Calculation studies of the influence of exhaust gas recirculation on the characteristics of the natural gas-fueled diesel engine

II Libkind and A V Gonturev

FSUE "NAMI", Moscow, Russian Federation

E-mail: ivan.libkind@nami.ru

Abstract. When converting diesel engines to run on natural gas on the gas-diesel cycle, additional problems arise associated with the high thermal stress of the exhaust valves and valve seats at high loads and engine speeds. There is also an increase in NOx emissions due to higher combustion temperatures of natural gas. One of the ways to improve the economic and environmental performance of engines operating on a gas-diesel cycle with a lean air-fuel mixture is to optimize the combustion of the air-fuel mixture by using an exhaust gas recirculation system (EGR). The principle of operation of this system is as follows: exhaust gas entering the intake manifold and further into the combustion chamber reduces the oxygen concentration in the air-fuel mixture, which leads to a dilution effect and, accordingly, to a decrease in combustion temperature and a decrease in NOx content. In order to study the influence of EGR on the dual-fuel gas and diesel engine parameters in the AVL Boost software package, a computer model of the existing 6ChN13/15 engine was developed. A low-pressure EGR system with an exhaust gas cooler was simulated on this engine. Values of NOx emissions, brake specific fuel consumption (BSFC) and brake efficiency have been obtained at different recirculation rate by calculation method. These values allow to estimate the feasibility of using a cooled EGR in a natural gas-fueled diesel engine.

1. Introduction

A significant disadvantage of the natural gas-fueled diesel engine is a thermal efficiency decreasing at low and medium engine loads. Accordingly, at high load, an increase in the amount of supplied gas fuel leads to an increase in the gas content in the mixture, an increase in the rate of heat release and a corresponding improvement in the thermal efficiency. However, due to this improvement, the temperature in the combustion chamber also increases, which is the reason for the growing NO\textsubscript{x} emissions [1-4].

To overcome these disadvantages, it is advisable to use the EGR. The principle of operation of this system is as follows: exhaust gas entering the intake manifold and then into the combustion chamber (CC) reduces the oxygen concentration in the air-fuel mixture. This leads to the dilution effect and thus a lower combustion temperature and a lower amount of NO\textsubscript{x}. This is confirmed in publication [4-6].

The diesel engine load characteristics with three types of cooled gas recirculation were simulated earlier in FSUE "NAMI". It showed that the introduction of EGR in the range from 55% at low engine loads and up to 20% at full engine load practically does not decrease the fuel efficiency and energy characteristics of the engine [7].
The aim of this work is a computational study of the possibilities of using cooled EGR in engines operating on the dual-fuel mode. The calculations were carried out at engine full load for a certain range of engine speeds. According to the experimental data, the base engine without EGR system was simulated and calibrated. The use of EGR was simulated for several calculation points of the base engine with different engine speed. The results for the effective performance of the engine, combustion characteristics and emissions of nitrogen oxides have been obtained and presented.

2. Object of study
The object of the study was the 6ChN13/15 natural gas-fueled diesel engine with four-valve cylinder heads. The injection system – “common rail”, with the fuel injector located in the center of the combustion chamber. The gaseous fuel supply system with multi-point injection has been installed during the converting of the base diesel engine into the dual-fuel engine. The intake manifold has been modified to maintain gas injectors. The characteristics of the natural gas-fueled diesel engine are shown in table 1.

| Parameter | Value |
|-----------|-------|
| Engine type | In-line 6 cylinders, four-stroke, dual-fuel engine, turbocharged, intercooled |
| Bore | 130 |
| Stroke (mm) | 150 |
| Engine capacity (l) | 11.946 |
| Geometric compression ratio | 17.5 |
| Rated power (kW) | 345 |
| Maximum torque (N∙m) | 1870 |
| Engine speed at maximum torque (min⁻¹) | 1300…1500 |
| Rated engine speed (min⁻¹) | 1900 |
| Intake valve | |
| - opening | 44° BTDC |
| - closing | 60° after BDC |
| Exhaust valve: | |
| - opening | 94° before BDC |
| - closing | 56° ATDC |

The computational study included the determination of the regulation curves depending on the EGR rate. Further, in accordance with the optimal values of EGR rate, obtained from these curves, the full-load curve of a dual-fuel engine with EGR was compiled for comparative analysis with the full-load curve of the dual-fuel engine without EGR.

3. Description of the computer model
To carry out computational studies, a computer model of the investigated gas-diesel engine (shown in Figure 1) was developed in the AVL Boost program.
Figure 1. Computer model of 6ChN13/15 dual-fuel engine with low-pressure cooled exhaust gas recirculation system.

The developed computer model includes air filter CL1, turbocharger TC1, charge air cooler CO1, air throttle TH1, intake manifold PL1, gas injectors for gas fuel supply I1 - I6, engine cylinders C1 - C6, restrictor R1 to restrict exhaust gas flow (used for simulating the bypass of part of the exhaust gas past the turbine), SB1 - boundary conditions at the inlet, SB2 - boundary conditions at the outlet. Pipes (1 - 37) are used to simulate the intake and exhaust manifolds and the EGR system. Measuring points MP1 - MP26 are set in the model in order to get information on specific segment of the model, where this point is set up. The EGR system in the model consists of a recirculated exhaust gas cooler CO2, a restrictor (throttle valve) R2 to simulate the operation of the recirculation valve.

4. Results
The results from of the calculation study carried out at full engine load in the speed range from 900 to 1900 rpm. The calculation of each engine speed value has been carried out for several different exhaust gas recirculation rates of in the range from 0 to 20%.

The exhaust gas recirculation regulation curve for brake specific fuel consumption and NOx emissions are shown in Figures 2 and 3, respectively. The graphs show that 20% recirculation rate is possible over the entire engine speed range. To do this, it is necessary to select a turbocharger different from the one installed in the basic version of engine (without EGR). This turbocharger must provide such an air flow rate that is required to keep the air–fuel equivalence ratio $\lambda$ within the limits required for normal combustion of the air-fuel mixture.

Despite the further reduction in the amount of NOx emissions, increasing of the EGR rate leads to excessive decreasing of air concentration in the gas-air mixture (Figure 4). With a decrease of the air–fuel equivalence ratio $\lambda$ lower than 1.2, unstable operation of the engine is observed. There is a
significant impairment in the combustion process and, accordingly, an increase in brake specific fuel consumption is also observed.

Figure 2. Brake specific fuel consumption for different EGR rates.

Figure 3. NOx concentration for different EGR rates.
Figure 4. Air–fuel equivalence ratio $\lambda$ for different EGR rates.

Figure 5 shows the full-load curve of the dual-fuel engine without EGR and with 20% EGR rate. The recirculation rate in this engine was previously selected in accordance with the optimal values of $\lambda$, BSFC and NO$_x$ concentration.

It can be seen from the graphs that due to the replacement of oxygen in the air-fuel mixture with inert gases from the EGR system causes a decrease in the air–fuel equivalence ratio over the entire engine speed range. This leads to a reduction in the rate of heat release and in temperature in the combustion chamber. Therefore, there is a decrease in the formation of NO$_x$ by the thermal mechanism. The NO$_x$ content in the exhaust gas decreased by 4 times at the nominal mode and by 5 times at the maximum torque engine speed.

A decrease in temperature, however, worsens the combustion process and leads to an increase in brake specific fuel consumption by about 3%. Decreasing in the air–fuel equivalence ratio at 1500 rpm may be a consequence of the influence of various hydrodynamic factors at the point where exhaust gases are taken from the exhaust manifold and at the point where exhaust gases enter the intake manifold. In general, the use of the EGR system has significantly reduced the NO$_x$ emissions, while not negatively affecting the efficient characteristics of the engine.

The addition of EGR also reduces the peak combustion pressure at the rated engine speed (Figure 6). This is a possible reason of a large decrease in power in this operating mode (6% versus 4% at the maximum torque speed).

The peak combustion temperature $T_z$ at the maximum torque engine speed decreases with increasing EGR. Figure 7 shows that the temperature drop stops when the EGR rate rises to 15% or more. Supposedly, at a given degree of recirculation, a large amount of unburned hydrocarbons (HC) begins to enter the combustion chamber. These hydrocarbons burn out together with the main fuel-air mixture, thereby increasing the rate of heat release. The combination of these effects leads to a stabilization of the combustion temperature.
Figure 5. Full-load curve of 6ChN13/15 engine without EGR and with 20% EGR rate.

At nominal engine speed with 20% exhaust gas recirculation, there is a slight increase in $T_x$. The reason for this can also be the afterburning of unburned hydrocarbons. At the same time, in this operating mode the air–fuel equivalence ratio approaches the best value for the combustion of natural gas ($\approx 1.4$). This leads to an increase in the rate of combustion and heat release. Therefore, this leads to an increase in temperature in combustion chamber.
5. Conclusions
Analysis of the data obtained in the course of computational studies shows that the use of the EGR system makes it possible to reduce the concentration of NOx in the exhaust gas. At the same time, taking into account the selection of the turbocharger, there is no negative effect on the brake specific fuel consumption. Similarly, engine power and torque are not reduced.

However, in order to clarify the data on the effect of EGR in full engine load, it is necessary to calculate the intermediate points of the VLC of the gas-diesel engine. The results obtained from the calculations will be confirm in the course of experimental studies.

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