Vol. 35, No. 02, pp.552-565/Junio 2022

ISSN-E 1995-9516
Universidad Nacional de Ingeniería

http://revistas.uni.edu.ni/index.php/Nexo
https://doi.org/10.5377/nexo.v35i02.14634

Comparative analysis of the concentration of CO_2, CO, CH, and O_2 in the exhaust gases of BelAZ dump trucks that use liquefied natural gas as a motor fuel

Análisis comparativo de la concentración de CO2, CO, CH, O2 en los gases de escape de BelAZ camiones volquete que utilizan gas natural licuado como combustible para motores

Alexander R. Bogomolov [1,2,*], Georgiy M. Dubov [3], Sergey S. Azikhanov [2,4]

[1] Department of Thermal Power Engineering, T.F. Gorbachev Kuzbass State Technical University, Kemerovo, Russia.
[2] Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia.
[3] Department of Mechanical engineering technology, T.F. Gorbachev Kuzbass State Technical University, Kemerovo, Russia.
[4] Department of Energy-saving Processes in Chemical and Oil and Gas Technologies, T.F. Gorbachev Kuzbass State Technical University, Kemerovo, Russia.

[*]Corresponding author E-mail: barom@kuzstu.ru

(recibido/received: 18-marzo-2022; aceptado/accepted: 15-junio-2022)

ABSTRACT

The paper aims to compare the CO_2, CO, CH, and O_2 concentrations in the exhaust gases of Cummins KTA 50 diesel engines of BelAZ 75131 mining dump trucks equipped with an onboard cryogenic fuel system and running on diesel and gas-diesel fuel at coal mines of Kuzbass (Russia). The research novelty lies in determining ecological efficiency when using liquefied natural gas (methane) as a motor fuel for heavy-duty mining dump trucks. In the near future, the use of this type of motor fuel will minimize the anthropogenic impact on the environment by reducing harmful emissions and provoking the environmental safety of the region where a large amount of mining equipment is used in coal mining enterprises. The demand for mining dump trucks, their operating conditions, and the world experience in converting mining equipment to liquefied natural gas (methane) were briefly analyzed. The use of alternative fuel sources for heavy-duty mining trucks is a promising way to reduce harmful emissions into the atmosphere. This paper presents a research technique. The data on the study of the CO_2, CO, and CH groups and O_2 concentrations in the exhaust gases of Cummins KTA 50 diesel engines of BelAZ 75131 mining dump trucks hauling rock mass are presented. The obtained data on the CO_2, CO, and CH groups and O_2 concentrations during diesel and gas-diesel operation of empty and laden BelAZ 75131 mining dump trucks when going uphill and downhill were substantiated. The results of calculating the average weighted emissions of the CO_2, CO, and CH groups in the exhaust gases of Cummins KTA 50 diesel engines were presented.

Keywords: Mining dump truck, Exhaust gases, Liquefied natural gas, Diesel fuel, Gas-diesel operation

RESUMEN

El documento tiene como objetivo comparar las concentraciones de CO2, CO, CH y O2 en los gases de escape de los motores diesel Cummins KTA 50 de los camiones volquete mineros BelAZ 75131 equipados con un sistema de combustible criogénico a bordo y que funcionan con diesel y gas diesel en las minas de carbón de Kuzbass (Rusia). La novedad de la investigación radica en determinar la eficiencia ecológica cuando se utiliza gas natural licuado (metano) como combustible de motor para camiones volquete de minería pesados. En un futuro próximo, el uso de este tipo de combustible para motores minimizará el impacto antropogénico en el medio ambiente al reducir las emisiones nocivas y provocar la seguridad ambiental de la región, donde se utiliza una gran cantidad de equipos de minería en las empresas mineras de carbón. Se analizó brevemente la demanda de camiones volquete mineros y sus condiciones de operación, así como la experiencia mundial en la conversión de equipos mineros a gas natural licuado (metano). El uso de fuentes alternativas de combustible para camiones pesados de minería es una forma prometedora de reducir las emisiones nocivas a la atmósfera. Este artículo presenta una técnica de investigación. Se presentan los datos del estudio de las concentraciones de CO2, CO, grupo CH y O2 en los gases de escape de los motores diesel Cummins KTA 50 de los volquetes mineros BelAZ 75131 que transportan masa rocosa. Se corroboraron los datos obtenidos sobre las concentraciones de CO2, CO, grupo CH y O2 durante la operación diesel y gas-diesel de los camiones volquete mineros BelAZ 75131 vacíos y cargados al subir y bajar. Se presentaron los resultados del cálculo de las emisiones medias ponderadas de los grupos CO2, CO y CH en los gases de escape de los motores diesel Cummins KTA 50.

Palabras clave: Camión volquete minero, Gases de escape, Gas natural licuado, Combustible diesel, Operación gas-diesel.

1. INTRODUCTION

The demand for solid minerals is increasing annually. The program for the development of the coal industry in Russia presupposes an increase in coal production to 500 million tons per year by 2030. This situation will lead to a significant increase in the number of equipment used by mining companies (Dubov, Trukhmanov, Chegoshev & Ashikhmin, 2018).

The increase in the number and depth of open pits, the complication of mining and geological conditions, and the intensification of mining operations determine the concentration of equipment in a limited space, which means an increase in the emissions of harmful impurities into the atmosphere. The increase in open-pit mining operations contributed to an increase in diesel fuel consumption by open-pit equipment. A billion liters of diesel fuel are consumed annually by the global mining industry, with 70%–80% of the total fuel consumed by laden dump trucks on the slopes of the mine workings at a relatively low speed. This situation leads to significant emission of harmful (toxic) substances, such as carbon oxides, nitrogen, hydrocarbons, aldehydes, lead, soot, and sulfur oxides, into the atmosphere (Chernetsov, 2010; Khazin, 2019; Khazin & Tarasov, 2018).

The ecological and economic efficiency of open-pit mining depends directly on the type of vehicle used. Heavy-duty mining dump trucks are the main type of vehicle for rock mass hauling (Dubov, Trukhmanov Nokhrin & Sergel, 2019). BelAZ heavy-duty mining dump trucks with diesel internal combustion engines are the most widely used for hauling rock masses in Russian mining companies. The fleets of mining companies are mainly equipped with BelAZ-75131 mining dump trucks and their modifications (Dubov, Trukhmanov & Nokhrin, 2020; Dubov, Trukhmanov, Kuznetsov & Nokhrin, 2019a; Kuznetsov, Panachev, Dubov & Nokhrin 2019; Kuznetsov, Panachev, Dubov & Nokhrin, 2020). In 2019, the largest share of the total shipment volume of BELAZ OJSC – the management company of BELAZ-HOLDING (Zhodino, Belarus) – fell on mining dump trucks with a carrying capacity of 110–130 tons – 27%. At the same time, the best-selling model was BelAZ-75131, accounting for 23% of the total sales of BelAZ mining dump trucks.

When operating heavy-duty mining dump trucks, one of the promising ways to reduce the number of harmful emissions into the atmosphere and, as a result, the anthropogenic impact on the environment can be the use of alternative (more environmentally friendly) types of fuel. Today, many countries actively work to convert non-road equipment, such as tractors, tugs, drilling rigs, high-capacity vehicles, and mining dump trucks, to liquefied natural gas. For example, in Mexico in 2016 and in Turkey since 2018, the first experimental gas-diesel Caterpillar 785C and Caterpillar 793D mining dump trucks (130 and 220 tons, respectively), equipped with onboard cryogenic fuel systems, have been operating in gold mines. The operating data for these mining trucks showed a significant fuel savings of 30%. The average degree of diesel fuel replacement with liquefied natural gas was 65%, and the peak was 85%. The reliability of the onboard cryogenic fuel systems used is confirmed by the total operating time of the equipment of over 10 million hours. When using natural gas as a motor fuel, less harmful substances in exhaust gases were emitted (Dubov, Trukhmanov, Nokhrin & Sergel, 2020).

In Russia, the first integrated project for the production of liquefied natural gas and the conversion of BelAZ heavy-duty mining dump trucks to gas-diesel operation was successfully implemented by the following companies: (1) Resurs LLC (Novokuznetsk, Russia); (2) Sibir-Energo LLC (Novokuznetsk, Russia); (3) TechnoEko LLC (Prokopyevsk, Russia) with scientific and engineering support of the T. F. Gorbachev Kuzbass State Technical University (Kemerovo, Russia); (4) BELAZ – the management company of BELAZ-HOLDING (Zhodino, Belarus); and (5) KAMSS LLC (Novokuznetsk, Russia).

In 2017, during the implementation of the project, a technical project was developed for the conversion of BelAZ 75131 mining dump trucks (with a carrying capacity of 130 tons) to gas-diesel operation. The conversion method is patented. As part of the project, several modifications of onboard cryogenic fuel systems for BelAZ 75131 heavy-duty mining dump trucks were developed and implemented. A unique measuring system was designed to ensure the uniformity of the gas supply to the internal combustion engine cylinders, providing the stability of its operation, excluding detonation under dual-fuel operation, and, finally, monitoring gas consumption at the current time and for a certain period. Currently, more than 60 dual-fuel BelAZ 75131 mining dump trucks with Cummins KTA 50 diesel engines are equipped with onboard cryogenic fuel systems and successfully operated in the open-pit mines of Kuzbass (Azikhanov, Bogomolov, Dubov & Nikhrin, 2019; Dubov, Trukhmanov, Kuznetsov & Nokhrin, 2019b; Dubov, Trukhmanov, Nokhrin & Sergel, 2019).

Until now, the composition of the exhaust gases of gas-diesel BelAZ 75131 mining dump trucks equipped with an onboard cryogenic fuel system, which use liquefied natural gas, methane, as a partial replacement for diesel fuel, has not been studied. In this regard, the research and calculation techniques, including the instrument base, were described in the present work. The results of studies on the quantitative CO_2, CO, and CH groups and O_2 concentrations in the exhaust gases of Cummins KTA 50 engines of gas-diesel BelAZ 75131 mining dump trucks under both diesel and gas-diesel (duel-fuel) operation were presented. Substantiations and conclusions were given regarding the reasons for their concentrations in exhaust gases.

2. MATERIALS AND METHODS

The key task of the present study is to determine the influence of the use of liquefied natural gas (methane) as a motor fuel on the concentration of harmful substances in exhaust gases in the field. The most interesting issue was determining the concentration of carbon dioxide (CO_2) in the exhaust gases.

The research was carried out on four gas-diesel BelAZ 75131 mining dump trucks with side numbers 3576, 3327, 3642, and 3588. During the research, diesel fuel replacement with liquefied natural gas averaged

25%–30%. The tests were performed at the maximum rotational speed of the Cummins KTA 50 engine. For a comparative analysis of the CO_2, CO, and CH groups and O_2 concentrations in exhaust gases, measurements were carried out along the same route: under diesel and then under gas-diesel operation of mining dump trucks. The measurements were carried out on difficult sections of the mine work: laden gas-diesel BelAZ 75131 mining dump trucks going uphill and downhill. The analysis of exhaust gases was conducted using the AUTOTEST-01.03M gas analyzer; the test date was June 2020. The components measured during the research, measurement range, and error limits are listed in Table 1.

Table 1: Components, measurement range, and error limits

Measured component	Measurement range	Graduation value	Measurement range section	Absolute error	Percentage error
CH group	0-3,000 mln^{-1}	1 mln^{-1}	0/333 mln^{-1} 333/3,000 mln^{-1}	± 20 mln^{-1} –	– ± 6%
CO	0%–7%	0.01%	0/3.3% 3.3/7%	± 0.2% –	– ± 6%
CO_2	0/16%	0.1%	0/16%	± 1%	–
O_2	0/21%	0.1%	0/3.3 % 3.3/21%	± 0.2% –	– ± 6%

Exhaust gas intake pipes 1 and 2 (Fig. 1) were mounted into the exhaust gas collectors of the Cummins KTA 50 gas-diesel BelAZ 75131 mining dump trucks. Then, they were connected through the tee (3) into a common metal hose (4), which was connected to the AUTOTEST-01.03M gas analyzer through the flexible hose and the filter element.

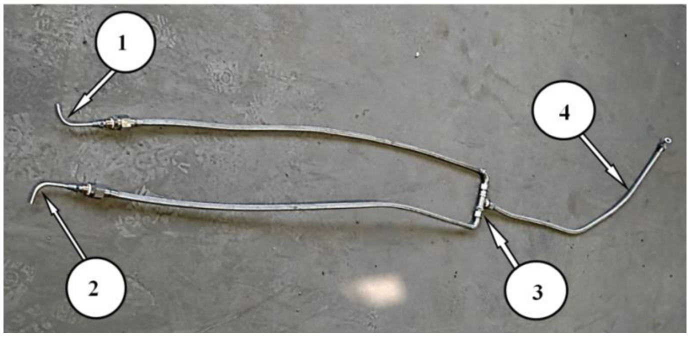

Figure 1: Flow metal hose for supplying exhaust gases to the gas analyzer

GOST R 51249-99 (Standartinform, 2000) defines the specific weighted average emission of harmful substances as the number of harmful substances emitted into the atmosphere with exhaust gases per 1 kWh of actual engine operation at completing a full test cycle, that is, g/(kWh). Maximum permissible values of specific weighted average emissions of harmful substances for newly manufactured ship, industrial, and diesel engines during their bench tests must correspond to the values given in Table 2 (Standartinform, 2000).

Table 2: Maximum permissible values of specific weighted average emissions of harmful substances

Rated parameter		Symbol	Rate of specific weighted average emissions	
			Emission before 2000	Emission after 2000
Specific weighted average emission of carbon monoxide (CO), g/(kWh)		e_{CO}^{p}	6.0	3.0
Specific weighted average emission of hydrocarbons (CH group) reduced to CH, g/(kWh)		e_{CH}^{p}	2.4	1.0
Specific weighted average emission of carbon dioxide (CO_2), g/(kWh)		e_{CO2}^{p}	–	–

For engines after overhaul, the values of the specific weighted average emissions of harmful substances with exhaust gases from the engines $[e_i^p]_{\mathrm{rep}}$ were determined based on the data in Table 2 using adjustment factors according to the following formula:

$$[e_i^p]_{\mathrm{rep}} = k_{\mathrm{rep}} e_i^p \tag{1}$$

The values of the adjustment factors depending on the harmful substances were determined according to the data in Table 3 (Standartinform, 2000).

Table 3: Adjustment factor values

Harmful substance	Adjustment factor values $k_{\text{рем}}$
Carbon monoxide (CO)	1.2
Hydrocarbons (CH group)	1.25
Carbon dioxide (CO_2)	–

The following indicators were measured:

- Effective power P_e, kW;
- Crankshaft speed n, min^{-1};
- Airflow rate reduced to normal atmospheric conditions (P_0 = 101.3 kPa,
- T_0 = 273 K) – V_{air}, m^3/h;
- Carbon dioxide concentration C_{CO2} in exhaust gases, vol. %;
- Carbon monoxide concentration C_{CO} in exhaust gases, vol. %;
- Oxygen oxide concentration C_{O2} in exhaust gases, vol. %;
- Concentration of the sum of hydrocarbons (reduced to $CH_{1.85}$) – C_{CH} in exhaust gases, ppm or vol. %.

The specific weighted average emission of the i-th harmful substance was calculated using the following formula:

$$e_i^p = 0.446\mu_i \frac{\sum_{j=1}^{m} C_{ij} V_{exhj} \omega_j}{P_{en} \sum_{j=1}^{m} \bar{P}_{ej} \omega_j} \tag{2}$$

where: μ_i – the molecular weight of the i-th harmful substance or its equivalent in terms of reduction (μ_{CO} = 28, μ_{CH} = 13.85, μ_{CO2} = 44), kg/kmol; m – number of test modes in a test cycle; j – serial number of the test mode in the test cycle; i – harmful substance index; C_{ij} – the concentration of the i-th harmful substance in the exhaust gases measured during tests in the j-th specified mode, vol. %; V_{exhj} – exhaust gas consumption reduced to normal atmospheric conditions (P_0 = 101.3 kPa, T_0 = 273 K), m^3/h, in a *wet* or *dry* state; P_{ej} – the ratio of the effective power of the diesel engine in the given test mode to the rated effective power; ω_j = 0.1–0.15 – mode weighting factor; P_{en} – diesel rated effective power, kW.

The volumetric flow rate of the exhaust gases V_{exh} (m^3/h) was calculated from the measured values of the flow rate of air and fuel in each test mode according to the following formula:

$$V_{exh} = V_{air} + F_f B_f \tag{3}$$

where: V_{air} – the volumetric airflow reduced to normal atmospheric conditions (P_0 = 101.3 kPa, T_0 = 273 K) m^3/h; F_f – the coefficient of reduction to normal atmospheric conditions of consumption of undiluted combustion products of various fuels (m^3/kg), taken according to the data given in Table 4 for the *dry* or *wet* state of exhaust gases; B_f – fuel mass, kg/h; Mass (diesel) fuel at a rated frequency of 1,900 rpm and a rated power of 1,200 (1,194) kW was 207 g/(kWh) or B_f = 248.4 kg/h.

The *wet* state of the exhaust gases was taken for cases when the moisture content of the undiluted gas sample supplied to the gas analyzer corresponded to the full composition of the combustion products. The *dry* state of the exhaust gases was taken for cases when the moisture content of the undiluted gas sample supplied to the gas analyzer was less than or equal to the equilibrium one at a temperature below 298 K. For the other cases, the *dry* state of the exhaust gases was obtained (Table 4).

Table 4: Fuel composition factor values.

Fuel	Value of the fuel composition factor F_f, m^3/kg for the state of the exhaust gases	
	wet	dry
Diesel	0.75	–0.77
Natural gas	1.33	–1.34

3. RESULTS

The task was to study the composition of the exhaust gases of the Cummins KTA 50 engine when driving in difficult terrain. The exhaust gas analysis data for laden dump trucks when going uphill are presented below. Therefore, the data obtained can be attributed to one mode – a mode close to the engine power at maximum load.

The values of the concentrations of the CH group (hydrocarbons) in the exhaust gases of the Cummins KTA 50 engine of gas-diesel BelAZ 75131 mining dump trucks at maximum load (driving uphill) under diesel and gas-diesel operation are shown in Fig. 2.

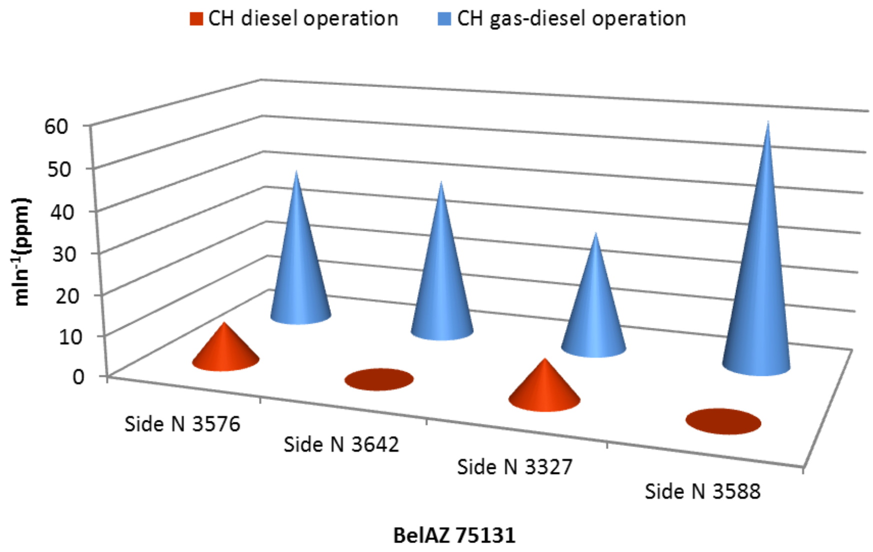

Figure 2: Concentrations of the CH group (hydrocarbons) in the exhaust gases of the Cummins KTA 50 engine under diesel and gas-diesel operations of gas-diesel BelAZ 75131 mining dump trucks at maximum load

Under diesel-only operation, the concentration of the CH group in the exhaust gases of the mining dump trucks with side numbers 3576 and 3327 was 10 ppm. There was no hydrocarbon content in the exhaust gases of the BelAZ trucks with side numbers 3642 and 3588. The presence of CH group hydrocarbons in exhaust gases was recorded under gas-diesel operation. The concentration of the CH group in the exhaust gases varied from 30 to 60 ppm. The presence of unreacted fuel in the form of CH group hydrocarbons in exhaust gases is explained by the supply of the fuel gas-air mixture under gas-diesel operation and the exit of a part of the gas-air mixture from the piston chamber to the exhaust manifold.

The CO concentrations in the exhaust gases of the Cummins KTA 50 engine under diesel and gas-diesel operation of BelAZ 75131 mining dump trucks at maximum load are shown in Fig. 3.

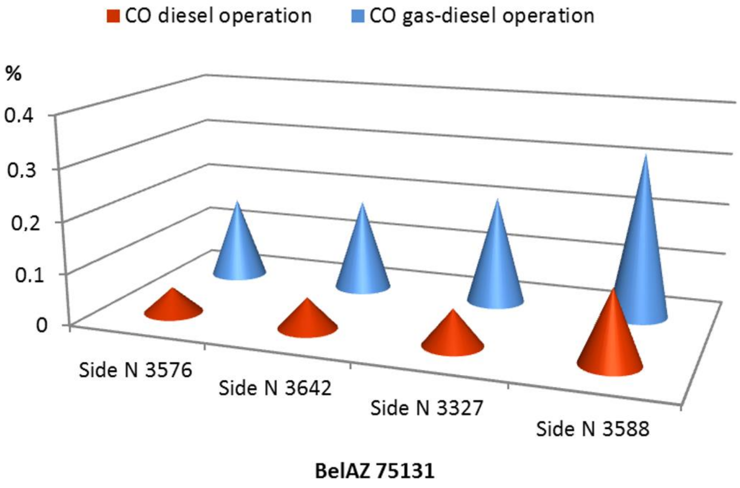

Figure 3: CO concentration in the exhaust gases of the Cummins KTA 50 engine under diesel and gas-diesel operation of BelAZ 75131 mining dump trucks at maximum load

The analysis of the presented bar graphs (Fig. 3) suggests that under gas-diesel operation, the carbon monoxide (CO) content in the exhaust gases of Cummins KTA 50 engines studied in this work exceeded that under diesel operation. The lowest CO concentration in exhaust gases under gas-diesel operation was recorded for BelAZ 75131 mining dump trucks with side numbers 3576 and 3642.

The values of oxygen (O_2) concentrations in the exhaust gases of the Cummins KTA 50 engine under diesel and gas-diesel operation of BelAZ 75131 mining dump trucks are shown in Fig. 4. The O_2 content in the exhaust gases of BelAZ 75131 mining dump trucks under gas-diesel operation was 3%–6% higher than that under diesel operation. This situation is probably due to incomplete intermediate reactions (b) and (d) (see Discussion), leading to the oxidation of CO in the presence of oxygen to form CO_2.

The values of the carbon monoxide (carbon dioxide) concentration in the exhaust gases under diesel and gas-diesel operation of the Cummins KTA 50 engine are shown in Fig. 5. As can be seen from the bar graphs, the decrease in CO_2 concentration under gas-diesel operation compared to that under diesel operation occurred on average by 5%–6%. It should be emphasized that a decrease in the CO_2 concentration in the exhaust gases occurred when diesel fuel was replaced by liquefied natural gas by only 25%–30%. Given this circumstance, we can assert that with an increase in the diesel fuel replacement with liquefied natural gas, an even greater decrease in the CO_2 concentration in the exhaust gases will occur.

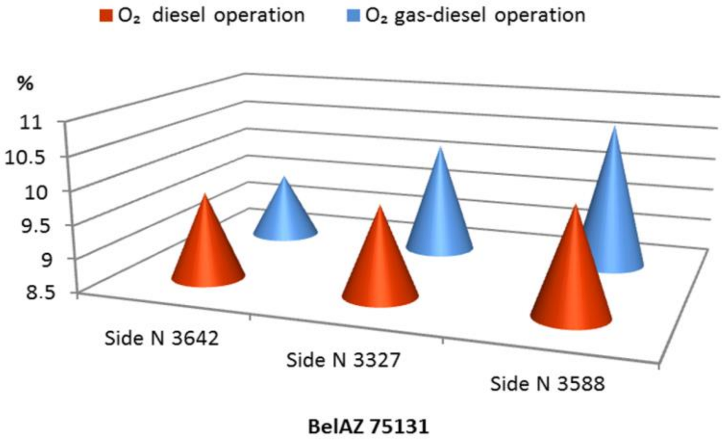

Figure 4: O_2 concentration in the exhaust gases of the Cummins KTA 50 engine under diesel and gas-diesel operation of BelAZ 75131 mining dump trucks at maximum load

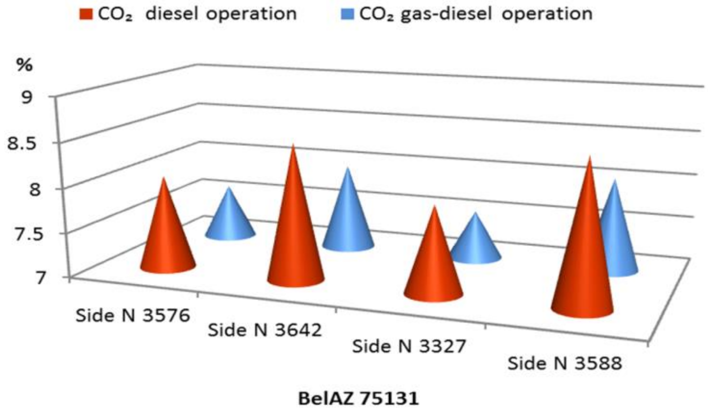

Figure 5: CO_2 concentration in the exhaust gases of the Cummins KTA 50 engine under diesel and gas-diesel operation of BelAZ 75131 mining dump trucks at maximum load

As a rule, the process of rock mass hauling is carried out along routes with different relief: smooth, uphill, and downhill. For this reason, it is crucial to conduct comparative studies of exhaust gases of laden and empty BelAZ 75131 mining dump trucks under diesel and gas-diesel operation when going uphill and downhill.

Tables 5–6 show the results of measurements of the CO, O_2, CO_2, and CH group concentrations of empty and laden BelAZ 75131 mining dump trucks under diesel and gas-diesel operation when going uphill. At the same time, the engine speed varied from 1,870 to 1,970 rpm when laden and from 1,920 to 1,930 rpm when empty.

Table 5: CO, O_2, CO_2, and CH group concentrations of empty and laden BelAZ 75131 mining dump trucks under diesel operation when going uphill

Measured component	Uphill – diesel fuel			
	Side N 3588		Side N 3327	
	laden	empty	laden	empty
CO, %	0.14	0.13	0.05	0.03
O_2, %	10.1	9.28	9.83	10.6
CO_2, %	8.59	8.83	8.18	7.25
CH, ppm	0	20	10	30
Engine rpm speed	1,870	1,930	1,970	1,920

Table 6: CO, O_2, CO_2, and CH group concentrations of empty and laden BelAZ 75131 mining dump trucks under gas-diesel operation when going uphill

Measured component	Uphill – gas-and-diesel fuel			
	Side N 3588		Side N 3327	
	laden	empty	laden	empty
CO, %	0.32	0.31	0.21	0.19
O_2, %	10.7	10.7	10.2	10.3
CO_2, %	8.05	7.97	7.55	7.12
CH, ppm	60	50	30	40
Engine rpm speed	1,940	1,940	1,940	1,930

Tables 5–6 show that when laden BelAZ 75131 mining dump trucks under diesel and gas-diesel operation go uphill, the CO, O2, CO_2, and CH group concentrations in the exhaust gases change slightly in comparison with those of empty BelAZ 75131 mining dump trucks.

Tables 7–8 show the results of measurements of the CO, O2, CO2, and CH group concentrations when laden and empty BelAZ 75131 mining dump trucks under diesel and gas-diesel operation go downhill. As shown by the results of the studies (Tables 7–8), the difference in the CO, O_2, CO_2, and CH group concentrations in exhaust gases for laden and empty BelAZ 75131 mining dump trucks under diesel and gas-diesel operation when driving downhill is insignificant. The concentration of the CH group under gas-diesel operation varied from 100 to 470 ppm.

Table 7: CO, O_2, CO_2, and CH group concentrations of empty and laden BelAZ 75131 mining dump trucks under diesel operation when going downhill

Measured component	Downhill – diesel fuel		
	Side N 3588		Side N 3327
	laden	empty	laden
CO, %	0.07	0.06	0.04
O_2, %	19.3	19.2	18.2
CO_2, %	2.48	1.54	3.73
CH, ppm	0	10	10
Engine rpm speed	1,300		

Table 8: CO, O_2, CO_2, and CH group concentrations of empty and laden BelAZ 75131 mining dump trucks under gas-diesel operation when going downhill

Measured component	Downhill – gas-and-diesel fuel		
	Side N 3588	Side N 3327	
	laden	laden	empty
CO, %	0.21	0.17	0.16
O_2, %	19.1	19.2	19.1
CO_2, %	2.2	1.61	1.51
CH, ppm	470	380	340
Engine rpm speed	1,300		

Table 9 shows the calculation of the weighted average emissions of the CO, CO_2, and CH groups in the composition of the exhaust gases at a rated load of laden BelAZ 75131 mining dump trucks under diesel and gas-diesel operation when driving uphill. The calculation was carried out according to Eq. (2).

Table 9: Weighted average emissions of the CO, CO_2, and CH groups in the composition of the exhaust gases of Cummins KTA 50 engines

Component	Diesel fuel			
	Sides numbers of BelAZ 75131 mining dump trucks			
	3,576	3,642	3,327	3,588
CO	1.47	1.76	2.06	4.11
CO_2	371.70	393.4	368.00	396.63
CH group	1.45E-04	0	1.45E-04	0
Component	Gas-diesel fuel			
	Sides numbers of BelAZ 75131 mining dump trucks			
	3,576	3,642	3,327	3,588
CO	4.70	5.29	6.17	9.40
CO_2	351.84	368.47	348.61	371.70
CH group	5.81E-04	5.81E-04	4.36E-04	8.72E-04

According to the data presented in Table 9, under gas-diesel operation, all studied Cummins KTA 50 engines have a decrease in emissions of carbon dioxide in exhaust gases with some excess of CO and CH group emissions in exhaust gases.

The results of the analysis of exhaust gases given above made it possible to obtain some key and reasonable conclusions of practical interest at this stage of research:

- Under gas-diesel operation of BelAZ 75131 mining dump trucks, there was a decrease in harmful emissions of carbon dioxide, which is one of the main greenhouse gases that negatively affect the global warming of the Earth. This fact is due to the relatively low (75%) relative carbon content in natural gas methane relative to diesel fuel, where the carbon content is 87%. Thus, we can assume that when diesel fuel is replaced by natural gas with an equivalent energy charge, CO_2 emissions are reduced.

- Oxygen concentration values in the exhaust gases increased under gas-diesel operation of BelAZ 75131 mining dump trucks.

- The presence of CH group hydrocarbons in the exhaust gases is explained by the fact that during the periods of overlap of the Cummins KTA 50 diesel engine valves, a part of the gas-air mixture flows from the piston chamber into the exhaust manifold. In other words, the presence of unreacted fuel in the form of CH group hydrocarbons in the exhaust gases occurred because of the supply of the fuel gas-air mixture under the dual-fuel operation of the Cummins KTA 50 diesel engine.

- With a decrease in the Cummins KTA 50 diesel engine speed, an increase in the content of CH group hydrocarbons in the exhaust gases occurred due to an increase in the scavenging period (valve overlap period). Simultaneously, CO emissions decreased as a result of an increase in the time required for the second stage of the intermediate chemical reaction.

- The concentration of CH group hydrocarbons under gas-diesel operation of mining dump trucks increased insignificantly and averaged 40 ppm. Therefore, almost all natural gas is burned in the Cummins KTA 50 diesel engine cylinders.

- Average weighted emissions of harmful CH group substances are insignificant compared to the Euro 5 standards for all Cummins KTA 50 diesel engines.

- Under gas-diesel operation, all studied Cummins KTA 50 diesel engines exceeded the weighted average harmful carbon monoxide (CO) emissions. The weighted average CO emissions under diesel operation did not exceed the Euro 5 standards.

- At the maximum load (driving uphill) of laden BelAZ 75131 mining dump trucks under diesel and gas-diesel operation, the concentrations of CO_2, CO, and CH group and O_2 components in the exhaust gases did not change compared to those of an empty mining dump truck driving uphill. The same effect was observed when the gas-diesel BelAZ 75131 mining dump truck went downhill.

4. DISCUSSION

According to some scholars (Lukanin, Morozov & Khachiyan, 1995), the content of the initial fuel in the exhaust gases in the form of a gas-air mixture is greatly influenced by gas exchange (i.e., the change in the working fluid during the exhaust and inlet processes). Experience shows that for better gas exchange during the valve overlap period, the inlet valve is traditionally opened approximately 10–30° before the piston reaches the top dead center, and the exhaust valve is closed 10–50° after the top dead center is reached. During this period, both valves were open (valve overlap period). In the optimal case, under the condition of lower pressure in the exhaust manifold relative to the pressure in the cylinder ($p_{vyp}<p$) and lower pressure in the cylinder relative to the pressure in the inlet manifold ($p<p_{vp}$) supplying the gas-air mixture, an incoming charge enters the cylinder through the inlet valve, and exhaust gases are removed through the exhaust gas. This gas exchange is known as scavenging. During the scavenging period, there was a slight overflow of the initial gas-air mixture into the exhaust manifold. This situation is evidenced by the presence of CH group hydrocarbons in the exhaust gases under gas-diesel operation.

I. D. Nigmatulin (2014) has argued that severe fuel combustion is observed under nominal gas-diesel operation. An increase in the emissions of CH group hydrocarbons and carbon monoxide was noted. More significant CH group emissions are especially typical for gas-diesel operation with low loads and high excess air ratios. This situation is due to the incomplete combustion of gaseous fuel in gas-diesel when working on lean mixtures. Under these conditions, deterioration in fuel efficiency was also observed.

Thus, the research results have shown the feasibility of converting to diesel operation under light-load and no-load conditions to reduce hydrocarbon emissions and fuel consumption. Studies have also shown that in order to improve the performance of an engine under gas-diesel operation, it is necessary to optimize the composition of a combustible mixture under all conditions, control the injection time of the ignition dose of diesel fuel, and select and adjust the valve timing.

The Department of Road Transport of the Ministry of Transport of the Russian Federation (Department of Road Transport of the Ministry of Transport of the Russian Federation, 2003) has asserted that the reduced combustion rate compared to that of liquid petroleum fuel one is one of the disadvantages of natural gas when used in gas-diesel operation. Other scholars (Morev, Erokhov & Beketov, 1992) have claimed that the combustion rate of methane is up to 0.8 m/s, and the explosive combustion rate of methane is 500–700 m/s. The combustion rate depends on the concentration of the combustible gas, the temperature of the medium, and other factors. During the normal combustion of fuel oil, the flame spread at a speed of 10–15 to 30–35 m/s. During the detonation combustion, the flame propagation speed ranges from 1,500 to 2,500 m/s (Nagiev, 1961). In this regard, it can be assumed that with a reduced combustion rate of natural gas, the combustion reaction for the example of methane proceeds through both the main reaction (a) and sequentially through the intermediate reactions (b), (c), and (d):

$$\mathrm{CH_4} + 2\mathrm{O_2} = \mathrm{CO_2} + 2\mathrm{H_2O}, \tag{a}$$

$$\mathrm{CH_4} + 1{,}5\mathrm{O_2} = \mathrm{CO} + 2\mathrm{H_2O}, \tag{b}$$

$$2\mathrm{CO} + \mathrm{O_2} = \mathrm{CO_2}, \tag{c}$$

$$\mathrm{CH_4} + \mathrm{H_2O} = \mathrm{CO} + 3\mathrm{H_2} \tag{d}$$

In this regard, it can be argued that under gas-diesel operation, due to the reduced combustion rate of natural gas compared to that of diesel fuel, intermediate reactions (b) and (d) with the formation of carbon monoxide do not have time to occur before the formation of CO_2. At the same time, the CO_2 content in the exhaust gases under gas-diesel operation decreased.

5. CONCLUSION

Equipping BelAZ mining dump trucks with onboard cryogenic fuel systems, as well as converting them to gas-diesel operation, is a promising area for their modernization in terms of optimizing environmental and economic performance indicators. In the conditions of a relatively small mining region of Russia – Kuzbass –where more than two thousand BelAZ mining dump trucks are operated in coal mines, work in this field is quite relevant. However, the absence of the necessary scientifically grounded engineering solutions and methods for assessing the cost-performance ratio of onboard cryogenic fuel systems hinders the ongoing work on converting mining dump trucks to gas-diesel operation. In this regard, studies in the field of substantiation and development of design and circuit solutions for the placement and layout of onboard cryogenic fuel systems for heavy-duty mining dump trucks in conjunction with environmental, mining, and ergonomic requirements, as well as the subsequent study of their operating characteristics, are quite relevant today.

REFERENCES

Azikhanov, S. S., Bogomolov, A. R., Dubov, G. M., & Nikhrin, S. (2019). Development of the instrumentation system for gas-and-diesel fuelled BelAZ dump truck. MATEC Web of Conferences, 297, 03001.

Chernetsov, D. A. (2010). Toxicity of the fulfilled gases of diesel engines and their anthropogenous effect. Problems of Contemporary Science and Practice. Vernadsky University, 10-12(31), 54-59.

Department of Road Transport of the Ministry of Transport of the Russian Federation. (2003). Guideline for the organization of operation of compressed natural gas vehicles in supersession of RD-200-RSFSR-12-0185-87, MU-200-RSFSR-12-0163-87, MU-200-RSFSR-12-0016-84, MU-200-RSFSR-17-0229-89, R 3107938-0252-88 (January 1, 2003). Moscow, Russia.

Dubov, G. M., Trukhmanov DS, Kuznetsov IV Nokhrin, S. A (2019b). Prospects for the use of liquefied natural gas as a motor fuel for haul trucks. E3S Web of Conferences, 105, 03018.

Dubov, G. M., Trukhmanov, D. S., Kuznetsov, I. V., Nokhrin, S. A. (2019a). Procedure for haul truck onboard LNG fuel systems performance evaluation. E3S Web of Conferences, 105, 03019.

Dubov, G. M., Trukhmanov, D. S., Nokhrin, S. A., & Sergel, A. (2019). Development of technical requirements for on-board cryogenic fuel systems of BelAZ dump trucks. MATEC Web of Conferences, 297, 03002.

Dubov, G. M., Trukhmanov, D. S., Nokhrin, S. A., & Sergel, A. (2020). Method for installing cryogenic fuel tanks on the deck of BelAZ 7513 mining dump truck. E3S Web of Conferences, 174, 03016.

Dubov, G., Trukhmanov, D., Nokhrin, S., & Sergel, A. (2019). Method of installing cryogenic fuel tanks on a quarry dump truck, Patent 2701133C1 (September 24, 2019). Moscow, Russia.

Dubov, G.M., Trukhmanov, D.S., & Nokhrin, S. A. (2020). The use of alternative fuel for heavy-duty dump trucks as a way to reduce the anthropogenic impact on the environment. IOP Conf. Series: Earth and Environmental Science, 459, 042059.

Dubov, G.M., Trukhmanov, D.S., Chegoshev, A.A., & Ashikhmin, V. (2018). Substantiation of the need to create an eccentric cycloidal gearing transmission of geokhod. E3S Web Conferences, 41, 03008.

Khazin, M. L. (2019). Conversion of mining dump trucks to gas operation in the north. Bulletin of the Perm National Research University. Geology, 19(1), 56-72.

Khazin, M. L., & Tarasov, A. P. (2018). Eco-economic assessment of open-pit trolleys. Bulletin of the Perm National Research University. Geology, 17(2), 66-80.

Kuznetsov, I. V., Panachev, I. A., Dubov, G. M., & Nokhrin**, S. A.,** (2019). Energy evaluation of the operation of gas and diesel dump trucks BelAZ – 75131 on the cuts of Kuzbass. Handbook. An Engineering Journal, 4(265), 19-23.

Kuznetsov, I. V., Panachev, I. A., Dubov, G. M., & Nokhrin, S. A., (2020). Energy assessment of BelAZ-75131 gas-diesel mining dump trucks operation at Kuzbass open casts. E3S Web of Conference, 174, 03010.

Lukanin, V. N., Morozov, K. A., & Khachiyan, A. S. (1995). Internal combustion engines. Work Process Theory. Moscow, Russia: Vysshee Obrazovanie.

Morev, A. I., Erokhov, V. I., & Beketov, B. A. (1992). Gas vehicles. A Handbook. Moscow, Russia: Transport.

Nagiev, M. F. (1961). Chemistry, technology and calculation of the synthesis of motor fuels. Baku, Aizerbajdan: Academy of Sciences of the Azerbaijan SSR.

Nigmatulin, I. D. (2014) Study of operational and technological indicators of agricultural tractors equipped with gas equipment (Dissertation of Candidate of Technical Sciences). Saratov, Russia: Saratov State University.

Standartinform. (2000). Internal combustion reciprocating engines. Emissions of Harmful Substances with the Exhaust Gases. Limit Values and Test Methods, GOST R 51249-99 (January 1, 2000). Moscow, Russia.