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RESEARCH ARTICLE | AUGUST 03 2026

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AIP Conf. Proc. 3520, 090001 (2026)
https://doi.org/10.1063/12.0044848

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Adaptive Control of Diesel-Biodiesel Fuel Blend Composition to Improve Diesel Engine Efficiency and Emissions

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Abstract. The paper investigates the influence of variable composition of diesel-biodiesel fuel blends on the technical, economic, and environmental performance of a diesel engine and substantiates the feasibility of using an improved fuel supply system with adaptive regulation of the biodiesel fraction depending on the engine operating mode. Based on experimental studies conducted on an SMD-15 diesel engine equipped with a loading unit, datasets were obtained for effective power, fuel consumption, exhaust gas smoke opacity, and dynamic characteristics at different rotational speeds and load conditions. It was established that with an increasing biodiesel content, maintaining the nominal torque required an increase in the cyclic fuel supply, which compensated for the net calorific value of the fuel blend. At the same time, a significant reduction in exhaust gas smoke opacity and soot concentration was observed. A mathematical model of the system "Engine – diesel-biodiesel fuel supply system" was developed and verified, the adequacy of which was confirmed by small deviations between calculated and experimental data. The results demonstrate that adaptive regulation of the fuel blend composition ensures the preservation of the baseline engine performance parameters while improving its environmental characteristics.

Keywords: biodiesel, diesel engine, torque stability, soot emissions, fuel injection, alternative fuels.

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INTRODUCTION

An analysis of current trends in the development of renewable energy indicates an active search for alternatives to conventional petroleum fuels, among which biodiesel occupies a leading position due to its environmental advantages. Research in the field of renewable energy sources is increasingly focused on optimizing the properties of biodiesel fuel as a strategic substitute for petroleum-based diesel fuel. Numerous studies emphasize the significant potential of biodiesel in reducing environmental impacts [1-4], reporting a substantial decrease in emissions of unburned hydrocarbons (HC) and carbon monoxide (CO). However, the issue of increased nitrogen oxides (NOx) emissions in exhaust gases remains a significant challenge for researchers. The use of non-food feedstocks and agricultural waste is critically important for ensuring the economic and social sustainability of biofuel production, as it helps to avoid competition with the food sector.

Researchers' attention is also focused on the search for new feedstock sources. In particular, studies have been conducted to evaluate the potential of biodiesel derived from Spirulina microalgae [5]. The authors reported that low-concentration blends (specifically B10) demonstrated high efficiency in engines equipped with a swirl-chamber combustion system, providing a reduction in specific fuel consumption and hydrocarbon emissions without the need for engine design modifications.

The use of biodiesel in the agricultural sector leads to a reduction in engine power (up to 15.1%); however, it simultaneously provides a significant environmental benefit in the form of a 24.1% reduction in CO_2 emissions [6]. The most rational technological solution has been identified as the use of low-concentration blends (9.1-13.0%

Energy Systems and Alternative Energy Sources '2026
AIP Conf. Proc. 3520, 090001-1–090001-9; https://doi.org/10.1063/12.0044848
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biodiesel mixed with diesel fuel), which make it possible to improve the environmental performance of engines while maintaining minimal power losses (less than 4%).

The current stage of research on alternative fuels is characterized by a transition from simple analysis of biodiesel blends to the development of multicomponent fuel mixtures incorporating various additives. To improve the operational properties of biodiesel and mitigate disadvantages such as increased nitrogen oxide (NOx) emissions, nanotechnology-based approaches are increasingly being applied [7]. The use of nanoadditives not only enhances engine efficiency but also promotes more complete fuel combustion, thereby making biodiesel more competitive compared with conventional energy carriers.

The integration of nanomaterials into fuel blends opens new opportunities for improving engine performance. In particular, to optimize engine operation when using biodiesel blends, the addition of zinc oxide (ZnO) nanoparticles has been proposed [8]. This approach serves as an effective tool for intensifying the combustion process, making it possible to mitigate the increase in specific fuel consumption typically associated with biofuels, while simultaneously reducing emissions of NOx and particulate matter.

The introduction of cerium oxide nanoparticles (CeO_2) into biodiesel blends promotes improved fuel atomization and intensification of the combustion process [9]. The use of such nanoadditives not only enhances thermal efficiency but also enables a simultaneous reduction in the levels of unburned hydrocarbons (HC) and nitrogen oxides (NOx), which is critically important for compliance with modern environmental regulations. These findings highlight the significant potential of nanotechnology for improving the thermodynamic and environmental performance of internal combustion engines.

In parallel with improvements in fuel composition, considerable attention has been devoted to the adaptation of modern fuel supply systems. Studies investigating the effects of biodiesel on engines equipped with Common Rail fuel injection systems [10-11] demonstrate that the high injection pressures characteristic of these systems contribute to improved atomization of viscous biofuel blends. This results in more complete oxidation of hydrocarbons (HC) and carbon monoxide (CO). However, despite the environmental benefits and superior lubricating properties of biodiesel, the increase in nitrogen oxide (NOx) emissions remains a critical issue, requiring the implementation of additional injection control strategies or exhaust gas recirculation systems. Therefore, the synergistic integration of fuel additives, new types of biological feedstock, and advanced fuel supply systems represents a key direction for achieving sustainable development goals in the energy sector, particularly in terms of improving energy efficiency, reducing specific fuel consumption, and minimizing toxic emissions from internal combustion engines.

Most contemporary studies are focused on improving the properties of biodiesel through the use of various additives, the utilization of different feedstocks for fuel production, or by considering biodiesel as an additive to conventional diesel fuel in order to achieve a balance between the deterioration of certain parameters and the improvement of others. However, the issue of ensuring rational, mode-dependent regulation of the biodiesel fraction across the entire range of engine operating conditions remains insufficiently explored. Therefore, the development and substantiation of an adaptive control system for regulating the composition of diesel-biodiesel fuel blends represents a relevant scientific and applied problem aimed at stabilizing engine operating processes, maintaining technical and economic performance indicators, and improving the environmental efficiency of diesel engines.

The aim of this study is to provide a scientific justification and experimental-computational verification of an improved diesel engine fuel supply system with adaptive regulation of the diesel-biodiesel blend composition depending on engine speed and load operating conditions. The proposed approach ensures the preservation of effective torque and power at the level of the baseline engine while minimizing the increase in specific fuel consumption and improving the environmental characteristics of exhaust gases.

RESEARCH MATERIALS AND METHODS

The use of biodiesel and its blends with conventional diesel fuel significantly affects the course of the working processes in a diesel engine. Since the net calorific value of biodiesel is lower than that of conventional petroleum-derived diesel fuel, the complete combustion of an equivalent amount of biodiesel releases a smaller amount of energy. Consequently, when fuel blends are used, maintaining the required engine performance characteristics necessitates an increase in the cyclic fuel supply, which in turn leads to an increase in the hourly consumption of the fuel blend.

An increase in the cyclic fuel supply also results in a longer duration of fuel injection, evaporation, and combustion processes. Under conditions of high cyclic fuel injection and elevated engine crankshaft rotational speeds, incomplete combustion of the fuel blend may occur. This leads to disturbances in the engine working processes and negatively affects the technical, economic, and environmental performance indicators of the diesel engine.

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To eliminate these drawbacks, the application of an improved diesel engine fuel supply system capable of regulating the composition of the fuel mixture directly during engine operation is considered appropriate [12]. The implementation of such a system should ensure: efficient execution of the engine working processes, reliable engine start-up, long-term operational reliability, maximum approximation of performance parameters to those of the baseline engine, and improved environmental characteristics.

In the improved diesel engine fuel supply system, the composition of the diesel-biodiesel mixture influences the engine working processes; therefore, its regulation is carried out based on the following considerations [13]: ensuring the required effective torque; maintaining efficient progression of the working processes; and maximizing the utilization of biodiesel.

To ensure torque during diesel engine operation on biodiesel equivalent to that obtained when using conventional diesel fuel, the cyclic fuel injection may be increased by up to 12.4%, depending on the composition of the fuel blend. Increasing the cyclic fuel injection makes it possible to compensate for the lower net calorific value of the fuel mixture while simultaneously providing a sufficient amount of air for its complete combustion. At the same time, such an increase in fuel supply is accompanied by an extension of the duration of the working processes in the engine cylinders. The criterion for determining the optimal biodiesel fraction in the fuel mixture is the combustion duration of the corrected amount of fuel injected into the engine cylinder [14].

To determine the optimal composition of the diesel-biodiesel fuel blend for various load and speed operating modes of diesel engines, a series of experimental studies was conducted. As a result of these experiments, primary data were obtained and subsequently used to determine the approximation coefficients of the analytical relationships included in the developed mathematical model.

During the experimental investigations, the following parameters were determined: the engine load characteristics; the effect of variations in the fuel injection advance angle on fuel consumption and exhaust gas smoke emissions during engine operation on diesel fuel, biodiesel, and their blends; the engine acceleration time from idle to the maximum crankshaft rotational speed under no-load conditions when operating on diesel fuel and biodiesel; and the engine deceleration time from the maximum crankshaft rotational speed to idle under no-load conditions. The experimental measurement error did not exceed 3.6%. Selected results of the conducted studies are presented later in the article.

For the experimental investigations, a test bench consisting of an SMD-15E diesel engine, a GSM-30 generator, and a loading device was used (Fig. 1). The technical specifications of the diesel engine are presented in Table 1.

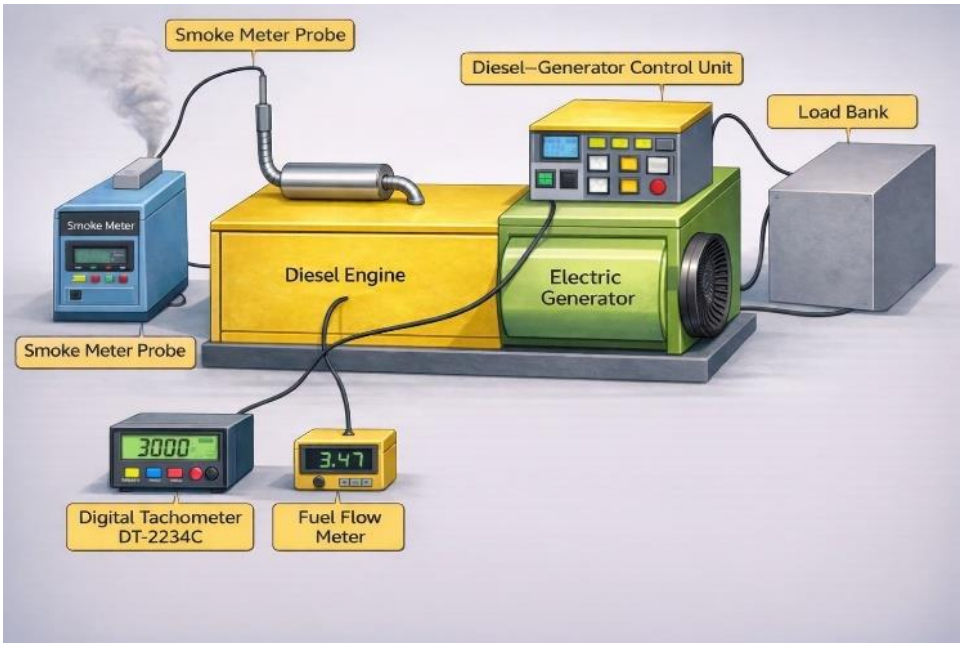


FIGURE 1. Experimental Test Bench for Conducting the Studies

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TABLE 1. Specifications of the SMD-15 Engine

№	Parameter	Value
1.	Rated crankshaft rotational speed, rpm	1,800
2.	Torque at rated rotational speed, N·m	312
3.	Rated power, kW	61.1
4.	Number of cylinders	4
5.	Compression ratio	17
6.	Minimum crankshaft rotational speed at idle, not more than, rpm	600
7.	Maximum crankshaft rotational speed at idle, not more than, rpm	1,950
8.	Specific fuel consumption at rated power, g/kWh	248
9.	Fuel injection start pressure, MPa	17.5-18
10.	Cyclic fuel injection (at 900 rpm), g/cycle (mm³/cycle)	0.085-0.087 (100-103)
11.	Fuel injection advance angle, degrees	22

Table 2 and Figure 2 present the results of experimental studies on the influence of biodiesel content in the fuel blend and the crankshaft rotational speed on the fuel blend consumption and effective power during diesel engine operation under steady-state conditions with different loads.

TABLE 2. Results of the Experimental Studies

№ experiment	Engine speed,	Fuel blend composition	Fuel consumption	Fuel blend composition	Fuel consumption	Fuel blend composition	Fuel consumption	Fuel blend composition	Fuel consumption	Fuel blend composition	Fuel consumption	Engine load
	rpm	%	*g/30 sec.*	%	*g/30 sec.*	%	*g/30 sec.*	%	*g/30 sec.*	%	*g/30 sec.*	*kW*
1.1	800	0	14	25	14.5	50	15.5	75	16	100	17	0
1.2	800	0	17	25	17.5	50	18	75	19	100	20	2.98
1.3	800	0	20.5	25	21	50	23	75	25	100	26	5.96
1.4	800	0	29	25	31	50	32	75	32.5	100	34	8.94
1.5	800	0	34	25	36	50	37	75	38	100	40	11.92
1.6	800	0	42	25	43	50	45	75	47	100	48	14.91
1.7	800	0	48	25	49	50	52	75	55	100	57	17.89
2.1	1,200	0	26	25	27	50	28	75	30	100	32	0
2.2	1,200	0	37	25	37	50	39	75	41	100	44	5
2.3	1,200	0	44	25	44.5	50	45	75	48	100	51	10
2.4	1,200	0	51	25	52	50	53	75	58	100	60	15
2.5	1,200	0	58	25	58	50	59	75	64	100	67	20
2.6	1,200	0	67	25	68	50	69	75	72	100	74	25
2.7	1,200	0	74	25	77	50	80	75	84	100	88	30
3.1	1,500	0	41	25	42	50	44	75	46	100	48	0
3.2	1,500	0	50	25	53	50	53	75	55	100	60	5
3.3	1,500	0	62	25	64	50	67	75	68	100	73	10
3.4	1,500	0	70	25	72	50	74	75	78	100	82	15
3.5	1,500	0	78	25	80	50	82	75	86	100	91	20
3.6	1,500	0	87	25	89	50	92	75	95	100	97	25
3.7	1,500	0	95	25	98	50	99	75	103	100	106	30

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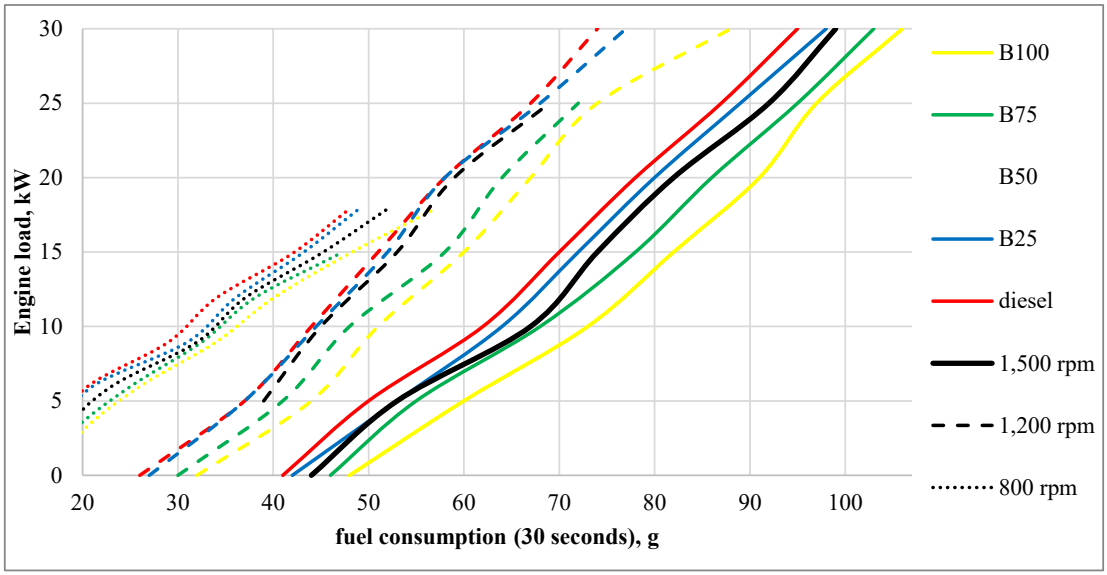


FIGURE 2. Dependence of effective power on fuel consumption for blends with different biodiesel content at various engine crankshaft rotational speeds

Table 3 presents the results of experimental studies on the influence of biodiesel content in the fuel blend on the smoke opacity of exhaust gases during diesel engine operation under steady-state conditions with different loads.

TABLE 3. Results of the Experimental Studies

Diesel Engine Load N_l, kW	Biodiesel content in the fuel blend n_b, 0 %			Biodiesel content in the fuel blend n_b, 25 %			Biodiesel content in the fuel blend n_b, 50 %			Biodiesel content in the fuel blend n_b, 75 %			Biodiesel content in the fuel blend n_b, 100 %		
	Light flux attenuation coefficient N, %	Natural light attenuation coefficient K, m^{-1}	Soot concentration C_s, g/m³	Light flux attenuation coefficient N, %	Natural light attenuation coefficient K, m^{-1}	Soot concentration C_s, g/m³	Light flux attenuation coefficient N, %	Natural light attenuation coefficient K, m^{-1}	Soot concentration C_s, g/m³	Light flux attenuation coefficient N, %	Natural light attenuation coefficient K, m^{-1}	Soot concentration C_s, g/m³	Light flux attenuation coefficient N, %	Natural light attenuation coefficient K, m^{-1}	Soot concentration C_s, g/m³
0	9.9	0.24	0.0433	6.5	0.16	0.0278	4.8	0.11	0.0204	5.1	0.12	0.022	5.3	0.13	0.0225
10	14.5	0.36	0.0652	9.1	0.22	0.0397	8.6	0.21	0.0373	9	0.22	0.0391	9.2	0.23	0.0403
20	30.2	0.84	0.1493	24.4	0.65	0.1162	21.6	0.57	0.1011	21.8	0.57	0.1021	23.4	0.62	0.1107
30	48.6	1.55	0.2764	46.5	1.45	0.2598	45	1.39	0.2483	45.3	1.4	0.2506	45.8	1.42	0.2544

The use of biodiesel and its blends with diesel fuel significantly affects the progression of working processes in a diesel engine. Experimental studies confirmed the possibility of compensating for energy losses by adjusting the cyclic fuel injection and simultaneously demonstrated improved environmental performance, particularly a reduction in exhaust gas smoke opacity with an increasing biodiesel fraction. The proposed adaptive control system for regulating the composition of the fuel blend ensures optimal progression of working processes across the entire

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range of speed and load operating modes, preserves the technical and economic characteristics of the base engine, and enhances its environmental performance.

APPROXIMATION OF EXPERIMENTAL DATA FOR THE MATHEMATICAL MODEL OF THE "ENGINE – DIESEL-BIODIESEL FUEL SUPPLY SYSTEM"

The derivation of analytical relationships describing large arrays of experimental data is carried out through approximation. This approach is based on replacing a discrete set of experimental data with an analytical function of a simpler form. The values of this function do not necessarily pass through all experimental points; however, they adequately reflect the overall trend in the variation of the investigated parameters and ensure a minimal value of the mean squared error (MSE) between the calculated and experimental data. The constant coefficients of the approximating polynomials were determined using a computer with the Statistica software package 10.

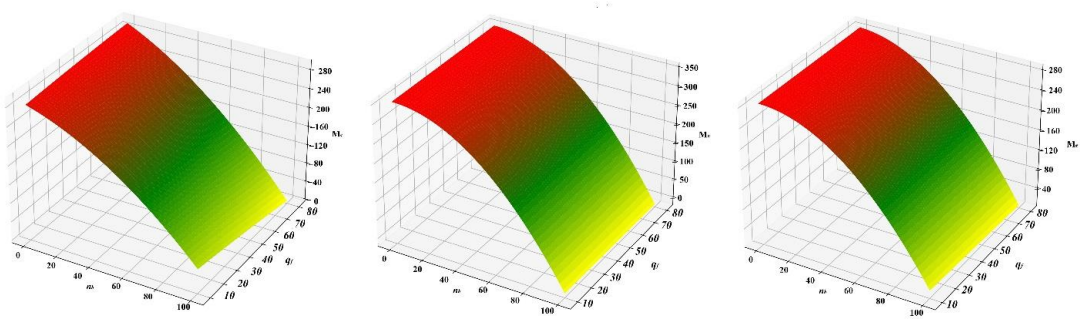
In this study, the approximation coefficients were determined for the following relationships:

- the effective torque as a function of the biodiesel content in the fuel blend (n_b), the cyclic fuel injection (g_c), and the crankshaft rotational speed of the diesel engine (n_e) (1);
- the exhaust gas smoke opacity as a function of the effective power of the diesel engine (N_i) and the biodiesel content in the fuel blend (n_b) (2).

The effective torque is determined by the following relationship:

$$M_e = (387.2063 - 0.9419\,n_e + 4.15 \cdot 10^{-4}\,n_e^2) + (-292.03 + 0{,}49\,n_e - 1.9186 \cdot 10^{-4}\,n_e^2)n_b + \\ +(-6.9161 + 0.0298\,n_e - 1.5744 \cdot 10^{-5}\,n_e^2)q_c + (300 - 0.56577\,n_e + 2.3794 \cdot 10^{-4}\,n_e^2)n_b^2 + \\ +(1.24 - 2.3345 \cdot 10^{-3}\,n_e + 6.5476 \cdot 10^{-7}\,n_e^2)n_b q_c + \\ +(-0.0264 - 4.8803 \cdot 10^{-5}\,n_e + 5.9045 \cdot 10^{-8}\,n_e^2)q_c. \quad (1)$$

The relationship was approximated by Equation (1), which was used to construct graphs of the effective torque as a function of the biodiesel content in the fuel blend and the cyclic fuel injection at crankshaft rotational speeds of 600 rpm (Fig. 3*a*), 1,200 rpm (Fig. 3*b*), and 1,500 rpm (Fig. 3*c*).



(a) (b) (c)

FIGURE 3. Graphs of the dependence of the effective torque M_e on the biodiesel content in the fuel blend n_b and the cyclic fuel injection q_c at 800 rpm (a), 1,200 rpm (b), and 1,500 rpm (c)

The dependence of soot concentration C_c on the fuel blend composition n_u and the diesel engine crankshaft load N_l was approximated by the following relationship:

$$C_c = 0.0474 - 0{,}0016 \cdot N_l - 0.0009 \cdot n_b + 0.0003 \cdot N_l^2 - 2.332 \cdot 10^{-6} \cdot N_l \cdot n_b + 7.22 \cdot 10^{-6} \cdot n_b^2, \quad (2)$$

and is presented in the graph (Fig. 4).

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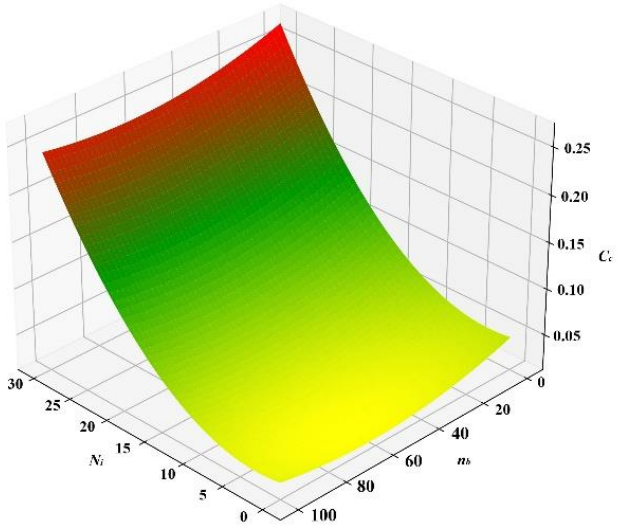


FIGURE 4. Graph of the dependence of soot concentration C_c in the exhaust gases on the fuel blend composition n_b and the load on the diesel engine crankshaft N_l

The adequacy of the developed mathematical framework was verified by determining the deviations between the calculated and experimentally obtained values of the diesel engine crankshaft acceleration time. It was established that during operation on conventional diesel fuel the maximum deviation does not exceed 2.8%, while when biodiesel fuel is used it reaches up to 5%. The deviation of the deceleration time does not exceed 4.8%. The corresponding root mean square deviations are 0.93%, 1.31%, and 1.46%, respectively. These results indicate a sufficient level of adequacy of the improved mathematical model of the "Engine – diesel-biodiesel fuel supply system".

Using the improved mathematical model, a computational study was carried out. Within this study, it was assumed that the control system regulating the composition of the diesel-biodiesel fuel mixture, depending on the engine operating mode, should ensure a rational component composition of the fuel. This approach is aimed at ensuring efficient working processes in the engine cylinders while maintaining the main technical and operational characteristics at the level of the baseline diesel engine.

RESULTS

The experimental study was conducted to determine the influence of the diesel–biodiesel blend composition on the techno-economic and environmental performance of a diesel engine. The analysis of the results indicates that an increase in the biodiesel fraction in the fuel blend leads to a systematic rise in fuel consumption. This effect is attributed to the lower heating value (LHV) of biodiesel compared to conventional diesel fuel, which necessitates an increase in cyclic fuel delivery to maintain the specified engine operating conditions.

In particular, at an engine speed of 800 rpm under maximum load, fuel consumption increases by 18.7%; at 1200 rpm under maximum load, it rises by 19%, and at 1500 rpm by 11.6%. On average, during engine operation on fuel blends with an increased biodiesel content, the cyclic fuel injection increases by up to 12.4%. This compensates for the lower calorific value of the fuel blend and ensures an adequate air supply for complete combustion.

At the same time, cost savings in fuel procurement reach up to 19%. The application of an improved fuel supply system provides economic benefits without deterioration of the engine's technical performance. Although the consumption of the fuel blend increases by 5.9%, its cost decreases by 8.6%.

An improvement in environmental performance has also been observed: increasing the biodiesel content reduces soot concentration by 8%, which is associated with the higher oxygen content of biodiesel and the more complete combustion of the fuel blend.

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DISCUSSION

A number of publications report that an increase in biodiesel content leads to higher fuel consumption due to its net calorific value, which on average ranges from 1.27% to 5.61% when transitioning from B10 to B50 [13]. The use of biodiesel in agricultural tractor engines results in an increase in specific fuel consumption, which averages about 3-10%, depending on the biodiesel fraction in the blend (B10-B100), the load regime, and the design features of the engine. At the same time, the use of biodiesel is accompanied by improved environmental performance, particularly through reductions in CO, HC, and smoke emissions, with a possible slight increase in NOx emissions [6]. Thus, the results presented in this article fall within the ranges observed in other experimental studies, confirming the adequacy and representativeness of the obtained results.

Further research is planned to investigate the effect of using the improved fuel supply system with adaptive regulation of the biodiesel fraction depending on the engine operating mode on the working processes of modern engines, taking into account various load conditions and operating environments. A promising direction involves conducting experimental studies with extended instrumental monitoring of combustion parameters, heat release, fuel efficiency, and exhaust gas emissions.

Particular attention should be paid to the optimization of control algorithms for the system in order to improve energy efficiency, reduce specific fuel consumption, and enhance environmental performance in accordance with current international requirements.

CONCLUSIONS

The use of biodiesel makes it possible to reduce fuel costs and dependence on conventional petroleum-based fuels, as well as to improve the environmental performance of the engine. In particular, a significant reduction in harmful exhaust emissions is achieved: CO, CnHm, particulate matter (PM) and soot. To achieve the maximum effect from the use of biodiesel, it is advisable to employ a diesel fuel supply system capable of adjusting the composition of the fuel blend depending on the engine operating mode.

Under conditions of electricity shortages in Ukraine and the intensive operation of mobile power plants equipped with diesel engines, the implementation of an improved diesel fuel supply system in such power units is considered appropriate. Mobile power plants are typically equipped with diesel engines whose rated power exceeds that of the electric generator. Such a configuration results in engine operation under partial load conditions even when the generator is operating at maximum load, while the crankshaft rotational speed remains close to its nominal value. Under these conditions, the use of fuel blends with an increased biodiesel content is advisable. The improved fuel supply system ensures reliable engine start-up on diesel fuel at low ambient temperatures and also minimizes the negative effects associated with biodiesel use during cold engine operation.

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ACKNOWLEDGMENTS

The authors would like to express their gratitude to Vinnytsia National Technical University.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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