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Increasing mining dump trucks operation efficiency with the use of gas piston engines

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Abstract

Research aim *is to analyze the prospects for increasing the efficiency of heavy-duty mining dump trucks operation through the use of natural gas as the main energy carrier.*

Research methodology *included bench tests of a gas piston engine (GPE) KAMAZ mod. 820.60-260 with a capacity of 191 kW and the construction of forecast values of GPE parameters for the BELAZ-75319 mining dump truck with a load capacity of 240 tons.*

Results. *A mathematical model and technique have been developed that allows predicting the main parameters of a gas piston engine and optimizing its economic and environmental characteristics. The use of natural gas as a motor fuel, with an unchanged engine design, leads to a decrease in its power. Currently, gas modifications are being created on the basis of existing diesel engines, and it is not always possible to implement any design measures at this stage. To realize all the capabilities of a gas engine, it should initially be designed for gas motor fuel. This technique is based on the experimental data of low-power gas piston engines and can be used for high-power gas engines studies intended for installation on mining dump trucks.*

Conclusions. *Increasing the efficiency of mining dump trucks in the near future is possible through the use of natural gas as the main energy carrier. The use of natural gas as a motor fuel allows to increase the life of the engine, reduce the noise level and toxicity of exhaust gases, and reduce fuel costs.*

Key words: *mining dump trucks; open pit mining; diesel fuel; natural gas; gas piston engine; environmental and economic efficiency.*

Introduction. A feature peculiar to the contemporary period is the growth of excavation depth together with more complex mining and geological conditions of fields. When mining with an open pit, automobile is the main means of utility vehicles and is used to transport about 80% of the total rock mass. Global mining industry consumes billions of tons of diesel fuel annually, while the loaded dump trucks going up the hill consume 70–80% of the total fuel.

Researches at a number of open pits [1–3] have determined that with highly intensified and concentrated production and the grows of excavation depth, the air gets polluted with harmful impurities with the maximum permissible concentration (MPC) of carbon oxides being exceeded by 1.5–3 times and nitrogen oxides by 5–7 times. Constant impact of exhaust fumes on the human body may cause immunodeficiency and bronchitis, brain blood vessels, nervous system and other organs are affected; miners exposed to exhaust fuels over the course of 10–20 years were diagnosed with lung cancer [4–6].

Alternative fuels are considered today as a means of expanding the base of energy resources and reducing anthropogenic impact on the environmental [7–9]. Practice

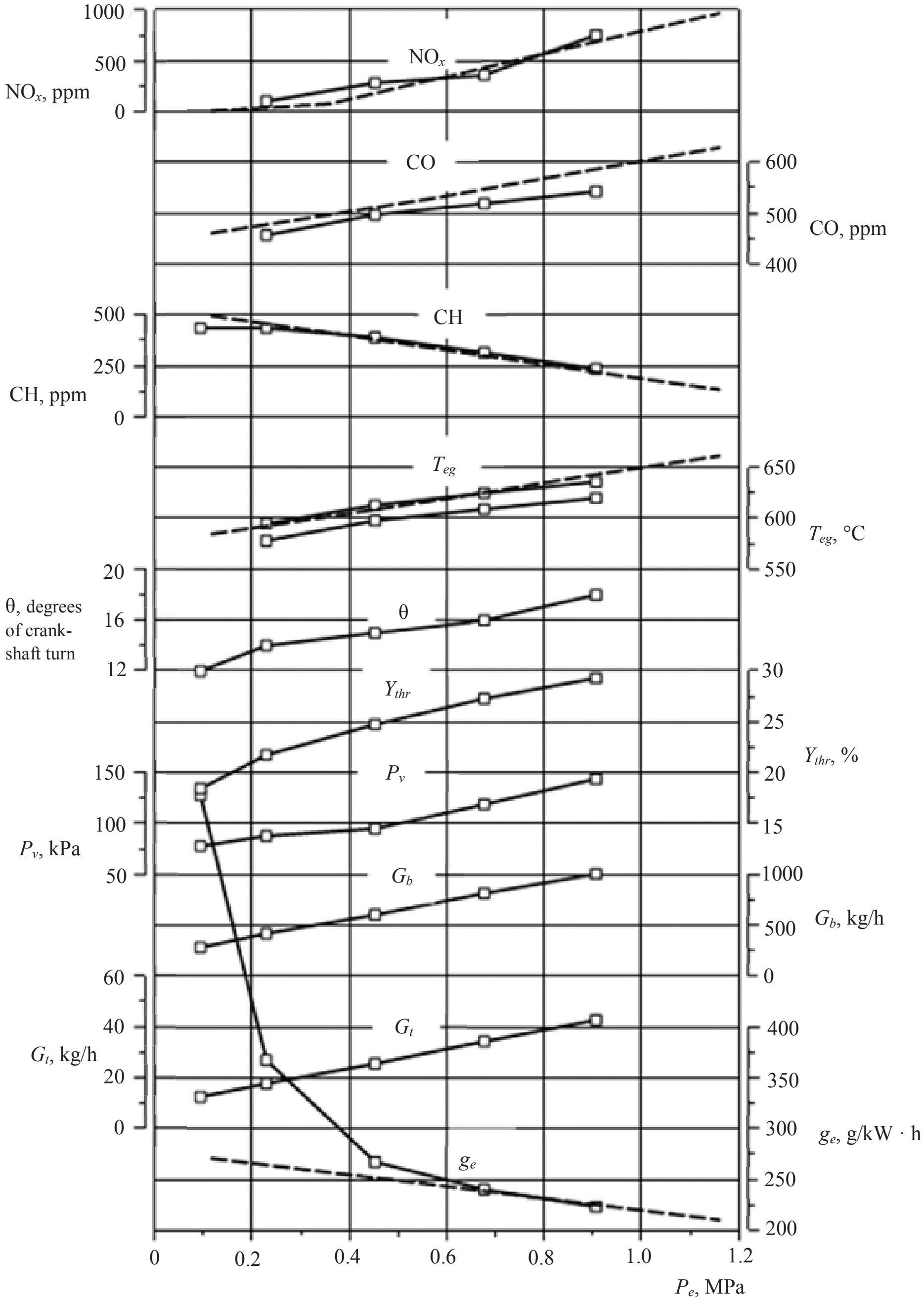

Fig. 1. Load performance of KAMAZ 820.60-260 gas engine under n = 2200 r/mn:
G_b – mass air flow, kg/h; G_t – mass fuel flow, kg/h

Рис. 1. Нагрузочная характеристика газового двигателя КАМАЗ модели 820.60-260 при n = 2200 об/мин:
G_b – массовый расход воздуха, кг/ч; G_t – массовый расход топлива, кг/ч

proves that the most promising trend for transport vehicles is the application of gas fuel [10–16]. Natural gas doesn't form deposits in the fuel system, doesn't wash off the firm of oil at the cylinder walls reducing friction and engine wear. The use of the natural gas as motor fuel will make it possible to increase the life of engine by 1.5–2 times.

Gas has another important advantage – it is much cheaper than diesel fuel. For that reason, Kovdorskiy GOK (Kovdorskiy mining and processing plant) has begun switching its mining dump trucks to liquefied natural gas (LNG) since 2015. Kovdorskiy GOK is the first enterprise in Russia to set to the realization of such project (https://www.hibiny.com/news/archive/75172).

Research aim is to analyze the prospects for increasing the efficiency of heavy-duty mining dump trucks operation through the use of natural gas as the main energy carrier.

Research methodology. Automotive manufacturers currently turn out dump trucks with gas pistol engines, for example, KAMAZ PTC and URAL AZ manufacture dump trucks with the capacity up to 20 tons, OJSC BELAZ – up to 45 tons. The use of gas pistol engines at heavy-duty dump trucks is at the stage of research and development.

When switching mining dump trucks to gas fuel it should be noted that if engine construction is not changed, its power loss can reach 30%. It is due to the fact that *natural gas–air* mixture burns only with 5 to 15% of gas volume fractions. Consequently, for effective burning and exhaust toxicity norms compliance, the stoichiometric ratio of fuel mixture should be maintained, which makes up 9.53 for the natural gas for the volume fractions of fuel and air. Therefore, the natural gas makes up almost 10% of the mixture volume entering the cylinder which prevents from obtaining significant inflation of a cylinder with air. Diesel fuel enters the motor cylinder through the injection nozzle at the compression stroke and therefore doesn't have an effect on the volumetric inflation of a cylinder with air. For this reason the application of gas engines at mining dump trucks requires the development of some measures on uprating the engine.

The main problem for the high dimension engines when changing to the natural gas is to ensure stable combustion of the air-fuel mixture in the cylinder. It is known that natural gas combustion in the cylinder is relatively slow as compared to diesel fuel. It imposes certain constraints on the choice of the cylinder diameter and, therefore, performance per liter. Currently, for the gas engines fueled by the natural gas, the maximum performance per liter is 25 kW/l [9].

In order to improve the performance of the dump truck engine, the engine displacement should be increased by means of increasing the number of cylinders, which adversely affects the dimensions and utilization efficiency of the motor.

A way of improving the utilization efficiency of heavy-duty dump trucks is to determine the dependence between the mean effective pressure P_e of a gas engine and the adjustment parameters if the optimum economic and ecological features are reached.

The research was based on the results obtained during the bench test of KAMAZ 820.60-260 engine (Euro-4) [17, 18]. The following parameters of the motor were studied: P_e – mean effective pressure, MPa; g_e – brake-specific efficient fuel consumption, g/kW · h; T_{eg} – the temperature of the end gas in front of the centrifugal compressor turbine, °C; NO_x – nitrogen oxide concentration in the end gas, ppm; CO – carbon oxide concentration in the end gas, ppm; CH – unburned hydrocarbons concentration in the end gas, ppm.

In the course of the experiments the following factors varied: P_v – pressure in front of the inlet valves, kPa; θ – ignition advanced angle, degrees of crankshaft turn; Y_{thr} – the rate of opening of the throttle, %.

The indicated factors have been chosen as having the greatest influence on the engine parameters under investigation.

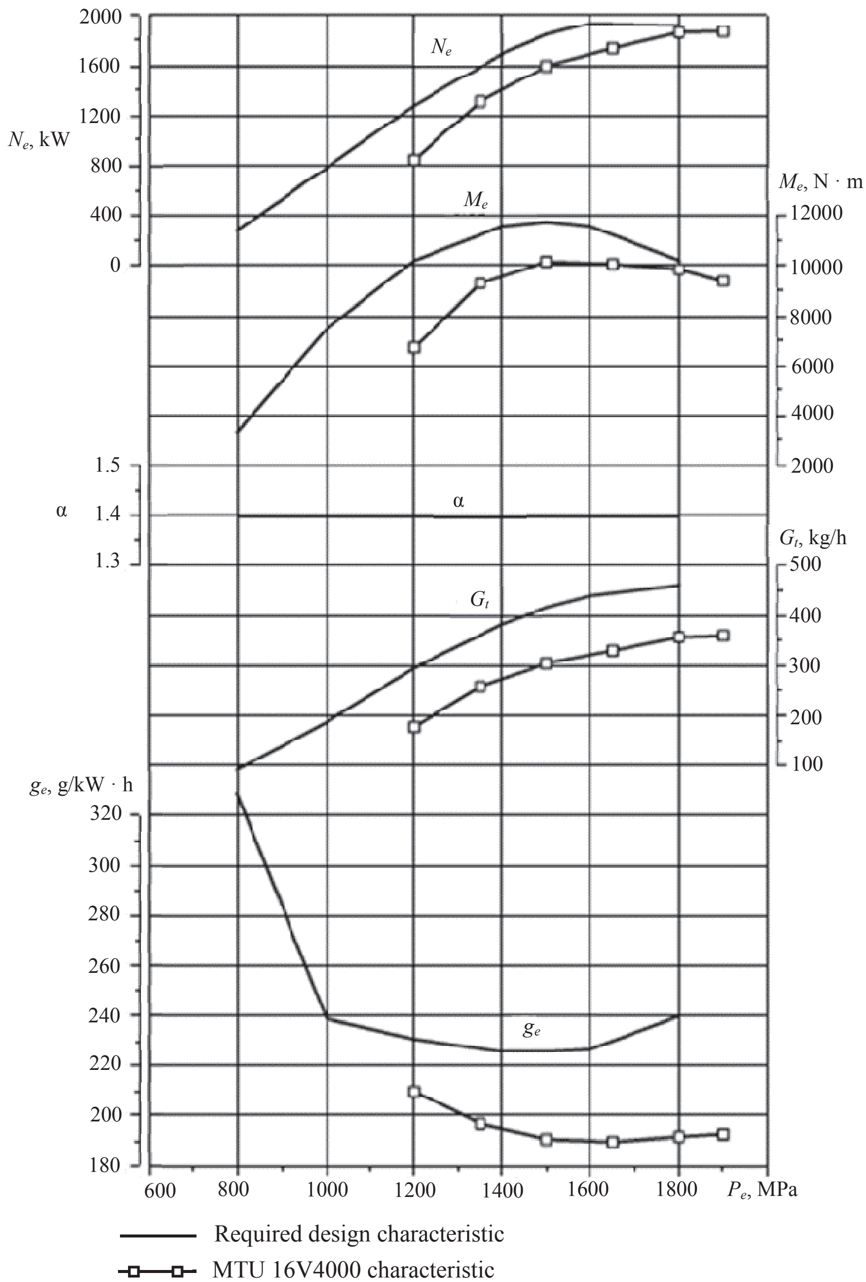

Fig. 2. Required external speed characteristic of gas engine 12DM-185A (initial data) as compared to the characteristics of diesel engine MTU 16V4000:
N_e – efficient power, kW; M_e – effective torque, N · m; n – crankshaft speed, r/mn; α – excess air ratio
Рис. 2. Требуемая внешняя скоростная характеристика газового двигателя 12ДМ-185А (исходные данные) в сравнении с характеристикой дизельного двигателя MTU 16V4000:
N_e – эффективная мощность, кВт; M_e – эффективный крутящий момент, Н · м; n – частота вращения коленчатого вала, об/мин; α – коэффициент избытка воздуха

In the course of investigation the task of optimization was being solved, i. e. reaching minimum values of the parameters which characterize economic and ecological indicators of the engine when reaching the required power indices.

Pressure effect in front of the admission valves. The data about the optimum values of boost pressure obtained when calculating and in bench tests have shown that the level of pressure should be about 90 kPa. Pressure reduction significantly reduces fuel efficiency, while pressure growth leads to the growth of harmful substances release volume with the end gas.

Ignition advanced angle effect. The data about the effect of the ignition advanced angle are fully studied [17, 18]: as the angle measure increases, the fuel efficiency grows, but at the same time, harmful substances release volume grows. The results of the research have shown that the most optimum is the angle of 18–20 degrees of crankshaft turn at full load.

The effect of throttle rate of opening. The issue of the effect from the percent opening of a throttle has not been studied on purpose. The data from practice and experiments show that it is advisable to maintain the rate of opening about 30%. From practical experience it is known that the reduction of the opening angle of the throttle in mode of full load can vary within a rather narrow range. It is connected with the fact that the throttle for the engine is structurally oversized.

To study the engine parameters, fractional factorial experiment has been carried out based on the two-level orthogonal planning (norm and deviation from a norm) for each factor with the number of experiments 2^3. After the experiments and after calculating the corresponding coefficients, the following equations of regression have been obtained in the variables and natural values:

$$\begin{cases} P_e = -1,38 + 0,007P_v - 0,019\theta + 0,064Y_{thr}, \\ g_e = 356,5 - 0,43P_v + \theta - 3,5Y_{thr}, \\ \mathrm{NO}_x = -1866 + 7,638P_v - 22,56\theta + 72,78Y_{thr}, \\ \mathrm{CO} = 237,25 + 1,43P_v - 6\theta + 10Y_{thr}, \\ \mathrm{CH} = 1006 - 2,48P_v + 9,88\theta - 23,75Y_{thr}, \\ T_{eg} = 478,75 + 0,58P_v - 2,63\theta + 5Y_{thr}. \end{cases} \tag{1}$$

Statistical analysis with Student and Fisher's criterion [19] has shown that all coefficients in regression equations are significant and the equations obtained are adequate to experimental data under the 5% level of significance (fig. 1).

In the course of solving the problem, the threshold values were chosen based on the following:

– achievement of the maximum value of power must ensure minimum value of brake-specific fuel consumption, thus the economic efficiency of the engine;

– at the present time for gas engines the values of 210–220 g/kW · h are the best minimum values of brake-specific fuel consumption [9];

– with the purpose of maintaining the resource of the centrifugal compressor turbine the temperature of the end gas in front of the turbine must not exceed 650 °C;

– the values of harmful substances release volume in the end gas were not considered as soon as the mathematical model allows only forecasting their finite targets.

Based on the obtained equations (1) let us solve the following problem:

$$\begin{cases} -1,38 + 0,007P_v - 0,019\theta + 0,064Y_{thr} \rightarrow \max, \\ 356,5 - 0,43P_v + \theta - 3,5Y_{thr} \leq 220, \\ 478,75 + 0,58P_v - 2,63\theta + 5Y_{thr} \leq 650, \\ 120 \leq P_v \leq 240, \\ 10 \leq \theta \leq 30, \\ 30 \leq Y_{thr} \leq 100. \end{cases} \quad (2)$$

The solution to system (2) are the values of the controlled parameters: P_v = 120 kPa; θ = 20 degrees of crankshaft turn; Y_{thr} = 30%, where target P_e = 1.02 MPa; g_e = 220 g/kW · h; T_{eg} = 646 °C; NO_x = 785 ppm; CO = 589 ppm; CH = 194 ppm.

The obtained rated value P_e = 1.02 MPa corresponds to the power N_e = 220 kW (300 hp – horsepower). In the line of KAMAZ gas engines, the highest power corresponds to 820.92-300 (Euro-5) engine: N_e = 220 kW (300 hp); g_e = 209 g/kW · h (the forecast value of the mathematical model is 220±11 g/kW · h).

For further improvement of engine power it is necessary to:

– increase the boost pressure and at the same time increase the gas pressure in the system;

– use high-temperature resistant materials for the parts of the centrifugal compressor turbine;

– use the system of the end gas aftertreatment.

Let us fulfill the preliminary analysis of the required characteristics of the gas piston engine for the mining dump truck with the capacity of 240 tons. For example, let us consider the use of diesel engine 12DM-185A produced by OOO UDMZ (Ekaterinburg) for the mining dump truck BELAZ-75319 with the capacity of 240 tons [20]. Diesel engine 12DM-185A develops the power of 1865 kW under the crankshaft speed of 1800 r/mn. To analyse the possibility of changing the diesel engine for the gas one, the required characteristics (fig. 2) were calculated as compared to the parameters of the diesel engine MTU 16V4000 (https://www.mtu-online.com/mtu/company). The obtained model provides rather good agreement with the actual characteristics of the engine.

The change of heavy-duty mining dump trucks to gas fuel requires the development of some measures on uprating the engine power. Computation and experimental studies have shown the possibility of increasing the efficient parameters of the power module based on the gas piston engine for mining dump trucks. In order to concert all capabilities of the gas engine, it should be initially designed for the gas fuel.

Summary. The analytical-experimental model of the gas engine has been developed together with the technique making it possible to forecast its basic parameters and optimize economic and environmental characteristics. The technique was based on the experimental data of the low-power gas piston engine, but due to the similarity of the adiabatic processes it can be applied to study heavy-duty engines for mining dump trucks.

Taking into account that in the nearest future the natural gas will be used as the only cheap and reasonable fuel, the gas piston engine becomes perhaps the one and only alternative of the power set for the heavy-duty mining dump trucks of the future.

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Повышение эффективности эксплуатации карьерных самосвалов при использовании газопоршневых двигателей

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Реферат

Цель работы *– анализ перспектив повышения эффективности эксплуатации карьерных самосвалов большой грузоподъемности за счет применения природного газа в качестве основного энергоносителя.*

Методология проведения исследования. *Проведение стендовых испытаний газопоршневого двигателя (ГПД) КАМАЗ модели 820.60-260 мощностью 191 кВт и построение прогнозных значений параметров ГПД для карьерного самосвала БЕЛАЗ-75319 грузоподъемностью 240 т.*

Результаты. *Разработаны математическая модель и методика, позволяющие прогнозировать основные параметры газопоршневого двигателя и проводить оптимизацию его экономических и экологических характеристик. Использование природного газа в качестве моторного топлива при неизменной конструкции двигателя приводит к снижению его мощности. В настоящее время создаются газовые модификации на базе уже существующих дизельных двигателей, и осуществить какие-либо конструктивные мероприятия на этом этапе не всегда можно. Для реализации всех возможностей газового двигателя его следует изначально проектировать под газомоторное топливо. Данная методика построена на экспериментальных данных ГПД малой мощности и может быть применена для исследований газовых двигателей большой мощности, предназначенных для установки на карьерные самосвалы.*

Выводы. *Повышение эффективности эксплуатации карьерных самосвалов в ближайшей перспективе возможно за счет применения природного газа в качестве основного энергоносителя. Использование природного газа в качестве моторного топлива позволяет увеличить срок службы двигателя, уменьшить уровень шума и токсичность отработанных газов, снизить затраты на топливо.*

Ключевые слова: *карьерные самосвалы; открытые горные работы; дизельное топливо; природный газ; газопоршневой двигатель; экологическая и экономическая эффективность.*

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