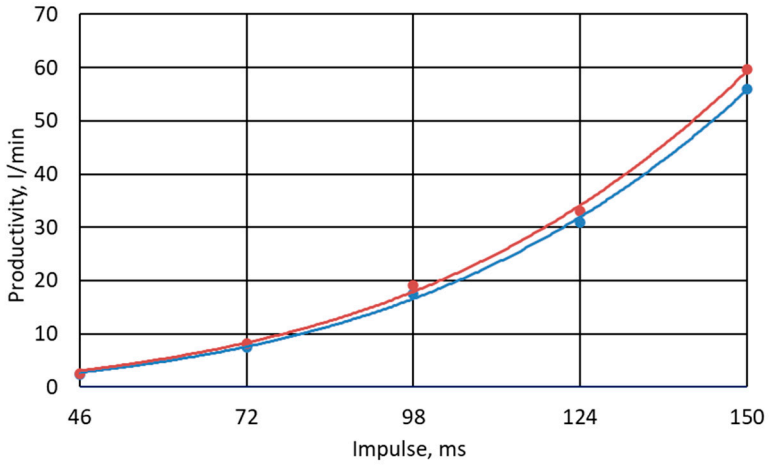


Figure 2. Study of contingent productivity and linearity of Barracuda gas injectors.

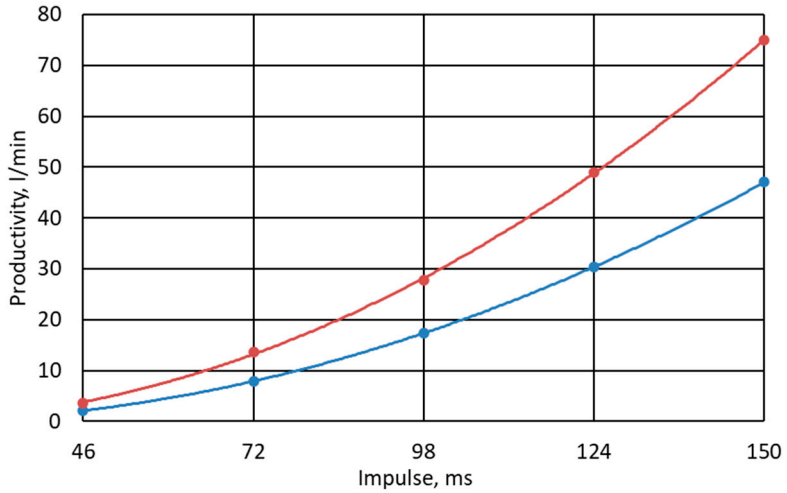


Figure 3. Study of contingent productivity and linearity of Valtek gas injectors.

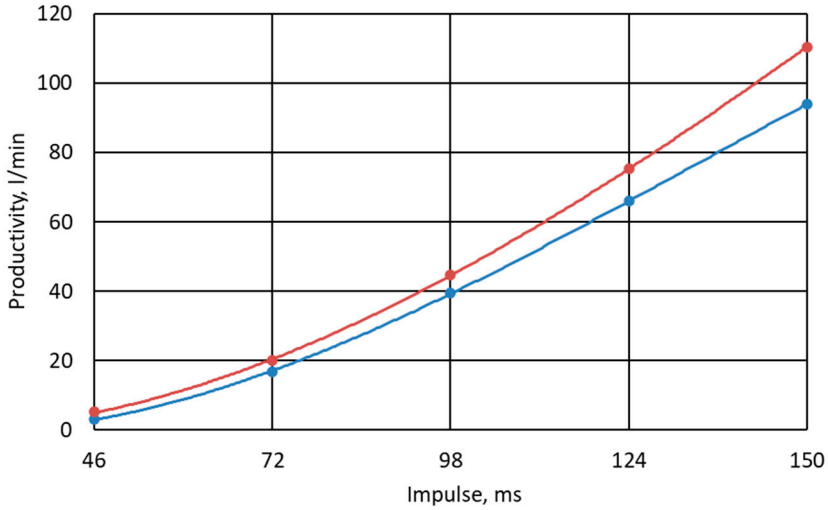


Figure 4. Study of contingent productivity and linearity of Hana gas injectors.

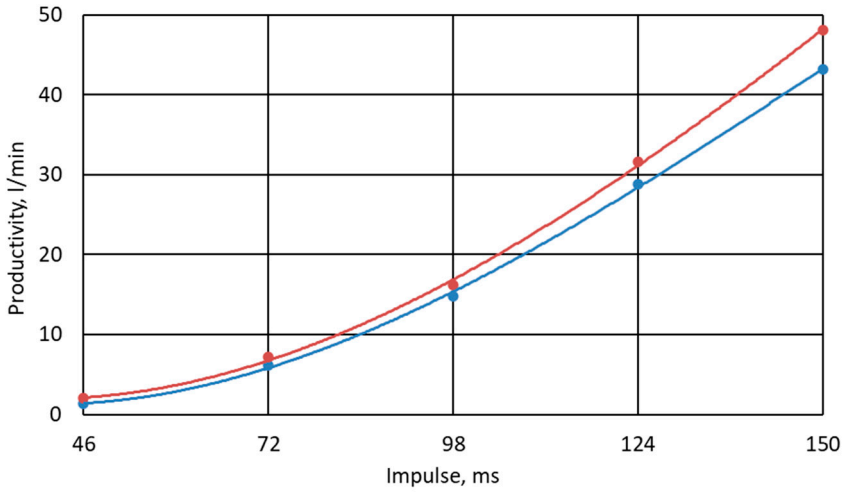


Figure 5. Study of contingent productivity and linearity of Keihin gas injectors.

The obtained graphic dependences of Figures 1–5 are described by the following characteristic equation:

$$V = a \cdot I^3 + b \cdot I^2 + c \cdot I + d, \quad (1)$$

where V represents the contingent productivity of the injectors, L/min;

I represents pulse duration, ms;

a, b, c, and d are coefficients, the values of which for the different injectors are given in Table 7.

Table 7. The values of the coefficients of Equation (1) for different injectors at minimum and maximum productivity.

The Name of the Coefficient	Values for Injectors									
	Matrix		Barracuda		Valtek		Hana		Keihin	
	V_{max}	V_{min}	V_{max}	V_{min}	V_{max}	V_{min}	V_{max}	V_{min}	V_{max}	V_{min}
a	2×10^{-5}	8×10^{-6}	2×10^{-5}	2×10^{-5}	2×10^{-7}	4×10^{-7}	-2×10^{-7}	-3×10^{-5}	-1×10^{-5}	-2×10^{-5}
b	−0.0022	0.0006	−0.0015	−0.0014	0.0041	0.0028	0.0105	0.0127	0.0068	0.0072
c	0.1996	−0.019	0.1519	0.13	−0.1229	−0.1022	−0.4409	−0.6205	−0.4915	−0.5109
d	−3.3834	0.0676	−2.7951	−2.3661	−3.3834	0.9529	4.8382	7.6112	11.522	11.233

The correlation coefficients of the dependences of Figures 1–5 are within 0.99–1.

Analyzing the graphical dependences of Figures 1–5, according to the indicators of productivity and linearity in the process of using biogas, it was established that the parameter deviations for Matrix injectors are 32.9%; Barracuda—7.5%; Valtek—38.8%; Hana—19.1; and Keihin—15.3%. As you can see, according to this indicator, the experimental injectors have different values. Valtek injectors (Figure 3) have the highest deviation in productivity and linearity of work, with an average of 38.8%, and the lowest deviation in Barracuda injectors is 7.5%. Keihin (15.3%) and Hana (19.1%) injectors also showed good performance indicators, and therefore can be effectively used for biogas fuel systems.

An important indicator that ensures the accuracy of fuel dosing is the injector response time. A significant increase in this indicator leads to inaccurate fuel dosing, overspending, and a possible loss of internal combustion engine power.

The results for the response time of the experimental injectors are presented in Figure 6.

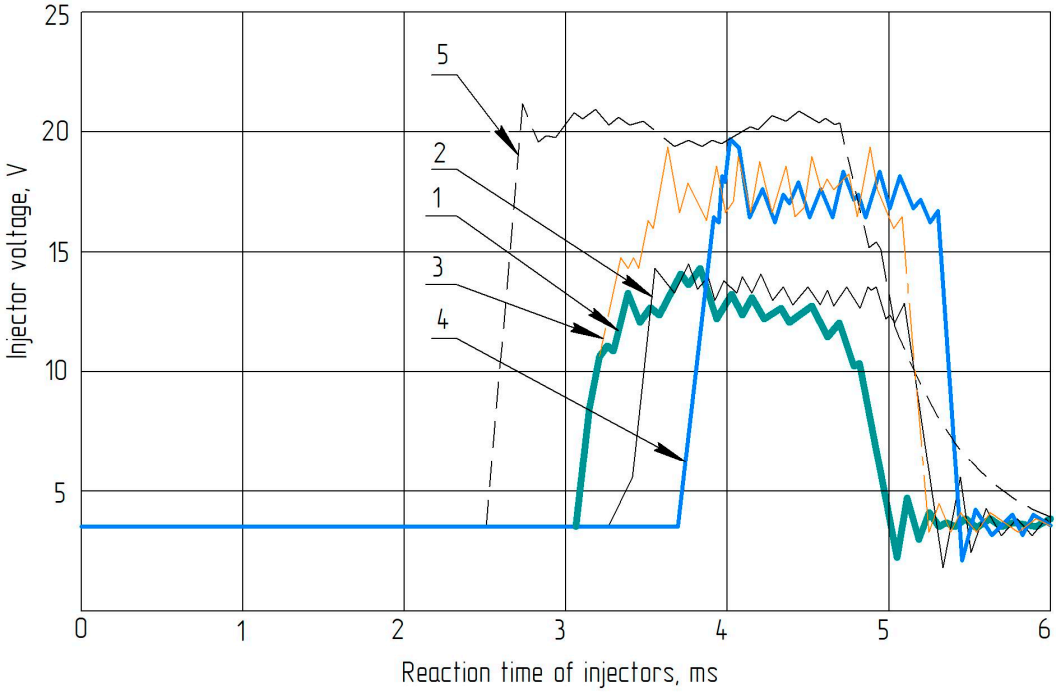


Figure 6. The results of research on the response time of gas injectors. 1—Keihin; 2—Valtek; 3—Barracuda; 4—Hana; 5—Matrix.

From the analysis of the results obtained in Figure 6, the Hana injectors had the lowest response time (1.75 ms), followed by Keihin (1.99 ms). The Valtek injectors showed good response rates (2.07 ms), as did Barracuda (2.19 ms), and the highest response time was found for the Matrix injectors (2.44 ms).

Also, coil resistance and the ability to maintain factory characteristics in operating mode are important operating indicators of the injectors that affect their efficiency. The internal resistance of the test injector coil was measured using a UT30C digital multimeter under environmental parameters of 19 °C and 45% humidity, with an accuracy of ±0.8%.

The results for coil resistance and the ability to maintain factory characteristics in operating mode are shown in Figures 7 and 8.

According to the injector resistance indicator results, Keihin injectors have the lowest average value, with an indicator of 1.25 Ohms, and Valtek injectors have the highest value of this indicator (3 Ohms).

According to the research results shown in Figure 8, the Keihin, Matrix, and Barracuda injectors have the best ability to maintain factory performance when using biogas fuel at 2 to 5%, and Valtek injectors have the worst performance up to 20%.

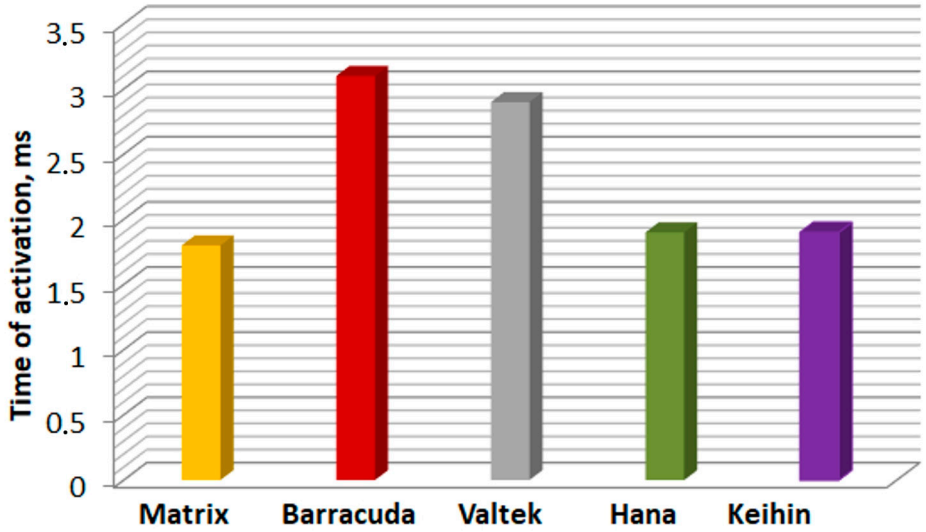


Figure 7. Comparison of coil resistances of test injectors.

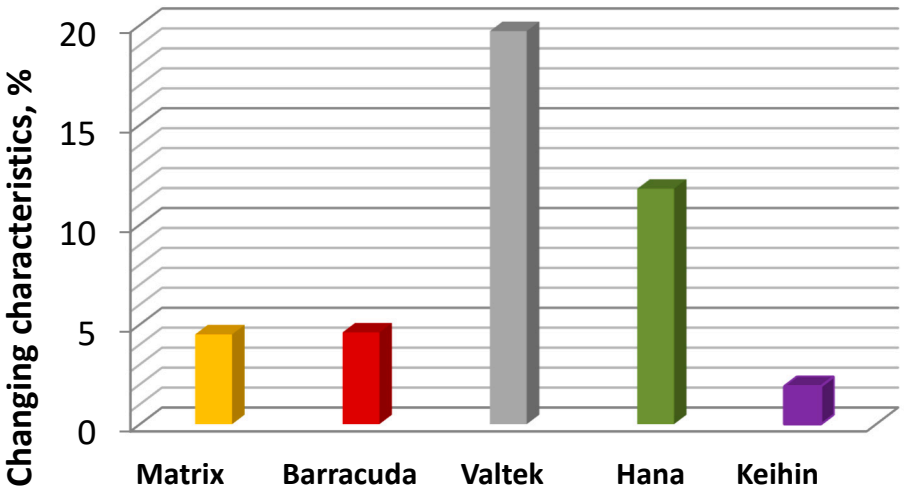


Figure 8. Comparison of changes in operating characteristics of test injectors.

The resources of the injectors (Figure 9), which were investigated according to the data of the "PROFIGAS" service station in Ivano-Frankivsk (Ukraine), were the largest for the Keihin, Barracuda, and Hana injectors (from 200 to 250 thousand km of vehicle mileage), and the lowest for the Valtek and Matrix injectors (whose mileage varied from 70 to 100 thousand km).

In study [38], the authors suggested obtaining pyrolysis fuel gas. It was established that, during the pyrolysis of aquatic plants and algae, the mixture of gases obtained had the highest values of lower calorific value: 17.10–17.15 MJ/kg for Microcystis and 16.45–16.00 MJ/kg for Elodea. The gas obtained during the pyrolysis of pine wood had the highest value of lower calorific value in the range from 13.8 to 13.85 MJ/kg. The lower calorific value of pyrogas obtained from reed samples ranged from 12.6 MJ/kg to 12.65 MJ/kg. Therefore, a promising direction of research is the use of pyrolysis gas as the main fuel in dual-fuel diesel internal combustion engines. And, therefore, the question arises regarding the choice of gas injectors; in the future, research can be conducted in this direction.

The authors of [40] emphasize the potential that biomass has, and therefore many technologies are being developed in the direction of converting biomass into biofuel. This has great advantages in terms of reducing carbon emissions and dependence on oil due to biofuel's production from renewable and organic sources.

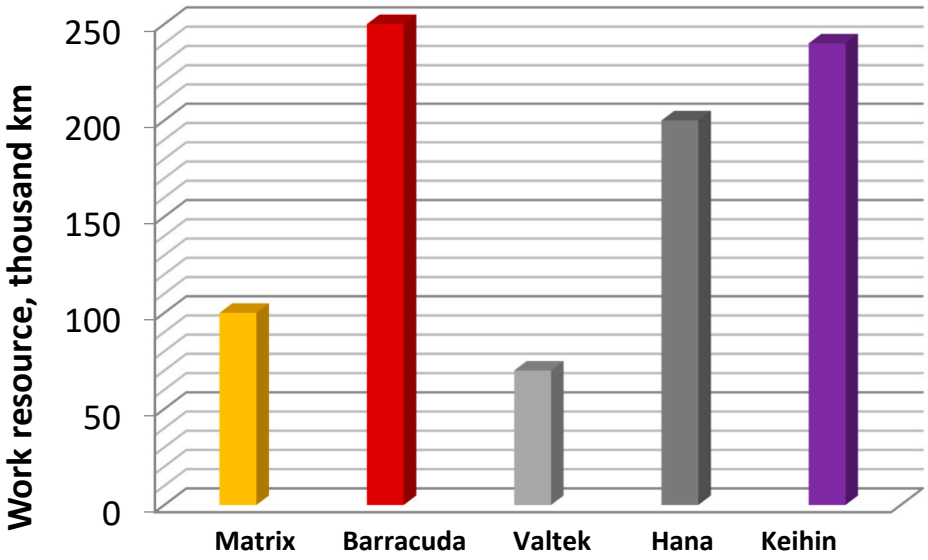


Figure 9. Evaluation of work resources of test injectors.

For the efficient use of biogas in the future, dual-fuel diesel engines have great prospects [5–8]. And, therefore, the research carried out in [33,36] can be used to ensure the operation of dual-fuel engines and further optimize the process of supplying biogas as the main fuel.

4. Conclusions

According to the indicators of performance and linearity of work, Valtek injectors have the highest deviation in productivity and linearity of work, with an average of 38.8%, and the lowest deviation of Barracuda injectors is 7.5%. Keihin (15.3%) and Hana (19.1%) injectors also showed good performance indicators, and therefore can be used effectively for biogas fuel systems.

In the study of injector response times, Hana injectors had the best indicators (1.75 ms), followed by Keihin (1.99 ms), and Matrix injectors had the highest response time of 2.44 ms.

Keihin injectors had the lowest average resistance value of 1.25 ohms, and Valtek injectors had the highest resistance value of 3 ohms.

According to these research results, Keihin, Matrix and Barracuda injectors provide the best ability to maintain factory performance when using biogas fuel at 2 to 5%, and Valtek showed the worst performance up to 20%.

Keihin, Barracuda, and Hana experimental injectors have the highest service life, which is from 200 to 250 thousand km of car mileage, and the lowest indicator was found for Valtek and Matrix injectors, the service life of which varied from 70 to 100 thousand km of mileage.

Therefore, according to the results of the study of the performance parameters of gas injectors using biogas fuel, Keihin and Barracuda injectors are recommended for use in spark-ignition engines in the process of being converted to biogas fuel and diesel engines in the context of dual-fuel power systems. Their application will ensure the maximum efficiency and economy of the diesel engine according to the studied indicators.

Hana injectors also have good properties; using them can prevent the significant deterioration of the technical and operational performance of biogas-fueled internal combustion engines.

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visualization, B.K. and Y.M.; supervision, M.B.; project administration, V.M.; funding acquisition, M.B., T.R. and B.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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