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Review / Обзор

USE OF GAS-TURBINE ENGINES FOR MINING DUMP TRUCKS IN THE CONDITIONS OF THE NORTH

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ПРИМЕНЕНИЕ ГАЗОТУРБИННЫХ ДВИГАТЕЛЕЙ ДЛЯ КАРЬЕРНЫХ САМОСВАЛОВ В УСЛОВИЯХ СЕВЕРА

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A steady trend of growing open pit depths and the corresponding increase in the hauling distance in the world practice of open-cast mining have determined the main direction of the development of mining dump trucks towards enhancing their carrying capacity, which leads to an increase in the capacity of a power plant, weight-size parameters of the engine, and the quantity of the fuel consumed. In winter, the preparation of a diesel engine for the start-up with a special heating system at the air temperature of –40 °C takes up to 40–50 min. Due to the problems of starting the engine at low temperatures, diesel engines are often not shut off during the entire winter period, resulting in the engine eoveraging, significant overconsumption of fuel and an increase in exhaust emissions.
The main advantages of gas turbine engines include high efficiency at loads close to nominal, high aggregate capacity combined with low weight and dimensions (energy consumption is 1000–3000 kW/m3, 1000–2000 kW/t), high maneuverability and readiness for action (preparation for action takes 10-15 minutes with the start-up time of 120-180 s), adaptability to automation, high reliability, relatively simple design and maintenance, high manufacturability, possibility of aggregate repair, easy and reliable start-up at low temperatures and lower exhaust emissions. The specific gravity of a gas turbine engine is much less and does not exceed 25-30% of a piston engine weight, making it possible to lighten the engine frame and increase the load capacity of the dump truck. The power-to-size ratio of a gas turbine engine is also higher than that of a piston-type one, therefore the former is characterized by a 2-3-fold reserve in terms of space in the engine compartment of the dump truck. Besides, the gas turbine engine can work for a long time in the conditions of high dust, use cheaper gas fuel and requires practically no oil.
Low weight and compact size, the option of getting high capacity in a single unit and remote control, along with easy and reliable start-up at low temperatures make gas turbine engines very attractive for use on heavy-duty mining dump trucks, road trains with active trailers and semi-trailers, especially in the northern and arctic areas.

Ключевые слова:
карьерные самосвалы, экология, открытые горные работы, дизельный двигатель, газотурбинный двигатель, экологическая и экономическая эффективность.

Устойчивая тенденция роста глубины карьеров и соответствующего увеличения плеча откатки в мировой практике открытой разработки месторождений определили главное направление развития карьерных самосвалов – повышение их грузоподъемности, что приводит к увеличению мощности энергосилового агрегата, массогабаритных показателей двигателя, количества потребляемого топлива. В зимний период подготовка дизельного двигателя со специальной системой подогрева при температуре воздуха –40 °С к пуску составляет 40–50 мин. Из-за проблем запуска двигателя при низких температурах дизели часто не глушатся в течение всего зимнего периода, вследствие чего вырабатывается ресурс двигателя, происходит значительный перерасход топлива и увеличение объемов выбросов выхлопных газов.
Основными преимуществами газотурбинных двигателей являются высокая экономичность при нагрузках, близких к номинальной, большие агрегатные мощности при малых массе и габаритах (энергоемкость составляет 1000–3000 кВт/м^3, 1000–2000 кВт/т), высокая маневренность и готовность к действию (приготовление к действию – 10–15 мин, время запуска – 120–180 с), приспособленность к автоматизации, высокая надежность, относительная простота конструкции и обслуживания, высокая технологичность, возможность агрегатного ремонта, легкий и надежный пуск при низких температурах и более низкая токсичность выхлопных газов. Удельная масса газотурбинного двигателя значительно меньше и не превышает 25–30 % массы поршневого двигателя, что позволяет облегчить моторную раму и повысить грузоподъемность самосвала. Габаритная мощность газотурбинного двигателя также выше, чем у поршневого, поэтому для первого характерен 2–3-кратный запас по габаритам пространства в моторном отсеке самосвала. Кроме того, газотурбинный двигатель позволяет длительно работать в условиях высокой запыленности воздуха, использовать более дешевое газовое топливо и практически исключить расход масла.
Малая масса и компактные размеры, возможность получения большой мощности в одном агрегате и дистанционного управления, наряду с его легким и надежным пуском при низких температурах, делают газотурбинные двигатели весьма привлекательными для использования на большегрузных карьерных самосвалах, автопоездах с активными прицепами и полуприцепами, особенно в северных и арктических районах.

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Introduction

A steady trend of growing open pit depths and the corresponding increase in the hauling distance in the world practice of open-cast mining have determined the main direction of the development of mining dump trucks towards enhancing their carrying capacity, which is currently set back by the engine capacity and tire characteristics. In the period 1950–2015, the carrying capacity of the mining dump trucks increased almost 14 times [1]. At the moment, manufactured mining dump trucks include Caterpillar 797F (2009) and Liebherr T 284 (2012) with the carrying capacity of 363 tons, Komatsu 980E-4 (2016) and XCMG XDE400 (2015) with the carrying capacity of 400 tons, BelAZ-75710 (2013) with the carrying capacity of 450 tons (the biggest truck in the world). Further growth of the carrying capacity of the mining dump trucks drives an increase of the capacity of the power plant, weight-size parameters of the engine, and, therefore, the volume of the engine compartment.

The capacity of the power plants of the modern mining dump trucks BelAZ, Liebherr, Terex, Caterpillar, Komatsu, Hitachi, Sanyi, XCMG generally does not exceed 2000 kW with the carrying capacity of no more than 250 tons. The mining dump trucks with the carrying capacity over 250 tons usually deploy two engines, or an engine with increased dimensions (with 18, 20 cylinders). At the same time, the ratio of the engine's power to the carrying capacity of the dump truck declines from 10 to 7.5 kW/t. Similarly, power-to-weight ratio also declines from 6,9 to 3,7 kW/t, while the specific consumption of materials (the ratio of the weight of an empty dump truck to the engine capacity) is increased from 54,4 to 122,0 kg/kW. The increase of the engine power drives an increase of the consumed fuel and exhaust emissions to the atmosphere. The increase of the production volumes also contribute to the power consumption and increased exhaust volumes.

The analysis of the open-cast mining development in the fields of Russia shows their gradual shift to the remote northern areas with an increase of the mining pits' depth to 500–600 m. We know from practical experience that for each 100 m of the mining depth the cost of transportation of the rock increases by 20–30 %, while the environmental situation in the mining pit deteriorates [2, 3–6].

The movement of the mining dump trucks in case of mining pit depth of over 200 m goes along a serpentine road with steep grades. Due to a high ascending angle, the engine of the dump truck is loaded to the full capacity at a low movement speed, increasing the volumes of toxic substances exhaust and the fuel consumption by 2-3 times.

As the horizon lowers, the terms of natural ventilation of the working area deteriorate, causing the exhaust gases to accumulate in the mining pit. When this polluted air gets into a running engine, it results in the incomplete combustion of fuel and, therefore, increased consumption of motor fuel and higher volume of exhaust gases. This additionally impairs the environmental situation, poses a threat to the health of the working staff and has a significant influence on the work productivity due to the increased pauses in the work caused by the mining pits' gas pollution [3, 7–10].

Lately, more stringent requirements apply to the vehicles' engines in terms of reduction of the level of exhaust gases' toxicity. The main controlled toxic components of the engines' exhaust gases are the carbon oxide, nitrogen oxide and hydrocarbons. Their content is primarily determined by the quantity of oxygen present in the engine's combustion camera, that is, the excess air ratio and a number of other factors.

The purpose of this paper is to analyse the possibility of using gas-turbine engines for mining dump trucks in the conditions of the north.

The long-standing environmental problem of open-cast mining operations is further complicated by high transportation costs as a result of continuing growth of motor fuel prices. The deficit of liquid oil motor fuel and high air pollution with its combustion products caused the necessity to look for alternative fuels. At the moment, natural gas is acknowledged to be the only economically justified alternative fuel that can be used as a motor fuel without any processing, except for the compulsory technological stage of gas production and transportation.

According to the forecasts, natural gas will become the main motor fuel in the nearest term [11–14]. Currently, the world engine manufacturing is considering the opportunities to extend the use of natural gas. Natural gas is used as a motor fuel in the form of liquefied hydrocarbon gas, liquefied natural gas and compressed natural gas. The advantage of using gas motor fuel consists in the low level of harmful emissions to the atmosphere and relatively low production costs.

Research Methodology

As early as in 1969, BelAZ created a 120-ton gas-turbine truck BelAZ-459V with a turbine of 1200 hp (produced in Yaroslavl), and in 1970, the State Committee for Science and Technology approved a plan of gas-turbine engines' implementation: it involved GAZ, MAZ, MoAZ, BelAZ and KrAZ. In the city of Gorky, a family of gas-turbine engines GAZ-99 with the capacity of up to 250 hp was created. In 1973, the first gas turbine MAZ was constructed, and then KrAZ-260 appeared. GAZ brought the aggregate's capacity to 350 hp. The turbine required a bulky reduction gearbox: the axle rotated with a speed of 35 thousand rpm, which no transmission can endure. As USSR didn't have any suitable gearboxes and coupling engagements, they were bought from Hungary. The resulting engine weighed half as much as a customary diesel engine for heavy-duty trucks produced by the Yaroslavl Motor Plant, the exhaust was 3-6 times cleaner, and the fuel consumption in nominal modes was as much as 20 % lower than that of the diesel engine. It is known that the truck has gone 2500 km, and most problems were caused by the Hungarian transmission: as specified in the book about the plant's history, it "didn't stand up to criticism". In 1976, the second specimen was designed, and the aggregate was made more compact. At the same time, the capacity was increased by another 10 hp, and the fuel consumption in the steady condition was very modest – 1,4 times less than that of the diesel engine. However, in the transition modes (drive/brake) the fuel consumption was great. Other quite evident issues added up to this one: the dynamics left much to be desired and the transmission continued to break. Despite many merits of the gas-turbine engine, its only disadvantage – the fuel consumption – set back all the advantages. This was ethe end to the experiments.

In the last 50 years, new materials and technologies appeared in the engine-building industry. Today, gas turbine engines are widely used in the aviation [15], ship-building [16–18], gas- and oil-pumping units [19, 20], and are also being tried on the railway transport [21, 22]. Lately, the interest to the use of gas turbine engines for the power plants of the ground transport has revived. This is confirmed by the efforts of Kurganmashzavod LLC (promising IFV Knight (Rytzar)), KamAZ LLC (light series platform), and the ongoing follow-up works in the engines for the gas turbine locomotives in the Samara's Kuznetsov OJSC and Federal State Unitary Enterprise Engineering and Production Centre of the Gas Turbine Construction Salute [27, 28].

Automotive turbine engines are intended for the mining dump trucks and trailer trucks, i.e. the vehicles with high unit capacity. The carrying capacity of such vehicles reaches 100-450 tons with the engine capacity of 750-3500 kW.

For comparison purposes, the indicators of the modern piston-type engines for the mining dump trucks produced by the Yaroslavl Motor Plant, Cummins, MTU, DEUTZ, Detroit Diesel, and gas-turbine engines produced by the firm United Engine-Building Corporation were analysed. The comparison was carried out based on the evaluation of the following indicators: g_e is the specific fuel consumption (g/kW·h) taken on the basis of the data in the catalogues,

$$M_{\text{уд}} = \frac{M_{\text{дв}}}{N_e},$$

$$N_{\text{г}} = \frac{N_e}{V_{\text{дв}}},$$

where M_{spec} is the specific weight of the engine, kg/kW; M_{eng} is the weight of dry (unfuelled) engine, kg; N_e is the nominal engine capacity, kW; N_{pts} is the power-to-size capacity of the engine, kW/m^3; V_{eng} is the engine volume in the engine room, m^3, defined as the product of its overall dimensions, m, length, width and height.

Work Result

Our country has rich research and practical experience of studying gas-turbine engines. The existing materials, for example, [25, 27–36], and the performed comparative analysis of piston-type and gas-turbine engines of similar capacity to be used on vehicles (see Figure) allow to point out the following technical and operational advantages of the gas turbine engines:

1. The specific gravity of a gas turbine engine is much less and does not exceed 25–30 % of a piston-type engine weight (see Fig., *a*) , making it possible

to lighten the engine frame and increase the load capacity of the dump truck.

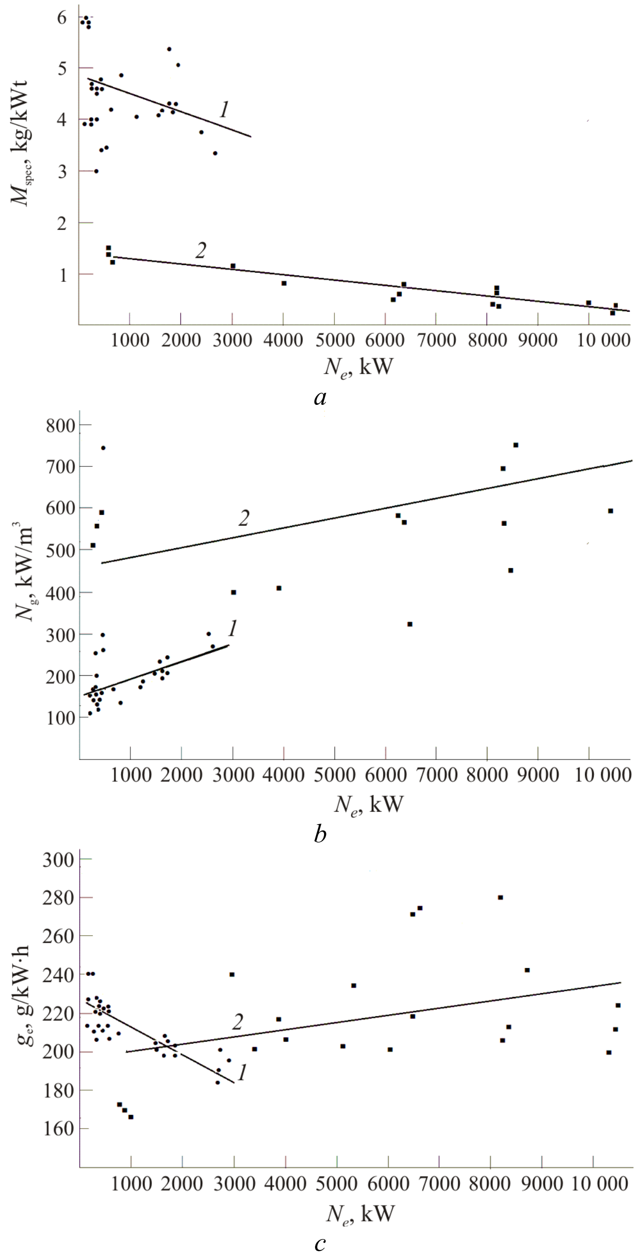

Fig. Dependence of the engine's specific weight on its capacity (*a*); power-to-size ratio (*b*); specific engine fuel consumption (*c*); *1* – piston-type; *2* – gas turbine

2. The gas turbine engine has a higher specific capacity (the ratio of engine capacity to its weight).

3. The power-to-size ratio of a gas-turbine engine is higher than that of a piston-type engine (see Fig. *b*). For example, in case of a piston-type engine with the capacity of 2000 kW, it is possible to get approximately 200 kW from 1 m^3 of the engine, while the same indicator of a gas-turbine engine will be almost 2.5 times higher – approximately 500 kW/m^3. Therefore, a gas-turbine engine has a 2-3-fold reserve in terms of space in the engine compartment of the truck.

4. Favourable change in the engine torque depending on the engine shaft rotation frequency (the torque increases if the rotation frequency goes down).

5. The possibility to use cheaper gas fuel and almost no oil consumption.

6. Considerably lower number of engine details (primarily, sliding friction pairs and lower load on the frictionless bearing, increasing the intervals between overhauls) [25–27, 31–33, 35].

7. Low toxicity of the exhaust gases. In connection with the specifics of the gas-turbine engine operation (the air consumption by the engine is 3-4 times higher than that of the diesel with an equal capacity), its exhaust gases have a significantly lesser toxicity (Table 1) [28, 36–39].

8. The start-up at low temperatures of the ambient air is easier. In Siberia and the Far North, due to the difficulty of starting-up the engine at low temperatures, diesel engines are often not shut down throughout the entire winter period. As a result, the engine is overaging, there is significant overconsumption of fuel and an increase in exhaust emissions. The time of preparation for the start-up of the vehicle piston-type diesel engine with a special heating system at the temperature of –40 °C amounts to 40–50 min. It is necessary to warm up the engine prior to the start-up in order to reduce friction in the crankshaft, in the cylinder piston – sleeve pair, and to warm up the oil to reduce its viscosity, whereas for a gas-turbine engine the preparation of the engine for the start-up takes 3-5 min. at the temperature of – 40 °C due to the absence of impact stress and reversal load in the supports and the use of low-viscosity oil [27, 36, 37, 40].

9. Low labour intensity and cost of maintenance. The scope of maintenance of the gas turbine engine is much smaller than that of the diesel engine due to the absence of liquid-cooling system, scheduled fuel feed system adjustment and oil replacement. The difference in the maintenance scope is especially manifested in the winter (north) conditions, when there is no need in the heating system. According to different estimates, including the experience of operation on the GAZ truck [28, 36, 41], labour intensity and cost of maintenance of the gas turbine engine is 50 % of the diesel engine with the

simultaneous increase of the car park use ratio from 5 to 15 %. Besides, with the equal capacity of the diesel and gas-turbine engine, the vehicle's productivity increases due to a better traction characteristic (in case of a mechanical gearbox transmission) or a higher transmission efficiency.

Table 1

Indicators of engines' exhaust gases toxicity

Engine	Toxic component, g/kW h			
	NO_X	CO	CH	soot
Diesel Cummins (TierII)	6,0	3,5	1,1	0,3
Gas Turbine Engine GAZ	1,2	0,73	0,16	0,01
Gas Turbine Engine GTD-1250	1,2	0,73	0,14	0,01

10. Opportunity to use a simpler, more reliable and cheaper transmission.

11. Almost complete absence of vibrations and torque vibrations.

12. Opportunity of extended work in the conditions of high dust content in the air reaching about 2,0–2,5 g/m^3 and sometimes higher at the inlet to the air cleaner of the power plant, which is especially important for the mining dump trucks.

As compared to the equivalent piston-type engine, gas-turbine engines work smoothly and quietly, they can function with different types of hydrocarbon fuel and are characterized by a simple mechanic construction, resulting in enhanced reliability and extension of the service life.

When torque converters are installed in the vehicles with high carrying capacity with a diesel power plant, additional losses arise and are manifested as the increase of fuel by 10-16% in the transformation mode and by 4-6% in the blocking mode. Besides, the diesel units feature large capacity losses on the cooling system ventilator drive (10–12%) [24, 35–37, 41].

At the same time, the level of specific fuel consumption is slightly higher for the gas-turbine engine than for the piston-type engine and it increases with the growth of the engine capacity. This is related to a lower efficiency of gas-turbine engines (see Fig., *c*).

High cost efficiency of the diesel engine is generally acknowledged, however, it is not absolute and depends on the terms of operation of the mining dump truck. For example, if the ambient temperature is lowered (in the winter period or in the northern areas), the cost effectiveness of the gas turbine engine increases. If the temperature is reduced from +20 to –20^{o}C, the minimal specific consumption of fuel by gas-turbine engine GAZ-902 is reduced by more than 10 %, whereas the diesel fuel consumption, on the opposite, is increased by 8–10 % [31, 34, 36, 40].

The specific fuel consumption by the diesel engine of a mining dump truck amounts to 182–212 g/kW·h on average. For example, in the Udachninsky Mining Plant of Joint-Stock Company ALROSA the specific consumption of fuel by the diesel engine of the mining dump truck Cat-785V amounts to 209 g/kW h [42] with the minimal load. The modern samples of gas turbine engines of the cars and ships have the specific fuel consumption of 200–270 kg/kW h [28, 35, 43], which is comparable to the diesel engine indicators.

As the performed research have shown [25], modern gas-turbine engines can be used for the powerful off-road vehicles, including mining dump trucks. Thus, for example, a serial industrial mining dump truck BelAZ with the carrying capacity of 90 tons is already in the market. Gas-turbine engine GTD-1250 with the capacity of 1250 hp (920 kW) produced by Kaluzhsky Dvigatel PJSC [44]. The engine has the weight of 1050 kg, the specific fuel consumption of 225 g/l (Table 2) and a significantly lower level of exhaust of the toxic substances.

The following are the advantages of using the gas turbine engine GTD-1250:

– maximum efficiency of the drive due to high adaptability of the gas turbine engine and the use of mechanic transmission without a torque converter;

– record-breaking in its class low weight and dimensions of the pump's power plant;

– opportunity to perform hydrofracturing with the engine running at the top gear with the maximum productivity owing to a flexible gas drive of the power turbine without a threat of the transmission destruction (the work is performed by a smaller number of the pumping units UN2250 as compared to the diesel units);

– opportunity to transmit torque to the stopped pump shaft during the pressure check;

– absence of an external starting device; start-up without a pre-start heating with an in-built electrical starter in 60 sec with the temperature of –40^{o}C;

– less engine wear of the gas-turbine engine due to the absence of friction pairs and actual absence of burning oil consumption;

– environmental safety of exhaust gases of gas turbine engines, their use in winter time for the effective heating of the engine and transmission compartment, plunger pump and its systems (10–15 min. of heating to reach full capacity);

Table 2

Comparison of the engines GTD-1250 with a diesel engine of the even capacity [45]

Characteristic	Diesel engine with the capacity of 23250 hp	Two engines GTD-1250, total capacity of 2250 hp
Weight net of mounted systems, kg	6155	2100 (2×1050)
Specific capacity, kW/kg	0,298	0,875
Adjustability factor (M_{max} at n_{min}/M at n corresponds to P_{max})	1,3	2,5
Number of gears in a geared transmission	8	4
Capacity of a liquid cooling engine system, l	830–850	0
Capacity of the engine oil system, l	210–240	90 (2×45)
Engine oil consumption, kg/h	2	0,02
External drive for the start-up	Hydraulic	Not required
Capacity of the hydraulic starter external drive and ventilator of the radiators, hp	160	0
Capacity of the starter oil system, l	100	0
Type of air filters	Contact (replaceable)	Cyclone
Indicators of exhaust gases toxicity NO_x /CO/soot, g/kW h	3,5/3,5/0,1 (TIER4)	1,2/0,73/0,01
Winter start-up devices and systems	Webasto 30 kW, spirit injection	Not required

Note: M_{max} is the maximum torque effect of the engine, M is the torque effect of the engine at the crankshift speed n, corresponding to the maximum capacity P_{max}, n_{min} is the minimum crankshift speed.

– very simple three-point fixture of the engines without shock absorbers due to ideal balance of the gas turbine engine and absence of vibration;

– minimal number of external connections; possibility of replacing the gas turbine engine on site within 4 hours;

– absence of a bulky liquid cooling system and significant loss of capacity at the drive of its ventilator, less costs of the oil system cooling.

Gas-turbine engine GTD-1250 is intended to be used as a propulsion engine for ground heavy track-mounted and wheel-mounted vehicles.

Conclusions

Low weight and compact size, the option of getting high capacity in a single unit and remote control, along with easy and reliable start-up at low temperatures make gas turbine engines quite attractive for use on heavy-duty mining dump trucks, road trains with active trailers and semi-trailers, especially in the northern and arctic areas.

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