Influence of the single EGR valve on the concentration level of selected toxic compounds in exhausts of a multi-cylinder compression ignition engine

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Abstract. The most important problem faced by engineers constructing modern combustion engines is to meet stringent standards for the emission of toxic and harmful compounds in exhaust gases. One of the ways to reduce the emission of toxic compounds, in particular nitrogen oxides, is the use of various configurations of EGR systems in single and multi-cylinder engines. Its task is to introduce a certain amount of exhaust gas into the combustion chamber, which directly affects the combustion process, and ultimately the reduction of nitrogen oxides. However, the effectiveness of the EGR system is usually presented basing of emissions reduction or decrease of toxic compounds concentration in the exhaust manifold system, without division into the share of emissions from individual cylinders.

This article presents the results of the tests carried out in order to verify the degree of uneven distribution of concentrations between cylinders of a multi-cylinder engine with the use of a single EGR valve. As a research object, a compression ignition engine with symmetrical intake manifold and a centrally located EGR valve was used.

1. Introduction

Nowadays, the most popular combustion engines used in road transport are compression ignition (CI) engines. These engines are characterized by relatively high thermal efficiency. This is due to the high compression ratio required to obtain the mixture's ignition temperature and the combustion of weak mixtures, which are characterized by an excess of air in the combustion chamber, required to completely burn the fuel. However, the excess of oxygen contributes to the formation of a high combustion temperature in the areas where the stoichiometric mixture is present, which dominates the inhomogeneous combustion process. A good dispersion of the fuel dose in the combustion chamber promotes stoichiometric combustion in the microscopic sense. This is because the formation of auto-ignition points is located near the stoichiometric areas of a weak but heterogeneous mixture. As a consequence, CI engines generate large amounts of nitrogen oxides due to the flame propagation in a charge full of oxygen and nitrogen.

Designing new engines must consider the reduction of toxic and harmful compounds as well as fuel consumption in order to meet the latest emission standards and increasingly stringent designing demands. Currently, in CI engines, a reduction in the level of toxicity of fumes is obtained by using [1]:

- new air supply systems,
- new shapes of combustion chambers,
- Exhaust Gas Recirculation (EGR) systems,
• high-pressure fuel injection system (CR -Common Rail),
• selective catalytic reduction systems,
• downsizing,
• electronic control of actuators.

The device commonly used, since the seventies, in every intake system is the exhaust gas recirculation system, whose task is to introduce a certain amount of exhaust gas into the intake system. This process is beneficial in terms of chemical reactions taking place in the combustion chamber. The flue gas, as an inert gas, does not take part in the combustion process. Carbon dioxide contained in them has a higher specific heat than air, which significantly reduces the combustion temperature. Less oxygen reacts with nitrogen, thereby reducing NOx emissions. In addition, exhaust gas recirculation promotes evaporation of fuel and oxidation of unburned hydrocarbons [2]. It should be noted, however, that the excessive proportion of combustion gases in the combustion process contributes to increased particulate emissions, increased fuel consumption and reduced engine efficiency. This is caused by insufficient amount of oxygen in the flame zone, which can cause its extinguishment. In addition, the proportion of exhaust gases slows down the combustion process, which contributes to an increase in the temperature of the exhaust gas, causing large exhaust losses and deterioration of the engine's effective parameters [3][5][6].

The use of exhaust gas recirculation systems in internal combustion engines is a frequently addressed issue in modern research which are aimed at reducing emissions of toxic compounds in exhaust gases with various EGR system configurations, both for single and multi-cylinder engines. In both cases, the effectiveness of the EGR system concepts is presented on the basis of the reduction of emissions or concentrations of toxic compounds in the collective exhaust system. This article presents the results of tests carried out to check the degree of uneven distribution of concentrations between cylinders of a multi-cylinder engine using a single EGR valve.

The research involved a turbocharged, two-liter, sixteen-valve compression ignition engine of the Volkswagen group with the 2.0 TDi BKD designation, equipped with a symmetrical intake manifold with centrally located EGR valve - figure 1.

![Figure 1. View of the intake system of the tested engine unit: 1 - symmetrical intake manifold, 2 - EGR valve](image-url)
The collector with eight separate wires supplying the cylinders - two per cylinder. Each pair of wires is connected to the inlet channels of the head, whose task is to generate turbulence of charge in the cylinder. Their construction and location for a single cylinder is shown in figure 2.

![Image of exhaust and inlet ports](image)

**Figure 2.** Shape of inlet channels, and arrangement of valves in the head of the test engine [4].

2. **The experiment**

During the tests, measurements of NOx, CO concentrations and smoke in the exhaust gases from individual cylinders of the tested drive unit were made. This was accomplished by using four connection pipes placed in the exhaust manifold. The exhaust gas was aspirated via a probe located in the engine head at the connection point of each pair of exhaust ducts of a single cylinder. In fig. 4 numbers from 1 to 4 exhibits connecting ducts for cylinders from the first to the fourth, while the number 5 is placed behind the turbine, used for collective exhaust intake. The Horiba PG350 gas analyzer and the AVL 415S smoke gauge were used to measure the toxicity of exhaust gases.

The tests began with the external characteristics of the 2.0 TDI BKD compression ignition engine of the VW concern and the determination of engine operation parameters within the scope of which the exhaust gas flow through the EGR valve was controlled. Initially, bench measurements were made to determine the correlation between the maximum values of speed and torque for which the EGR valve is closed. It was noted that for idling, exhaust gas flow through the EGR valve was in the speed range from 800 to 3500 rpm, while the increase in load to 110Nm caused a reduction of the maximum value to 3000 rpm. In figure 3, the maximum load range at which the EGR valve opening was regulated is marked in red. During the experiment, the most important factor was maintaining the speed and torque at the set time by the test drive unit. It was the main determinant enabling independent measurement of NOx, CO and smokiness concentrations coming from individual cylinders with given engine operation parameters. The authorial controller of the motor-brake unit was used for this purpose, which did not use PID regulators maintaining the set speed and torque. This was to eliminate possible changes in the fuel dose, which would affect the course of the combustion process, and thus different NOx, CO and smoke emission over time. As a result of using the proprietary controller of the engine-brake unit, it was difficult to maintain a constant speed above 2350 rpm for given loads. Therefore, the bench tests were decided for rotational speeds in 1000, 1200, 1400, 1600, 1800, 2000 and 2200 rpm range, and 20, 60 and 110Nm loads. Figure 3 shows the measuring points with the marked area of external characteristics and the range of changes in the EGR valve of the tested engine.
Figure 3. Determination of measuring points of the tested engine: a) external characteristics, b) range of EGR valve opening, c) measuring points for 20Nm load, d) measuring points for 60Nm load, e) measuring points for 110Nm load

Figure 4. The exhaust system of the tested engine with marked gas collection points

The tests of NOx, CO and PM concentrations in the flue gas were carried out using the same measurement path, while maintaining the same external operating conditions of the drive unit without and with the participation of the EGR valve. For individual measurement points, an independent sampling of exhaust gases from each engine cylinder and the exhaust pipe was carried out, because the analyzers used were equipped with only one measuring channel. The time of performing a single measurement from a specific output for the Horiba PG350 gas analyzer was defined for two minutes, with the acquisition of samples with a two-second time quantum. As a result, 60 repetitions were
achieved at each measuring point. This time was selected experimentally. It aimed to record the maximum changes in the concentration of individual compounds during a single measurement. Performing further tests required cyclic switching of the sampling line between the measuring points, while the recording of the next correct reading was possible after the time of two minutes, which took into account the response delay of the applied measuring line. Additionally, during each gas test, a threefold measurement of smoke opacity was carried out in order to obtain a correlation between the emission of nitrogen oxides and smoke.

Figure 5. Rate of change in concentrations of selected exhaust components depending on the sample number, at n = 1000min⁻¹ and Mo = 20Nm.

Figure 5 presents an exemplary collection of measurements gathered for four cylinders and an exhaust pipe. The averaged values with the standard deviation of samples are shown in figure 6. The above data processing procedure was used to analyze the tests performed, a summary of which is presented in Chapter 3.
3. Results and discussion

The results of the NOx, CO and smoke tests in individual cylinders are presented for the selected load of 60Nm and subsequent rotational speed values for the off and on EGR valve.

In both cases, when measured without and with EGR, different concentrations of nitrogen oxides in individual cylinders were observed. The reason for this is the uneven filling level of the cylinders with the charge, resulting from wave phenomena and flow resistance occurring in the intake system, as well as a different residual combustion gas in the cylinders originating from the previous combustion process. Comparing the two systems, at the same rotational speeds, a different tendency of the distribution of nitrogen oxide concentrations in subsequent cylinders is noticeable. This is caused by a different proportion of recirculated gases in individual charges. Additionally, there is a different degree of swirling of the load resulting from different flow velocities in a single pair of intake channels of each cylinder.

The dependence of the nitrogen oxides concentration is related exponentially and inversely proportional to the concentration of solid particles, which results from the course of the combustion process of fuel in excess or depletion of oxygen. Figure 8 presents the results of smoke measurements made for the tested systems. The lowest concentrations were achieved for the system with disengaged
EGR valve (figure 8a), for which the combustion process was always in excess of oxygen. It can also be observed that for all tested work points, the smoke in the first and second cylinders is higher than the others.

![Figure 8. PM concentration for Mo = 60Nm: a) EGR valve disengaged, b) EGR valve controlled by EDC](image)

In the case of concentration of carbon monoxide its lowest share in exhaust fumes was found for the system with disengaged EGR valve - figure 9a. When using exhaust gas recirculation, its concentration increased, which was caused by incomplete combustion. It resulted from lowering the temperature and prolonging the combustion process due to the supply of exhaust gases in a fresh charge, containing CO from the previous combustion process. This is confirmed by the fact that the increase in the proportion of recirculated gases in the fresh charge contributes to lowering the combustion temperature, thus reducing the formation of new NOx, while increasing the CO, which is the effect of incomplete combustion.

![Figure 9. Concentration of CO for Mo = 60Nm: a) disengaged EGR valve, b) EGR valve controlled by EDC](image)

4. Summary

Analyzing the results, it can be concluded that for a given working point of a multi-cylinder engine, NOx, CO concentrations and smoke in individual cylinders are not the same. This is due to the fact that in each cylinder charges are combusted with different composition of air and exhaust gases. This
is caused by the dynamics of changes in wave phenomena being the result of the sequence of opening of intake valves and resistance of charge flow in the intake manifold, changing along with the rotational speed and engine load. Based on the tests, it can be concluded that with a single EGR valve, it is not possible to compensate the concentrations of toxic compounds in individual cylinders. This is caused by obtaining a constant percentage of flue gas in the charge delivered to each cylinder, which means that for cylinders with a lower degree of filling, oxygen deficiency will occur and the combustion process will be incomplete. In addition, the different course of the combustion process resulting from the uneven concentrations of NOx, CO and smokiness, causes uneven energy distribution from individual cylinders. This can affect the variable crankshaft speed during individual working strokes. The elimination of this unfavourable phenomenon would be possible in the case of selection of an individual degree of exhaust gas recirculation for each cylinder taking into account its filling level with a fresh charge.

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