TEKA Kom. Mot. Energ. Roln., 2006, 6A, 128–137

AN INFLUENCE OF EXHAUST GAS RECIRCULATION ON NO_X AND OTHER TOXIC COMPONENTS EMISSION IN DIESEL ENGINES

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Summary. In the paper one of the methods reducing contents of nitrogen's oxides in exhaust gas in Diesel engines has been described. Exhaust gas recirculation is an effective method to reduce these components, however it results in an increase in emission of CO, HC and particulate matter (PM) and reduces engine's power. To meet obligatory standards referring to emission of NO_x, designers of Diesel engines are forced to develop optimal design, so also to take into consideration exhaust gas recirculation (EGR) systems. Conditions and reasons of formation of NO_x in Diesel engines have been characterized. The essence and methods of exhaust gas recirculation have been described, referring also to the results of research works published in literature. Initial experimental works with EGR system operating in the 4C90 traction engine have been presented. In this case the external system with constant recirculation ratio has been used. Research test of toxicity of exhaust gas has been carried out according to 12-stages cycle (Hot ECE Urban + Extra Urban Driving Cycle simulation). However, a reduction of NO_x resulted in the reduction of an engine's power and an increase in unit fuel consumption.

Key words: exhaust gas recirculation (EGR), nitrogen's oxides, Diesel engines

INTRODUCTION

Emission of nitrogen's oxides still remains an important ecological problem of Diesel engines. Contents of carbon monoxides and hydrocarbons, due to their lower amount, do not create comparably difficult problems to be solved. Till now technical solution commonly recognized to be satisfactory has not been found. Exhaust gas recirculation systems belong to the more effective methods.

In Diesel engines there are fundamentally two types of nitrogen's oxides: NO and NO_2. In a smaller amount also nitrogen monoxide N_2O and higher oxides as N_2O_3, N_2O_4, N_2O_5 are generated. Nitrogen dioxide NO_2 is the most harmful one because joining with water contained in the air gives nitric acid which causes serious irritation of mucous membranes and swelling of the lungs. In respect of influence on human constitution nitrogen's oxides are approx. 10 times more dangerous than carbon oxide [Bernhardt *et al.* 1976, Merkisz 1995]. The main reason of formation of nitrogen's oxides is the fact that at high combustion temperatures in an engine, nitrogen ceases to be inert and reacts with oxygen. Due to indurability of higher oxides, practically at high temperatures (900 – 1000ºC) there is a possibility of occurrence of only nitric oxide NO. Exactly this compound forms during combustion and then initiates the formation of the subsequent higher oxides [Zabłocki 1986, Merkisz 1995]. Nitric oxide, generated during combustion, reacts at decreasing temperature with oxygen left in exhaust gas and creates higher oxides, particularly NO_2. Formation of nitrogen dioxide is possible only at lower temperatures (below approx. 650^{o}C), because above this level it dissociates almost completely into NO and O_2. Therefore it can be assumed that during decompression cycle the concentration of NO practically does not change. So, nitrogen dioxide forms after exhaust gas leaves cylinder and its formation rate is proportional to the amount of oxygen. Concentration of oxygen in exhaust gas of Diesel engine usually consists of approx. 3% (at full load) to approx. 18–20% of volume (at idle running). So, at lower load there are more advantageous conditions to form NO_2, however at the same time due to lower combustion temperature there is a smaller amount of NO formed. That is why the measurement of contents of nitrogen's oxides NO_x is performed at full load of the engine.

ESSENCE AND METHODS OF EXHAUST GAS RECIRCULATION

Recirculation of exhaust gas consists in conveying a certain part of engine's exhaust gas back into the cylinder inlet duct. By this means the amount of oxygen is reduced and a decrease in maximum combustion temperature is obtained. Higher thermal capacity of exhaust gas results in an increase of thermal capacity of sucked in charge. EGR systems make use of increased thermal capacity of exhaust gas to reduce combustion temperature, which reduces emission of NO_x (mainly NO). Reduction of oxygen in the delivered charge results in an elongation of combustion time and an increase in emission of HC, CO and particulate matter [Levendis *et al.* 1994, Arcoumanis *et al.* 1995, Walsh 1995]. It occurs mainly due to an increase of extinction zone of flame on combustion chamber walls and shift of ignitability boundary of the mixture. Because of this, the use of recirculation is limited and in case of Diesel engines does not exceed 20–25% (Fig.1). The positive effect of recirculation is intensified during cooling of exhaust gas. An advantageous effect of EGR towards reduction of NO_x has been proved for engines with direct injection, with segmented chambers and with forced induction [Zabłocki 1986, Levendis *et al.* 1994].

It should be pointed out that apart from reduction of NO_x , recirculation has many additional advantages connected with combustion control, for example – considering loudness of engine's operation, simplification of cold starting, multi-fuel feed and the like. Recirculation of exhaust gas, reducing amount of oxygen enclosed in a cylinder, requires approximately proportional reduction of fuel charge and in this way results in a decrease of torque and engine's power. Reduction of fuel charge depends upon individual engine's features and recirculation ratio. In general, percentage reduction of charge is slightly smaller than recirculation ratio (maintaining unchanged level of exhaust gas' smokiness). It is the next confirmation of an advantageous influence of recirculation on the course of combustion [Heywood 1988, Walker and Speronello 1992].

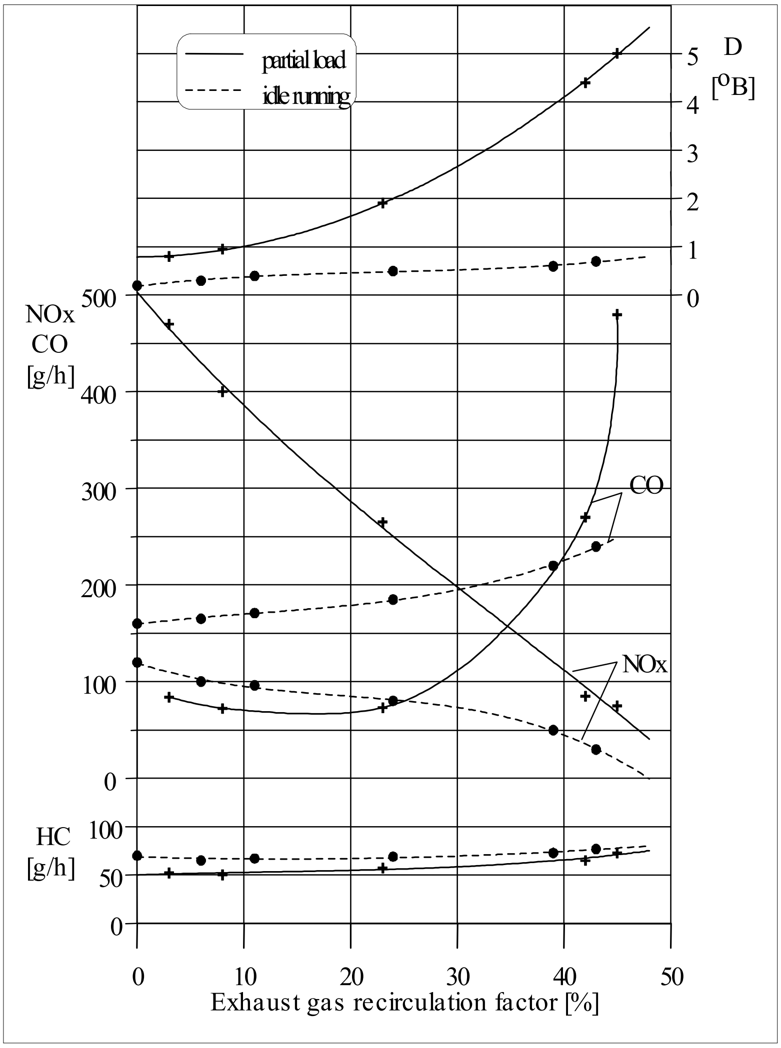

Fig. 1. An effect of exhaust gas recirculation on the emission of toxic components

In Diesel engines the control of recirculation ratio presents considerable design and operational difficulties. Because the flow of air on inlet is not restricted, the mass of consumed charge does not practically depend upon engine's load and to a small degree depends upon speed. It is similar for exhaust gas because mass of fuel is maximum 4–5% of mass of air. However, composition of that exhaust gas under different operating conditions is different, so that their influence on recirculation's effects can change considerably.

In principle, three methods of exhaust gas recirculation are used [Lejda 2004]:

- constant recirculation ratio,
- changeable recirculation ratio,
- proper cylinder scavenge system.

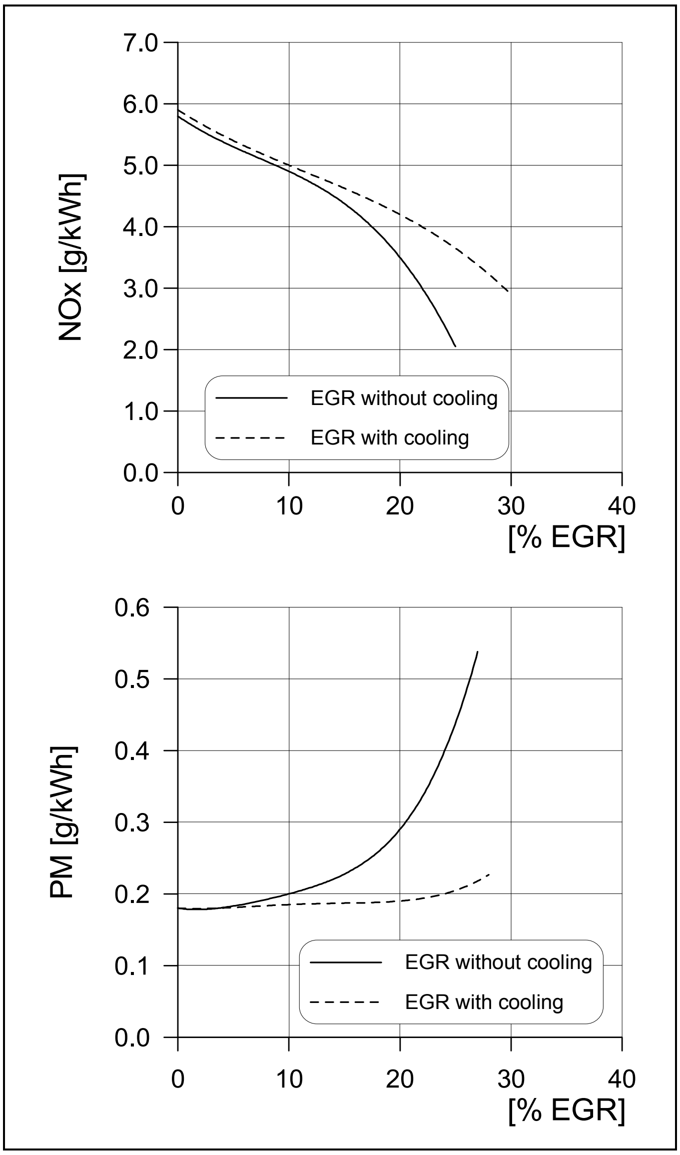

Fig. 2. Level of NO_x and PM emission versus participation of EGR in Diesel and direct-injection engines.

The first method is the simplest one and is switched on or off at a defined constant level of recirculation. It is used in small engines with engine cubic capacity up to 3,0 dm^3. In bigger engines a more complicated system is used which enables to change recirculation ratio during different operating conditions. It is the closed loop system connected with an electronic control of the amount of injected fuel. Both these methods belong to the so-called external recirculation. Cylinder scavenge system is the so-called internal recirculation and consists in proper choice of timing angle which has an effect on the volume of exhaust gases remaining in a cylinder from the previous cycle. This action most often consists in reduction of delay angle of exhaust valve's shut off after TDC. However, it should be pointed out here that due to high temperature of exhaust gas remaining in a cylinder (approx. two times higher in Kelvin temperature scale than in exhaust system) it has considerably lower mass than in case of external recirculation. Having the same effect on emission of toxins, internal recirculation system causes a higher decrease in an engine's power.

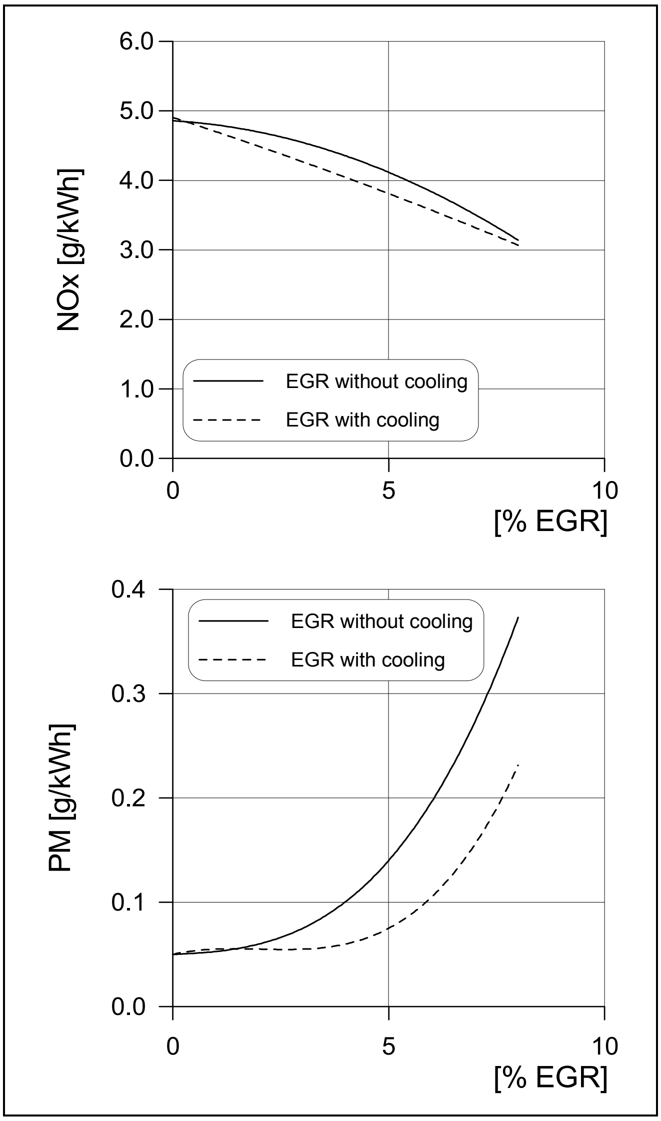

Fig 3. Level of NO_x and PM emission versus participation of EGR in Diesel engines with swirl chamber

External EGR systems can be equipped with systems with or without cooling. In systems with cooling a considerably more advantageous reduction of contents of particulate matter is obtained, specially under big loads. In systems without cooling, under small loads, the similar values are obtained for NO_x and particulate matter. In Fig. 2 and Fig.3 emission levels of NO_x and PM are shown for Diesel engines with direct injection and swirl chamber, respectively, at different exhaust gas recirculation ratio [Zabłocki 1986]. In case of direct injection, it is clearly seen (Fig. 2) that permissible NO_x reduction, coming up to 3 g/kWh occurs under operation of EGR at the level of approx.20%, because a further increase of recirculation ratio, specially in systems without cooling, results in a radical increase of particulate matter.

External recirculation can be used together with internal recirculation. Through an optimal control of both systems the most advantageous compromise can be achieved in the reduction of toxic components and decrease in engine's power.

TESTS OF THE 4C90 ENGINE WITH EXHAUST GAS RECIRCULATION SYSTEM

The 4C90 engine is produced by Diesel Engines Factory „Andoria” in Andrychów (Poland). It is a high speed Diesel engine assigned mainly for delivery trucks with load capacity up to 3,5 tons. It can be also used for small cross-country vehicles being used by power and oil companies. The engine underwent among others the research test cycles in England and received RICARDO certificate. Basic technical data of the 4C90 engine are seen in Table 1.

Table 1. Technical data of the 4C90 engine

Parameter	Quantity; type
Number of cylinders	4
Arrangement of cylinders	vertical
Type of chamber	RICARDO-COMET, swirl
Diameter of cylinder	90 mm
Piston stroke	95 mm
Displacement volume	2417 cm^3
Compression ratio	20.6 :1
Rated horse power	51.5 kW
Rated horse power rotation	4200 rpm
Max torque	146 Nm
Max torque rotation	2500 rpm
Idle running rotation	800 rpm
Sense of rotation of shaft	right
Sequence of injections	1-3-4-2
Injection pressure	15±0.5 MPa
Dry weight of engine	230 kg

Tests of the engine were carried out on test bench in the Engine Laboratory of Rzeszow Technical University. Recirculation system was designed and made in Automotive Vehicle and Combustion Engines Institute. A constant recirculation ratio system, switched on by an operator during research test, was used. The control system enables to obtain two exhaust gas recirculation ratios: 12 and 20%. Exhaust gas toxicity test was carried out according to 12-stages cycle (Hot ECE Urban + Extra Urban Driving Cycle simulation).

Table 2. Results of external characteristic after correction without EGR

n rpm	M_o Nm	G_h kg/h	B_j mm^3/injection	N_e kW	g_e g/kWh
1400	123,8	4,80	34,2	18,1	264,7
1600	126,8	5,54	34,5	21,2	260,5
1800	128,9	6,28	34,8	24,3	258,4
2000	134,0	7,19	35,9	28,1	256,2
2200	138,4	8,22	37,3	31,9	257,9
2400	141,6	9,21	38,3	35,6	258,6
2600	142,9	10,14	38,9	38,9	260,7
2800	143,0	11,03	39,3	41,9	263,1
3000	140,0	11,79	39,2	44,0	268,0
3200	137,9	12,50	39,0	46,2	270,4
3400	133,9	13,21	38,8	47,7	277,1
3600	129,8	13,79	38,2	48,9	281,7
3800	125.8	14.45	38.0	50.1	288.7
4000	121,7	14,99	37,4	51,0	294,1
4200	117,6	15,66	37,2	51,7	302,6
4400	87,2	13,21	30,0	40,2	329,0

Table 3. Results of external characteristic after correction with 12% recirculation factor

n rpm	M_o Nm	G_h kg/h	B_j mm^3/injection	N_e kW	g_e g/kWh
1400	118.7	4.75	33.86	17.4	273.0
1600	121.2	5.47	34.12	20.3	269.5
1800	124.2	6.25	34.65	23.4	267.1
2000	128.4	7.15	35.68	26.9	265.8
2200	134.1	8.20	37.20	30.6	268.0
2400	135.7	9.24	38.42	34.1	271.0
2600	137.0	10.12	38.85	37.3	271.3
2800	137.1	11.06	39.42	40.2	275.1
3000	134.3	11.74	39.06	42.2	278.2
3200	132.2	12.54	39.11	44.3	283.1
3400	128.4	13.23	38.83	45.7	289.5
3600	124.4	13.74	38.09	46.9	293.0
3800	120.6	14.40	37.82	48.0	300.0
4000	116.7	14.92	37.23	48.9	305.1
4200	112.8	15.70	37.31	49.6	316.5
4400	83.8	13.18	29.89	38.6	341.5

Table 4. Results of external characteristic after correction with 20% recirculation factor.

n rpm	M_o Nm	G_h kg/h	B_j mm^3/injection	N_e kW	g_e g/kWh
1400	111.9	4.78	34.07	16.4	291.5
1600	114.6	5.55	34.62	19.2	289.1
1800	116.7	6.26	34.71	22.0	284.5
2000	121.3	7.21	35.98	25.4	283.9
2200	125.0	8.22	37.29	28.8	285.4
2400	128.1	9.20	38.26	32.2	285.7
2600	129.3	10.10	38.77	35.2	286.9
2800	129.3	11.00	39.21	37.9	290.2
3000	126.7	11.72	38.99	39.8	294.5
3200	124.7	12.52	39.05	41.8	299.5
3400	121.1	13.18	38.69	43.1	305.8
3600	117.3	13.78	38.20	44.2	311.8
3800	113.8	14.48	38.03	45.3	319.6
4000	110.1	14.96	37.33	46.1	324.5
4200	106.2	15.65	37.19	46.7	335.1
4400	78.8	13.24	30.03	36.3	364.7

Tabela 5. Results of toxicity tests per 12-stages cycle
(Hot ECE Urban + Extra Urban Driving Cycle)

Method of recirculation	Smokiness Bosch	NO_X g/kWh	CO g/kWh	PM g/kWh
Without EGR system	1.0	6.8	3.7	0.12
EGR system with 12% recirculation factor	1.4	5.6	3.9	0.14
EGR system with 20% recirculation factor	1.9	4.5	4.2	0.17

A broad range of tests covering speed and control characteristics was performed and the toxicity of exhaust gas was evaluated. Due to the limited volume of the present paper, only results for an external characteristics and toxicity test of exhaust gas have been presented. Tables 2, 3, 4 show the corrected results of calculations of external characteristics according to BSAU 1410 specifications for an engine without EGR, with 12% recirculation factor and 20% recirculation factor respectively. Graphical illustration of the obtained results is shown in Fig. 4.

Results of toxicity tests per 12-stages cycle for the engine without EGR, with 12% recirculation factor and 20% recirculation factor are given in table 5. In these tables there are values of smokiness of exhaust gas according to Bosch scale as well as values of emission for NO_x, CO and PM.

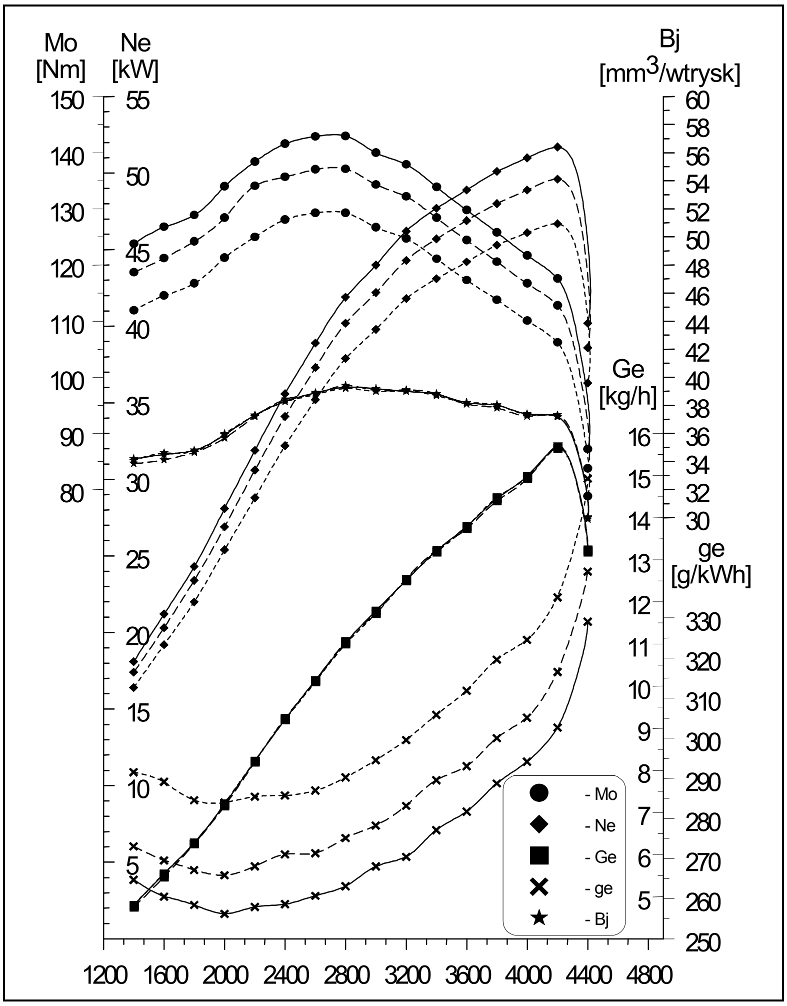

Fig. 4. External characteristic of the 4C90 engine (—— without EGR, – – – – 12% recirculation factor , - - - - - 20% recirculation factor)

EVALUATION OF TESTS' RESULTS – RECAPITULATION

The performed tests of the 4C90 engine gave interesting information for an analysis and evaluation of the used exhaust gas recirculation from the point of view of functional and ecological parameters. Generally known relations were confirmed with utilization of EGR systems between the amount of toxic components and engine's functional parameters. Maximum engine's power N_e = 51.7 kW at the speed of n = 4200 rpm was achieved without utilization of EGR system. Emissions of toxic components were as follows: NO_x = 6.8 g/kWh, CO = 3.7 g/kWh, PM = 0.12 g/kWh. With utilization of EGR system with 12% recirculation factor the rated horse power decreased by 4.1% and was

49.6 kW. Contents of CO and PM increased slightly: CO = 3.9 g/kWh, PM = 0.14 g/kWh, while contents of nitrogen's oxides decreased considerably: NO_x = 5.6 g/kWh. With utilization of EGR system with 20% recirculation factor, the rated horse power decreased by 9.6% in relation to the power obtained without recirculation and was 46,7 kW. Carbon monoxide and particulate matter increased achieving values: CO = 4.2 g/kWh, PM = 0.17 g/kWh, while contents of nitrogen's oxides decreased to value NO_x = 4.5 g/kWh.

The issues, referring to exhaust gas recirculation in Diesel engines, presented in the paper confirm that it is one of the more effective methods to reduce NO_x. Nitrogen's oxides and particulate matter are the basic group of toxins in these engines. At present, the value of their emission causes a serious obstacle to the use of Diesel engines. It was the ecological reason which considerably has considerably speeded up theoretical and experimental works in order to adapt the design of Diesel engines to meet EURO-3 standard for NO_x and PM emission. Particulate matter are in high degree soaked in heavy hydrocarbons and high toxic aldehydes and create special hazard for live organisms. So, it should be born in mind that just an introduction of exhaust gas recirculation allows to reduce emission of NO_x, however at the cost of an increase of emission of incomplete combustion products. Therefore, development works on a new generation of Diesel engines are carried out multi-directionally. Apart from utilization of EGR systems, accumulated fuel injection, new shapes of combustion chambers, supercharging and oxidation-reduction catalysts have been implemented.

REFERENCES

Arcoumanis C., Bae C., Nagwaney A., Whitelaw J. 1995: Effect of EGR on Combustion Development in a 1.9L DI Diesel Optical Engine. Diesel Engine Combustion Processes SAE/ SP-1092.

Bebernes J., Eberly D. 1989: Mathematical Problems from Combustion Theory. Series in Applied Mathematical Sciences, vol. 83.

Bernhardt M., Michałowska J., Radzimirski S. 1976: Motoryzacyjne skażenia powietrza. Wydawnictwa Komunikacji i Łączności, Warszawa.

Heywood B. 1988: Internal Combustion Engine Fundamentals. Series in Mechanical Engineering. ed. Mc Graw-Hill Book Company. New York.

Lejda K. 2004: Selected Problems of Fuel Supply in High-Speed Diesel Engines. Publishers „Meta", Lvov.

Levendis Y., Pavlatos J., Abrams R. 1994: Control of Diesel Soot, Hydrocarbon and NO_x Emissions with a Particulate Trap and EGR. Diesel Exhaust Aftertreatment, SAE/SP-1020.

Merkisz J. 1995: Specyfika pomiarów emisji cząstek stałych w silnikach spalinowych. Zesz. Inst. Pojazdów SIMR, 5/95.

Walker J., Speronello B. 1992: Development of a Ammonia SCR NO_x Reduction System for a Heavy Duty Natural Gas Engine. Diesel Combustion, Emissions and Exhaust Aftertreatment. SAE/SP-931.

Walsh M. 1995: Global Trends in Diesel Particulate Control-A. Update. Diesel Exhaust Aftertreatment. SAE/SP-1073/1995.

Zabłocki M. 1986: Wtrysk i spalanie paliwa w silnikach wysokoprężnych. Wydawnictwa Komunikacji i Łączności, Warszawa.