Experimental determination of the performance of a diesel engine using compressed natural gas under various load conditions

M I Araslanov
Department of thermal engines, automobiles and tractors, Vyatka State Agricultural Academy, 610017, Kirov, October prospect, 133, Russian Federation

E-mail Rossokhin.dvs@mail.ru

Abstract. The paper presents the results of bench tests of a four-cylinder diesel engine D-245.12C, in which the indicators of fuel combustion in the engine cylinder and the processes characterizing the heat release in this case were studied. The studies were carried out in a comparative way, since we were interested in how these indicators would change when the engine was converted to a new type of fuel. The entire range of engine load changes is considered from minimum to maximum, the necessary calculations are carried out, recommendations are given on adjusting and loading modes that allow introducing the proposed type of fuel and the engines running on it into production. Two values of the rotational speed of the crankshaft were taken as the calculated ones: the frequency corresponding to the nominal rotation frequency and the rotation frequency corresponding to the maximum torque mode, 2400 and 1900 rpm, respectively. The results are shown in graphical form and allow you to evaluate the change in the main parameters depending on the change in load.

1. Introduction
The use of compressed natural gas as a fuel for automotive diesel engines has obvious advantages both in terms of improving effective performance and in terms of environmental performance of the engine. And even more so, this type of fuel allows replacing non-renewable and expensive diesel fuel oil with a cheaper and widespread one. However, when using compressed natural gas as the main fuel, there are some difficulties associated with the fact that its motor characteristics differ from those of diesel fuel and this cannot be ignored. We are talking about such parameters as net calorific value, cetane number, propensity for self-ignition and detonation, flame propagation limits and the excess air coefficient required for combustion [1-9].

These indicators must be taken into account, since it directly depends on whether the engine will be operational and how efficiently it can work. In accordance with the test procedure adopted in the engine building industry, it is necessary to check the indicators of the combustion process and heat generation at all load conditions. In accordance with GOST 14846, a diesel engine is prepared for testing, determination of controlled parameters with a given accuracy, processing of the obtained results taking into account correcting coefficients and calculation of those indicators that cannot be determined experimentally. The accuracy of the experiments was provided using calibrated equipment and generally accepted mathematical calculation models [9-15].
2. Experimental

The object of our experimental and theoretical research is a liquid-cooled turbodiesel with a cone-shaped combustion chamber developed at the Minsk Motor Plant.

As mentioned earlier, the controlled parameters were first studied at a crankshaft speed of 2400 rpm. A graphical interpretation of the results is presented in figure 1a [16-24].

Thanks to the test bench, the load changed from the minimum possible, at which the engine worked stably to the maximum. Naturally, an increase in the load led to an increase in the maximum temperature of the mixture in the cylinder by more than a third and it reached 2100K, an increase in temperature entails an increase in the pressure of the mixture in the cylinder and its maximum pressure exceeds 10 MPa, i.e. it almost doubles compared to the minimum value. The increase in pressure and temperature leads to the fact that the rigidity of the combustion process increases by about 16%, but the duration of the ignition delay period, on the contrary, is reduced to 15 degrees.

When the engine was running on gas engine fuel, the load varied within the same limits as that of a diesel engine. But at the same time, the maximum temperature of the burning gases reached already 2500K, since the gas has a higher calorific value than DT, the maximum gas pressure in the cylinder will also increase and will reach 11 MPa, the rigidity of the combustion process will increase compared to the diesel base modification, but not so much will remain within acceptable limits. The duration of the ignition delay period has remained unchanged since diesel fuel ignites the air-fuel mixture [25-29].

If we compare the performance of the engine at nominal load mode, which is the main design mode of the engine, then when using gas, the maximum temperature will increase by 400K, the maximum pressure of the burning gases in the combustion chamber will increase by 1MPa, the working process will increase by 13% and only 1 degree turning the crankshaft will shorten the ignition delay period.

Figure 1b presents a graphical representation of the change in the considered indicators depending on the change in the amount of fuel supplied at a crankshaft rotation speed of 1900 rpm. Here the range of load changes expands, since we need to go into the area of engine overload. The maximum value of pe is already 0.92 MPa. The maximum temperature of gases increases with an increase in the amount of fuel burned and reaches 2000 K, the maximum gas pressure in the combustion chamber reaches 11 MPa, the rate of increase of gas pressure in the cylinder per unit time increases, and the duration of the ignition delay period decreases by almost a third [30-35].

After we started supplying natural gas as fuel while maintaining the firing portion of the diesel fuel, the maximum load had to be somewhat limited due to the overloads that arose. At the maximum of the fuel supply, the temperature in the cylinder reached 2350 K, the gas pressure rose to 11.5 MPa, that is, almost twice, the rigidity of the working process reached almost the limit values for this type of combustion chamber with a reduction of the ignition delay period by 40%. Large loads can damage the parts of the cylinder-piston group, so they were artificially limited.

If we compare the performance when working on diesel fuel and natural gas, then we can come to the following results. When using gas, the maximum temperature increases by 20%, the maximum pressure increases by 8%, the rigidity of the combustion process also increases, but does not go beyond acceptable limits. The duration of the ignition delay period remains almost at the level of the diesel process [36-41].

Moving from these indicators to effective, we get the following picture. When the load changes in a larger direction, air consumption increases, since the efficiency of the turbocompressor increases. Although slightly, the coefficient of filling the cylinder with a fresh charge will increase, due to an increase in the maximum combustion temperature, the temperature of the exhaust gases will almost double as well. An increase in air flow will entail almost a double inlet air temperature, up to 110 °C. The coefficient of excess air, in turn, will decrease due to the enrichment of the mixture and at full load will be 1.7. The effective engine efficiency will double and reach a value of 0.4. Of course, this will lead to an increase in fuel consumption, which will reach 19 kg / h at maximum [42-48].
Figure 1. Change in the performance of the 4CHN 11,0/12,5 turbocharged diesel engine depending on the load at $\Theta_{vpr} = 11^\circ$ p.k.v.: a - $n = 2400 \text{ min}^{-1}$, b - $n = 1900 \text{ min}^{-1}$; - diesel process; -- -- -- - gas-diesel process.

When switching to a gas-diesel process and changing the load from 0.10 to 0.85 MPa, the hourly air flow rate $G_v$ increases from 380 to 450 kg/h, i.e. by 18%, the filling coefficient $\eta_v$ of the cylinders is in the range of 0.95...0.96, the temperature $t_r$ of the exhaust gas increases from 220 to 430°C, i.e. by 95%, the temperature $t_k$ of the charge air increases from 72 to 98°C, i.e. by 36%. The coefficient of excess air $\alpha$ decreases from 2.7 to 1.7, i.e. by 37%, the effective efficiency $\eta_e$ increases from 0.14 to 0.38, i.e. 2.6 times, $G_T$ increases from 8 to 17 kg/h, i.e. 2 times, and $g_e$ is reduced to 208 g/(kW•h). At the same time, $g_e$ at low load conditions when working on the gas-diesel process is higher, but at a rate higher than 0.7
MPa, the gas-diesel \( g_e \) becomes lower than when working on diesel fuel. Accordingly, the effective efficiency \( \eta_e \), which determines the degree of heat use, in a gas diesel at less than 0.7 MPa is less important than the diesel version and becomes higher at more than 0.7 MPa. The pressure \( p_k \) of the charge air with increasing load increases from 0.12 to 0.16 MPa, i.e. by 36% [43-49].

When switching from a diesel to a gas-diesel process at a nominal operating mode (i.e. \( n = 2400 \text{min}^{-1}, p_e = 0.84 \text{MPa} \)), the hourly air flow rate \( G \) decreases from 490 to 450 kg/h, i.e. 8%, the temperature \( t_e \) decreases from 480 to 420°C, i.e. by 12%, temperature \( t_k \) decreases from 103 to 98°C, i.e. by 5%, the coefficient \( \alpha \) decreases from 1.8 to 1.6 (by 11%), and the effective efficiency \( \eta_e \) in this case increases from 0.36 to 0.38, i.e. by 6%, and \( G_T \) is reduced from 19 to 17 kg/h, i.e. by 10%. The pressure \( p_k \) during the transition to the gas-diesel process decreases from 0.17 to 0.16 MPa, i.e. by 6%. In this case, \( g_e \) decreases from 218 to 208 g/(kW•h), i.e. by 5%. The value of the firing portion of the diesel fuel varies in the range from 3.0 to 2.8 kg/h (a decrease of 7%) [50-54].

When working on a diesel process, the load change was from 0.13 to 0.92 MPa. The main dependences of the changes in the considered indicators on the load in this mode are preserved. Air consumption with increasing load monotonically increases from 325 to 380 kg/h, i.e. by 17%, the fill factor \( \eta_f \) of the cylinders is in the range of 0.98...0.99 in the entire load range under consideration, the temperature \( t_c \) of the exhaust gas increases from 200 to 430°C, i.e. 2 times, the temperature \( t_k \) of the charge air increases from 35 to 80°C, i.e. 2 times. The coefficient of excess air \( \alpha \) decreases from 4.7 to 2.3, i.e. 2 times, and the effective efficiency \( \eta_e \) increases from 0.25 to 0.38, i.e. by 50%, hourly fuel consumption \( G_f \) increases from 5 to 14 kg/h, i.e. 3 times, and the specific effective fuel consumption of \( g_e \) is reduced to 198 g/(kW•h). The pressure \( p_k \) of the charge air with increasing load increases from 0.118 to 0.145 MPa, i.e. by 23% [55-57].

3. Conclusion
When working on the gas-diesel process at \( n = 1900 \text{min}^{-1} \) and changing the load from 0.13 to 0.85 MPa, the hourly air flow rate \( G \) increases from 300 to 320 kg/h, i.e. by 7%. A slight decrease in the filling coefficient \( \eta_f \) of cylinders from 0.99 to 0.95, i.e. by 4% with increasing load. The temperature \( t_c \) of the exhaust gas increases from 200 to 340°C, i.e. 1.7 times, the temperature \( t_k \) of charge air rises from 48 to 84°C, i.e. 1.75 times. The coefficient of excess air \( \alpha \) decreases from 3.3 to 2.0, i.e. 1.7 times, the effective efficiency \( \eta_e \) increases from 0.2 to 0.4, i.e. 2 times, hourly fuel consumption \( G_f \) increases from 5 to 12 kg/h, i.e. 2.5 times, and \( g_e \) is reduced to 195 g/(kW•h). In this case, \( g_e \) at low load conditions when working on the gas-diesel process is higher, but at a rate higher than 0.5 MPa, the gas-diesel \( g_e \) becomes lower than when working on diesel fuel. The pressure \( p_k \) of the charge air with increasing load increases from 0.11 to 0.14 MPa, i.e. by 19%. The size of the ignition portion \( G_T \) app DT in this case decreases from 3.1 to 2.9 kg/h, i.e. by 6% [58, 59].

When switching from diesel to gas-diesel process at \( n = 1900 \text{min}^{-1} \) and \( p_e = 0.84 \text{MPa} \), the hourly air flow rate \( G \) decreases from 375 to 320 kg/h, i.e. by 14%, the temperature of the exhaust gas decreases from 420 to 320°C, i.e. by 24%, temperature \( t_k \) increases from 76 to 83°C, i.e. by 9%, the coefficient \( \alpha \) decreases from 2.3 to 2.0 (by 13%), and the effective efficiency \( \eta_e \) in this case increases from 0.4 to 0.41, i.e. 5%, and \( G_T \) is reduced from 13 to 12 kg/h, i.e. by 9%. The pressure \( p_k \) during the transition to the gas-diesel process decreases from 0.14 to 0.13 MPa, i.e. by 4%. In this case, \( g_e \) decreases from 199 to 195 g/(kW•h), i.e. on 2%. The filling coefficient \( \eta_f \) decreases from 0.99 to 0.95, i.e. by 4%.

References
[1] Likhanov V A and Lopatin O P 2018 IOP Conf. Series: Materials Science and Engineering 457 012011
[2] Romanyuk V, Likhanov V A and Lopatin O P 2018 Theoretical and Applied Ecology 3 27-32
[3] Lopatin O P 2020 IOP Conf. Series: Materials Science and Engineering 862 062087
[4] Anfilatov A A and Chuvashev A N 2020 IOP Conf. Series: Materials Science and Engineering 862 062064
[5] Marchuk A, Likhanov V A and Lopatin O P 2019 Theoretical and Applied Ecology 3 080-6
[6] Anfilatov A A and Chuvasesh V N 2020 Journal of Physics: Conf. Series 1515 022635
[7] Likhanov V A and Lopatin O P 2019 Journal of Physics: Conf. Series 1399 055016
[8] Skryabin M L and Likhanov V A 2020 IOP Conf. Series: Materials Science and Engineering 734 012075
[9] Likhanov V A and Lopatin O P 2019 Journal of Physics: Conf. Series 1399 055020
[10] Chuvasesh V N and Chuprakov A I 2019 Journal of Physics: Conf. Series 1399 055085
[11] Likhanov V A and Rossokhin A V 2020 IOP Conf. Series: Materials Science and Engineering 862 062046
[12] Likhanov V A, Lopatin O P and Yurlov A S 2019 Journal of Physics: Conf. Series 1515 042048
[13] Likhanov V A and Lopatin O P 2020 IOP Conf. Series: Earth and Environmental Science 421 072018
[14] Anfilatov A A and Chuvasesh V N 2020 IOP Conf. Series: Materials Science and Engineering 862 062069
[15] Anfilatov A A 2020 Journal of Physics: Conf. Series 1515 042049
[16] Lopatin O P 2020 IOP Conf. Series: Earth and Environmental Science 421 072019
[17] Likhanov V A, Kozlov A N and Araslanov M I 2020 IOP Conf. Series: Materials Science and Engineering 734 012211
[18] Likhanov V A and Rossokhin A V 2020 IOP Conf. Series: Materials Science and Engineering 862 062047
[19] Likhanov V A and Lopatin O P 2017 Thermal Engineering 64(12) 935-44
[20] Skryabin M L 2020 IOP Conf. Series: Earth and Environmental Science 421 072012
[21] Lopatin O P 2020 Journal of Physics: Conf. Series 1515 042021
[22] Chuvasesh V N and Chuprakov A I 2020 IOP Conf. Series: Materials Science and Engineering 862 062089
[23] Likhanov V A and Lopatin O P 2020 Journal of Physics: Conf. Series 1515 052002
[24] Likhanov V A and Lopatin O P 2020 IOP Conf. Series: Materials Science and Engineering 862 062014
[25] Kopchikov V N and Fominykh A V 2020 Journal of Physics: Conf. Series 1515 042028
[26] Likhanov V A and Anfilatov A A 2020 IOP Conf. Series: Materials Science and Engineering 862 032048
[27] Anfilatov A A and Chuvasesh V N 2020 Journal of Physics: Conf. Series 1515 042052
[28] Lopatin O P 2020 Journal of Physics: Conf. Series 1515 042009
[29] Devetyarov R R and Chuvasesh V N 2020 Journal of Physics: Conf. Series 1515 042080
[30] Likhanov V A and Lopatin O P 2019 Ecology and Industry of Russia 23(9) 60-5
[31] Chuvasesh V N, Chuprakov A I and Anfilatov A A 2020 IOP Conf. Series: Materials Science and Engineering 734 012184
[32] Likhanov V A and Rossokhin A V 2020 IOP Conf. Series: Materials Science and Engineering 734 012207
[33] Likhanov V A and Lopatin O P 2020 Journal of Physics: Conf. Series 1515 042008
[34] Lopatin O P 2020 Journal of Physics: Conf. Series 1515 052004
[35] Chuvasesh V N and Chuprakov A I 2020 IOP Conf. Series: Materials Science and Engineering 862 062083
[36] Likhanov V A and Lopatin O P 2020 Journal of Physics: Conf. Series 1515 042019
[37] Skryabin M L and Likhanov V A 2019 Journal of Physics: Conference Series 1399 044063
[38] Likhanov V A and Anfilatov A A 2020 IOP Conf. Series: Materials Science and Engineering 862 032050
[39] Skryabin M L 2020 Journal of Physics: Conf. Series 1515 042107
[40] Likhanov V A and Anfilatov A A 2020 IOP Conf. Series: Materials Science and Engineering 862 032044
[41] Likhanov V A and Lopatin O P 2018 Ecology and Industry of Russia 22(10) 54-9
[43] Likhanov V A and Rossokhin A V 2018 *IOP Conf. Series: Materials Science and Engineering* **457** 012007
[44] Likhanov V A and Skryabin M L 2019 *IOP Conf. Series: Earth and Environmental Science* **315** 032045
[45] Likhanov V A and Rossokhin A V 2019 *Journal of Physics: Conf. Series* **1399** 044038
[46] Likhanov V A and Lopatin O P 2020 *IOP Conf. Series: Materials Science and Engineering* **734** 012202
[47] Likhanov V A, Lopatin O P and Yurlov A S 2020 *IOP Conf. Series: Materials Science and Engineering* **734** 012208
[48] Lopatin O P 2020 *IOP Conf. Series: Materials Science and Engineering* **734** 012199
[49] Kozlov A N, Anfilatov A A and Chuvashev A N 2019 *Journal of Physics: Conf. Series* **1399** 055051
[50] Rossokhin A V and Anfilatov A A 2020 *IOP Conf. Series: Materials Science and Engineering* **862** 062065
[51] Anfilatov A A and Chuvashev A N 2020 *Journal of Physics: Conf. Series* **1515** 042077
[52] Anfilatov A A 2020 *Journal of Physics: Conf. Series* **1515** 042098
[53] Likhanov V A, Lopatin O P and Vylegzhanin P N 2020 *IOP Conf. Series: Materials Science and Engineering* **862** 062074
[54] Chuvashev A N and Chuprakov A I 2020 *Journal of Physics: Conf. Series* **1515** 042094
[55] Likhanov V A, Kopchikov V N and Fominykh A V 2020 *Journal of Physics: Conf. Series* **1515** 042026
[56] Anfilatov A A and Chuvashev A N 2020 *IOP Conf. Series: Materials Science and Engineering* **862** 032052
[57] Likhanov V A, Rossokhin A V and Devetyarov R R 2020 *Journal of Physics: Conf. Series* **1515** 042064
[58] Skryabin M L and Grebnev A V 2020 *Journal of Physics: Conf. Series* **1515** 052052
[59] Likhanov V A and Lopatin O P 2020 *IOP Conf. Series: Materials Science and Engineering* **862** 062027