Nitrogen oxide formation with nonuniform fuel distribution in diesel engine

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Abstract. The high requirements for limiting the toxic components of exhaust gases of modern internal combustion engines require significant expenditures both for the improvement of existing engines and for the development and implementation of new types of engines. Some European organizations are raising the issue of limiting the use of diesel engines and even a possible cessation of their production in the next 5-10 years. This article reflects the results of studies on the formation of one of the most toxic components of exhaust gases - nitrogen oxides. The calculations were carried out according to the thermodynamic cycle model, which makes it possible to estimate the main characteristics of the operating cycle as the fuel-air charge burns out. Calculations are carried out with regards to a gas-diesel modification of an air-cooled engine with a dimension of 120 x 120 mm, which assumes the supply of the main gas-air charge through the inlet pipeline and a limited dose of diesel fuel injected into the cylinder to ignite the charge. The model shows the conditions for the burnout of the charge and the formation of nitrogen oxides in 10 equal in mass and successively burnout zones of the charge in the diesel cylinder. Calculations show that the formation of nitrogen oxides can be significantly reduced by 50 ... 80% by adjusting the charge stratification scheme, that is, by changing the fuel concentration in the burnt-out portions, due to the mutual regulation of diesel and gas fuel supplies. The results of experimental verification of the calculations are presented below, which confirms the adequacy of the model. The effect in the total reduction of NOx emissions can be significantly improved by using partial charge throttling and using exhaust gas recirculation. The data obtained confirm the feasibility of further fine-tuning the working process of gas-diesel engine modifications and meeting the requirements of toxicity standards.

The piston internal combustion engines are still widely used in various sectors of our economy due to a number of their advantages. At the same time, the necessity to protect the environment, the problems of climate change on the planet, determine the intensive work of scientists to find the ways to improve them. Among them, studies of the conversion of engines to gaseous fuel [1], the use of alternative energy sources [2], including renewable ones [3], the use of dual-fuel power supply schemes for engines [4, 5], the use of various additives to fuel [6, 7] and other methods. Moreover, any of the proposed solutions require deep attention to understand the physics of the working processes of internal combustion engines. It is possible to significantly increase the efficiency of studies of the processes of air-fuel mixture formation and it’s combustion in a diesel engine, especially with an uneven distribution of the two used types of fuel [8, 9] by using the computational modeling of the operating cycle.
The development of internal combustion engines requires increased attention to improving their environmental performance. The European Union standards for the toxicity of exhaust gases on the period 1993-2009 (Euro1-Euro-5) contributed to reduction of the emission of the main harmful components - CO, C\textsubscript{n}H\textsubscript{m} and NO\textsubscript{x} by several times. The implementation of Euro-6 recommendations pays special attention to further reduction of the toxicity of diesel engines, and in comparison with Euro-5 requires reducing NO\textsubscript{x} emissions by 26 ... 56% for cars and commercial vehicles (0.180 ... 0.080 and 0.280 ... 0.125 g / kWh); and for heavy diesel engines - 5 times (from 2.0 to 04 g / kWh). The engine manufacturers must also ensure reducing of hydrocarbons C\textsubscript{n}H\textsubscript{m} emission. Due to complexity of this issue, the possibilities of significant limitation of diesel engines and replacing them by other engines are being considered. The studies presented below are aimed at to find a solution for this problem.

The mechanism of nitrogen oxides (NO\textsubscript{x}) formation during combustion of hydrocarbon mixtures is well studied and described in the classical literature [10, 11]. The extended mechanism of NO\textsubscript{x} formation proposed by Y.B. Zeldovich, is accepted by most researchers and suggests that the main condition for the nitrogen oxides formation is a presence of necessary concentrations of oxygen, nitrogen, and high temperatures. Studies of the nitrogen oxides formation in internal combustion engine show that under conditions of uneven temperatures and fuel concentrations in individual zones of the combustion chamber, NO\textsubscript{x} emission with exhaust gases (EG) can be reduced by decreasing the oxygen concentration in combustion zones with high temperatures, as well as by decreasing of temperature in areas with increased oxygen concentration.

The real impact on engine workflows during experimental tuning is always complex. And it is often difficult to identify the degree of influence of certain factors on the formation of NO\textsubscript{x}, such as the features of internal mixture formation, the distribution of fuel and (residual) exhaust gases in the combustion chamber zones, using of dual-fuel mixtures, possible recirculation of exhaust gases, dynamics of heat generation and other factors.

This article reflects theoretical studies of possibilities to reduce NO\textsubscript{x} emissions for a gas-diesel engine modification that runs on diesel fuel supplied through a nozzle into the engine cylinder and a propane-butane mixture of liquefied gas supplied to the intake manifold. The aim of the study was to analyze the conditions for formation and reduction of NO\textsubscript{x} by increasing an efficiency of regulating the distribution of the fuel mixture in the cylinder of a gas-diesel engine - changing the concentration of diesel and gas fuel in separate combustion zones, as well as using exhaust gas recirculation.

The research was carried out using the model of the working cycle by A L Maksimov [12], adapted for the calculation with stratified charge [13]. The calculation of the engine operating cycle assumes division of the working charge in the combustion chamber into ten zones of equal mass, which burn out in sequence. As the charge burns out in the zone, the initial mixture composition is instantly replaced by combustion products. For each portion, the equilibrium composition of the combustion products of CO, CO\textsubscript{2}, H\textsubscript{2}O, H\textsubscript{2}, H, OH, O, O\textsubscript{2}, N\textsubscript{2} is sequentially calculated. It is believed that the formation of nitrogen oxides proceeds according to the extended mechanism of Y.B. Zeldovich. It is assumed that the main component of nitrogen oxides in exhaust gases is the emission of nitrogen oxide NO. To simulate the law of fuel burn up, it is allowed to use the experimentally obtained heat release curve for the engine running on diesel fuel. [13]. Experiments have shown that the calculated model of operating cycle, taking into account the uneven fuel distribution in the combustion chamber, provides adequate results when studying engines operating on two types of fuel [13, 14]. Uneven fuel distribution over ten charge zones is set by the fraction of the cyclic fuel supply, residual gases; the possibility of changing the density of air in the cylinder due to throttling of charge at the inlet manifold is taken into account.

The calculations of operating cycle are carried out for an air-cooled diesel engine with a piston group dimension S x D = 120 x 105mm. The investigated zone of operating modes corresponds to the engine speed n = 2000 min\textsuperscript{-1}, the coefficient of admission η\textsubscript{v} = 0.6 ... 0.9, the average over-charge air-
fuel ratio $\alpha_S = 1.2 ... 3.0$, and the air-fuel ratio for the gas-air mixture $\alpha_{gas} = 1.2 ... 2.5$. For the design modes, it was allowed to use the corresponding heat release curves for the base diesel engine.

An example of modeling (figure 1) - the dynamics of changes in temperatures and NO concentrations over ten sequentially burning zones of a fuel-air mixture with a uniform distribution of fuel and the assumption of spot ignition of mixture in the first zone, shown as a function of crankshaft angle. The results reflect a typical idea of the highest local combustion temperatures in the charge portions that burn first [13]. Accordingly, for assumed homogeneous lean mixtures ($\alpha = 1.2$), the highest rate of NO formation is observed in the first burnout portion of the charge. The total NO emissions are determined by the amount of nitric oxide produced in the first five portions 1-5. Portions 6-10 have significantly less NO formation due to lower combustion temperatures. The final "frozen" concentration of nitric oxide during the expansion of the working cycle was 5130 ppm.

![Figure 1](image_url)

**Figure 1.** The dynamics of temperature and nitrogen oxide concentration changes over 10 charge zones with uniform fuel distribution in the engine cylinder as a function of the crankshaft angle.

Somewhat increased for a diesel engine NO emissions can be explained by the accepted initial data for the calculation: a sufficiently high concentration of fuel and a homogeneous charge for a diesel engine $\alpha = 1.2 ... 1.3$ and an assumed short duration of heat generation - 30° turn of crankshaft angle.

The calculations analyzed the conditions for NO formation for various air-fuel ratio distribution schemes, from uniform fuel distribution over 10 zones, to linear changes of fuel concentration from a rich mixture in the first zone and gradual (or stepped) mixture leaning-out to the last combustion zone.

In a general case of modeling of charge fuel distribution scheme, three areas can be conditionally distinguished:

- initially burning portions with an enriched mixture composition, for example, $\alpha = 0.87$ and a mass from 10 to 30% of a total mass of charge,
- transition zone with linear leaning-out of the mixture from portion to portion (and weighing from 0 to 90% of the total mass of the charge),
- and, finally, the lean portions of the charge, which burn out last.
For example, the 1-0 scheme implies a 10% rich first portion of the charge and the remaining 9 zones (90%) of a lean mixture with a uniform fuel distribution. And scheme 1-3 assumes the first rich portion of the charge, then 3 portions with “sequential linear” leaning-out from the second to the fourth portion and then 6 portions of a homogeneous lean mixture.

Calculations indicate that when the gas-diesel engine operates on lean mixtures of average air-fuel ratio higher than $\alpha > 1.2$, the implementation of any charge stratification option can reduce the concentration of nitrogen oxide in the exhaust gases. For example, figure 2 shows the combustion temperatures and the dynamics of NO formation by portions for the scheme 1-3. This scheme of uneven fuel distribution makes possible to reduce the NO emission by 2 times in comparison with a homogeneous charge.

A decrease in the total emission of NO is obtained by reducing the rate of formation of nitrogen oxide in almost all portions of the charge, except for the third. The formation of nitrogen oxide in the initial enriched portion ($\alpha_1 = 0.87$) is most sharply reduced, which is associated not only with a lack of free oxygen, but also with a noticeable decomposition of nitrogen oxide due to a sufficient time of reversible reactions between atomic nitrogen and oxygen during expansion process in high temperature conditions. A similar picture is observed in the second portion ($\alpha_2 = 0.99$). The third portion of the charge makes the most significant contribution to the final concentration of NO: the poor composition of the mixture ($\alpha = 1.1$) and sufficiently high combustion temperatures lead to intensive formation of NO during combustion, and a rapid decrease in temperature on the expansion line leads to the subsequent "freezing" of the achieved concentrations. The combustion of subsequent leaning out portions of the charge ($\alpha = 1.36$) due to low temperatures is accompanied by a slight formation of nitrogen oxide.

![Figure 2](image.png)

**Figure 2.** The dynamics of temperature and nitrogen oxide changes in charge zones with uneven fuel distribution (scheme 1-3) as a function of the crankshaft angle.
The final concentrations of NO in the exhaust gas for some schemes of uneven fuel distribution schemes are presented in Table 1.

Table 1. Influence of uneven fuel distribution in charge portions on nitrogen oxide emissions with exhaust gases (ppm).

| mass of first enriched zone, % | mass of transition zone, % |
|-------------------------------|----------------------------|
| 0                             | 0                          |
| 10                            | 5130                       |
| 20                            | 5290                       |
| 30                            | 980                        |

Calculations show the possibility of reducing the concentration of nitrogen oxide by controlling the uneven fuel distribution in the charge. An increase in the mass of the initially burning part of the charge from 10 to 30%, regardless of the size of the transition zone, leads to decreasing of concentration of nitrogen oxide. The effect of the transition zone mass on NO emissions varies with the rich zone mass. So for schemes 1-0 ... 1-3 an increase in the transition zone reduces NO emissions, and for schemes 3-0 ... 3-3, on the contrary, leads to increasing NO. All other things being equal, a decrease in the mass of the transition zone is associated with the leaning out of the mixture in each portion of this zone, with a simultaneous slight enrichment of the mixture in the last portions of the charge. For schemes with a 10% enriched first zone, leaning out of the portions of the transition zone at high temperatures leads to increasing of nitrogen oxide emissions. With a large mass of the enriched zone (schemes 3-0 ... 3-3), the temperature in the transition zone is lower, and its leaning out leads to decreasing of nitrogen oxide emissions. For different layering schemes, the total emission of nitrogen oxide is determined by the formation of NO in the first four portions of the charge.

Calculations show that the modification of fuel distribution by portions of charge during engine operation close to full loads (α∑ = 1.3), in frame of the limits of schemes 1-0 and 1-3, provides NO concentrations decreasing and show possible preservation of power (pi) and economic (gi) parameters of working cycle (Table 2).

Table 2. Changing the engine parameters at sharp and smooth uneven fuel distribution.

| fuel-distribution scheme | NO, ppm | p, MPa | g, g/kWh |
|--------------------------|---------|--------|----------|
| 1-0                      | 980     | 0.89   | 195      |
| 1-3                      | 1340    | 0.89   | 190      |

Regulation of work obtained in a working cycle is possible by two ways - by a general change in the degree of leaning-out (or enrichment) in all zones while maintaining the fuel distribution scheme by zones, or by leaning-out only portions of the second half of the charge and keeping the mixture composition of the enriched zones unchanged. Table 3 shows the results of leaning-out of the average charge composition of the mixture for two layering schemes 1-0 and 1-3.

In case of engine load decreasing the best results of NO reduction can be achieved by using imitation of power control typical to the diesel principle. For a sharp fuel distribution according to the 1-0 scheme - maintaining a rich first ignition zone and leaning-out of all other subsequent combustion portions. However, it should be noted that in the case of operation on average relatively rich air-fuel mixture compositions α2 ≤ 1.2, the first burnout portion of the charge may have mixture compositions α ≈ 1.0 and cause increased formation of nitrogen oxide.

Despite an effective suppression of the NO formation during a sharp fuel-distribution of charge, the implementation of the 1-0 scheme of sharp separation of charge in a real engine can be limited by a
possible increase in the emissions of incomplete combustion products - carbon monoxide CO and hydrocarbons CnHm. Especially when engine works at partial loads. It can be assumed that this will depend on the type of gaseous fuel and, in particular, on the values of the concentration limits of flammability of the gas-air mixture, which is important for lean mixtures of the last burning combustion portions of the charge.

**Table 3.** Change of concentration of nitrogen oxide with mixture leaning-out for different fuel-distribution scheme (ppm).

| fuel-distribution scheme | 1.2  | 1.4  | 1.6  |
|--------------------------|------|------|------|
| 1-3                      | 2500 | 1200 | 700  |
| 1-0                      | 3300 | 700  | 300  |

Table 4 shows some results of experimental studies for engine run at 2000 rpm and different engine load N_e = 20…100% of nominal load. An average air-fuel ratio for diesel fuel and propane-butane mixture was α_0 = 1.3 (calculated by energy equivalent of MJ / kg). Portion of diesel fuel through nozzle is fixed as 20% of total diesel and gas fuel supply. The load was decreased by leaning-out air-gas mixture. The air-fuel ratio of the propane-butane gas mixture α_gas is calculated according to supply through the inlet manifold.

**Table 4.** Changes in concentration of toxic components NO_x, CO and CnHm with a decrease in load due to reducing of gas supply to inlet manifold.

| N_e, %   | 100 | 80  | 60  | 40  | 20  |
|----------|-----|-----|-----|-----|-----|
| α_gas   | 1.8 | 1.9 | 2.3 | 4.5 | -   |
| NO_x, ppm | 1940 | 1520 | 1360 | 1200 | 800 |
| CO, ppm | 100 | 1000 | 2600 | 2000 | 300 |
| CnHm, ppm | 50 | 1100 | 3200 | 4100 | 500 |

Experimental researches support theoretical studies and confirm expected reduction of the NO_x concentration in exhaust gases, when the load is reduced by leaning-out of air-gas mixture. However, even with a relatively large proportion of diesel fuel, a decrease in engine load by 20% from the nominal one causes a sharp emission of incomplete combustion products - CO and CnHm. The concentration of CO and CnHm decreases to an acceptable level only when switching to light loads, where operation is provided only by the supply of diesel fuel.

It is logical to suppose that in order to ensure stable combustion of the main gas-air mixture evenly distributed over the combustion chamber, it is necessary to provide a transition to a smoother charge distribution in the chamber. Another way should be throttling of the air charge at the inlet manifold to maintain a stable ignition of these mixtures.

In the first case, easy regulation of the engine is provided due to the mutual change in the ratio of diesel and gas fuel supplies: at full load, the diesel fuel supply is minimal, but when the load decreases due to a decrease in the gas supply through the inlet pipeline, the diesel supply increases. The regulation is simple, but it contradicts the idea of maximum replacement of diesel fuel with gaseous fuel. At the same time, this will lead, as shown above, to an increase in the intensity of formation of nitric oxide in the transition zone.

It is logical to suppose that improving the combustion stability of the main gas-air charge is possible while maintaining the gas concentration within the flammability concentration limits. This can be achieved by throttling the air charge at the intake.

The mathematical model makes possible to analyze the joint engine regulation by acting on the change in gas and diesel fuel supply and throttling the air charge through the inlet manifold. The throttling level can be conventionally set by the pressure value of the end of the intake process (bottom dead center) P_a. In calculations, the value of P_a varied in the range from 0.9 MPa without throttling to
0.5 MPa with maximum throttling. The minimum value of $P_a = 0.5$ MPa was limited by the minimum required air temperatures to ensure self-ignition of diesel fuel.

\[ \text{Figure 3. The formation of NO as a function of } P_a - \text{the cylinder pressure at BDC and } \alpha - \text{gas-air mixture in a cylinder.} \]

The above calculation results show that control of the air throttling in intake manifold allows to reduce the concentration of nitrogen oxide in a wide range of engine operating modes figure 3. A conclusion can be made that a decrease in the mass of the incoming charge, pressure and combustion temperatures in the cylinder, which directly affect the NO formation, could be considered as the main mechanism to reduce NO. An additional effect of air throttling is a decrease not only in NO concentration, but also in a decrease of mass of total NO emissions with exhaust gases due to a decrease of the absolute amount of air involved in combustion.

The degree of throttling should be selected depending on the operating mode of the engine under the conditions of maintaining the composition of the gas-air mixture in the chamber within the flammability range. The goal is to ensure stable combustion of the last portions of the charge providing an acceptable level of emissions of carbon monoxide and hydrocarbons, which should also be reduced together with nitrogen oxides according to the terms of EURO-6.

The degree of throttling depends on the type of used gas. According to the results of experimental studies [6], when working on propane-butane mixtures with a load decrease from 100 to 60%, it is advisable to gradually increase throttling and decrease the cylinder filling factor by 0 to 20% ($P_a = 0.09 \ldots 0.07$). This ensures the maintenance of the excess ratio of the gas-air mixture at the level of $\alpha_{\text{gas}} = 1.8 \ldots 2.0$. Further load reduction requires only high-quality regulation due to depletion of the gas-air charge. This allows you to keep the concentration of carbon monoxide at 400 ... 600 ppm, and hydrocarbons 400 ... 700 ppm. Further reduction of CO and $C_nH_m$ is possible when changing gas to methane or installing a neutralizer.

When operating at high loads with charge enrichment of air-fuel ratio up to total $\alpha_{\Sigma} = 1.2 \ldots 1.3$ and $\alpha_{\text{gas}} = 1.8 \ldots 2.0$ for the air-gas mixture, the concentration of NO can be further reduced due to recirculation of exhaust gases.

This model allows to work out a parametric analysis of the nitrogen oxide reduction using an exhaust gases recirculation. The introduction of recirculated gases into the charge is simulated by an increase in the coefficient of residual (exhaust) gases $\gamma_r$ in portions of the charge. It is assumed that the
exhaust gas is recirculated through the intake manifold, evenly together with the supply of the gas-air mixture. The concentration of combustion products is assumed to be the same in all portions of the charge. Table 5 shows the results of calculations for the layering scheme 1-3 and three levels of γr: 5, 10 and 15%, assuming that the 5% level corresponds to the initial concentration of residual gases in the charge, and the levels of 10 and 15% reflect the introduction of exhaust gas recirculation. The use of exhaust gas recirculation causes an effective reduction in the formation of nitrogen oxide concentration by reducing the concentration of free oxygen and lowering combustion temperatures [15]. The obtained results are in good agreement with studies on a gas-diesel engine run on compressed natural gas [16], which has to be supplied in a way with a similar charge stratification scheme.

**Table 5.** Nitric oxide concentration during exhaust gas recirculation scheme 1-3).

| residual and recirculated gases | NO, ppm | NO reducing, % | contribution of portions to NO reduction 1-5 | 6-10 |
|--------------------------------|---------|----------------|---------------------------------------------|------|
| 5 %                            | 2500    | -              | -                                           | -    |
| 10 %                           | 1900    | 24 %           | 82 %                                        | 18 % |
| 15 %                           | 1100    | 56 %           | 84 %                                        | 16 % |

The inhomogeneity of the temperature field that occurs in a piston engine, in this case, is enhanced by the inhomogeneous composition of the mixture. As a consequence, the contribution of individual portions of the charge to the total reduction of NO is different. The most powerful are recirculated gases entering the transition zone of the first half of the charge. With a uniform supply of 10% and 15% of recirculated gases, the overall reduction in NO emissions from the exhaust gas is 24% and 56%, respectively. Moreover, the main effect of reducing - 82-84% is achieved by reducing the intensity of NO formation in the first half of the charge (portions 1-5). A decrease in the intensity of NO formation in the second half of the charge (portions 6-10) is also noted, however, due to the low initial values, their role in the overall decrease in nitric oxide is 16-18%.

**Conclusions**

The calculated model of the nitrogen oxide formation, taking into account the unequal fuel distribution of the charge, shows the high efficiency of the parametric analysis for predicting the NO emissions for the designed engines with uneven fuel distribution charge, for example, operating on the gas-diesel cycle.

A decrease in the concentration of nitrogen oxide in the exhaust gas by 40-50% is achieved by applying different layering schemes of the charge in the combustion chamber. The most effective method is the separation of the charge into a small-mass enriched first portion and a main lean-out charge.

The over leaning-out of last burning portions of air-gas mixture can be a cause of the incomplete combustion and high emission of CO and CnHm under decreasing of engine load. Ensuring CO, CH and NO standards will require mixed engine regulation

Recirculation of 15% exhaust gas reduces NO emissions by about 50%.

**References**

[1] Devyanin S N, Kovalenko V P, Ulyukina E A and Todoriv A V 2017 Prospects for the operation of agricultural machinery on compressed natural gas *Autogas refueling complex + Alternative fuel* 16(7) 313-5

[2] Kryshtopa S, Panchuk M, Dolishni B, Kryshtopa L, Hnyp M and Skalatska O 2018 Research into emissions of nitrogen oxide when converting the diesel engine to alternative fuel *Eastern-European Journal of Enterprise Technologies* 10(91) 16-22 DOI: 10.15587/1729-4061.2018.124045

[3] Vinokurov V A, Barkov A V, Krasnopol'skaya L M and Mortikov E S 2010 New methods of
manufacturing alternative fuels from renewable feedstock sources Chemistry and Technology of Fuel and Oil 46(2) 75-8

[4] Markov V A, Gladyshev S P, Devyanin S N, Mihalsky L L and Drobyshev O V 2009 Perfection of the processes of the fuel spraying and the fuel-air mixture creating in a high-speed diesel engine, working on the bio-fuel mixture SAE Technical Papers

[5] Chumakov V L 2016 Features of using gas fuel in diesels (Reports of the TSHA) 234-7

[6] Devyanin S N, Bigaev A V and Markov V A 2018 Influence of Method of Adding Water to Combustible Mixture on Diesel Engine Performance IOP Conference Series: Materials Science and Engineering

[7] Markov V A and Trifonov V L 2015 Mixed biofuels with linseed oil addition for diesel engines Proceedings of higher educational institutions. Mechanical engineering 7 34-44

[8] Khakimov R T 2018 Mathematical modeling of a two-phase medium of elements of LPG fuel supply system of automotive equipment Bulletin of the St. Petersburg State Agrarian University 3(52) 220-6

[9] Markov V, Gladyshev S P, Devyanin S and Mikhalsky L 2010 Method of estimating the quality of the process of creating the fuel-air mixture in a high-speed diesel engine SAE Technical Papers

[10] Zel'dovich Ya B, Sadovnikov P Ya and Frank-Kamenetskiy D A 1947 Oxidation of nitrogen during combustion (M: Publishing house of the Academy of Sciences of the USSR) 145 p

[11] Voinov A N 1977 Combustion in high-speed piston engines (M: Mechanical Engineering) 276 p

[12] Maksimov A L 1976 The calculated model of the actual cycle of an internal combustion engine. Proceedings of the Moscow Automobile and Road Institute (M: MADI) 74-81

[13] Chumakov V L, Bizhaev A V and Putan A A 2020 Calculation model of main parameters of diesel working cycle using different types of fuels (M: Reports of the TSHA) 244-7

[14] Khakimov R T, Didmanidze O N and Afanasyev A S 2018 Research of heat generation indicators of gas engines Electromechanics and Mechanical Engineering Journal of Mining Institute 229 50-5

[15] Chumakov V L and Bizhaev A V 2019 Reducing emissions of nitrogen oxides with exhaust gases of gas diesel (M.: OOO Megapolis) 118-22

[16] Mahla S K, Das L M and Babu M K 2010 Effect of EGR on Performance and Emission Characteristics of Natural Gas Fueled Diesel Engine Jordan Journal of Mechanical and Industrial Engineering 4 523-30