# Assessment of the Effect of Diesel Fuel and Natural Gas Blend on the Diesel Locomotive Intra-Cylinder Parameters

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**Abstract.** The article presents a computational and experimental evaluation of the effect of blended fuel on the indicator values and heat release characteristics of a diesel locomotive converted to operate according to the gas and diesel cycle. The novelty of this research is the implementation of the method of natural gas supply into the diesel fuel on the low-pressure line with the use of a mixing device.

## 1 Introduction

The huge stock of natural gas in the Russian Federation and the wide possibilities of its use in transportation power plants to improve technical and economic performance prove the relevance and high importance.

OAO RZD plans to purchase locomotives that operate on natural gas and other alternative energy sources, namely locomotives with gas piston and gas and diesel engines in early 2025. It is planned to convert 25% of the fleet to gas by 2030 [1].

The Energy Strategy of OAO RZD as of 11.02.08 No. 269p sets a task to replace up to 25% of diesel fuel consumed by locomotives with natural gas by 2030, reduce the cost of the life cycle up to 8.5%, as well as reduce the environmental load up to 95% [1].

According to expert evaluation, the use of natural gas as a motor fuel has a number of advantages, including:

– allows to reduce the cost of transportations by 15–25%, which is due to the lower price of natural gas;

– reduce emissions of toxic substances into the environment (carbon monoxide — 2.5 times, nitrogen oxide — 2 times, hydrocarbons — 3 times, smokiness — 9 times);

– increase the service life of diesel engines, thereby increasing the life cycle of diesel locomotives.

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Electricity, diesel fuel, coal, fuel oil and natural gas account for about 95% in the total energy balance of OAO RZD, which in turn includes 93.0% of financial investments for their

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purchase. In this case, the part of the consumption of fuel and energy resources (FER) attributable to OAO RZD varies up to 3% of the entire domestic market of the country.

The results of the analysis show a high dependence of the transportation complex on petroleum increases. Consequently, with the ever-increasing cost of petroleum products and the reduction of petroleum reserves on a global scale, it becomes the most urgent direction for mankind – the renewal of fuel and energy potential in terms of using alternative fuels instead of conventional fuels.

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The fuel system of diesel locomotives operates in a wide range of loads, including with various changes in operating modes. In this regard, the need to find technical solutions for the development of dual-fuel engines, which will ensure the reliable operation of gas turbine locomotives on conventional fuel with the addition of natural gas in different ratios, is increasing [1, 2].

The positive effect of power plants operating according to the gas and diesel cycle is ensured by a fast transition with the use of electronic control system in the mode of operation from diesel fuel to natural gas and in the opposite direction (Table 1).

**Table 1.** Comparison of gas and diesel and gas cycle engines

| **Gas and diesel cycle** | **Gas cycle** |
|---|---|
| Advantages | |
| 1. making minor design changes and capital investments;<br>2. operation in dual fuel mode;<br>3. implementation of transients with a rapid power gain by using diesel fuel as an additive;<br>4. power indicators are not inferior to the diesel cycle;<br>5. easier starting compared to diesel fuel | 1. possibility of one hundred percent replacement of diesel fuel with natural gas;<br>2. possibility of storing one type of fuel on the locomotive;<br>3. reduction of cost of maintenance and repair of the fuel system |
| **Disadvantages of** | |
| 1. need to place tanks for storing diesel fuel and natural gas;<br>2. incomplete substitution of diesel fuel with natural gas | 1. 25% power reduction depending on the load;<br>2. premature failure of the spark ignition module;<br>3. limited use due to reduced power;<br>4. lack of the necessary fuel reserve on the locomotive;<br>5. increase of specific consumption of natural gas by 12% depending on load;<br>6. limited range of possible excess air ratio |
| **Effect** | |
| Have an economic benefit in the existing operating conditions | Have an economic benefit in the case of a developed gas filling infrastructure |

Shunting locomotives are characterized by specific operating conditions that are associated with intensive and rapidly changing modes of operation. Taking these features into account, as well as taking into account the inertia of the gasifier, liquefied natural gas (LNG) is difficult to use on shunting locomotives. For this reason, the use of pressurized compressed natural gas (CNG) is relevant for shunting locomotives operating according to the gas and diesel cycle. In this regard, the paper suggests a new way of supplying CNG to the diesel cylinders, namely to the diesel fuel in the fuel manifold on the low-pressure line in order to minimize design changes.

Numerous studies have established that for the effective use of this supply method, in order to improve the environmental and economic performance of diesel engines of autonomous locomotives, the problem of qualitative mixing and uniform distribution of the resulting mixed fuel in the entire volume of the combustion chamber should be solved. This problem is solved by using the developed mixing device [4].

## 2 Materials and Methods

It is feasible to estimate parameters of diesel locomotives operating on diesel fuel with the addition of CNG in the low-pressure line by conducting a set of studies, both experimental and computational ones.

Meanwhile, to assess the quality of the flow of the operating process, the diagrams, which can be used to assess the change in the pressure of gases in the diesel cylinder, depending on the angle of rotation of the crankshaft (crankshaft rotation), are the most informative.

Direct and indirect indication is used to estimate the intra-cylinder parameters of diesel engines [3–5]. These methods are technologically complex and difficult to implement, which requires high costs for purchase, since additional instrumentation is not standard equipment of the rheostat testing station of the locomotive service depot. For example, to perform direct indication of a diesel locomotive diesel engine, it is necessary to use imported pressure sensors, which are installed in the injector.

To carry out indirect indication the substantial experimental work is necessary, which includes: the use of signals of irregular crankshaft rotation; determination of pressure by load sensors installed on the gas joint gasket; installation of a steel washer with strain gauges mounted on it under the nut or bolt cylinder head (head) mounts [5].

In order to obtain a detailed indicator diagram, there is an alternative option as well, which is convenient and less costly — using analytical methods of calculating of the operation cycle based on known theoretical provisions [3, 5, 10].

The considered theoretical provisions allow to estimate the influence of blended fuel on the intra-cylinder parameters of diesel locomotives, which are characterized by combustible mixture burnout and heat release.

The characteristics of the rate of heat release for medium-speed diesel engines are distinguished by the presence of two maximums. The presence of the second maximum is caused by the overflow of the fuel-air mixture in the overpressure space, into which a fresh portion of the air charge enters, which contributes to an increase in the combustion rate.

A sharp increase in pressure and temperature in the engine cylinder is caused by the high rate of heat release during the initial period of combustion, resulting in an excessive dynamic load on the crank mechanism parts and crankshaft bearings and, as a consequence, the rigidity of the operating process, which is accompanied by an increased noise level, is increased.

Based on the direct dependence between the value of the first maximum of the heat release rate and the concentration of nitrogen oxides, which are formed in the combustion chamber to reduce emissions of harmful substances in exhaust gases, it is necessary to reduce the first maximum of the heat release rate and increase the second.

The composition of harmful emissions in the exhaust gases was analyzed in this paper on the basis of the obtained characteristics of heat release, as well as models for calculating the processes of formation of toxic components.

The tangible effect of using blended fuel according to the proposed CNG supply method can be seen in the indicator diagrams shown in Figure 1. When a diesel locomotive operates on diesel fuel with the addition of natural gas, the combustion process proceeds smoothly, approaching the isobaric process. The results show a 0.3 MPa or 3.4% decrease in maximum cycle pressure and a 1.8% decrease in process stiffness.

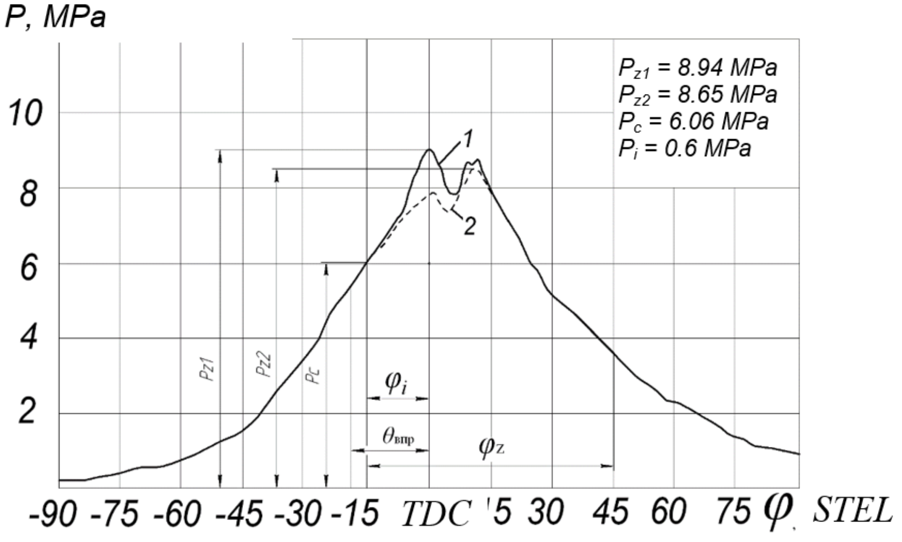


**Fig. 1.** Indicator diagrams of a diesel engine of a shunting locomotive when operating on diesel fuel (1) and with the addition of natural gas (2)

The addition of natural gas to diesel fuel under pressure is accompanied by intense release of natural gas from the jet of atomized diesel fuel in the combustion chamber volume in the event of a sharp decrease in the pressure exerted on the natural gas. Thus, natural gas contributes to the destruction of the jet of diesel fuel fed by the nozzle into small drops, which leads to a much faster evaporation. As a result, the formed fuel vapors mix with the air charge with greater intensity, after which they heat up and ignite, which affects the entire combustion process, namely, the self-ignition delay period is reduced, the maximum cycle pressure is reduced, and the rate of pressure build-up during combustion is reduced.

The positive effect of diesel fuel saturation with natural gas in the low-pressure line is the intensive course of the following physical processes: evaporation, heating, as well as mixing.

The positive effect of diesel fuel saturation with natural gas in the low-pressure line can also be traced by the characteristics of heat release and gas temperature in the diesel cylinders, which can be used to assess the perfection of the operating cycle in terms of thermodynamics, as well as the amount of emissions of harmful substances in exhaust gases formed in this process.

Figure 2 shows the characteristics of heat release and gas temperatures to assess the implementation of the method of natural gas supply to diesel fuel in the low-pressure line during rheostat tests of the shunting locomotive in the service locomotive depot “Orsk” of the South Urals Railway — branch of OAO RZD. The results shown in Figure 2 were obtained on the basis of a computational experiment using the ENGINE software product [7]. The initial data given in [6, 7] were taken for the calculation.

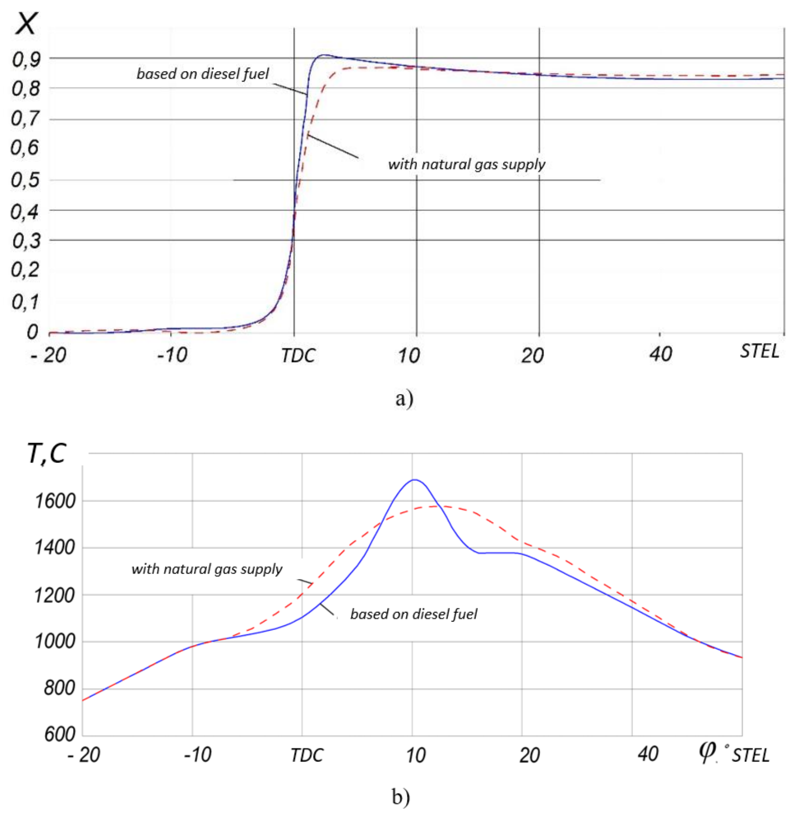


**Fig. 2.** Heat release characteristics (a) and gas temperatures (b) during operation of diesel locomotive on diesel fuel and with the addition of natural gas

Considering the curves presented in Figs 3a and 3b in the context of the indicator diagram shown in Fig. 2, the presence of a "flange" on the curve of the temperature of the gases in the cylinder in the range of 15...20 deg. of crankshaft rotation after TDC is explained by the presence of two processes. One process — the piston stroke, the volume increases, the pressure should drop, and the second process — it proceeds already with a lower intensity of fuel combustion. Burnout is upward, and expansion is downward. In total we have the flange vector in the Figure. The law of burnout of the gas part resulted in a flange.

The calculations carried out using the gas and dynamic model made it possible to determine the dynamics of changes in the concentrations of incomplete combustion products in the diesel locomotive cylinder from the angle of crankshaft rotation at various load modes (Fig. 3).

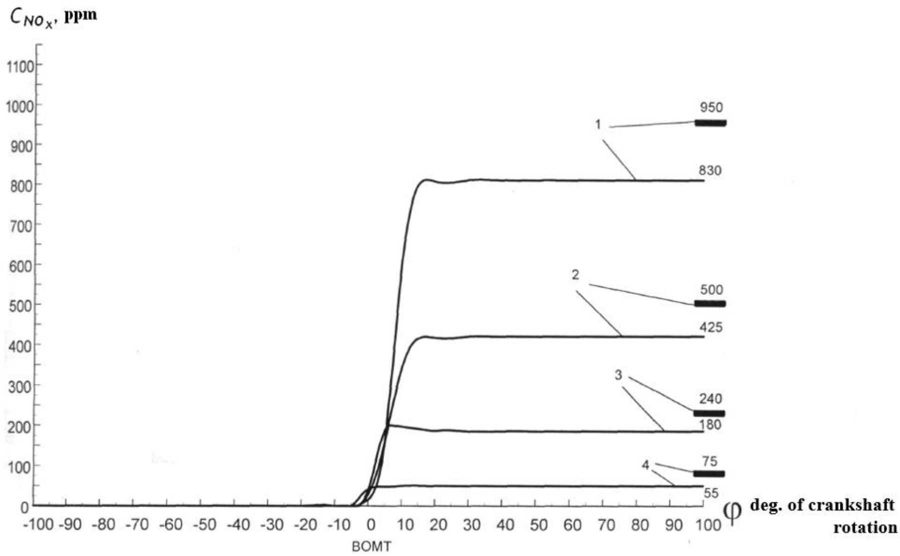


**Fig. 3.** Calculated and experimental concentrations of NOx emissions in exhaust gases of diesel shunting locomotive operating on diesel fuel with the addition of natural gas from the angle of crankshaft rotation (1 — 100% Ne; 2 — 0.75% Ne; 3 — 0.5% Ne; 4 — 0.25% Ne; — experimental data)

The results of the calculation and experimental studies show a decrease in the amount of formed NOx by an average of 26% as the crankshaft rotation angle approaches to TDC, depending on the operating mode of the diesel fuel at the saturation of the diesel fuel with natural gas.

## 3 Results and Discussion

Natural gas is harder to ignite and burn than diesel fuel. However, the addition of natural gas to diesel fuel under pressure, using a stirrer to dissolve the natural gas in the diesel fuel, results in its intense release from the stream of atomized diesel fuel in the combustion chamber volume, when the pressure exerted on the natural gas is rapidly reduced up to several hundred bar (600–1,000) to 60–80 bar.

As a result, the diesel fuel in the droplets seems to "boil", the droplets quickly break up into many small ones, which evaporate with high intensity. The fuel vapor generated in this process diffuses with the air and mixes with it much faster, then heats up from it and ignites.

As a result of the research we can say that the main advantage of the proposed method of natural gas supply is to accelerate the physical processes of evaporation, heating and mixing of diesel fuel.

As is known, the ignition delay period (tau) consists of the following sum: tau/physical + tau/chemical.

The ignition facilitation, i.e. the reduction of the ignition delay period is due to the reduction of the tau/phys, so it effects the whole combustion process as well.

Gas fuel burns earlier due to the nature of its combustion (compressed natural gas burns throughout the whole volume, and diesel fuel from the surface). Natural gas does not require preparation, when exchanged, it immediately seizes up, begins to burn and when it is added to diesel fuel, there is a destruction of the fuel jet by the products of combustion of gas due to a sharp increase in pulsation and temperature. As a result, this leads to a reduction in the autoignition delay period, a decrease in the maximum cycle pressure, and a decrease in the rate of pressure build-up during combustion.

## 4 Conclusion

Comparing the indicator diagrams, heat release and gas temperature curves obtained on the basis of known theoretical positions and the proposed method of natural gas supply to the diesel fuel in the low pressure line, an improvement in the intra-cylinder parameters is observed. In this case, there is a slight reduction in the autoignition delay period, and the heat release characteristic lacks the pronounced maximum that is characteristic of explosive combustion.

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