This paper reports a study into the fuel, economic, energy, and environmental indicators of the diesel engine operating in the diesel-gas cycle. It was established that the injection timing has a significant impact on the diesel engine indicators, in particular emissions of harmful substances with exhaust gases. The gas injection timing was investigated at crankshaft speeds n=1,300 rpm and n=1,600 rpm. At these crankshaft speeds, measurements were carried out at three different values of the injection timing. It has been determined that for each crankshaft speed of the diesel engine, the rational values of the injection timing of compressed natural gas are different. This is due to the time limits for supplying compressed natural gas to cylinders.

Bench motor tests were carried out to analyze the effect of change in the gas injection timing on the diesel engine performance indicators operating in the diesel-gas cycle. The diesel engine performance indicators were also determined during a diesel cycle and during a diesel-gas cycle. The analysis has established the effect of change in the injection timing on the concentrations of carbon monoxide, hydrocarbons, nitrogen oxides, and the smoke of exhaust gases under different speed and load modes of diesel engine operation. This effect manifests itself by a slight decrease in the concentration of carbon monoxide and hydrocarbons, by the increase in the concentration of nitrogen oxides (up to 30 %), and by a significant reduction in the smoke of exhaust gases (up to 90 %). The improvement of environmental indicators of the diesel engine has been confirmed when switching its operation to the diesel-gas cycle, by 10–16 %, with similar fuel, economic, and energy indicators.

Thus, there are grounds to assert the importance of choosing and establishing the rational value for the injection timing of compressed natural gas, depending on the speed and load modes of diesel engine operating in the diesel-gas cycle

Keywords: diesel-gas cycle, compressed natural gas, natural gas injection timing, exhaust gases

DETERMINING THE EFFECT OF CHANGE IN THE GAS INJECTION TIMING ON THE PERFORMANCE INDICATORS OF THE DIESEL ENGINE OPERATING IN THE DIESEL-GAS CYCLE

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1. Introduction

The use of gas fuels can reduce emissions of harmful substances by internal combustion engines without losing power and reducing the running reserve. The application of compressed natural gas (CNG) could become one of the ways to replace conventional diesel fuel (DF) [1–3].

It is rational to use natural gas in the diesel engines operating in the diesel-gas cycle. There are two ways to supply natural gas (NG) to the diesel combustion chamber. The first is to supply gas to the intake manifold where NG is mixed with air. The second is to directly supply NG under high pressure to the combustion chamber with its subsequent ignition by an pilot dose of diesel fuel [1].

The use of CNG by the diesel engines in the diesel-gas cycle has several advantages. It makes it possible to expand the fuel base of road transport (two-fuel system). CNG is an environmentally friendlier fuel because it contains mainly methane (96–98 %), is safer compared to liquid petroleum fuels, as well as has a high octane number (120).

Therefore, it is a relevant task to explore the conversion of diesel engines to gas-diesel engines during operation. That could reduce diesel fuel consumption and improve the environmental performance of diesel engines in vehicles.

2. Literature review and problem statement

Paper [1] reports ways to use NG in diesel engines and spark-ignition engines. In addition, the energy and environmental indicators of NG-operated engines are considered. However, the cited paper did not consider power systems for the engines operating in the diesel-gas cycle. Work [2] investigated the impact of change in the compression ratio on the energy, fuel, economic, and environmental performance indicators of the diesel engine, transferred to operate on NG. The compression ratio was changed between 9 and 10.5. It was established that at the compression ratio of 9.5 there is the highest thermal efficiency and the lowest specific fuel consumption. It was determined that the com-

pression ratio affects the environmental performance of the engine. In particular, as the compression rate increases, NOx emissions grow. Paper [3] focuses on finding a correlation between the DF quality and the delay in ignition of the mixture in the diesel engines operating in the diesel-gas cycle. Fuel quality was estimated by the cetane number. A study into the process of combustion of gas fuels in the diesel engine operating in the diesel-gas cycle and the analysis of reactions related to methane and other types of fuels are reported in works [4–9]. Paper [4] addresses the effect of change in the ignition dose and the injection angle of DF on the indicators of the diesel engine operating in the diesel-gas cycle. One result is to establish an increase in NOx emissions and reduce hydrocarbon emissions with an increase in the ignition dose of DF. In addition, work [5] tackled the issues of the impact of the injection pressure of DF and the share of replacement of diesel fuel with CNG on the energy and environmental indicators of the diesel engine. The influence of changes in the angle and pressure of injection of DF on environmental indicators, as well as on the pressure and estimated heat of combustion in the diesel engine cylinder has been established.

The authors of [6] considered the chemical kinetic process that explains the formation and process of hydrocarbon oxidation. The processes of fuel combustion in the engine, taking into consideration the chemical process, were also studied. Paper [7] focuses on the experimental research measuring the value of the laminar flame velocity of fuels such as NG, methane, ethane, propane, and n-butane. Work [8] also studied the NG combustion parameters when mixing it with various hydrocarbon fuels. In works [7, 8], the authors acquired experimental results that confirmed the estimated data on hydrocarbon formation and the impact of this process on fuel combustion indicators. Testing the addition of hydrogen and dimethyl ether to methane and determining fuel ignition indicators were addressed in work [9]. Thus, works [6–9] report studies into the direct formation of hydrocarbons and the process of fuel combustion under different conditions. However, the processes of formation of other harmful substances were not paid attention to.

When the diesel engine is operating in the diesel-gas cycle, a significant role belongs to the quality of DF, the amount of DF ignition dose, the air temperature entering the engine cylinders, and the time of DF supply [10, 11]. Paper [11] shows that under the right angle of DF injection and heating the air entering the engine, soot and carbon monoxide emissions are reduced.

However, there are drawbacks. The main disadvantage of diesel-gas systems is the significant mass of gas tanks installed in a car. In addition, the number of gas fuel stations is significantly less than that for conventional motor fuels. In the case of CNG, the disadvantage is that the gas equipment to the gas reducer is under high pressure (25 MPa).

Despite the shortcomings, diesel-gas systems are being developed and designed by companies and scientists around the world. The construction of diesel-gas power systems with electronic control makes it possible to get the advantages of using NG. For example, such systems are being developed both at universities [12] and by commercial companies such as Bosch, Valtra, Caterpillar, and others [13–18]. Works [13–16] present schemes of the developed diesel-gas power systems, features of their use, and advantages. However, the above studies do not note the shortcomings of the designed diesel-gas power systems. Diesel-gas power systems

are developed for both obsolete diesel engines [17] and modern diesel engines [18]. The cited papers note a decrease in the emissions of harmful substances in exhaust gases. The DF ignition dose can vary from 14 % to 50 %.

Our review of the scientific literature has revealed that CNG supply systems in gas diesel engines change over time, become more complex, the regulation and gas supply techniques improve, etc. However, all those works failed to consider the issues related to determining the required CNG injection time into the engine cylinder.

Many researchers continue to work on improving existing diesel-gas power systems. One of the ways of improvement may be to determine the effect of the NG injection timing on the performance indicators of the diesel engines in vehicles. After all, these issues remained unresolved.

All this suggests that it is advisable to design an original electronic-controlled power supply system, which would ensure the possibility to determine different values for CNG injection timings.

3. The aim and objectives of the study

The purpose of this study is to determine the impact of changing the timing of natural gas injection on the fuel and economic, energy, and environmental indicators of the diesel engine. This would make it possible to expand the diesel engine fuel base and reduce the total toxicity of harmful emissions from the diesel engines.

To accomplish the aim, the following tasks have been set:
– to study the energy indicators of the diesel engine operating in the diesel and diesel-gas cycles;
– to determine the concentrations of harmful substances in the exhaust gases from the diesel engine operating in the diesel and diesel-gas cycles;
– to establish the fuel and economic indicators of the diesel engine operating in the diesel and diesel-gas cycles;
– to determine the total toxicity of exhaust gases and find the rational values for the natural gas injection timing in the diesel engine operating in the diesel-gas cycle.

4. Materials and research methods to establish the effect of the injection timing on the performance indicators of the diesel engine

For our research, we designed an original diesel-gas electronic power system [19, 20] with the possibility to change injection timing of natural gas; it was installed on an experimental vehicle with a high-pressure mechanical fuel pump. The scheme of the power system installed on the vehicle is shown in Fig. 1.

The research was carried out on a truck with a four-cylinder diesel engine, which operates in the diesel and diesel-gas cycles at the bench that investigates dynamometric traction properties. The diesel engine specifications are given in Table 1. The installed diesel-gas power supply system ensures the operation of the diesel engines in the diesel and diesel-gas cycles while maintaining a standard fuel system. The system consists of gas-cylinder equipment, a set of sensors, an pilot dose setting mechanism, gas electromagnetic injectors, a gas reducer, and an electronic control unit. The system is equipped with a mode switch for swapping the diesel and diesel-gas operation modes.
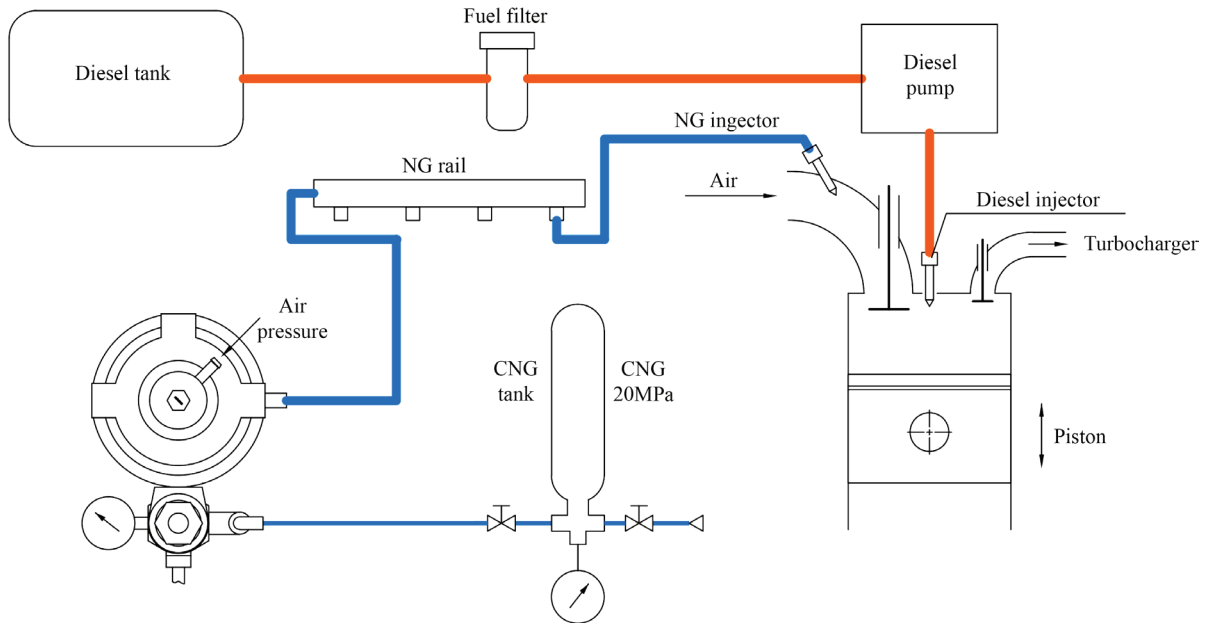
Fig. 1. Schematic showing the diesel-gas power system

Table 1

Parameters of the examined diesel engine

Title	Value	
Number of cylinders	4	
The diesel engine type	Turbocharged and liquid-cooled	
Bore x stroke, mm	110×125	
Volume, l	4.75	
Compression ratio	15.1	
Rated power, kW	90	
Rated crankshaft speed, rpm	2,400	
Gas distribution mechanism valve operation	Open	Close
Inlet	16° before TDC	46° after BDC
Outlet	56° before BDC	18° after TDC

ders, the time of the gas injection itself, and the moment of injection.

We studied injection timing changes during three different injection timings and crankshaft speeds $n=1,300$ rpm and $n=1,600$ rpm. For the crankshaft speed of $n=1,300$ rpm, the first NG injection timing corresponds to $\psi=15°$ after TDC, the second NG injection timing is $\psi=40°$ after TDC, and the third NG injection timing is $\psi=65°$ after TDC. For the crankshaft speed of $n=1,600$ rpm, the first NG injection timing corresponds to $\psi=0°$ after TDC, the second NG injection timing is $\psi=15°$ after TDC, and the third NG injection timing, $\psi=30°$ after TDC. The results are shown in Fig. 4–11 with a load of about 35 % and under full load (100 %) for two frequencies.

To check the operation of the system and investigate the effect of changing the gas injection timing, the diesel-gas power supply system was installed on the diesel engine with a high-pressure mechanical fuel pump (25 MPa). The dosage of CNG entering the diesel engine cylinders implies adjusting the open state of gas electromagnetic injectors in accordance with the algorithm of the electronic control system.

To determine the onset of a gas injection cycle and form a single pulse signal from the steel pin-counter, mounted on the pin drive of a high-pressure fuel pump, a injection timing sensor is installed. The operation of gas supply elements in the diesel engine operating in the diesel-gas cycle is shown in a diagram in Fig. 2.

An example of system operation at different injection timings of gas (ψ) is shown in Fig. 3. It illustrates a possibility to change a gas injection timing in the system.

Gas injection in a given system is implemented at the intake stroke. Fundamentally, the possibility to supply gas to the diesel engine cylinders exists throughout the entire intake. But it is necessary to take into consideration the time required for the passage of gas from the injectors to the engine cylin-
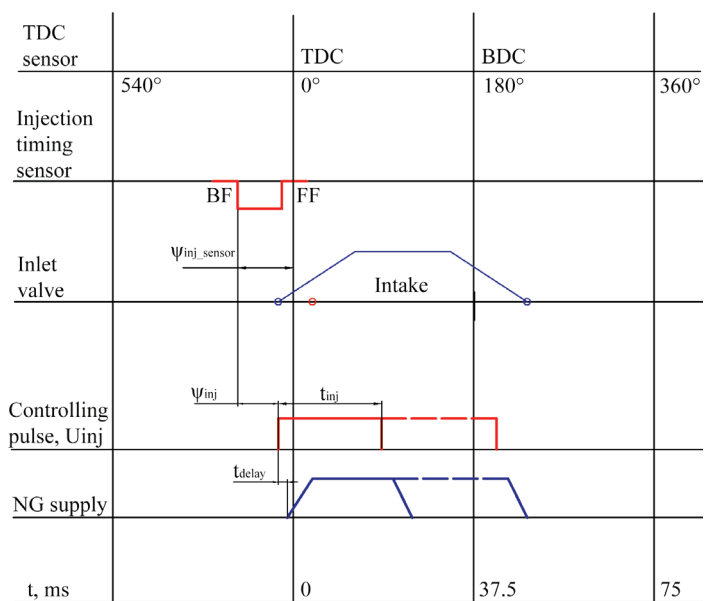

Fig. 2. Operational diagram of the elements in a gas supply system of the diesel-gas power system
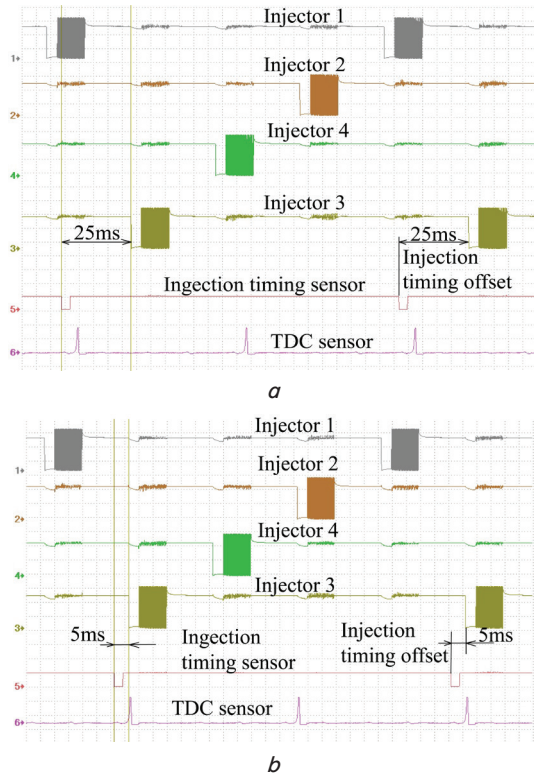
Fig. 3. Oscillogram of diesel-gas electronic power system operation at different injection timings ($n=1,000$ rpm):
a — the value of NG injection timing 90° after TDC;
b — the value of NG injection timing 20° after TDC

During bench studies, we used a DF flow meter (ONO SOKKI), an air flow meter (GF-90), a CNG flow meter (FCI FlexCOR) to determine the fuel and economic indicators of the diesel engine operating in the diesel and diesel-gas cycles. To determine environmental indicators, a modern gas-analytical measuring complex (BOSCH BEA 060) and a smoke meter (Hartridge MK-3) were used. Traction efforts were determined at a dynamometric bench of traction properties. We also calculated values for a replacement proportion of the diesel fuel with CNG (SR) for diesel operation in the diesel-gas cycle and a value of the DF ignition dose (DFD). The results of our experiments are given in Table 2.

The share of the diesel fuel substitution rate with CNG:

$$SR = \frac{m_{CNG}}{m_D^{dualfuel} + m_{CNG}} \cdot 100\,\%, \tag{1}$$

where m_{CNG} is the CNG fuel consumption, kg; $m_D^{dualfuel}$ is the consumption during operation in the diesel-gas cycle, kg.
Pilot dose of the diesel fuel:

$$DPD = \frac{m_D^{dualfuel}}{m_D^{original}} \cdot 100\,\%, \tag{2}$$

where $m_D^{original}$ is the DF consumption in the diesel cycle, kg.
To obtain reliable results, the procedure for treating experimental data included the repeated acquisition of the diesel engine performance indicators.
The comparison of the environmental indicators for the diesel engine operating in the diesel and diesel-gas cycles is the result of calculating the value of total mass emissions in exhaust gases reduced to CO emissions (ΣCO):

$$\sum CO = \sum_{i=1}^{m} R_i \cdot G_i, \tag{3}$$

where R_i is the coefficient of relative aggressiveness of the i-th harmful substance in exhaust gases (EG). $R_{CO}=1$; $R_{CH}=3.16$; $R_{NOx}=41.1$; $R_C=200$; G_i is the mass emissions of the i-th toxic component of exhaust gases.

5. Results of studying the effect of the injection timing on the performance indicators of the diesel engine

5. 1. Investigating energy indicators of the diesel engine operating in the diesel and diesel-gas cycles

A change in the traction force on a wheel, which reflects the level of power in the diesel engine operating in the diesel and diesel-gas cycles, is shown in Fig. 4. As can be seen from the Fig. 4 shows that a change in the traction force under a partial load of about 35 % depending on the change in NG injection timing ψ is almost the same at crankshaft speeds $n=1,300$ rpm and $n=1,600$ rpm. Under a full load at the injection timing value $\psi=15°$ after TDC for speeds $n=1,300$ rpm and $\psi=0°$ after TDC for speed $n=1,600$ rpm there is a significant decrease in the traction force, and, therefore, engine power, compared to operation in the diesel cycle. For crankshaft speed $n=1,300$ rpm, the traction force is less by 11.66 %, compared to the effort obtained in the diesel cycle. For crankshaft speed $n=1,600$ rpm, the traction force is less by 14.84 %, compared to the effort obtained in the diesel cycle. This decrease is explained by the fact that the injection timing coincided with the engine blowing and part of the fuel was not used. At other NG injection timing values at crankshaft speed $n=1,300$ rpm, the traction effort is almost the same compared to operation in the diesel cycle. And, at crankshaft speed $n=1,600$ rpm, it is larger by 3.23 % than the effort obtained in the diesel cycle operation.

Table 2

Conducted experimental tests

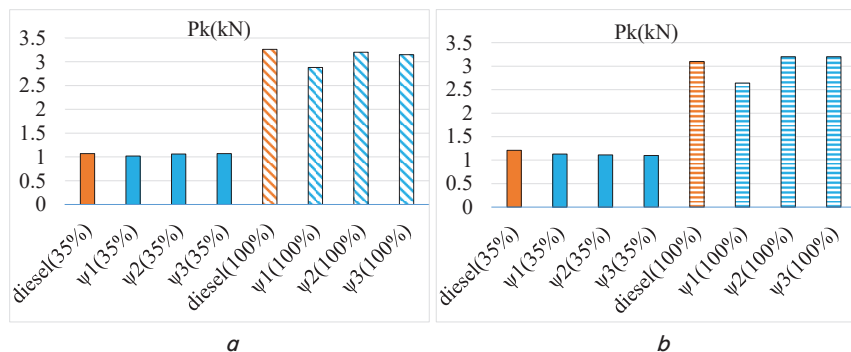| Engine speed, rpm	CNG injection timing designation	CNG injection timing, rotation angle ° of crankshaft after TDC	Load on engine, %	SR, %	DFD, %
1,300	ψ_1	15	≈35	82.19	17.32
				77.31	20.79
				78.32	20.79
	ψ_2	40	100	80.52	15.68
				74.43	22.09
	ψ_3	65		74.98	21.38
1,600	ψ_1	0	≈35	82.05	18.94
				76.07	25.32
				76.51	25.32
	ψ_2	15	100	86.15	11.06
				82.30	15.77
	ψ_3	30		81.36	16.94

Fig. 4. Traction force on the wheels of a truck equipped with the diesel engine operating in the diesel and diesel-gas cycles at different values of gas injection timings: *a* − *n*= 1,300 rpm; *b* − *n*= 1,600 rpm

5. 2. Determining the concentrations of harmful substances in the diesel engine exhaust gases operating in the diesel and diesel-gas cycles

The concentrations of CO obtained during the experiment involving the diesel engine operating in the diesel and diesel-gas cycles are shown in Fig. 5. It shows that the change in the concentrations of carbon monoxide depending on a change in the timing of gas injection, for the diesel engine operating in the diesel-gas cycles, is similar under different loads and crankshaft speeds. However, under a partial load at crankshaft speed *n*=1,300 rpm, the concentration of CO at different injection timings is less than the values obtained for the diesel engine operating in the diesel cycle. For crankshaft speed *n*=1,600 rpm, the values of CO concentrations, on the contrary, are higher.

The concentrations of hydrocarbons from the diesel engine operating in the diesel and diesel-gas cycles are shown in Fig. 6. It demonstrates that the concentrations of hydrocarbons from the diesel engine operating in the diesel-gas cycle at different timings of gas injection are much higher than those from the diesel engine operating in the diesel cycle. The nature of change in concentrations depending on the injection timing is similar under different loads, both for crankshaft speed *n*=1,300 rpm and crankshaft speed *n*=1,600 rpm. But it is worth noting that the smallest difference in hydrocarbon concentrations is observed during the phase ψ=40° after TDC for crankshaft speed *n*=1,300 rpm and ψ=15° after TDC for *n*=1,600 rpm.

Fig. 7 shows a change in NOx concentrations at different timings of gas injection from the diesel engine operating in the diesel-gas cycle compared to the diesel cycle operation. It demonstrates that the injection timing change affects the value of the NOx concentration in

exhaust gases. The lowest concentration value per injection timing value ψ=15° after TDC is observed for speed *n*=1,300 rpm and ψ=0° after TDC for speed *n*=1,600 rpm. However, the value of concentrations under full load for crankshaft speed *n*=1,300 rpm and for the value of injection timing ψ=15° after TDC, on the contrary, is the largest. There is also a higher concentration of NOx under a full load for the diesel engine operating in the diesel-gas cycles compared to working in the diesel cycle.

The results of smoke of EG in the diesel engine operating in the diesel and diesel-gas cycles are shown in Fig. 8.
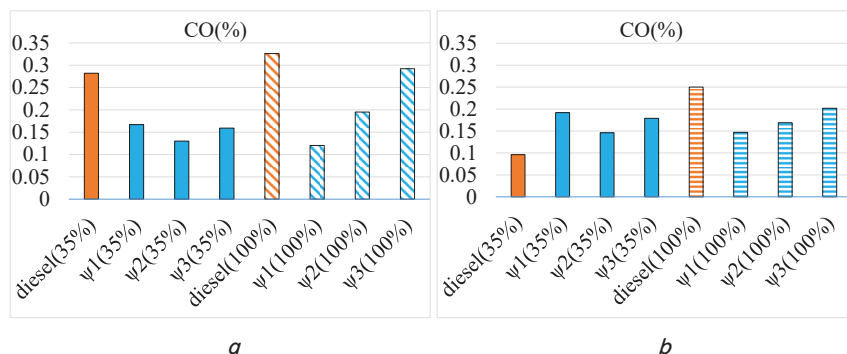

Fig. 5. Concentrations of carbon monoxide from the diesel engine operating in the diesel and diesel-gas cycles at different timings of gas injection: *a* − *n*= 1,300 rpm; *b* − *n*= 1,600 rpm
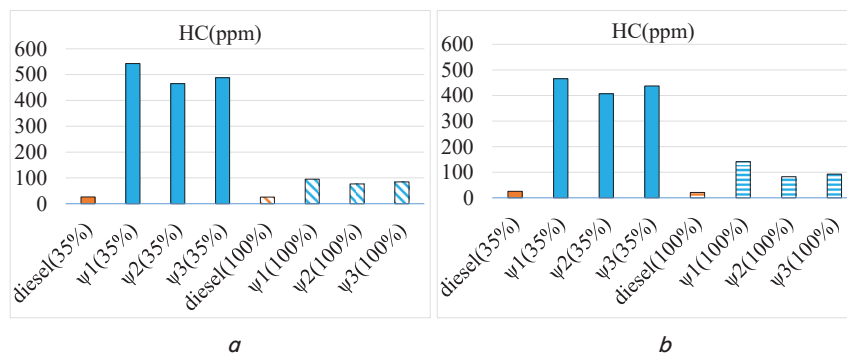

Fig. 6. Concentrations of hydrocarbons from the diesel engine operating in the diesel and diesel-gas cycles at different timings of gas injection: *a* − *n*= 1,300 rpm; *b* − *n*= 1,600 rpm
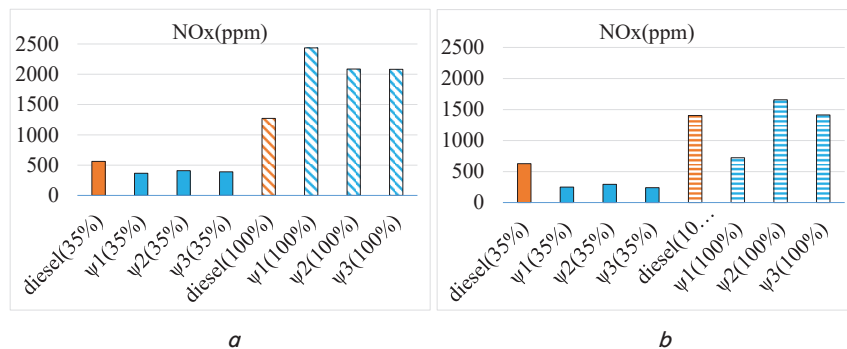

Fig. 7. Concentrations of nitrogen oxides for the diesel engine operating in the diesel and diesel-gas cycles at different timings of gas injection: *a* − *n*= 1,300 rpm; *b* − *n*= 1,600 rpm
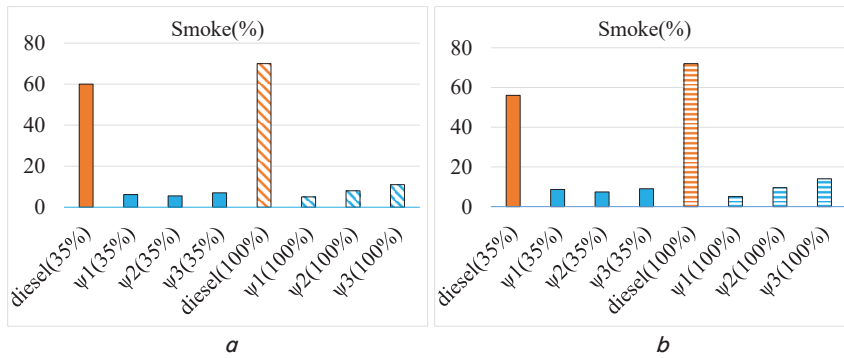
Fig. 8. The smoke of exhaust gases from the diesel engine operating
in the diesel and diesel-gas cycles at different timings of gas injection:
$a - n = 1,300$ rpm; $b - n = 1,600$ rpm

thermal equivalent in the diesel-gas cycle is mostly almost the same as that in the diesel cycle, but there are modes under which the caloric value is greater.

Considering our results (Fig. 10, 11), one can argue about the possibility of improving fuel efficiency in the diesel engine operating in the diesel-gas cycle compared to working in the diesel cycle. However, controlling fuel consumption (DF and CNG) using the developed electronic system in the diesel-gas cycle requires revision and adjustment.

Fig. 8 shows that the smoke of EG in the diesel engine operating in the diesel-gas cycles is much less than that in the diesel cycle operation. The nature of change in the value of smoke, depending on a change in the timings of gas injection, is the same pairwise for the partial and full loads at different crankshaft speeds.

5. 3. Results of studying the impact of the injection timing on the fuel and economic indicators of the diesel engine

The specific fuel consumption in different phases of injection, load, and crankshaft speeds by the diesel engine operating in the diesel-gas cycles compared to work in the diesel cycle is shown in Fig. 9.

It demonstrates that the specific fuel consumption in proportion to a change in the injection timing has a similar character with the smallest value obtained in the second (middle) injection timing.

Except for the values obtained under a partial load at crankshaft speed $n = 1,600$ rpm. Not taking into consideration these values, it can be argued about a lower specific fuel consumption by the diesel engine operating in the diesel-gas cycle compared to working in the diesel cycle.

For crankshaft speed $n = 1,300$ rpm in injection timing $\psi = 40°$ after TDC and partial load, the specific fuel consumption is less by 7.48 %, under full load – by 12.09 %. For crankshaft speed $n = 1,600$ rpm in injection timing $\psi = 15°$ after TDC and under a partial load, the specific fuel consumption is greater by 15.29 %, and, under full load, less by 13.68 %.

However, under a partial load at crankshaft speed $n = 1,600$ rpm, the specific consumption at different injection timings is greater, by 13.02 % to 18.6 %, compared to the diesel engine operation in the diesel-gas cycle.

Fig. 10 shows fuel consumption in the thermal equivalent by the diesel engine operating in the diesel and diesel-gas cycles. It demonstrates that fuel consumption in the
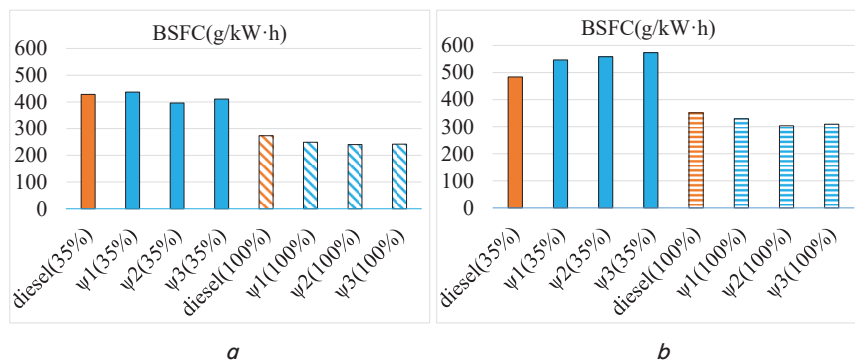

Fig. 9. Specific fuel consumption by the diesel engine operating
in the diesel and diesel-gas cycles at different timings of gas injection:
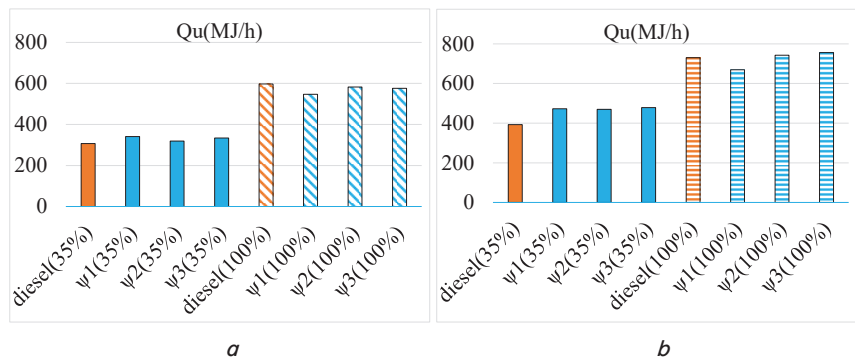$a - n = 1,300$ rpm; $b - n = 1,600$ rpm

Fig. 10. Fuel consumption in the thermal equivalent by the diesel engine operating
in the diesel and diesel-gas cycles at different timings of gas injection:
$a - n = 1,300$ rpm; $b - n = 1,600$ rpm

5. 4. Determining the total toxicity of exhaust gases and establishing the rational values for a gas injection timing

The calculated total mass emissions of harmful substances, reduced to CO emissions (ΣCO), are shown in Fig. 11. It illustrates that under full load, ΣCO from the diesel engine operating in the diesel-gas cycle is larger by an average of 6 % than for the diesel cycle operation. This is due to the excessive concentration of NOx at crankshaft speed $n = 1,300$ rpm and under full load.

Based on the results of ΣCO calculation, one can argue about the improved environmental indicators of the diesel engine operating in the diesel-gas cycle, compared to the diesel engine operating in the diesel cycle.
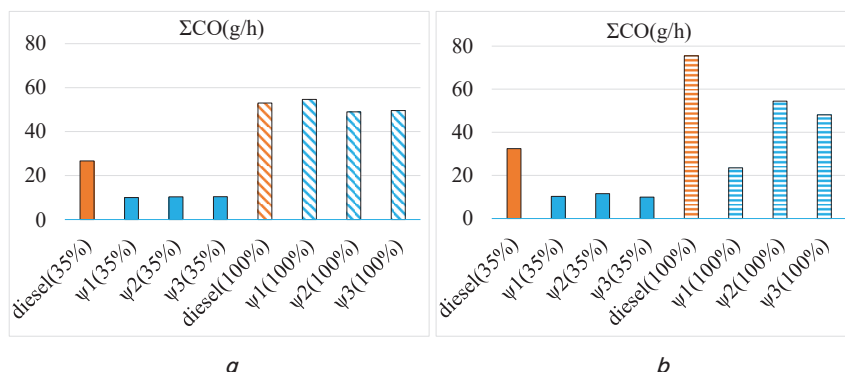
Fig. 11. Total mass emissions of harmful substances, reduced to CO emissions, from the diesel engine operating in the diesel and diesel-gas cycles at different timings of gas injection: *a* — $n=1,300$ rpm; *b* — $n=1,600$ rpm

At crankshaft speed $n=1,300$ rpm and under a partial load, ΣCO from the diesel engine operating in the diesel-gas cycle are less, by 61.06 % to 62.36 %, depending on the selected timing of gas injection. For crankshaft speed $n=1,600$ rpm and under a partial load – from 64.43 % to 69.41 %. Under full load at crankshaft speed $n=1,300$ rpm, the following values for each timing of gas injection were obtained. In injection timing $\psi=15°$ after TDC, ΣCO are larger by 3.06 %; in injection timing $\psi=40°$, after TDC, are 7.67 % lower, and in injection timing $\psi=65°$, after TDC, are also 6.54 % lower.

For crankshaft speed $n=1,600$ rpm, the following values were obtained for each timing of gas injection. In injection timing $\psi=0°$, after TDC, ΣCO are smaller by 68.88 %, in injection timing $\psi=15°$, after TDC, are 27.9 % lower, and in injection timing $\psi=30°$, after TDC, are also 36.33 % lower.

As the result of our analysis of the data acquired during the study and calculations, the value for the rational injection timings of CNG was obtained in the entire high-speed range of the experimental diesel engine. The range of values of the injection timing from $\psi=12.5°$ before TDC to $\psi=60°$ after TDC is defined (Fig. 12).

The value of the rational timing of gas injection was established, based on the experimental characteristics of the total mass emissions reduced to carbon monoxide emissions. In addition, the specific fuel consumption and fuel consumption in the thermal equivalent were taken into consideration.
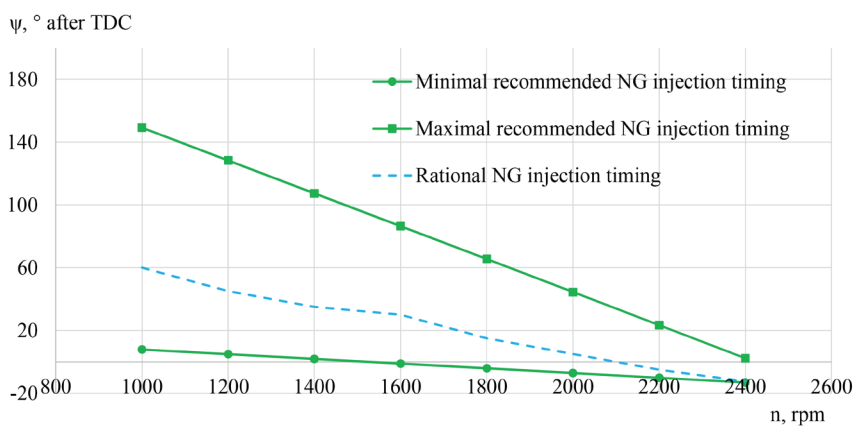
6. Discussion of results of studying the effect of the injection timing on the diesel engine performance indicators

Our results (Fig. 4–11) confirm the effect of changing the value of the CNG injection timing on the diesel engine performance indicators for its operation in the diesel-gas cycle. Fig. 4 shows the effect of injection timing change on energy indicators, namely a traction effort on the wheel. Employing the traction effort created by the bench, one can compare the power of the diesel engine operating in the diesel and diesel-gas cycles and analyze them. Fig. 4 shows that at certain values of the CNG injection timing, in the diesel-gas cycle, the traction effort is 5–15 % less than that obtained in the diesel cycle. This is due to the fact that part of CNG is fed at the time of engine blowing and is not disposed of. At other values of the injection timing, the effect on energy indicators is almost the same.

The effect of injection timing change on environmental indicators is illustrated in Fig. 5–8, 11; it indicates a significant impact in the case of hydrocarbon and NOx concentrations. A change in the hydrocarbon concentration values in different injection timings indicates that there is a injection timing value at which hydrocarbons are disposed of the most. According to our study, this value corresponds to one after the moment of engine blowing.

The values of NOx concentrations indicate that by choosing a later timing of gas injection, their smallest value can be obtained. Since NOx are formed at increased pressure and temperature in the combustion chamber, choosing a later injection timing can affect the temperature and pressure inside the combustion chamber.

A change in the value of CO concentrations when changing the value of the injection timing indicates the effect of fuel quality on the combustion process. Therefore, by changing the value of the injection timing, one can influence the mixture formation in the combustion chamber. In addition, our results testify to a correlation between CO and NOx concentrations, which confirms the effect of changing the gas injection timing on changes in the mixture formation, pressure, and temperature in the combustion chamber.

Fig. 12. Rational values for the injection timing of CNG, determined for the diesel engine as a result of tests

Fig. 9, 10 demonstrate a noticeable impact of change in the gas injection timing on the diesel engine fuel and economic indicators. Under full load and in the smallest injection timing, a decrease in specific fuel consumption and consumption in the thermal equivalent costs is noticeable. This is due to the incomplete disposal of CNG. In addition, the results reported here show that determining the injection timing after blowing the engine has the best effect on its fuel and economic indicators. So, when choosing such a phase value, we can expect better diesel engine workflows compared to the later CNG injection timing.

Therefore, the use of the method of changing the injection timing of CNG for the diesel engine operating in the diesel-gas cycle makes it possible to get better energy, environmental, and fuel-economic indicators of the diesel engine.

However, one of the main limitations of this method is the impossibility of establishing the values of the injection timing in a wide range on diesel engines whose crankshaft speed is greater than 2,000 rpm. The possibility of changing the injection timing in such diesel engines is limited by time segments. It is possible to reduce the impact of this deficiency by installing a controller-reducer instead of a conventional gas reducer.

The disadvantage of this method is that it is necessary to install a injection timing sensor to control and change the values of the injection timing. In addition, the range of possible injection timing values depends on the diesel engine crankshaft speeds and the operation of the gas distribution mechanism. And, for different diesel engines, it is necessary to select other values of the CNG injection timing.

In further studies, it would be advisable to establish the range and choose the optimal injection timing values depending on the operational factors and geometry of the gas distribution mechanism.

7. Conclusions

1. Energy indicators in the diesel engine operating in the diesel-gas cycle are close to the indicators for the diesel operation using conventional fuel. However, at full load, the values of the gas injection timing of 15° after TDC at crankshaft speed $n=1,300$ rpm and TDC at crankshaft speed $n=1,600$ rpm are the worst since there is a decrease in the traction effort and, therefore, power of the diesel engine.

2. Environmental indicators at different injection timings are estimated by the concentrations of harmful substances and total emissions reduced to CO emissions. The rational values of the CNG injection timing have been established, at which environmental indicators of the diesel engine operating in the diesel-gas cycle are better than the indicators for the diesel cycle operation. The following rational injection timing values have been established for crankshaft speed $n=1,300$ rpm and under a partial load. To obtain the lowest value of hydrocarbon concentrations (465 ppm), the value of injection timing 40° after TDC was chosen. The lowest concentrations of nitrogen oxides are in injection timings 15° and 65° after TDC with concentrations of 367 ppm and 389 ppm, respectively. At full load and crankshaft speed $n=1,300$ rpm, the lowest value of hydrocarbon concentrations is at the value of injection timing 40° after TDC (77 ppm). The concentrations of nitrogen oxides are 40° and 65° after TDC (2,087 ppm and 2,081 ppm, respectively). For crankshaft speed $n=1,600$ rpm, it is rational to choose injection timing 30° after TDC under a partial load, and 15° after TDC at full load. Our results demonstrate that in order to obtain the lowest concentrations of hydrocarbons, it is better to choose the value of the injection timing immediately after blowing the engine, to obtain the lowest concentrations of nitrogen oxides, it is better to choose a later injection timing. To obtain the lowest total toxicity, reduced to CO emissions, the choice of the value of the rational injection timing significantly depends on the concentrations of harmful substances; we, however, focused on the NG injection timing at which the concentrations of nitrogen oxides are the lowest.

3. The fuel and economic indicators of the diesel engine in the diesel-gas cycle have been estimated by the specific fuel consumption. A rational value for crankshaft speeds $n=1,300$ rpm and $n=1,600$ rpm is the value of the injection timing 40° and 15° after TDC, respectively. At crankshaft speeds $n=1,300$ rpm and $n=1,600$ rpm under a partial load, the specific fuel consumption is less, by 2.8 % to 9 %, and, at full load, by 1 % to 8 %, respectively.

4. The results of our experimental studies have established the rational values of the injection timing for all modes of the diesel engine operating in the diesel-gas cycle. According to the calculations of total toxicity, for the diesel engine operating in the diesel-gas cycle, the established values for the rational injection timing could yield a decrease in the total toxicity by 10–16 %.

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