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EXPERIENCE OF DIESEL ENGINES CONVERSION FOR OPERATION ON NATURAL GAS OBTAINED IN MADI

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RESEARCH ARTICLE

ABSTRACT: Analysis of different methods of diesel engines conversion for operation on natural gas was carried out showing feasibility of these methods for engines of various applications. The KAMAZ V8 120/120 mm diesel engine was converted to operate on natural gas by spark ignition cycle and Cummins Kama 6L 104/127 mm diesel engine – by gas diesel (dual fuel) cycle. Gas feed and electronic engine control systems were developed for both the methods of engine conversion. For gas diesel version, modular gas feed and engine control systems were developed which could be mounted both on high-speed and medium-speed gas diesel engines. These systems were perfected during engine tests. CR fuel system for the perspective medium-speed D200 6L 200/280 mm gas diesel engine was developed jointly with the industrial partner. A computer model for simulation of engine operation was developed and calibrated on the basis of engine tests and used for the development of gas feed and engine control systems, experimental results analysis and forecasting of the parameters of the medium-speed D200 gas diesel engine.

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Engine tests of the gas and gas diesel engines demonstrated considerable decrease of CO_2 and NO_x emissions, practically no soot and lower fuel consumption compared to the base diesel engine.

KEY WORDS: gas engine, gas diesel engine, dual fuel engine, engine conversion, engine simulation

ISKUSTVO KONVERZIJE DIZEL MOTORA ZA RAD NA PRIRODNI GAS REALIZOVANO U MADI-JU

REZIME: Analiza različitih metoda konverzije dizel motora za rad na prirodni gas razvijena je pokazala mogućnosti izvođenje ovih metoda za motore za različite primene. Dizel motor KAMAZ V8 120/120 pretvoren je za rad na prirodni gas ciklusom paljenja motora varnicom i Cummins Kama 6L 104/127 mm dizel motorom – gasnim dizel (dvogorivi) ciklusom. Sistemi za dovod gasa i elektronski upravljački sistemi motora su razvijeni za obe metode konverzije motora. Za verziju gasnog dizel motora, modularni sistem za napajanje gasom i upravljački sistem motora su razvijeni kako bi se mogli postaviti i na gasnim brzohodim dizel motorima i na gasnim dizel motorima srednjih brzina. Ovi sistemi su usavršeni tokom ispitivanja motora. CR sistem za napajanje gorivom za budući gasni motor srednjih brzina D200 6L 200/280 mm je razvijem zajedno sa industrijskim partnerom. Kompjuterski model za simulaciju rada motora je razvijen i kalibrisan na osnovu testova motora i korišćen za razvoj sistema za napajanje gasom i upravljanje motorom, analizu eksperimentalnih rezultata i predviđanje parametara gasnog dizel motora srednjih brzina D200. Testiranje gasnog i gasnog dizel motora pokazao je značajno smanjenje emisije CO_2 i NO_x, nepostojanje čađi i nižu potrošnju goriva u odnosu na osnovni dizel motor.

KLJUČNE REČI: gasni motor, gasni dizel motor, dvogorivi motor, konverzija motora, simulacija motora

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1. INTRODUCTION

Conversion of diesel engines to operate on natural gas is relevant because gas is almost twice cheaper than diesel fuel in Russia. In our days, the main reason of replacement of diesel engines by gas and gas diesel (dual fuel) engines on city transport is ecology. Most of the municipal vehicles operated in the towns: buses, delivery trucks, garbage collectors, etc., as well as civil engineering machines which are permanently working on construction sites are equipped with diesel engines which, in addition to nitrogen oxides, emit soot. Soot contains carcinogens such as benzapyrene which threaten the health and life of millions of people living in megapolices. The influence of the exhaust gases of diesel engines on human health is so evident that authorities of many European towns are already putting bans on entrance of vehicles with diesel engines to the city centers or to the whole cities. Restriction for diesel vehicles to enter Copenhagen is planned for 2019, and for entering Mexico, Paris, Madrid and Athens – for 2025.

There are many ways of conversion of diesel engines to operate on natural gas and they decrease significantly or eliminate fully content of soot in the exhaust gases.

Conversion of diesel engines to spark ignition gas engines operating on a stoichiometric gas-air mixture is described in details in [8]. When the gas is supplied to the intake system, a portion of air entering the cylinders is substituted by gas which results in decrease of filling efficiency and correspondingly engine power by about 10%. The engine power is also lost due to reduction of the "diesel" compression ratio by 5-6 points to avoid knock. The chance for knock origination in stoichiometric gas engines is much lower than in gas engines working on a lean gas-air mixture. Using stoichiometric gas-air mixture instead of a lean mixture that was in the base diesel engine helps to compensate considerably for power loss. Additional advantages are stable combustion of gas and possibility to use a three-way catalyst similar to that mounted on petrol engines which decreases emissions of carbon oxide, nitrogen oxides and hydrocarbons. Soot emissions are close to zero. Stoichiometric gas engines have a high temperature of exhaust gases that is dangerous for turbine wheel and impedes considerable engine power augmentation. This is a good method for naturally aspirated engines because of minimal loss of power. As modern diesel engines are turbocharged, this method of conversion is reasonable in case of overhauling old diesel engines having no turbochargers to give them the second "clean" life or for turbocharged diesel engines having low power augmentation. Using a stoichiometric gas-air mixture does not improve fuel efficiency compared with the base diesel engine, but taking into account the lower price of natural gas compared to diesel fuel, expenses for fuel decrease. Research of fuel consumption by buses having gas engines with stoichiometric gas-air mixture in Serbia showed that despite the growth of fuel consumption by 10-25% compared with buses having diesel engines, expenses for fuel decrease considerable because natural gas in Serbia is by 52% cheaper than diesel fuel [3].

Lean mixture gas engines have low exhaust gases temperature and this enables to raise boost pressure and hence to get a high power augmentation, high fuel efficiency and low NO_x emissions which allows to meet the ecological standards without a reduction catalyzer. For medium-speed gas engines such as Jenbacher J624 (type 6) having D/S=190/210 mm operating on a lean gas-air mixture and used for electric energy generation, prechamber with enriched mixture is used to inflame the lean mixture in the main combustion chamber. The advanced Miller cycle is implemented to avoid knock. It ensures high thermal efficiency and reduces NO_x emissions. Two-stage turbocharging system is used to compensate for filling efficiency drop caused by the Miller cycle [2, 7]. This is a good application for power generation because the engine operates constantly at a high speed which enables it to avoid knock. The use of this working process on medium-speed high boosted transport engines with large cylinder bore is impeded by knock which originates at low speeds and transfer modes. But for high-speed engines having relatively small cylinder bore, the origination of knock is less probable and it can be eliminated by engine electronic control system. Therefore gas cycle with lean mixture is widely used on engines of trucks and buses.

The advantages of gas diesel engines compared to gas engines are high power, fuel efficiency and hence less CO_2 emissions, no knock, no need to change the combustion chamber shape in order to decrease the compression ratio [1, 11]. Modern high pressure Common Rail diesel fuel injection systems ensure small portions of ignition diesel fuel. Disadvantages are higher price because the engine has gas and diesel fuel supply systems and the need to refuel the vehicle with two types of fuel.

2. RESEARCH OBJECTS

All three methods of diesel engine conversion were realized in the Engine Laboratory of MADI for high-speed diesel engines mounted in different times on KAMAZ trucks and buses. Also systems for a gas diesel version of the medium-speed diesel engine D200 whose mass production has not yet started were developed and gas diesel engine parameters were forecasted. The main data for the four engines are given in Table 1.

Table 1. Main data of the engines investigated

Engine	Number and arrangement of cylinders	Cylinder diameter (mm)	Cylinder stroke (mm)	Rated speed (rpm)	Rated break mean effective pressure (MPa)	Comp-ression ratio
Naturally aspirated KAMAZ gas engine	V8	120	120	2200	0.704	13:0
Turbocharged KAMAZ gas engine	V8	120	120	2200	1.01	11.0:1
Cummins KAMA gas diesel engine	L6	107	124	2300	1.73	17.0:1
D200 gas diesel engine (parameters were forecasted)	L6	200	280	1000	2.00	15.0:1

3. CONVERSION OF KAMAZ DIESEL ENGINES TO GAS ENGINES

In gas engines, the combustion chamber shape had to be changed to reduce the compression ratio from 17:1 of the base diesel engine to 13.0:1 for naturally aspirated and 11.0:1 for turbocharged versions to avoid knock and a spark plug was mounted in place of a fuel injector. Cross section of the KAMAZ gas engine cylinder is shown in Figure 1. Compression ratio for the gas engines shown in Table 1 was selected on the basis of the world experience with the aim to find the best compromise between high power and fuel efficiency, as well as absence of knock.

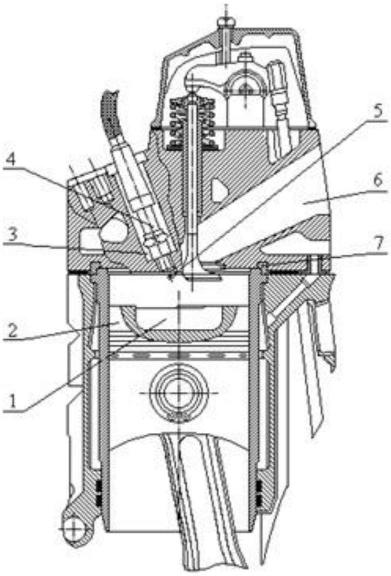

Figure 1. Cross section of the KAMAZ gas engine cylinder
1 – combustion chamber; 2 – piston; 3 – diesel engine injector mounting channel; 4 – spark-plug; 5 – spark-plug electrodes; 6 – exhaust port; 7 – steel sealing ring

The first engine converted for operation on gas fuel was naturally aspirated KAMAZ-7403.10 using a stoichiometric gas-air mixture. A gas-feed system with electronic control was developed. Its basic diagram is shown in Figure 2. Two injectors ensure a central gas supply to each row of cylinders which ensures the minimal difference of air-excess ratio values in the cylinders and this is important for operation of a three-way catalyst. The stoichiometric mixture is supported by electronic metering devices at loads higher than 70% and at idle mode. Rhodium was added to the three-way catalyst to oxidize the emissions of unburned methane. Catalysts developed by specialists of the NAMI Research Institute reduced the content of carbon oxide and also hydrocarbons including unburned methane. The systems of the gas engine were calibrated to get the same rated power as the base diesel engine.

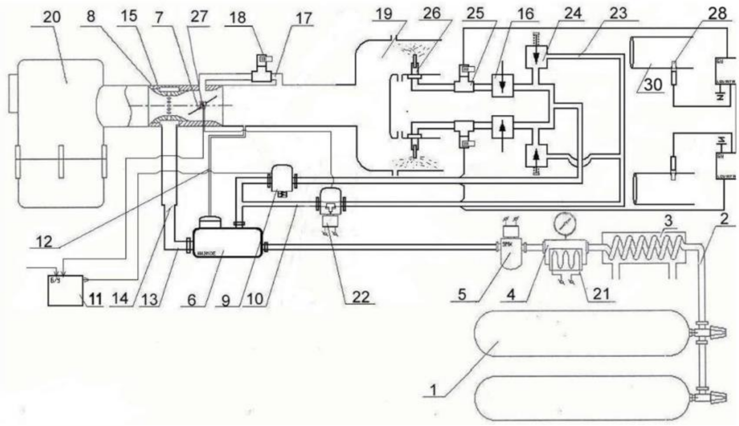

Figure 2. Basic diagram of the gas feed system for naturally aspirated KAMAZ engine

1 – reservoir for storage of gas; 2 – high pressure line; 3 – gas heater; 4 – high pressure reducer; 5 – electromagnet valve-filter; 6 – low pressure reducer; 7 – throttle valve; 8 – mixer; 9 – valve; 10 – idle mode channel; 11 – control module; 12 – vacuum tube; 13 – main channel; 14 – metering unit; 15 – ventury; 16 – throttle valve; 17 – bypass channel; 18 – control valve; 19 – intake manifold; 20 – air filter; 21 – thermistor electric heater; 22 – electromagnetic valve; 23 – idle mode channel; 24 – idle mode needle; 25 – control valve; 26 – injector; 27 – position sensor; 28 – oxygen sensor; 29 – control unit; 30 – exhaust manifold

The second converted engine was a turbocharged KAMAZ-7409T with a completely new electronic ejection gas supply system shown in Figure 3. Gas was supplied to the inlet of the compressors. The electronic throttle valve was mounted at the outlet of the compressors. The use of ejector gas supply makes it possible to decrease considerably the time of engine perfection and simplifies the engine control system. Two-stage system of after-cylinder exhaust gases treatment oxidation catalysts developed in the NAMI Research Institute was used.

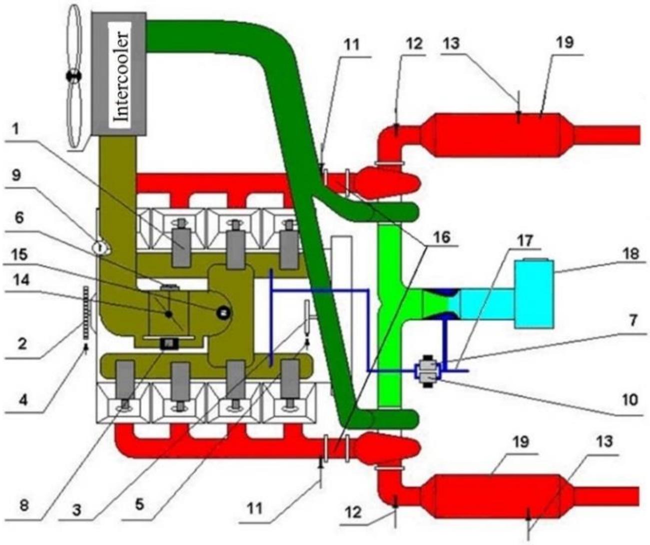

Figure 3. Elements of gas feed and electronic control systems on the turbocharged KAMAZ gas engine

1 – ignition coil; 2 – special disc (60-2); 3 – cylinder position sensor; 4 - crankshaft position sensor; 5 - camshaft position sensor; 6 – throttle valve position sensor; 7 – engine start electromagnet gas valve; 8 –bypass channel electromagnet gas valve; 9 – engine coolant temperature sensor; 10 – acceleration electromagnet gas valve; 11, 12, 13 – exhaust gas temeprturte sensors; 14 - throttle valve; 15 – absolute pressure sensor; 16 – first step exhaust gas catalyzer; 17 – supply of natural gas from the gas reducer; 18 – air filter, 19 - second step exhaust gas catalyzer

As a part of intake air is replaced by gas, if the same turbocharger as on the base diesel engine is used on the gas engine, this results in considerable decrease of engine power and efficiency, especially at low engine speed when the boost pressure is low. Therefore on gas engines, turbochargers producing a higher boost pressure than on the base diesel engine should be used. Few turbochargers having smaller turbine minimal flow section Ft0 were tested and finally the Czech B 65-1 turbochargers having the Ft0 value 5.6 cm2 with bypass valve were selected (the base diesel engine has turbochargers with the Ft0 value 12.0 cm2 and no by-pass valves). The bypass valves open approximately at the middle of the speed range to avoid too high maximal combustion pressure and overrun of the turbocharger. Turbochargers with smaller turbines enabled the gas engine to get even higher power and torque than the base diesel engine (Figure 4). Though the gas engine efficiency was lower due to lower compression ratio [5].

All three gas engines were tested for emissions by the ESC cycle. The results are shown in Table 2 jointly with the maximal permitted values of emissions for heavy-duty diesel engines, which generally include trucks and buses.

Table 2. EU Emission Standards for heavy-duty Diesel Engines (g/kWh)

	Date of introduction	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PT (g/kWh)
Euro-3	October 2000	2.1	0.66	5.0	0.1
Euro-4	October 2005	1.5	0.46	3.5	0.02
Euro-5	October 2008	1.5	0.46	2.0	0.02
Euro-6	September 2014	1.5	0.13	0.4	0.01
KAMAZ-7403.10 naturally aspirated engine without catalyst		3.75	5.45	6.85	-
KAMAZ-7403.10 naturally aspirated engine with catalyst		0.2	0.56	2.62	-
KAMAZ-7409 turbocharged engine with catalyst		0.485	0.545	1.741	-

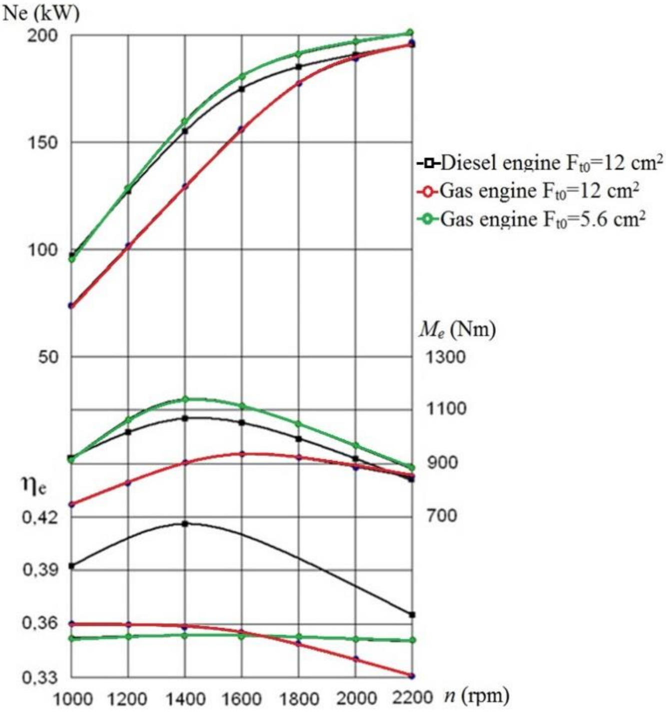

Figure 4. Speed performance of the base diesel engine and two gas engines having different turbochargers

Operation of the gas engine on a lean mixture with gas-air ratio 1.55-1.7 ensured the minimal emissions of NOx. Emissions of NOx and CO comply with Euro-5 emission standard and emissions of HC are only by 18% higher than the value set by Euro-5.

The naturally aspirated KAMAZ gas engine was mounted on the A-4216/17 bus which was successfully operated for three years in the town of Nevinnomyssk, Stavropolski region, without any damages. The average gas consumption was 48 m3/100 km. The expenses for the diesel engine conversion were paid back within 8 months [6].

4. CONVERSION OF CUMMINS KAMA DIESEL ENGINE TO GAS DIESEL ENGINE

Cummins KAMA diesel engine was converted to operate on natural gas by the gas-diesel cycle [9]. The gas-feed and electronic engine control systems were developed within the framework of the State program of creation of high- and medium-speed engines fed with natural gas. Therefore both the systems were designed in such a manner that they could be mounted on high- and medium-speed engines with minor modifications.

The gas feed system has a modular architecture. Each module (Figure 5) ensures pressure reduction and supply of natural gas. This enables to use a different number of modules depending on the engine size. One module is intended for the high-speed Cummins KAMA gas diesel engine and three modules – for the medium-speed D200 gas diesel engine. The gas feed system supplies natural gas with a working pressure of 1 MPa to the compressor inlet. It has metering valves with electronic control. When three modules are mounted on the D200 engine, three gas supply valves for each cylinder are used: two small valves of the Cummins KAMA engine for injection of small portions of gas at idle and one large valve – at high loads.

An electronic engine control system for 6-cylinder gas diesel engines was developed which controls supply of natural gas and diesel fuel [9, 12]. The system generates electric control impulses to control actuators and carries out synchronization and distribution of impulses by the cylinders depending on the engine operation mode on the basis of information received from many sensors.

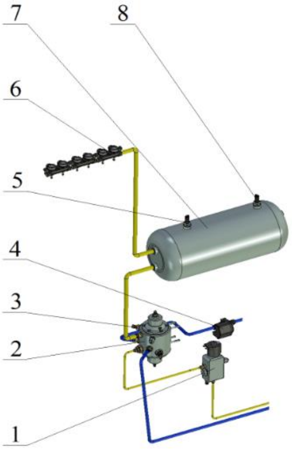

Figure 5. One module of gas supply system for the gas diesel engine:

1 – main high pressure solenoid valve; 2 – two-stage gas pressure reducer; 3 – pressure and temperature sensors in the reducer; 4 – cooling agent controller; 5 – gas pressure sensor; 6 – gas supply valves; 7 – gas receiver; 8 – gas temperature sensor

A high pressure Common Rail diesel fuel supply system of the base diesel engine was used. The new electronic engine control system after its thorough calibration ensured injection of small ignition portions of diesel fuel capable to ignite reliably the gas.

After experimental perfection of the modular gas feed and electronic engine control systems on the Cummins KAMA gas diesel engine, pretty high engine parameters were obtained (Table 3). The maximal effective efficiency ηe=0.46 was the same as on the base diesel engine.

Table 3. Comparison of ecological parameters of diesel and gas diesel versions of Cummins KAMA engine

Engine speed (rpm)	Engine torque (N·m)	Diesel fuel portion (%)	CO_2 emissions (%)		NOx emissions (ppm)	
			Diesel engine	Gas diesel engine	Diesel engine	Gas diesel engine
1220	660	4.5	9.0	7.5	2100	1570
	280	8.8	4.9	3.2	1260	162
1420	840	6.2	8.8	7.7	1123	949
	285	8.9	4.8	2.8	766	207
1625	940	6.0	8.5	7.6	1030	504
	260	8.7	4.6	3.9	540	51

Stable engine operation at a pretty small portion of igniting diesel fuel was attained: 4.5-6.2% at full load, 8.7-8.9% at 28-42% load and 33% at idle. On the average, emissions of NOx decreased 1.52 times and of CO2 – 1.18 times.

5. DEVELOPMENT OF FUEL SUPPLY SYSTEM FOR THE MEDIUM-SPEED D200 GAS DIESEL ENGINE AND FORECASTING OF ITS PARAMETERS

Common Rail fuel supply system for the perspective medium-speed D200 diesel/gas diesel engine was developed jointly with the industrial partner Noginsk Factory of Fuel Systems OAO (NZTA) [9, 10]. The CR system includes a high pressure fuel pump with six plunger sections located in radial direction by pairs along the circle over 120o. The plungers located in one row operate in reversed phase – delivery cycles take place every 180o of the crankshaft rotation. In this case, the HP fuel pump cycles of fuel delivery into the high pressure line occur every 60°. Such a sequence of working strokes of the plungers assures a low (compared with the in-line HP fuel pump) and uniform load on a drive camshaft and reduction of power consumption. The high pressure common rail is integrated into the injector body to smooth pressure oscillations which originate due to a fluctuating fuel supply from the HP pump, as well as due to operation of the injectors during injection process. As mass production of the D200 diesel engine has not yet started, parameters of its gas diesel version with the systems developed were forecasted using the MADI simulation model.

5.1 Simulation model

A one-zone simulation model of diesel/gas diesel/gas engine was developed which calculates the 4-stroke engine cycle and joint engine/turbocharger operation [4, 12]. Combustion is modeled by the I.Vieve formula and heat losses – by the empirical formula of

G.Woschni. Gas exchange processes are calculated using quasi-stationary method. Simulation model was used for the following:

Simulation of gas engines and gas diesel engines parameters required for the developement of gas-feed and engine control systems.

Analysis of parameters obtained during engine tests

Forecasting of parameters of the medium-speed D200 gas diesel engine with the modular gas-feed, electronic engine control and fuel supply systems developed.

It was demonstrated in [14] that if engines having different size (high- and medium-speed gas diesel engines) use the same method of their working process organization (including the same modular gas feed system and electronic engine control system), in certain comparison conditions: equal mean piston speed, air-access coefficient and brake mean effective pressure, their indicated parameters are pretty close. This enables to carry out the primary experimental perfection of the modular gas feed and electronic engine control systems for medium-speed engines on high-speed engines. This saves considerable time and money.

The locomotive performance of the medium-speed gas diesel engine D200 was calculated using 5% of the ignition portion of diesel fuel at all the points [13]. Turbocharger and intercooler of the base diesel engine were used which ensured a pretty high boost pressure 0.31 MPa and low boost air temperature 335 K at the rated mode. This resulted in a high air excess coefficient 2.22, ensuring good fuel efficiency, low emissions and thermal strength. At the rated mode, the required brake mean effective pressure p_e=2.0 MPa was attained with a safe value of maximal combustion pressure 18.5 MPa (maximal is 22 MPa for this engine). At engine speeds 1000, 750 and 500 rpm, high values of p_e were obtained: 2.0, 1.7 and 1.0 MPa ensuring good traction of the locomotive. The highest effective efficiency 0.450 was obtained at the rated mode corresponding to low brake specific fuel consumption 164 g/kWh.

5. CONCLUSIONS

1. A naturally aspirated KAMAZ diesel engine was converted for operation on natural gas by gas cycle with stochiometric gas-air mixture and was successfully operated on a city bus during 3 years.
2. A turbocharged KAMAZ diesel engine was converted to operate by gas cycle with a lean gas-air mixture. Using turbochargers with smaller tubine flow area enabled to get engine power and torque not less than of the base diesel engine. Special catalysts decreased emissions considerably. Emissions of CO and NO_x met the requirements of Euro-5 ecological standard.
3. Cummins KAMA diesel engine was converted to operate by gas diesel cycle. Modular gas feed and engine electronic control systems were developed which can be used both on high- and medium speed-engines. After experimental perfection of the systems, Cummins KAMA gas diesel engine showed the same effective efficiency as the base diesel engine, high degree of substitution of diesel fuel by gas (from 5.6% to 33.0% of diesel fuel as the load decreased from full value to idle), considerable decrease of toxic emissions: NO_x – 1.52 times and CO_2 – 1.18 times on the average.
4. Diesel fuel supply system for the perspective medium-speed D200 diesel/gas diesel engine was developed jointly with the industrial partner. Parameters of the D200 gas diesel with the systems developed in MADI were forecasted using the MADI one-zone model of diesel/gas diesel/gas engine.

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