

Advanced EGR Control Concept for HD-Truck-Engines

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ABSTRACT

Exhaust Gas Recirculation (EGR) is a proven method for in-cylinder NO_x reduction. A multitude of scientific work has focused on the temperature-lowering effect of exhaust gases.

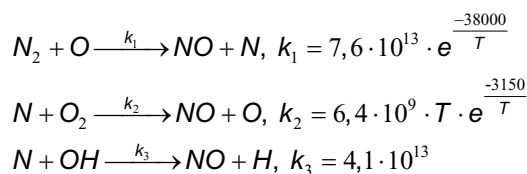
The disadvantage of a turbocharged heavy duty diesel truck engine is a high positive pressure gradient between intake and exhaust which complicates a High Pressure Exhaust Gas Recirculation (HP-EGR). In this study, a new technology will be presented to introduce EGR in the high pressure loop of a turbocharged HD-Truck engine without penalty of fuel economy caused by the increase of pumping losses.

INTRODUCTION

Like in-cylinder emission reduction developments exhaust aftertreatment systems become more and more stringent to fulfill emission legislation. Since the conversion rates of exhaust aftertreatment systems are limited, reduction of engine-out emissions gets even more into the focus of investigations. The tradeoff between the main pollutant components NO_x and PM is particularly critical in diesel engines.

The diffusion combustion process causes high burning temperatures and consequently high emissions of nitrogen oxides according to the Zeldovich mechanism (which describes a high temperature formation of NO). The Fenimore mechanism and the N_2O pathway have to be mentioned but they will not be described in this essay.

Below the three reactions of the reduced Zeldovich mechanism are shown [1]:



Since the amount of nitrogen monoxide produced in the engine cylinder from atmospheric nitrogen and oxygen is an exponential function of combustion temperature, even a moderate decrease in the combustion temperature will result in a significant decrease in nitrogen monoxide production.

A reduction of the cylinder bulk temperature can be achieved by EGR which is a well-known and effective possibility to lower NO_x -emissions of diesel engines. First attempts in recycling exhaust gases go back into the 30's of the last century concerning diesel engines for mining vehicles. At the beginning of the 1950's an improvement of the knocking characteristics of SI-engines was expected by the recycling of exhaust gases. In 1960 R. D. Kopa and other researchers presented EGR as an effective procedure for the lowering of nitrogen oxide emissions [2].

The effect of EGR essentially takes place via the following influences:

- The heat capacity of the recirculated exhaust gas is higher than that of air due to the triatomic gases CO_2 and H_2O . This leads to a lower peak temperature in the burning zone within the same amount of heat-energy.
- Lowering the O_2 partial pressure and therefore the oxygen mass in the cylinder, by replacing a part of the combustion air with inert gases.
- Decrease of exhaust gas mass flow rate.
- Repeated participation of unburned pollutants at the combustion process.

The two first mentioned factors are most valuable in reducing emissions of nitrogen oxides [4].

In addition to decreasing NO_x emissions, lowering of the O_2 level as well as the combustion temperature leads to increasing PM emissions which is called the PM- NO_x -Tradeoff (Figure 1).

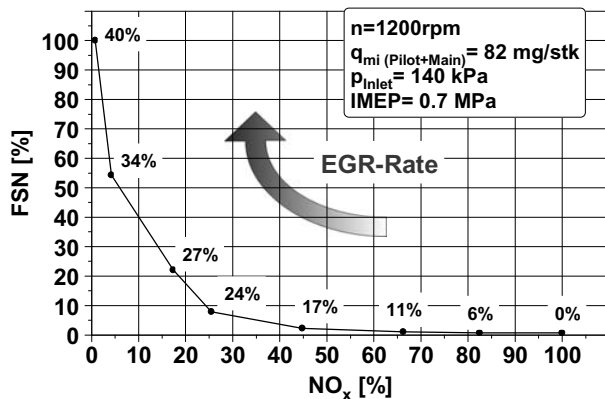


Figure 1: PM-NO_x-Tradeoff

In order to meet future on-Highway emission standards, transient optimization of HD-engines is necessary. Precise EGR control can offer a contribution to achieve these future requirements. With the aim to lower the transient raw emissions, response times of EGR-systems have to be reduced.

MAIN SECTION

EGR SYSTEMS

Exhaust Gas Recirculation is divided in internal and external EGR. Internal EGR can only be controlled by means of new variabilities in the gas exchange process like Variable Valve Actuation (VVA), but this is actually not a method to overcome the emission requirements. Consequently only external EGR is examined closer in the following paragraph.

External EGR is differentiated into low pressure EGR (LP-EGR) and high pressure EGR (HP-EGR).

In LP-EGR (Figure 2) systems exhaust gas is taken after the turbine (and the DPF) and supplied to the intake air before the compressor. This kind of EGR provides the advantage of a natural negative pressure gradient that leads to a BSFC-neutral recirculation of exhaust gases. As a result of the flow resistance in the EGR-cooler and the long EGR-piping it is necessary to increase the backpressure by an exhaust throttle for highest EGR-rates. In transient operation mode this design causes a retarded responding behavior which is crucial for existing and future transient exhaust emission tests. Furthermore particles abandoning the DPF may entail compressor damages.

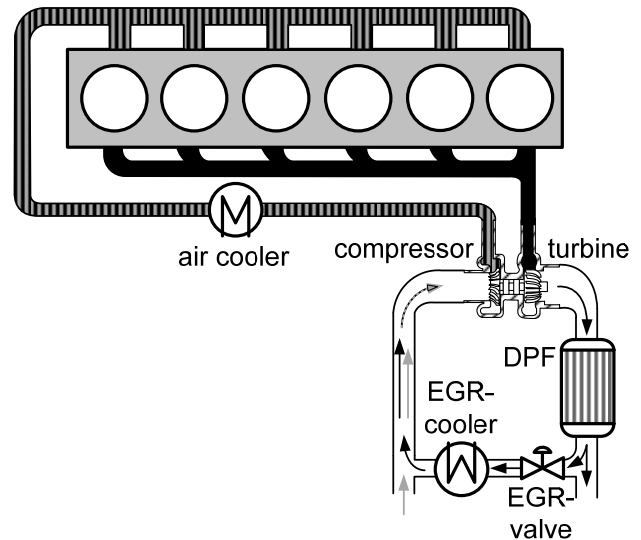


Figure 2: LP-EGR-System

In HP-EGR (Figure 3) systems exhaust gas is extracted before entering the turbine and supplied to the intake air after the compressor and the air cooler.

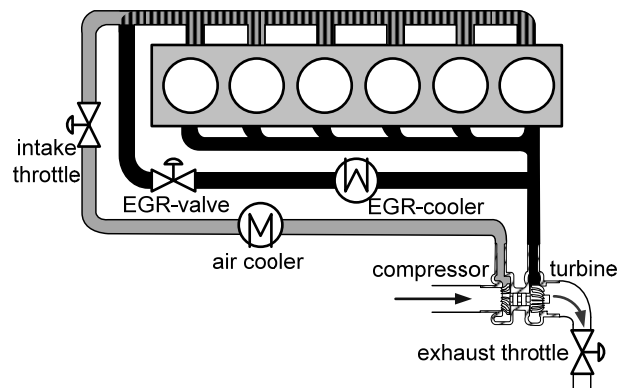


Figure 3: HP-EGR-System

In turbocharged HD-diesel-engines the intake air pressure after the compressor is in large load ranges higher than the exhaust pressure (before turbine) which causes a positive pressure gradient ($\Delta p_{ac-bt} > 0$). In order to allow HP-EGR, it is necessary to provide a negative pressure gradient between intake and exhaust manifold ($\Delta p_{ac-bt} < 0$). There are two possibilities to achieve a negative pressure gradient. The first option is to increase the exhaust backpressure which causes higher pumping losses and a higher level of internal EGR. Internal hot EGR is less effective for NO_x-reduction than cooled external EGR due to its higher charge temperature hence its higher combustion temperature. The second possibility is to lower the intake manifold pressure which is the more suitable way to achieve a negative pressure gradient. The exhaust gas passes the EGR-cooler and is then applied to the fresh air with lower temperature. It is obvious that higher suction work will appear. With the application of an inlet manifold throttle a smooth engine shut down is also feasible.

The problem of a positive pressure gradient will be intensified since future engine concepts are suggested to realize absolute boost pressures of up to 0.5MPa in addition to EGR-rates up to 30 percent.

In order to provide the negative pressure gradient there are different possibilities described in the next paragraph.

REEDVALVES

This technology depends on exhaust gas pressure peaks which are higher than the inlet gas pulses (Figure 4). A reed valve is a kind of check valve that allows the exhaust pressure peaks to flow into the inlet manifold. If the exhaust pressure drops beneath the inlet manifold pressure, the valve closes automatically and prevents a backflow of exhaust gases respectively charge air. For higher EGR rates throttling of the exhaust or intake pipe is necessary.

The pressure loss of reedvalves is about $\Delta p=4\text{kPa}$ at 180 kg/h EGR mass flow.

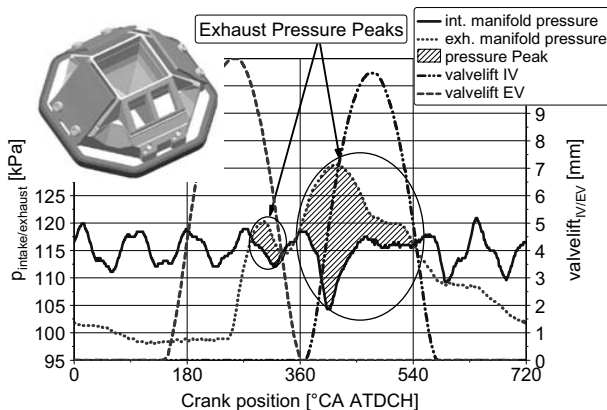


Figure 4: Function of a Reedvalve (RV[5])

EXHAUST/INTAKE THROTTLE

The use of a throttle valve in the intake and/or the exhaust pipe represents the simplest way to achieve the necessary negative pressure ratio. As described above throttling of the exhaust gas goes along with the disadvantage of pumping loss and a higher rate of hot internal EGR, compared to higher suction work if the throttle is attached to the intake manifold.

VG TURBOCHARGER

The application of a VG turbocharger (Figure 5) offers a possibility to provide the necessary negative pressure gradient between intake and exhaust manifold and thus over the EGR-line. By controlling the vanes of the VGT the exhaust back-pressure can be increased. Unfavorably higher internal (uncooled) EGR as well as pumping losses occur according to the exhaust throttle.

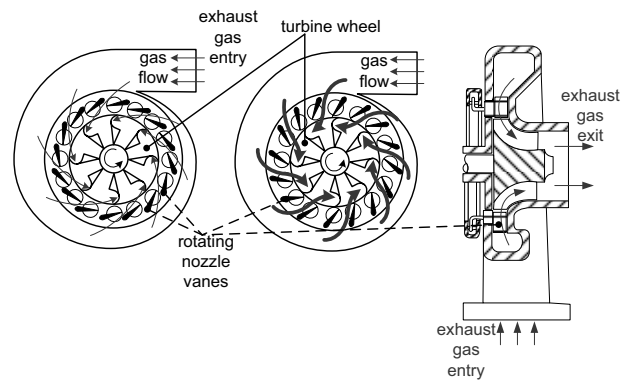


Figure 5: Schematic of VG Turbocharger [6]

VENTURI EGR SYSTEM

An option to obtain a negative pressure gradient is to lower the pressure of the intake manifold at the inlet of the EGR-line by a venturi-EGR-system (Figure 6). The disadvantage of a venturi mixer is the pressure loss ($A_3=A_1$ but $p_3 \neq p_1$) that results from the restriction in the intake system aside from the high cost/performance ratio.

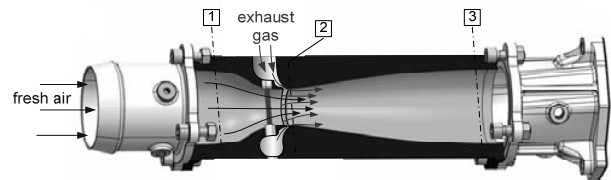


Figure 6: Venturi-EGR-System

According to Bernoulli's law the pressure in the restricted area decreases and enables exhaust gas flow:

$$\Delta p = p_1 - p_2 = \frac{1}{2} \cdot \rho \cdot (v_2^2 - v_1^2)$$

with the continuity equation

$$A_1 \cdot v_1 = A_2 \cdot v_2 \Leftrightarrow v_2 = \frac{A_1}{A_2} \cdot v_1$$

follows:

$$\Delta p = \frac{1}{2} \cdot \rho \cdot v_1^2 \cdot \left[\left(\frac{A_1}{A_2} \right)^2 - 1 \right]$$

DONOR-CYLINDER-CONCEPT

In the donor cylinder concept (Figure 7) the exhaust gas is recirculated from only one cylinder to the intake air of all cylinders. In order to overcome the pressure difference, only one cylinder has to be throttled. The consumption deficit resulting from the gas exchange