EXHAUST GAS RECIRCULATION - A NEW APPROACH

Dr.-Ing. Amin Velji
Institute for Reciprocating Engines (IFKM) - Karlsruhe Institute of Technology (KIT)

Abstract: *Diesel engines are the most efficient power plants among all known types of internal combustion engines. However, the noxious components, namely oxides of nitrogen (NO_X) and particulate matter (PM) in the exhaust are considered to be very critical. Using exhaust gas re-circulation, it is possible to reduce NO_X-emission to a considerable extent. On the other hand, a significant rise of PM-Emission is the result. The reason for this is the lower oxygen content in the gas mixture "fresh air + re-circulated exhaust gas." In this theoretical and experimental study it could be shown, that re-circulated NO_X from the exhaust gas into the engine highly reduces the formation of thermal NO. The drop in formation of thermal NO is approximately linearly proportional to the re-circulated amount of NO_X. Since oxygen content is hardly affected, the PM-Emission remains almost constant.*

Keywords: DIESEL COMBUSTION, NO_X-EMISSION

1. Introduction

Since the introduction of the Clean Air Act in 1970, world-wide legislatives have been put in force to limit air pollution caused by both gasoline and Diesel engines. Figure 1 shows the exhaust gas limits for oxides of nitrogen (NO_X) and particulate matter (PM) for Diesel passenger cars from 1998 till today. The limit for NO_X in the European Union (EU) during the New European Driving Cycle (NEDC) was reduced by 80% from 900 mg/km in 1998 to 180 mg/km today, whereas as in the same time period the PM-limit was reduced by 95% from 100 mg/km to 5 mg/km. Similar tendencies can be observed in the USA and Japan.

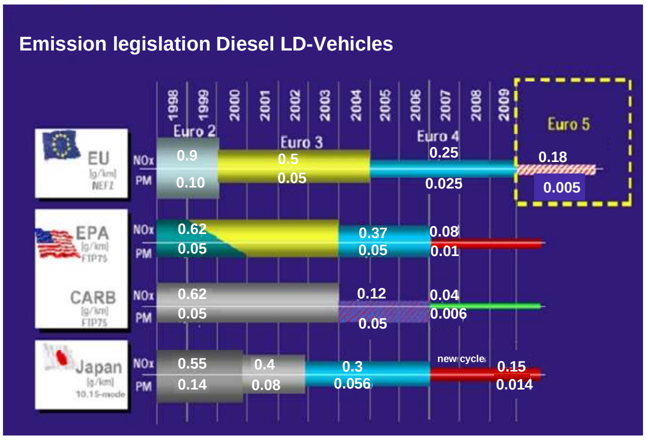


Fig. 1 *Exhaust gas limits for Diesel passenger cars.*

One method of reducing NO_X emission is the exhaust gas recirculation. However, this leads to a drastic rise in emission of particulate matter. The cause of this phenomenon is reduction of oxygen content.

In the following a method will be presented allowing a significant reduction of thermal NO-formation without having to reduce the oxygen content.

2. Basics of exhaust gas recirculation

During exhaust gas recirculation (EGR), a part of the exhaust gas is re-circulated into the combustion chamber. Figure 2 shows the relative change of NOX and particulate matter (PM) emissions as a function of EGR-rate. EGR-rate is defined as the mass of re-circulated exhaust gas divided by the sum of the mass of re-circulated exhaust gas and the mass of fresh (charge) air.

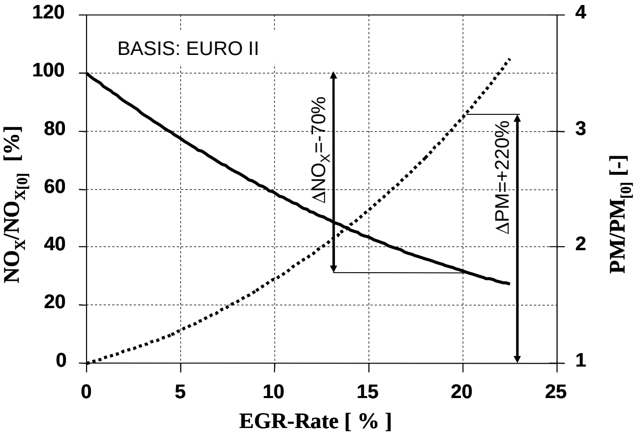


Fig. 2 *NO_X and particulate matter emission as a function of rate of exhaust gas recirculation [1].*

The NO_X falls continuously with a rise in the rate of EGR, whereas the particulate matter emission rises continuously. At an EGR-rate of 20%, the reduction in NO_X-emission is 70%. At the same time, the PM-emission increases more than three-fold. The cause of the rapid fall of NO_X–emission is due to the lower oxygen content of the gas mixture "fresh air + exhaust" compared to the oxygen content in the fresh air. Thereby, the composition of the combustion air changes to the extent that now more inert gas is required in order to provide the same quantity of oxygen as available in the normal air, i.e. the mass of inert gas rises and resultantly also the thermal capacity. This leads to a lower peak combustion temperature. A calculation of the temperature in the burned zone using a thermodynamic two-zone-model revealed a lower peak temperature of approximately 200 K. This explains the 70% reduction in NO_X [1]. Rise in PM-emission can similarly be attributed to reduction in oxygen content [2].

In the following a method will be presented allowing a significant reduction of thermal NO-formation without having to reduce the oxygen content.

3. NO_X-recirculation of exhaust gas to engine

3.1 The effect of the presence of NO on thermal NO-formation

More than 90% of NO_X-emission consists of NO. It can be led back almost entirely to thermal NO formed according to the Zeldovich-mechanism [3]. Following chemical reactions describe the formation of thermal NO:

$$N_2 + O\cdot \underset{k_{1B}}{\overset{k_{1F}}{\Leftrightarrow}} NO + N\cdot \quad (1)$$

$$O_2 + N\cdot \underset{k_{2B}}{\overset{k_{2F}}{\Leftrightarrow}} NO + O\cdot \quad (2)$$

$$N\cdot + \cdot OH \underset{k_{3B}}{\overset{k_{3F}}{\Leftrightarrow}} NO + H\cdot \quad (3)$$

State of equilibrium of these reactions is not achieved in an engine's combustion process. Quantitative characterisation of individual forward and backward reactions is possible through respective rate constants $k_{1F}...k_{3B}$. Rate constants can be calculated using the Arrhenius rate-equation:

$$k = 0.001 * A * T^B * e^{(-E)/(R * T)} \quad (4)$$

k	Rate constant [m^3/(kmol*s)]
A	Conditional frequency [cm^3/(kmol*s)]
B	Temperature coefficient [-]
E	Activation energy [kJ/kmol]
R	Gas constant [kJ/(kmol*K)]
T	Temperature [K]

Using values given in the literature for impact the conditional frequency, temperature coefficient and activation energy [4], following rate constants can be calculated assuming a temperature of 2200 K:

$k_{1F} = 3.66*10^3$ m^3/(kmol*s)
$k_{1B} = 2.80*10^{10}$ m^3/(kmol*s)
$k_{2F} = 3.37*10^9$ m^3/(kmol*s)
$k_{2B} = 4.37*10^5$ m^3/(kmol*s)
$k_{3F} = 4.20*10^{10}$ m^3/(kmol*s)
$k_{3B} = 3.97*10^6$ m^3/(kmol/s)

Using the above rate constants $k_{1F}…k_{3B}$ and the concentration of the substances involved, the reaction rates K_{1F} ... K_{3B} of the individual part reactions can be determined:

Forward reaction 1

$$K_{1F} = k_{1F} * [N_2] * [O\cdot] \quad (5)$$

Backward reaction 1

$$K_{1B} = k_{1B} * [NO] * [N\cdot] \quad (6)$$

Forward reaction 2

$$K_{2F} = k_{2F} * [O_2] * [N\cdot] \quad (7)$$

Backward reaction 2

$$K_{2B} = k_{2B} * [NO] * [O\cdot] \quad (8)$$

Forward reaction 3

$$K_{3F} = k_{3F} * [N\cdot] * [\cdot OH] \quad (9)$$

Backward reaction 3

$$K_{3B} = k_{3B} * [NO] * [H\cdot] \quad (10)$$

The NO-formation rate can be calculated as follows:

$$d[NO]/dt = K_{1F} - K_{1B} + K_{2F} - K_{2B} + K_{3F} - K_{3B} \quad (11)$$

$$= k_{1F}*[N_2]*[O\cdot] + k_{2F}*[O_2]*[N\cdot] + k_{3F}*[N\cdot]*[\cdot OH] - k_{1B}*[NO]*[N\cdot] - k_{2B}*[NO]*[O\cdot] - k_{3B}*[NO]*[H\cdot] \quad (12)$$

Arranging equation (12) according to NO yields:

$$d[NO]/dt = - (k_{1B}*[N\cdot] + k_{2B}*[O\cdot] + k_{3B}*[H\cdot]) * [NO] + (k_{1F}*[N_2]*[O\cdot] + k_{2F}*[O_2]*[N\cdot] + k_{3F}*[N\cdot]*[\cdot OH]) \quad (13)$$

Combining all constants results in:

$$d[NO]/dt = -D * [NO] + C \quad (14)$$

From equation (14), it can be concluded that there is a linear decrease in rate of NO-formation with rising concentration of NO. This is illustrated qualitatively in Figure 3:

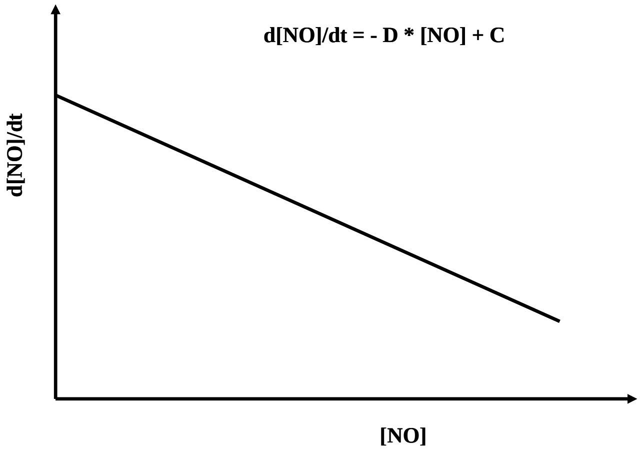


Fig. 3 *NO_X and particulate matter emission as a function of rate of exhaust gas recirculation [1].*

In the next chapter the validity of equation (14) will be verified with engine tests.

3.2 Experimental setup

Figure 4 shows a schematic of the experimental setup. A dosing valve is used to mix normal air with a mixture of 96 vol% nitrogen and 4 vol% NO_X ($NO+NO_2$, NO_2-content < 10%). Concentration of NO_X is set such that it lies between 0 and approximately 200% of raw emission for the respective engine operating point.

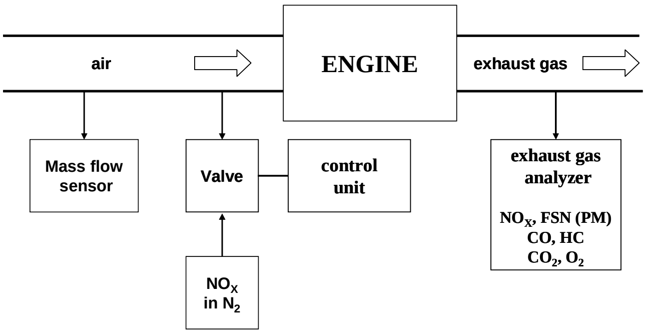


Fig 4 Schematic of experimental setup

The engine used in these tests is a single-cylinder engine, type 1B20 of Motorenfabrik Hatz. Technical specifications are listed under Table 1.

The tests were carried out at 6 engine operating points. Table 2 shows these test points and the corresponding raw NO_X emissions

Table 1 Engine specifications

Engine	Single-cylinder four-stroke Diesel engine
Bore/stroke	69mm/62mm
Engine displacement	232 cm³
Speed range	900 ... 3600 rpm
Max. torque (at 2500 rpm)	11 Nm

Table 2 Engine operating points with raw NO_X emissions

Engine test points	Engine speed [rpm]	Load [%]	Raw NOX emission [ppm]
1	3000	95	410
2	3000	65	305
3	3000	33	185
4	2600	95	400
5	2600	65	335
6	2600	33	230

3.3 Engine test results

Figure 5 shows the experimental procedure using testing point 1 as an example. First, the raw emission of NO_X was measured. It was 11.2 g/h and consisted of 10.3 g/h NO and 0.9 g/h NO_2. Thereafter, varying quantity of NO_X (NO content > 90 %) was injected and the NO_X emission in the exhaust was measured. This comprised of injected NO and/or NO_2 and the newly formed oxides of nitrogen (NO + NO_2).

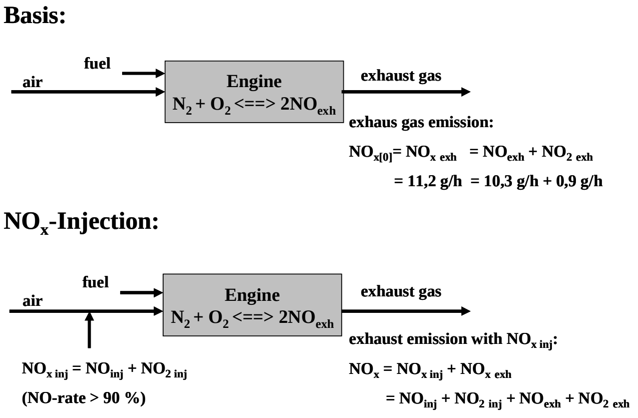


Fig 5 Experimental procedure shown exemplary for test point 1

Figure 6 shows NO_X emission as a function of injected quantity of NO_X. The solid line indicates the extent of NO_X emission provided the injected NO_X did not influence thermal formation of NO, i.e. this line is the sum total of raw emission (11.2 g/h) and the injected quantity of NO_X. The dashed line indicates measured values. Under the assumption that the injected NO_X, consisting essentially of NO, passes through the engine, following propositions can be made from the results of Figure 6:

Thermal NO, formed in the engine, decreases with increasing quantity of NO_X injected from outside. This confirms the accuracy of equation (14).

Thus, with an injected quantity NO_X of 10.1 g/h (9.6 g/h NO + 0.5 g/h NO_2) the newly formed NO_X reduces to 7.6 g/h (raw emission 11.2 g/h). NO content reduces from 10.3 g/h to 5.7 g/h. This corresponds to a reduction of 44.7%. With an injection of 22.6 g/h NO_X, formation of NO_X is only 2.5 g/h

Change in smoke number (SN) for test point 1 with NO_X-injections is shown in Figure 7. SN increases marginally with increase in NO_X -injection. The reason for this is the fall in oxygen content of combustion air as a result of “nitrogen oxides in nitrogen” due to injection of the mixture.

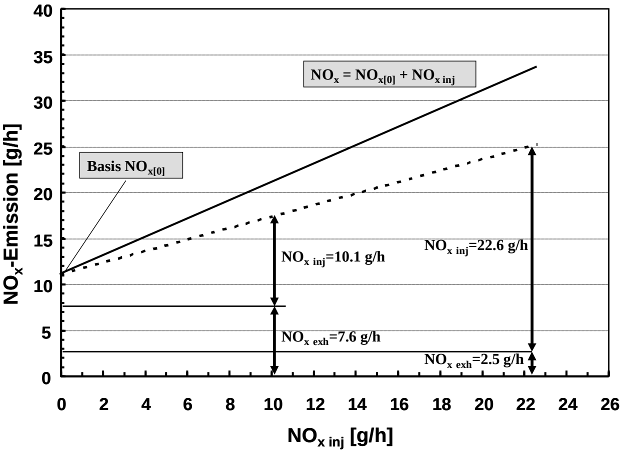


Fig 6 NO_X emission as a function of injected NO_X for test point 1

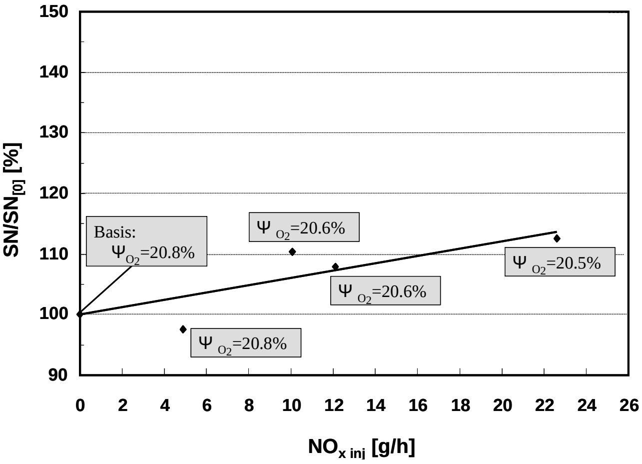


Fig 7 Changes in smoke number as a function of injected NO_X

Figure 8 shows newly formed NO_X as a function of injected NO_X for all six test points.

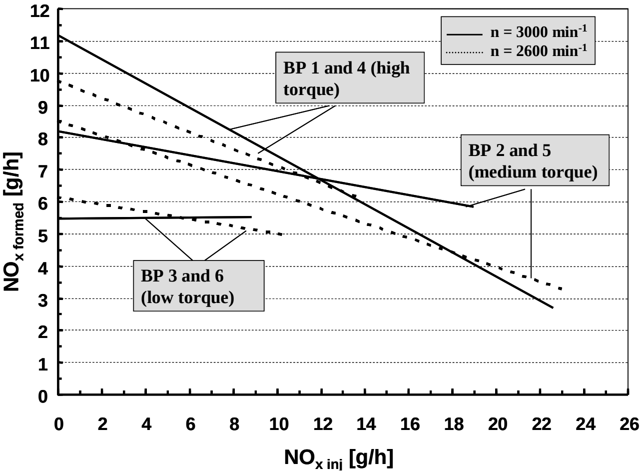


Fig 8 Formed NO_X as a function of injected NO_X

From the results shown in Figure 8, the following conclusions can be drawn:

- The correlation between NO-content of the combustion air and the thermal NO-formation in the combustion chamber discussed in Chapter 3.1 is valid for all six test points

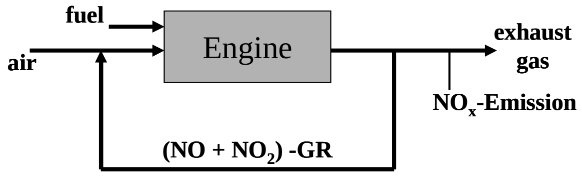
- The value of constant D of equation (14) rises with rising NO_X raw emission. This correlation can be seen in Table 3. A possible explanation for this phenomenon is the fact that starting from a specific temperature (< 2200 K [1]), the thermal NO-formation proceeds so slowly that no significant NO quantity is formed.

Table 3: NOX raw emission and constant D for all test points

NO_X raw emission	185	230	305	335	400	410
- D	0.005	0.114	0.125	0.229	0.266	0.375

4. Conclusion

If it is possible to eliminate NO_X from exhaust gas and re-circulate it to the engine, then the NO_X reduction can be determined for every single test point as a function of re-circulated NO_X quantity, Figure 9. NO_X-emission is specified as NO_2 mass flow according to the Directive 98/96/EG, i.e. NO emission is converted to the corresponding NO_2 mass flow.



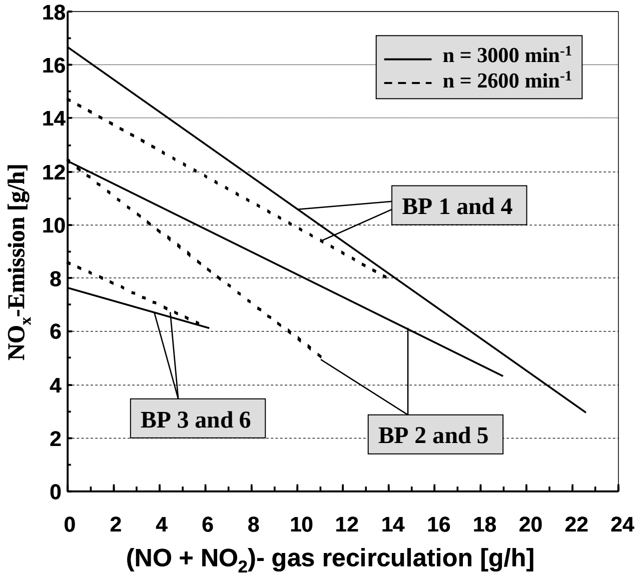


Fig 9 NO_X emission as a function of re-circulated NO_X quantity

It can be seen that NO_X emission falls with increasing re-circulated amount of NO_X from the exhaust gas for all the test points. For example, for test point 1 the NO_X emission resulting from re-circulated NO_X of 8 g/h reduces by approximately 30% and by 16% in case of re-circulated NO_X of 16 g/h.

The future task lies in finding means of separation of oxides of nitrogen from exhaust gas in order to feed it specifically to the combustion air.

5. Literature

[1] Remmels, W.; Velji, A.: Grundsatzstudie: Einfluß der Abgasrückführung auf Emission und Wirkungsgrad. 2. Dresdener Motorkolloquium, May 1997

[2] Velji, A.; Hofmann, U.; Bach, E.: On-Board-Beeinflussung der Verbrennungsluft zur Schadstoffreduktion bei Dieselmotoren. V. Conference on “Motorische Verbrennung: Aktuelle Probleme und moderne Lösungsansätze”, Haus der Technik, Essen 13./14. March 2001

[3] Zeldovich, Y. B.: The Oxidation of Nitrogen in Combustion and Explosions, Acta Physicochimica, USSR, Vol. 21 (1946), pp. 577-628

[4] Urlaub, A.: Verbrennungsmotoren. Springer-Verlag, 2nd Edition, 1994