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THE EFFECT OF EXHAUST GAS RECIRCULATION ON THE PROCESS OF COMBUSTION IN THE SELF-IGNITION ENGINE

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Abstract

The paper compares the basic parameters of the process of combustion in the Fiat MultiJet 1.3 SDE 90 KM with and without an exhaust gas recirculation system, running according to load characteristics with the following engine crankshaft rotational speeds: n=1200 rpm, 1750 rpm and 3000 rpm. During testing, the engine was supplied with commercial diesel oil. The tested engine was provided with external exhaust gas recirculation consisting in supplying a specific amount of exhaust gas back to the cylinder via an EGR electric solenoid valve. The exhaust gas delivered to the cylinder was cooled. Exhaust gas is composed of inert gases that do not take part in the combustion process. This causes, above all, a lower rate of pressure increase in the cylinder and a lower heat release rate. Thanks to exhaust gas recirculation, lower maximal temperatures prevail in the cylinder, and the engine's operation is "softer." During experimental testing, the variation of cylinder pressure and chamber pressure, the injector operation control current magnitude, effective power, torque and the hourly fuel consumption, as well as the exhaust gas recirculation rate. Actual indicator diagrams plotted were used for determining the heat release characteristics, based on which the percentage fractions of the burned out fuel charge injected during one engine running cycle namely 5, 10, 50 and 90% fractions were determined. In addition, the indicator indices were determined. The paper has demonstrated the effect of exhaust gas recirculation on the processes occurring inside the cylinder in the self-ignition internal combustion engine.

Keywords: *exhaust gas recirculation, diesel engine, start of combustion, nitrogen of oxides*

1. Introduction

The development of internal combustion engines is one of the crucial issues in the contemporary world, where endeavours are being made to minimize the pollutants that they emit to the human natural environment. The allowable limits of emission of individual harmful exhaust gas components are prescribed by relevant EU directives [9]. Numerous scientific research centres are conducting now studies aimed at reducing the harmful exhaust gas components and improving the combustion process in internal combustion piston engines [1-3, 10]. One of the solutions is reduce the harmful exhaust gas components and primarily nitrogen oxides. It involves the use of either an external or internal exhaust gas recirculation system [4-6, 8]. Currently, automotive vehicles are most commonly operated in the range of low and medium loads and crankshaft rotational speeds. Exhaust gas is an inert gas that does not participate in the combustion process and has greater specific heat compared to air. Therefore, its presence in the cylinder causes lower combustion process temperatures. Recirculated exhaust gas occurring in the combustion chamber results also in a reduced amount of air in the cylinder. A smaller amount of oxygen and lower charge temperatures in the cylinder cause a lower rate and amount of forming nitrogen oxides. Engines with an EGR system, compared to engines without this system, emit less harmful exhaust gas components, and primarily nitrogen oxides [7, 11].

2. The test stand, control and measuring apparatus

Experimental tests were carried out on an engine dynamometer test stand consisting of a FIAT MultiJet 1.3 SDE 90 KM self-ignition engine, a fast-variable quantity measuring system, an eddy-current brake and a control & measuring cubicle designed for the control of engine and the brake operation and providing basic operation parameter readout capabilities. The fast-variable quantity measuring system included a cylinder pressure measuring sensor, an injection line pressure measuring sensor, a system for measuring the injector operation control current intensity, and a crankshaft rotation angle encoder. Moreover, the test stand was furnished with a MEXA-1600 DEGR analyser manufactured by Horiba for measuring the exhaust gas recirculation rate and nitrogen oxide concentrations. A schematic diagram of the dynamometer test stand is shown in Fig. 1.

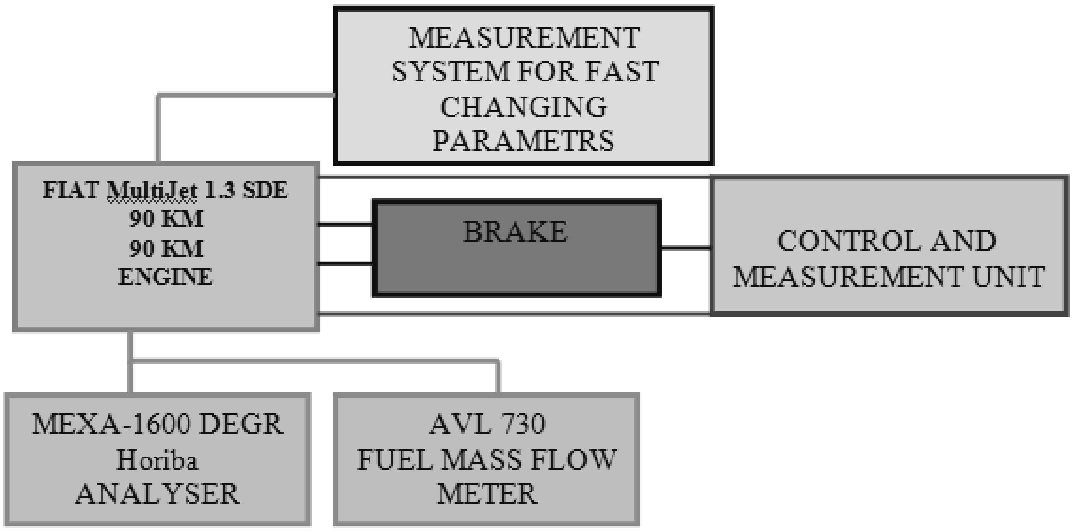

Fig. 1. Block diagram of the research stand

The subject of testing was a FIAT MultiJet 1.3 SDE 90 KM engine, whose basic technical specification is given in Tab. 1.

Tab. 1. Basic technical data of the engine FIAT 1.3 MULTIJET 90 KM

PARAMETER	VALUE
Engine type	four-stroke, four-cylinder in line, water cooled
Type of injection	direct, multiple injection
Compression ratio	17.6
Cylinder bore	69.6 mm
Piston stroke	82 mm
Displacement volume	1251 cc
Max power	66 kW at 4000 rpm
Max torque	200 Nm at 1750 rpm

3. Testing methodology

The 5, 10, 50 and 90% fractions of the combusted fuel charge were determined based on the characteristics shown in Fig. 2. These characteristics represent the relative quantity and rate of heat release during the combustion process.

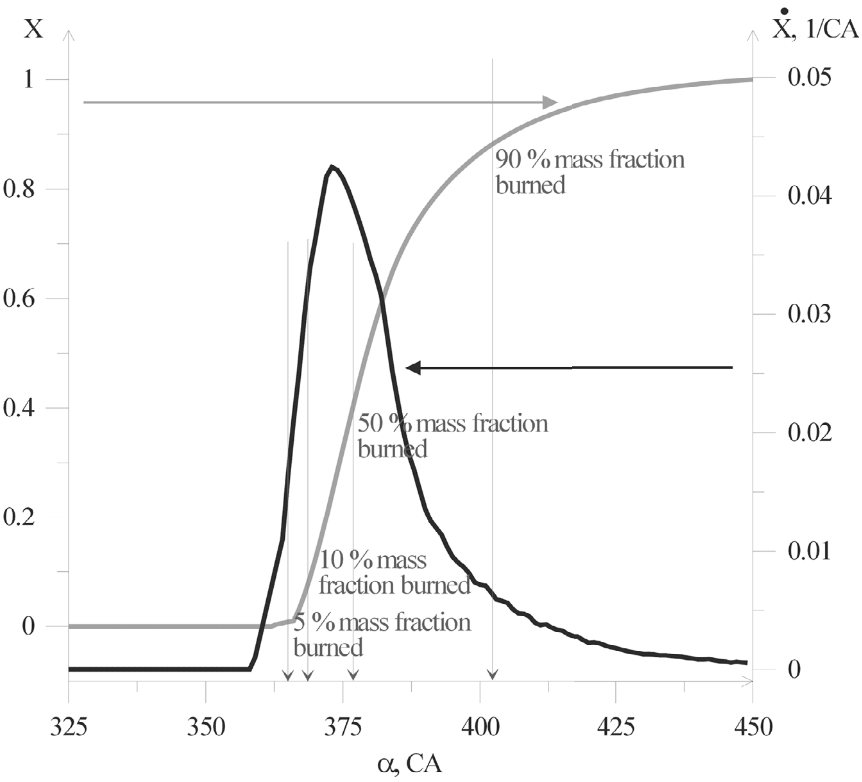

Fig. 2. Example characteristic curves of the relative quantity and rate of heat release during the process of combustion in the FIAT engine running following the load characteristics

The combustion process beginning, α_{SOC}, was determined from the indicator diagram represented on the double logarithmic scale. The transformation of the actual indicator diagram was done by representing it in the coordinates $\log\overline{p_c} - \log\overline{V}$, where the quantities $\overline{p_c}$ and $\overline{V}$ are dimensionless quantities, which are determined from relationships (1) and (2):

$$\overline{p_c} = \frac{p_c}{p_{air}}, \quad (1)$$

where:
p_c – actual cylinder pressure values,
p_{air} – ambient pressure values.

$$\overline{V} = \frac{V}{V_c}, \quad (2)$$

where:
V – momentary cylinder volume values,
V_c – combustion chamber volume values.

An example indicator diagram on the double logarithmic scale is shown in Fig. 3. The straight line defined by the equation $y=n_1 \cdot x+b$ represents the compression process. The slope of this straight line represents the value of the compression process polytropic exponent, n_1. The point of detachment of the double logarithmic scale indicator diagram curve from the above-mentioned line is the combustion process starting point.

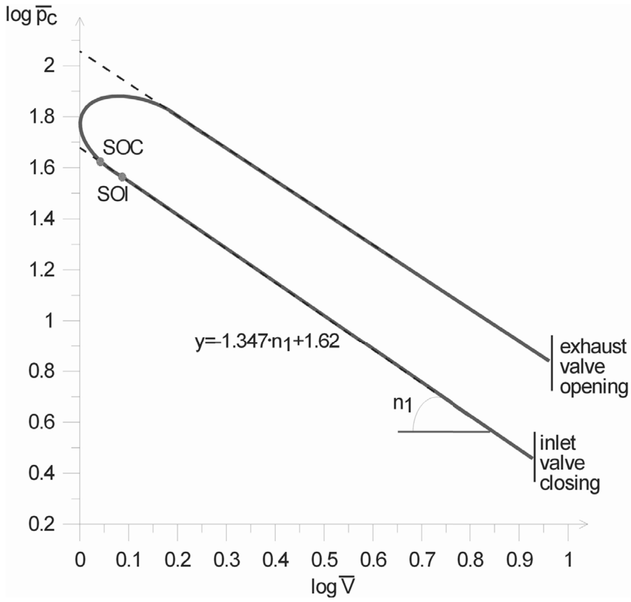

Fig. 3. The double logarithmic scale indicator diagram for the engine running following the load characteristics at n=1200 rpm and under a load of M_o=80 Nm, where: SOI – fuel injection process start, SOC – combustion process start

4. Results of research

On the basis of the experimental tests carried out, the heat release characteristics were drawn up based, on which 5, 10, 50 and 90% of the burned fuel charge were determined. The combustion process beginning, α_{SOC}, was determined from the double logarithmic scale indicator diagrams. The results are given in Tab. 2-4.

Tab. 2. Combustion process parameters for the engine running following the load characteristics at n=1200 rpm

M_o	with EGR					without EGR				
	α_{SOC}	AI05	AI10	AI50	AI90	α_{SOC}	AI05	AI10	AI50	AI90
N·m	CA	CA	CA	CA	CA	CA	CA	CA	CA	CA
10	365.9	366.6	367.0	369.9	380.1	364.5	365.6	365.9	368.2	375.3
20	371.3	372.2	372.8	376.2	386.3	357.4	358.7	359.1	362.6	376.4
40	355.3	357.3	357.9	361.8	381.1	355.1	356.1	356.9	361.9	378.3
60	354.2	356.0	356.6	363.3	382.6	354.1	355.4	356.3	362.1	380.0
80	350.4	352.0	352.8	359.2	380.3	350.9	351.6	352.6	358.7	378.7
93	349.0	350.2	361.1	356.5	380.4	350.0	350.7	351.8	358.1	380.8

Tab. 3. Combustion process parameters for the engine running following the load characteristics at n=1750 rpm

M_o	with EGR					without EGR				
	α_{SOC}	AI05	AI10	AI50	AI90	α_{SOC}	AI05	AI10	AI50	AI90
N·m	CA	CA	CA	CA	CA	CA	CA	CA	CA	CA
10	365.8	366.8	367.4	371.1	381.8	360.0	361.0	361.4	362.6	375.2
20	372.7	373.5	374.7	382.2	395.6	360.0	360.8	361.3	365.7	380.7
40	366.0	367.0	367.8	371.3	390.7	360.0	360.6	361.2	366.9	383.5
60	361.4	362.2	362.9	368.1	390.5	357.9	358.4	359.1	364.9	382.0
80	361.3	361.9	362.7	369.1	391.5	357.6	358.4	359.4	365.4	382.4
100	358.0	359.0	360.2	367.3	389.0	357.6	358.7	359.9	366.3	384.4
120	358.0	358.7	360.0	367.3	387.8	356.3	357.5	358.8	365.8	384.3
140	358.3	359.2	360.6	368.2	387.9	356.7	357.4	358.7	366.2	385.7
160	360.0	360.7	362.1	370.2	390.7	356.7	357.8	359.2	367.3	387.8
180	360.0	360.6	362.1	371.1	393.9	356.5	357.7	359.2	368.2	390.9
200	358.5	359.4	361.0	370.7	395.1	357.5	358.6	360.2	369.7	393.5
206	358.4	359.5	361.2	371.3	396.7	357.4	358.5	360.2	370.3	395.3

Tab. 4. Combustion process parameters for the engine running following the load characteristics at n=3000 rpm

M_o	with EGR					without EGR				
	α_{SOC}	AI05	AI10	AI50	AI90	α_{SOC}	AI05	AI10	AI50	AI90
N·m	CA	CA	CA	CA	CA	CA	CA	CA	CA	CA
10	350.9	351.9	352.3	356.6	370.7	349.8	350.7	361.3	356.4	369.6
20	350.9	351.8	352.5	358.1	373.6	349.8	350.7	351.5	357.9	371.2
40	350.9	351.6	352.5	359.8	378.6	349.5	350.4	351.4	358.5	372.7
60	351.3	352.3	363.4	362.0	381.9	349.1	350.1	352.3	358.8	373.3
80	349.9	350.9	352.5	351.4	381.5	349.9	350.8	362.4	360.1	373.5
100	355.0	355.8	357.6	367.3	387.8	351.9	352.6	354.4	363.1	377.2
120	353.6	354.7	356.7	366.3	386.9	350.7	351.3	353.3	362.8	377.7
140	352.4	354.1	355.9	366.1	384.8	350.4	351.7	353.6	363.2	380.9
160	350.9	351.8	353.6	364.3	383.8	350.0	351.0	353.0	363.0	382.7
180	349.5	350.6	362.7	364.9	397.9	349.5	350.8	352.7	364.4	385.6
195	349.3	350.6	352.8	365.5	390.0	349.4	350.6	352.7	365.4	389.7

Table 5 gives the values of the indicated work, L_i; indicated unit fuel consumption, g_i; and the exhaust gas recirculation rate, X_{EGR} for the engine running, respectively, with and without the exhaust gas recirculation system and according to the load characteristics, with n=1200, 1750 and 3000 rpm.

From the obtained results it can be found that within the entire range of loads at a crankshaft rotational speed of n=1200 rpm, the indicator work was greater for the engine running without the exhaust gas recirculation system, while the indicated fuel consumption was lower. For the engine running according to the load characteristics at n=1200 rpm and n=3000 rpm, when the exhaust gas recirculation rate was greater than 10%, the indicated work was smaller, while the indicated unit fuel consumption was greater compared to the engine that did not use exhaust gas recirculation.

Tab. 5. The indicated parameters, namely indicated work, L_i.; indicated unit fuel consumption, g_i; and exhaust gas recirculation rate, X_{EGR} of the engine operating, respectively, with and without the exhaust gas recirculation system, for the engine running according to the load characteristics at n=1200, 1750 and 3000 rpm

n=1200 rpm					n=1750 rpm					n=3000 rpm				
with EGR			without EGR		with EGR			without EGR		with EGR			without EGR	
X_{EGR}	L_i	g_i	L_i	g_i	X_{EGR}	L_i	g_i	L_i	g_i	X_{EGR}	L_i	g_i	L_i	g_i
%	J	g/kWh	J	g/kWh	%	J	g/kWh	J	g/kWh	%	J	g/kWh	J	g/kWh
31.1	39.2	243.9	67.9	243.0	29.4	59.0	209.3	86.0	165.5	19.1	117.1	150.3	152.9	127.6
31.2	76.8	244.2	101.1	190.4	33.0	75.7	256.1	127.1	159.2	15.8	145.6	151.8	179.3	138.3
23.8	146.7	214.7	162.0	191.4	28.6	160.8	197.2	190.6	170.9	16.5	195.3	174.1	218.2	180.1
14.2	212.4	214.2	219.0	193.0	22.1	231.3	191.2	249.3	207.0	16.4	257.0	177.9	289.3	158.7
8.8	277.3	239.0	289.1	198.1	19.5	296.2	196.2	315.6	190.1	15.7	305.2	189.7	346.3	166.4
8.8	301.3	226.5	328.7	209.2	14.7	364.3	193.2	386.1	181.6	13.9	359.2	196.0	410.1	163.6
---	---	---	---	---	10.2	428.1	198.2	443.9	185.4	11.2	428.6	192.5	468.7	165.4
---	---	---	---	---	4.2	476.8	198.8	480.2	192.8	8.5	474.1	195.3	477.4	184.3
---	---	---	---	---	4.2	523.4	205.0	537.6	199.3	1.8	557.3	186.3	558.9	187.8
---	---	---	---	---	3.2	582.6	208.0	585.6	212.3	1.5	618.4	171.6	620.0	189.5
---	---	---	---	---	1.6	645.1	223.0	646.3	216.5	1.0	655.3	197.3	656.1	198.4
---	---	---	---	---	1.5	659.8	220.1	660.3	219.1	---	---	---	---	---

Figure 4 represents the indicator diagrams of the engine running according to the load characteristics at n=1200 rpm, 1750 rpm and 3000 rpm with and without the exhaust gas recirculation system, respectively.

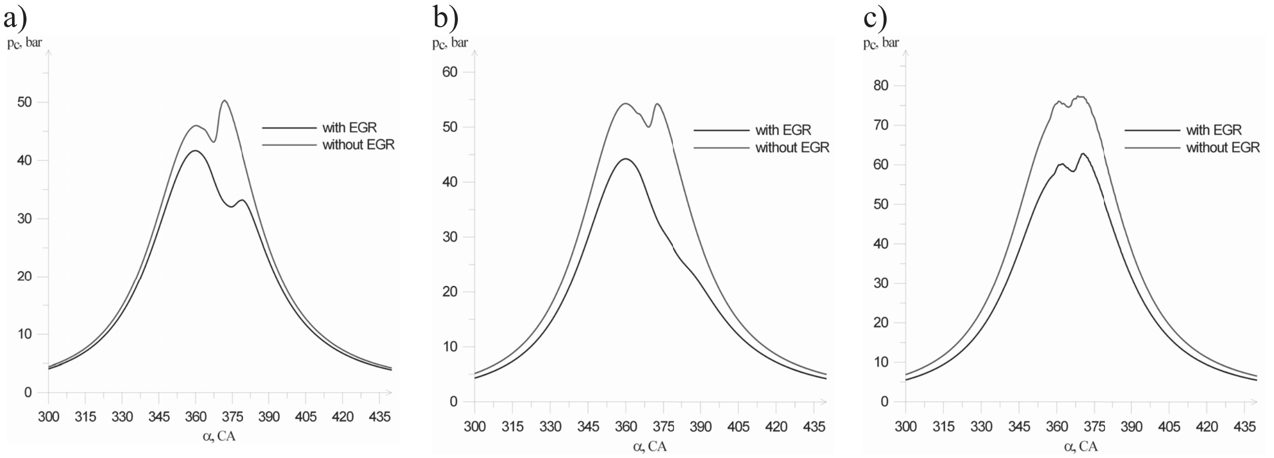

Fig. 4. The open indicator diagrams of the engine with and without the exhaust gas recirculation system, respectively, running according to the load characteristics at: a) n=1200 rpm and under a load of M_o=20 Nm; b) n=1750 rpm and under a load of M_o=20 Nm; c) n=3000 rpm and under a load of M_o=20 Nm

Figure 5 represents the characteristics of heat release during the combustion process, i.e. the relative quantity of released heat and the rate of the relative quantity of released heat in the engine, respectively, with and without the exhaust gas recirculation system running according to the load characteristics at n=1200 rpm, 1750 rpm and 3000 rpm.

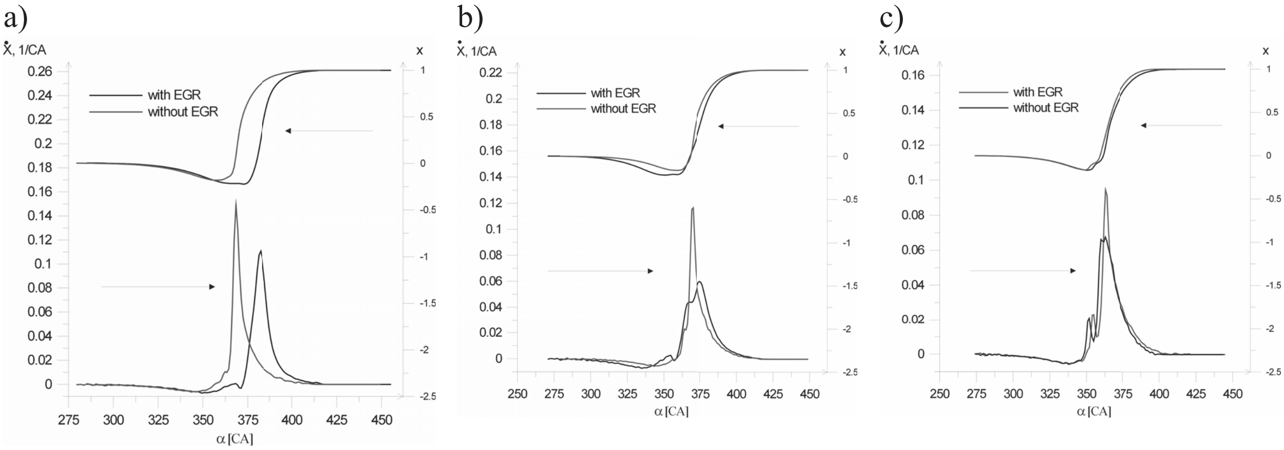

Fig. 5. The relative quantity of released heat and heat release rate for the engine with and without the exhaust gas recirculation system, respectively, running according to the load characteristics at: a) n=1200 rpm and under a load of M_o=20 Nm; b) n=1750 rpm and under a load of M_o=20 Nm; and c) n=3000 rpm and under a load of M_o=20 Nm

Figure 6 represents the nitrogen oxide concentrations for the engine, respectively, with and without the exhaust gas recirculation system running according to the load characteristics at n=1200 rpm, 1750 rpm and 3000 rpm.

5. Conclusions

The use of the exhaust gas recirculation system significantly influences the combustion process. For the engine running without exhaust gas recirculation for the identical operation points, i.e. at the same crankshaft rotational speed and loading, the combustion process start earlier and lasts shorter compared to the engine with exhaust gas recirculation implemented. The relative heat quantity release rate is more intensive in the case of the engine running with no exhaust gas recirculation system. For the engine operating with the exhaust gas recirculation system, lower

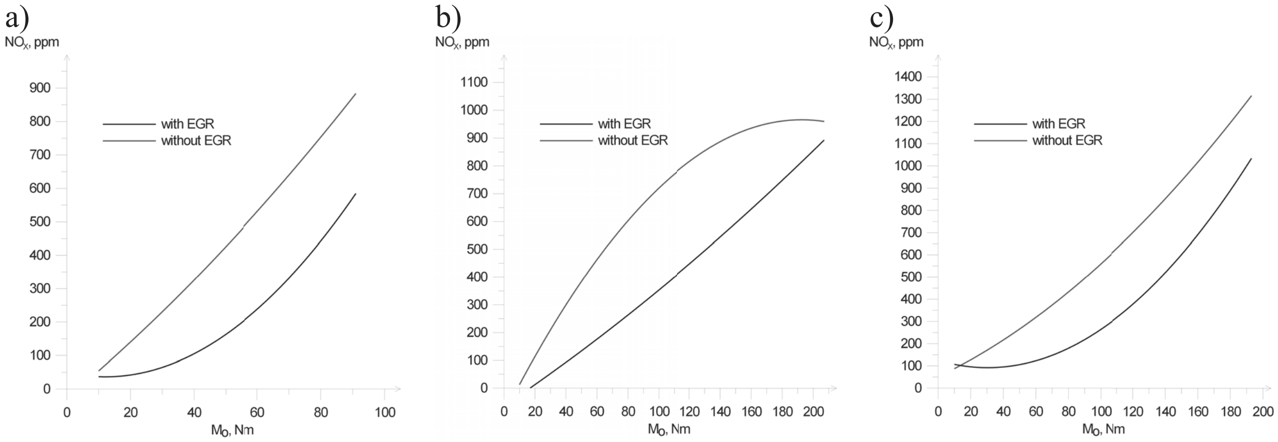

Fig. 6. Nitrogen oxide concentrations for the engine, respectively, with and without the exhaust gas recirculation system running according to the load characteristics at n=1200 rpm, 1750 rpm and 3000 rpm

maximum cylinder pressures were obtained. In addition, to reducing the mass of exhaust gas leaving the exhaust system, the exhaust gas delivered back to the cylinder causes the quantity of oxygen in the combustion chamber to be much less than for the engine with no exhaust gas recirculation system. Exhaust gas has also higher specific heat, so it has greater heat absorption capacity compared to air. The smaller quantity of oxygen in the chamber results in lower cylinder pressure increase rates. The lower heat release intensity involves also lower temperatures in the cylinder. Thanks to lower temperatures, less nitrogen oxides are formed, whereby the engine is more environmentally friendly. By entering into reaction with nitrogen oxides, the hydrocarbons contained in the exhaust gas reduce the nitrogen oxide emissions. For the engine operating with the exhaust gas recirculation system, lower indicated work was obtained compared with the engine without this system. To sum up, it can be stated that an engine equipped, with the exhaust gas recirculation system, operating in the range of low and medium loads, runs more silently and is distinguished by lower nitrogen oxide emissions.

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