Development of the instrumentation system for gas-and-diesel fuelled BelAZ dump truck

Sergey Azikhanov^{2*}, *Aleksandr Bogomolov*^{1,2}, *Georgiy Dubov*³ and *Sergey Nokhrin*⁴

¹T.F. Gorbachev Kuzbass State Technical University, Department of Heat Power Engineering, 28 Vesennya st., Kemerovo, the Russian Federation

²Kutateladze Institute of Thermophysics SB RAS, Academician Lavrentyev Prospect, 1, Novosibirsk, the Russian Federation

³T.F. Gorbachev Kuzbass State Technical University, Department of Mechanical Engineering Technology, 28 Vesennya st., Kemerovo, the Russian Federation

⁴OOO «Sibir-Energo», 13 Schyorsa st., Novokuznetsk, the Russian Federation

Abstract. The prospects for the use of natural gas as a motor fuel are considered. The state-run program for the development of natural-gas-fuelled vehicles will entail an increase in the share of transport operating on natural gas. The data on the thermal performance of natural gas from various fields, the volumetric heat values of the stoichiometric mixture of which is almost the same, are given. The analysis of the operation of gas-diesel-fuelled BelAZ dump truck, which burns liquefied natural gas, is conducted. The schematic diagram for engine power supply with liquefied natural gas is given. The calculation of the liquefied natural gas supply system with the replacement of diesel fuel by 33% was made. As a result of the calculation, the diameter of a fuel manifold after injectors, which provides the recommended gas velocity through a manifold, was determined. The instrumentation system for controlling the amount of supplied natural gas is proposed. The complex allows obtaining data on the instantaneous gas flow rate and the total flow rate over a period of time. A pulsation damper used as part of the system allowed reducing gas pulsation in fuel manifolds after injectors, to create conditions for the use of orifice plate flow meters, and ensured the uniform supply of natural gas to both banks of cylinders, which favourably affected the engine.

1 Introduction

The global consumption of mineral resources is increasing annually. This is increasingly leading to a significant demand from mining companies for high-quality mining equipment, ensuring optimum economic and environmental requirements [1].

Gas fuel is currently an alternative to traditional motor fuel. Natural gas is the most cost effective, environmentally friendly and safe type of fuel. The studies conducted have shown that the energy intensity of rock mass hauling by dual-fuel (gas and diesel) dump trucks is less than that for dump trucks operating on diesel only [2-10]. Adopted international strategies to reduce emissions of greenhouse gases, reduce emissions of nitrogen oxides and sul-

*Corresponding author: azikhanov@rambler.ru

phur will contribute to the search for alternative energy sources. In recent years, there has been an intensive development of gas engine vehicles. Russia is the world leader in natural gas reserves. At the end of 2018, gas consumption as a motor fuel amounted to 624 million m³. According to the long-term state strategy for the development of gas-engine market, by 2030 it is planned to increase this figure to 11 billion m³. The qualities of gas as a motor fuel can be divided into three groups: the actual motor qualities, i.e. properties that determine the course of the combustion process and the entire engine operating process; properties that determine the operation of the fuel equipment of the vehicle; properties that determine the conditions for the fuel production and its delivery to the consumer. The main factors determining the feasibility and efficiency of using gas motor fuel are the first group qualities. But other qualities also need to be taken into account, as they determine design and technology concepts. Natural gas as a fuel is used in compressed or liquefied states. The main consumers of compressed natural gas (CNG) are passenger cars and light-duty trucks. It is assumed that the main consumers of liquefied natural gas (LNG) will be water-borne transport, line-haul trucks, mining and agricultural vehicles [11-15].

Motor fuel quality is determined by the energy performance of gas, which mainly depends on the heat value.

The highest heat value of combustible components of natural gas of saturated hydrocarbons can be calculated by the formula:

$$Q_{vm} = 221.8 + 672.66n - 1.7778n^2 \quad (1)$$

where n – carbon number. Calculation error in comparison with reference data does not exceed 0,14%.

Table 1. Higher heat value of saturated hydrocarbon gases

Gas	Chemical formula	Heat value kJ/(mol)		Calculation error
		Reference data	By formula (1)	
Methan	CH ₄	891.6	892.5	0.10
Ethane	C ₂ H ₆	1562.1	1559.9	0.14
Propane	C ₃ H ₈	2223.2	2223.6	0.02
Normal butane	CH ₃ –CH–CH–CH ₃	2882.6	2886.2	0.12
Normal pentane	CH ₃ –CH–CH–CH–CH ₃	3541.2	3540.6	0.02

The lowest heat value of the gas mixture, in which combustible components are represented by normal saturated hydrocarbons, can be calculated by the formula

$$Q_{nv} = 7532 \sum_1^n r_n + 26290 \sum_1^n nr_n + 73.9 \sum_1^n n^2 r_n, \quad (2)$$

where r_n – the volume fraction of hydrocarbon gas, containing n carbon atoms in the molecule, in a mixture.

The actual heat values and volumetric stoichiometric mixture of natural gas from different fields are given in the table 2.

Table 2. Thermal performance of natural gas from various fields

Gas field	Heat value kJ/m ³		The volume of air required for the combustion of 1 m ³ of gas, m ³ /m ³	Volumetric heat value of stoichiometric mixture, kJ/m ³
	lower, Q_n	higher, Q_v		
Ukhta	33294	36923	8.84	3383
Saratov	35866	39763	9.50	3415

Bugurusla	36830	40643	9.72	3435
Kurdyum	33684	37392	8.94	3408
Melitopol	35158	39051	9.34	3400
Dashava	35711	39633	9.48	3407
Stavropol	35568	39470	9.44	3408
Shebelinka	35515	39344	9.41	3411
Komi	34312	37987	9.09	3401
Gazli	36956	40982	9.80	3421
Volgograd	35506	39386	9.42	3407
Astrakhan	36830	40794	9.75	3425
Nayip	36667	40702	9.73	3417
Orenburg	37132	41054	9.85	3412
Vuktyl	47007	51621	12.40	3507
Shatlyk	36227	40224	9.62	3411

We note (see Table 2) that the lower and higher heat values differ significantly for different fields. The highest heat values belong to the natural gas of Vuktyl field. Compared to other fields, the composition of this gas has a higher content of heavy alkanes and a smaller amount of methane. The volumetric heat value of the stoichiometric mixture of natural gas is almost the same for gases of the listed fields. This relationship is due to the stoichiometrically necessary, corresponding to a directly proportional relationship between the heat value and the volume of air required for the combustion of 1 m³ of gas. As follows from table 2, most of natural gases have the high heat value of the stoichiometric fuel-air mixture, which makes them desirable to be used as a motor fuel.

2 Results and discussion

One of the first Russian companies involved in the conversion of heavy-duty mining vehicles to gas and diesel operation is “Siberia-Energo” LLC (Novokuznetsk) and “TechnoEco” LLC (Prokopyevsk). Positive results were obtained of the operation of BelAZ with a 1200 kW KTA-50a engine using LNG.

The schematic diagram of the power supply of KTA-50a engine with liquefied natural gas is shown in Figure 1.

Fig. 1. Schematic diagram of the engine liquefied natural gas supply system: 1 – cryogenic fuel tank; 2 – control evaporator; 3 – main evaporator; 4 – injectors; 5 – air intakes; 6 – gas fuel manifold; 7 – fuel metering unit; 8 – relief valve.

Liquefied natural gas with a temperature of -115-135°C and a pressure of 1.0-1.5 MPa from the cryogenic fuel tank 1 enters the main evaporator 3, in which it boils and the overheats to required extent. After the evaporator, gas is reduced and at a pressure of 0.45-0.55 MPa enters the injector 4, and then is supplied into two air intakes 5, where it mixes with air, forming the fuel-air mixture. To maintain a constant working pressure in the cryogenic

fuel tank, the control evaporator 2 is used. It evaporates such a quantity of gas that, at working pressure in the cryogenic tank, compensates for the volume of fluid flowing from the tank. The relief valve 8 is provided to ensure that the gas pressure in the tank does not exceed the permissible magnitudes.

When converting an engine from diesel to gas-and-diesel operation, it is important to know the flow rate of natural gas supplied to the cylinders in order to determine the percentage of diesel fuel replacement. Analysing the operation of BelAZ-75137 dump truck, it was found that natural gas, passing through the evaporator and the gearbox, is supplied to the injectors racks. After the injectors, gas is supplied through the manifold with an internal diameter of 16 mm into two air intakes. Moreover, the gas supply line to one of the intakes was partially pinched during operation. This was due to gas pulsations after the injectors, which led to a pressure drop between the turbines and the engine detonation. According to the authors, this pinch, on the contrary, can lead to a deterioration of the engine, since one bank of cylinders remains less loaded.

The authors have calculated the natural gas supply system with diesel fuel replacement by 33%. As a result of the calculation, a diameter of the manifold after the injectors, which provides the recommended gas velocity through the manifold, was determined.

The volumetric heat value of natural gas is $Q_n^V = 34.15 \text{ MJ/m}^3$.

The density of natural gas composition under normal conditions:

$$\rho_{0sm} = \rho_{ch4} \cdot r_{ch4} + \rho_{c2h6} \cdot r_{c2h6} + \rho_{c3h8} \cdot r_{c3h8} = 0.73 \text{ kg/m}^3 \quad (3)$$

The density of natural gas after the injectors in the manifold that supplies natural gas to the air intake:

$$\rho = \rho_{0s} \frac{PT_0}{P_0T} = 0.73 \frac{0.1 \cdot 273}{0.1 \cdot 313} = 0.637 \text{ kg/m}^3. \quad (4)$$

The average velocity of natural gas in the manifold with a diameter of $d=0.016 \text{ m}$ after the injectors is $w=129 \text{ m/s}$, adjusted to operating conditions at a temperature of $+40^\circ\text{C}$ is $w=148 \text{ m/s}$.

Such a high velocity can be used for highly diluted or superheated gases (vapours). For gases at atmospheric pressure, the recommended velocity in the lines is 12-16 m/s, and for superheated vapours it is 30-75 m/s. Assume that the velocity of natural gas should not exceed 30 m/s. The volumetric flow rate of natural gas under operating conditions is $V=0.0298 \text{ m}^3/\text{s}$.

The manifold diameter after the injectors to ensure accepted recommended velocity is:

$$d = \sqrt{\frac{4 \cdot V}{\pi \cdot w}} = \sqrt{\frac{4 \cdot 0.0298}{3.14 \cdot 30}} = 0.0355 \text{ m} \quad (5)$$

To control the amount of natural gas supplied, the gas supply instrumentation system was proposed. It includes two flowmeters, two differential pressure sensors, two thermocouples, a pressure pulsation damper, an electronic unit and connecting lines. The operation of the flowmeter is based on the passage of gas through the orifice. Many methods and devices for measuring and controlling gas flow are known. Constriction flowmeters are widely used in measuring instruments. The advantages of such flowmeters are simple design and reliability. As a disadvantage, it is possible to identify difficulties in measuring pulsating flow rates. Thermocouples were installed in the flowmeters to adjust the density value with a change in the gas temperature. The dimensions of the orifice at a given performance and pressure drop are determined. The signal from the differential pressure sensor enters the

electronic unit, where it is converted to the gas flow rate, taking into account the temperature. The screen displays the average rate of natural gas flow. There is a flow integrator, which allows recording the gas flow for the period of engine operation (shift, day, etc.). To reduce the effect of gas pulsations on the operation of flowmeters, the authors proposed to install a pressure pulsation damper after the injectors. The scheme of natural gas supply from the injectors racks to the air intakes is shown in Figure 2.

In the tests, the existing fuel manifold after the injectors with an inner diameter of 16 mm was replaced by the manifold with a diameter of 38 mm. Natural gas was supplied uniformly in both lines, as evidenced by the testimony of the flowmeters, while the injectors were not clamped. Interruptions and detonations in the engine were not observed. In addition, there was a decrease in pressure drop between the right and left turbines when operating on gas-diesel in comparison with the diesel-fuelled operation. The data obtained indicate a reduction in the negative effect of gas pulsations, both on the operation of flowmeters and on the operation of turbines when using a pressure pulsation damper.

Fig. 2. The scheme of natural gas supply to the air intakes: 1 – injectors racks; 2 – tubing tee; 3 – pulsation damper; 4 – flowmeters; 5 – air intakes.

3 Conclusions

The introduction of the instrumentation system in the gas-and-diesel fuel system of BelAZ dump truck allows:

- to ensure the constancy of gas supply to both banks of engine cylinders;
- to ensure the engine stability;
- to exclude detonation when the engine is running on gas-diesel;
- to track online gas flow at the current time, as well as for a certain period of time (shift, day, etc.).

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