Computational studies of the influence of variable valve timing on the performance of a gas engine with Miller's thermodynamic cycle

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Abstract. Current development trends in the field of internal combustion engines aim at regulating all processes of the engine and individual units. A converted diesel to gas engine with Miller thermodynamic cycle is more energy efficient at partial loads than a gas engine with Otto thermodynamic cycle. The Miller cycle engine with variable valve timing and valve lift has been investigated to improve performance and energy efficiency across the load range. The aim of the work is to study the influence of the displacement of the valve timing phases of the intake and exhaust camshafts and the valve lift height on the performance of the gas engine with the Miller cycle. Computer modelling was based on data obtained from the full-scale experiment on the gas engine with the Miller thermodynamic cycle.

1. Introduction

The need to use alternative fuels is associated with an annual increase in the number of vehicles that have a negative impact on the environment, oil resources are depleted, currently more than 50% of the total oil production is consumed by vehicles [1]. Natural gas is currently one of the best alternatives to liquid fuels of petroleum origin, as it reduces emissions of greenhouse gases and pollutants into the atmosphere.

In addition to reducing the negative impact on the environment, economic benefit is also a factor in the transition to natural gas as an alternative fuel, the price of natural gas is about 0.22 $/m³ (09/22/2020), which is approximately 2.6 times cheaper than the equivalent heat of combustion of 1 liter of diesel fuel.

Converting a basic diesel engine to a gas engine with the thermodynamic Otto cycle involves equipping the engine with gas supply equipment, modifying the cylinder head by replacing the diesel nozzle with a spark plug, and installing a compression-relief piston to avoid combusting knock [2]. Switching to natural gas leads to the following problems: reduced indicator efficiency due to reduced compression ratio, increased heat stress of exhaust valves and seats, and reduced fuel efficiency. Despite this, the conversion of engines to gas fuel remains cost-effective [1].

The main tasks in improving gas engines are as follows: reducing the temperature of exhaust gases, harmful emissions and greenhouse gases, improving fuel efficiency.

Converting a diesel engine to a gas engine with the thermodynamic Miller cycle with early closing of the intake valve avoids knocking without reducing the compression ratio, therefore, without reducing the indicated efficiency. As a result of thermodynamic analysis carried out in [3], the authors showed that the Miller cycle with early closing of the intake valves can increase the effective efficiency by 18% at low loads compared to the standard valve timing of the Otto cycle. With early closing of the intake
valve, the piston continues to move to the bottom dead center, the charge expands and cools down, which reduces the tendency to knocking combustion, the exhaust gas temperature and nitrogen oxide emissions decrease [4].

The criterion for assessing energy efficiency in road transport is fuel consumption or carbon dioxide emissions CO₂ [5]. As a result of a full-scale experiment, the results were obtained for a basic diesel engine - the minimum CO₂ emissions in terms of the external speed characteristic are 591 g/kW·h, the conversion of the engine to natural gas with the Otto thermodynamic cycle reduces CO₂ emissions to 513 g/kW·h. Figure 1 shows a graph of the difference in CO₂ emissions from the Miller cycle gas engine compared to the Otto cycle in the operating mode field. Negative values on the graph correspond to a reduction in emissions, while positive values correspond to an increase for the two compared cycles.

![Figure 1](image_url)  
**Figure 1.** Comparison of CO₂ emissions for engines with Miller and Otto cycles.

Figure 1 shows that the energy efficiency of the gas engine with the Miller cycle is higher at partial loads than that of an engine with the Otto cycle. The CO₂ emission level are reduced by up to 17%.

Objective: to further improve the working process and increase the energy efficiency of the Miller cycle engine over the entire load range, it is necessary to conduct studies of a gas engine with adjustable valve timing and lifting height based on the experimental data obtained. The most interesting area is the one highlighted in red in figure 1.

2. Materials and Methods

A computer model for computational research was developed and validated based on a full-scale experiment of the gas engine with the Miller thermodynamic cycle. As a result of validation of the simulation model of the gas engine using the Miller cycle with two-stage supercharging, deviations of the calculated load characteristics from those obtained experimentally were verified. The deviation between the calculated and experimental load characteristics does not exceed 5% in most cases. A one-dimensional computer model developed in the AVL BOOS software is shown in figure 2. When
converting the basic diesel engine, a gas fuel supply system was installed in the intake channels, and a spark plug was installed instead of the diesel nozzle. The engine is equipped with individual four-valve cylinder heads. Table 1 shows the characteristics of a gas engine with the Miller thermodynamic cycle without a system for changing the valve timing and adjusting the valve lift height.

Figure 2. Computer model of the gas engine.

Table 1. Gas engine characteristics.

| Name of parameter                                      | Values                                      |
|--------------------------------------------------------|---------------------------------------------|
| Engine type                                            | Spark-ignition gas engine with two-stage turbocharging and intercooler |
| Geometric compression ratio                            | 17,5                                        |
| Net power according to GOST R 41.85-99 (UNECE Regulation No. 85), kW, ±2%, kW | 380                                         |
| Rated speed, rpm                                       | 2000±25                                     |
| Maximum torque according to GOST R 41.85-99 (UNECE Regulation No. 85), N-m, ±4% | 1951                                        |
| Speed of maximum torque, rpm                           | 1200…1800                                   |
| Minimum idle speed, rpm                                | 600±50                                      |
| Maximum idle speed, rpm                                | 2350                                        |
| Specific fuel consumption according to full-load curve, g/kW-h |                                  |
| - minimum at 1100-1600 rpm                            | 184,7                                       |
| - at the gross power                                   | 196,5                                       |
The design study plan includes determining the range of valve timing control, which is necessary to prevent the piston from colliding with the valve.

Timing shifting of the intake camshaft in the direction of reducing the overlap of more than 30 deg. will lead to an increase in negative work on the intake stroke until the intake valve opens, the actual compression ratio will increase, and the time for cooling the gas-air mixture will also decrease, which will lead to an increase in NOx emissions due to an increase in the maximum cycle temperature [1,6]. Increasing the actual compression ratio can lead to the occurrence of knocking. For the valve timing of the exhaust camshaft, the shift is more than 30 deg. in the direction of reducing the overlap will lead to a significant loss of work on the expansion and loss of heat with the exhaust gases, therefore, the temperature in front of the turbine will increase.

Adjustment of the valve timing of the exhaust camshaft is carried out up to 30 deg. in the direction of increasing overlap. Further displacement of the phases will lead to negative compression effects. The opening phase of the intake valve is shifted up to 30 deg. in the direction of increasing the overlap, the closing time of the intake valve remains unchanged to maintain the actual compression ratio [1]. A large angle of overlap of the valves will cause methane to be released into the exhaust manifold, which can disable the exhaust gas neutralization system. Figure 3 shows the extreme positions of the intake and exhaust valve timing control.

![Figure 3](image.jpg)

**Figure 3.** The extreme positions of the shift of the opening phases of the intake and exhaust valves.

### 3. Results

The influence of valve timing and valve lift on the performance of an engine with Miller thermodynamic cycle was analysed at 1000, 1400 and 1800 rpm in 300 Nm load steps.

Adjustment of the valve timing of the exhaust camshaft at 1000 rpm and 300 N·m with an excess air coefficient equal to 1 is shown in figure 4.
Figure 4. Adjusting the timing of the exhaust camshaft at 1000 rpm and 300 N·m.

From the graphs shown in figure 4, it can be seen that when the phases are shifted in the direction of reducing the overlap, the torque decreases to 282 N·m, the specific effective fuel consumption increases by 15 g/kW·h, CO emissions change insignificantly, NOx emissions decrease by 650 ppm, this is due to a decrease in the maximum cycle temperature and loss of expansion work due to early opening of the exhaust valve.

When the phase is shifted in the direction of increasing overlap, the torque increases by 20 N·m, the specific effective fuel consumption is reduced by 21 g/kW·h, NOx emissions are reduced by 730 ppm, the temperature in front of the turbine is reduced by 40 °C. due to improved venting with higher valve overlap.
The exhaust camshaft camshaft timing adjustment at 1800 rpm and 900 N·m while maintaining the excess air ratio at 1 is shown in figure 5.

![Adjustment of the valve timing of the exhaust camshaft at 1800 rpm and 900 N·m.](image)

**Figure 5.** Adjustment of the valve timing of the exhaust camshaft at 1800 rpm and 900 N·m.

From the graphs shown in figure 5, it can be seen that when the phases are shifted in the direction of reducing the overlap, the torque decreases by 133 N·m, the specific effective fuel consumption increases by 35.5 g/kW·h, CO emissions change slightly, NOx emissions decrease by 645 ppm this is due to a decrease in the maximum cycle temperature due to the early opening of the exhaust valve, while the temperature in front of the turbine increases by 14 °C.

Displacement of the exhaust camshaft phase to 15 deg. in the direction of increasing overlap leads to a decrease in the exhaust gas temperature in front of the turbine and NOx emissions by 20 °C and 420
ppm respectively, further phase displacement leads to a decrease in the performance of the gas engine, the torque is reduced to 884 N·m, the specific effective fuel consumption increases by 10 g/kW·h.

The effect of the timing shift of the exhaust camshaft on the performance of the gas Miller, shown in figures 4 and 5, is similar over the entire frequency and load range. Shifting the timing of the exhaust camshaft in the direction of reducing valve overlap does not have a positive effect on the performance of the gas engine with the Miller cycle. The shift in the direction of increasing the overlap at low and medium loads has a positive effect on the performance of the gas engine, at high loads the effect is insignificant.

Adjustment of the valve timing of the intake camshaft at 1000 rpm and 300 N·m with an excess air ratio of 1 is shown in figure 6.

![Figure 6. Adjusting the valve timing of the intake camshaft at 1000 rpm and 300 N·m.](image-url)

From the graphs presented in figure 6 it can be seen that when the intake phase is shifted towards decreasing overlap, the torque decreases to 270 N·m at 50 deg., respectively, the specific effective fuel
consumption increases, the temperature of the exhaust gases increases by 15 °C, NOx emissions increase by 1500 ppm.

Figure 7 shows the adjustment of the valve timing of the intake camshaft at 1000 rpm and 300 N·m with the excess air ratio equal to 1.

![Graph showing various parameters against intake VVT (deg).](image)

**Figure 7.** Adjusting the valve timing of the intake camshaft at 1400 rpm and 900 N·m.

From the graphs shown in figure 7, it can be seen that when the intake phase is shifted in the direction of reducing the overlap, the torque decreases to 820 N·m at 50 deg., respectively, the specific effective fuel consumption increases, the exhaust gas temperature increases by 30 °C, CO emissions remain unchanged, and NOx emissions increase by 1670 ppm.
A similar pattern is observed over the entire frequency and load range, so the shift of the timing phases of the intake camshaft in the direction of reducing overlap does not have a positive effect on the performance of the gas engine with the Miller thermodynamic cycle.

To shift the valve timing of the intake camshaft in the direction of increasing overlap, it is necessary to leave the moment of closing the intake valve unchanged, since this can significantly affect the actual compression ratio, which will lead to knocking combustion. The opening phase of the intake valve is shifted up to 30 deg. in the direction of increasing the overlap, a large angle of overlap of the valves at low loads will lead to the release of methane into the exhaust manifold due to the low inertia of the fresh charge, which can disable the exhaust gas neutralization system. Figure 8 shows the adjustment of the inlet valve opening angle to increase the overlap.

Figure 8. The shift of the valve timing for the intake camshaft in the direction of increasing overlap.

Adjustment of the valve timing of the intake camshaft in the direction of increasing overlap at a speed of 1000 rpm and 300 N·m with an excess air ratio of 1 is shown in Figure 9.

The graphs shown in figure 9 show that when the inlet valve opening angle is shifted in the direction of increasing overlap, the torque increases by 26.5 N·m, the specific effective fuel consumption decreases by 25 g/kW·h, and the temperature in front of the turbine decreases by 55 °C and NOx emissions are halved, this is caused by a decrease in the maximum cycle temperature by 200 °C, improved purging during valve overlap, and further increases in overlap will lead to natural gas being thrown into the exhaust manifold.

Figure 10 shows the inlet valve opening angle adjustment to increase the overlap at 1800 rpm and 900 N·m with an excess air coefficient of 1.
Figure 9. Adjusting the inlet valve opening angle to increase the overlap at 1000 rpm and 300 N·m.

From the graphs shown in figure 10, it can be seen that when the opening phase of the intake camshaft is shifted in the direction of increasing overlap, the torque increases by 28 N·m, the specific effective fuel consumption decreases by 8 g/kW·h, the exhaust gas temperature decreases by 62 °C, and NOx emissions are reduced by 800 ppm which is caused by a decrease in the maximum cycle temperature and improved purging.
Figure 10. Adjusting the inlet valve opening angle to increase the overlap at 1800 rpm and 900 N·m.

4. Conclusions
Studies of the influence of timing phases on the parameters of the gas engine with the Miller cycle have shown that the displacement of the exhaust phase towards an increase in valve overlap at low and medium loads has a positive effect on the engine parameters due to improved purge during overlap, a strong displacement of the exhaust phase will lead to an increase in negative compression work and the probability of throwing the working mixture into the exhaust manifold. Adjusting the timing of the exhaust shaft at 1000 rpm and 300 N·m allows you to increase the torque by 20 N·m, reduce the specific effective fuel consumption by 21 g/kW-h, reduce the temperature in front of the turbine by 40 °C and NOx emissions by 730 ppm. Adjusting the exhaust timing at medium to high loads reduces the temperature in front of the turbine, in the mode of 1800 rpm and 900 N·m, the displacement is up to 15
deg. in the direction of increasing overlap, it reduces the temperature of exhaust gases in front of the turbine and NOx emissions by 20 °C and 420 ppm respectively.

Adjusting the intake phases in the direction of reducing overlap leads to a deterioration of engine performance over the entire frequency range and loads, as negative work increases on the intake stroke until the intake valve opens, the actual compression ratio increases significantly, which can lead to knocking combustion, and the time for cooling the gas-air mixture decreases, which leads to an increase in NOx emissions. In the 1000 rpm and 300 N·m mode, when the intake phase is shifted in the direction of decreasing overlap, the torque decreases to 270 N·m at 50 deg. the specific effective fuel consumption increases accordingly, the exhaust gas temperature increases by 15 °C, and NOx emissions increase by 1500 ppm.

Shifting the opening angle of the intake valve in the direction of increasing the overlap at low and medium loads improves the performance of the gas engine, the specific effective fuel consumption is reduced by more than 10%, and NOx emissions are more than 30%. At high loads, there are slight improvements in engine performance.

To further improve the working process and increase the energy efficiency of the Miller cycle engine over the entire load range, it is necessary to study the effect of adjusting the valve lift height depending on its operating mode based on the data obtained.

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