

An In-Cycle based NO_x Reduction Strategy using Direct Injection of AdBlue

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ABSTRACT

In the last couple of decades, countries have enacted new laws concerning environmental pollution caused by heavy-duty commercial and passenger vehicles. This is done mainly in an effort to reduce smog and health impacts caused by the different pollutions. One of the legislated pollutions, among a wide range of regulated pollutions, is nitrogen oxides (commonly abbreviated as NO_x). The SCR (Selective Catalytic Reduction) was introduced in the automotive industry to reduce NO_x emissions leaving the vehicle. The basic idea is to inject a urea solution (AdBlue™) in the exhaust gas before the gas enters the catalyst. The optimal working temperature for the catalyst is somewhere in the range of 300 to 400 °C. For the reactions to occur without a catalyst, the gas temperature has to be at least 800 °C. These temperatures only occur in the engine cylinder itself, during and after the combustion.

In this paper a study is presented where a second injector is installed in a Scania D13 cylinder head for urea injection purposes. Additionally, a crank angle resolved in-cycle NO_x formation model is utilized to calculate the urea injection duration for each individual injection event. A gas temperature model based on the cylinder pressure is also used to decide the timing of the urea injection, although always occurring after the combustion and during the expansion stroke. A parameter sweep is conducted to evaluate the concept where also an SCR-catalyst has been introduced to the engine system. The parameter sweep done in the study contains sweeps of engine speed, rail pressure, engine load, EGR levels and timing of the urea injection (by changing the gas temperature limit at which the injection of urea is initiated). The engine tested is a modified single cylinder Scania D13 engine, rebuilt from a six-cylinder engine.

The results suggest that it is possible to reduce NO_x in-cycle, up to 30% at 4.3 bar and 7.7 bar IMEP_{net}, and 50% at an IMEP_{net} load of 11.8 bar, with direct injection of commercial AdBlue. This relates well to the earlier numerical evaluation studies, in the field of direct injection of mixed urea and water solutions.

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INTRODUCTION

It has been widely known for some time now that NO_x emissions can be reduced by mixing NO_x with ammonia or an ammonia-based molecule such as urea, (NH₂)₂CO. If temperatures are above 800 °C [1], reactions will occur that will convert the NO_x and urea into water and nitrogen. This type of reactions, when no catalyst is present, is called selective non-catalytic reduction (denoted SNCR). In automotive applications, it is not possible to obtain the high temperature necessary to convert NO_x SNCR reactions. Therefore an SCR catalyst is needed. However, according to Golovitchev's CFD simulation results [2], it is possible to obtain SNCR based reduction if Adblue (2/3 water and 1/3 urea) is injected in the cylinder where temperatures will be sufficiently high.

In this study, a novel in-cycle feedback based Adblue injection strategy is developed and tested by application of a second injector into a Scania D13 cylinder head. The purpose is to study the potential of the SNCR reduction mechanism in a heavy-duty engine. An FPGA based temperature and NO_x model has previously been developed that is used as feedback in the presented work [3]. Previously, the model has been used for fuel injection control in an effort to reduce NO_x formation as is explained in [4]. However, this was hard to achieve and the full potential of the model was not used due to the impact of ignition delay. A strategy involving direct injection of Adblue would use the full potential of model and cylinder pressure sensor.

EXPERIMENTAL SETUP

The engine used is a 13 liter Scania heavy duty diesel with direct fuel injection and a high-pressure common rail system. Before being customized to a single cylinder engine for experimental purposes, the original production engine had six cylinders. The EGR flow is controlled by a back-pressure and EGR valve. Before reaching and mixing with the inlet air, the EGR is cooled in an EGR cooler. The EGR cooler is located between the EGR valve and the back pressure valve.

The inlet air to the single cylinder engine is pressurized externally, where inlet pressures up to 5 bar are obtainable. The pressure is changed by adjusting an electrically actuated air valve. The pressurized air is heated with an air heater supplied from Leister, before it mixes with the EGR. The fuel injector is of solenoid type with hydraulic connection to the main needle. The injection of AdBlue is handled by a Bosch Piezo-based injector (used for example in a Mercedes CLS 350 GDI) with a 90° spray angle. The geometrical layout of the final cylinder head installation can be seen in [Figure 1](#). The cylinder pressure sensor had to be moved and side-mounted in order to fit the AdBlue injector inside the cylinder head. An external pump system was used to keep the injection pressure at approximately 180 bar for the AdBlue injection. In [Figure 2](#), the complete engine setup is presented. The Vanadium based SCR catalyst bought from Haldor Topsøe A/S is mounted between the exhaust pipe and back pressure valve and is thus pressurized by the engine exhaust pressure. NO_x emission concentration is measured both before and after the catalyst. Additionally, a NH₃ sensor is used to measure the slip of ammonia in the exhaust, after the SCR catalyst. Swedish MK1 diesel was used in the tests.

Table 1. Engine setup specifications for the AdBlue direct injection experiments. Adblue data is collected from [5].

Displaced volume	2100 cc
Stroke	160 mm
Bore	130 mm
Connecting Rod	255 mm
Compression ratio	18:1
Fuel injector type	Solenoid XPI
Spray angle	146°
AdBlue injector type	Piezo
Spray angle	90°, angled towards the flame
Fuel type	Swedish MK1 diesel
Adblue type	Commercial Adblue from Statoil
Adblue pump	Kränzler (180 bar pressure)
Urea content in Adblue	33.2 %
Adblue density at 20 °C	1.092 g/cm ³
SCR volume	19.5 dm ³

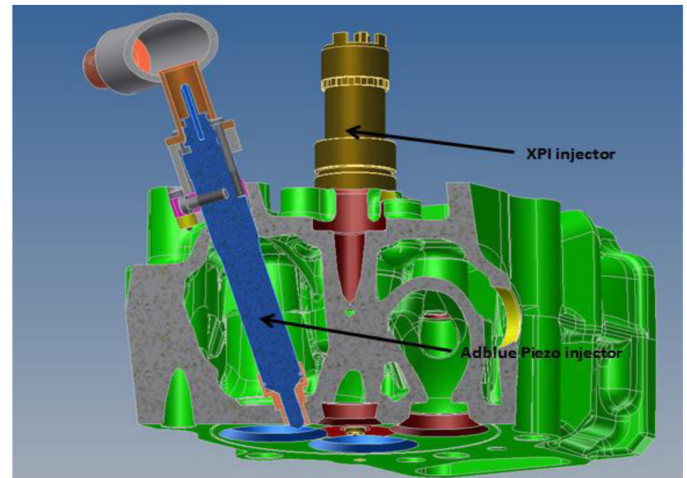


Figure 1. The Adblue injector location in the cylinder head. As can be seen, the injector is slightly tilted in an effort to aim the spray directly into the combustion area. The location of the Scania XPI fuel injector can also be seen. The Kistler cylinder pressure sensor is side-mounted (not seen in the figure).

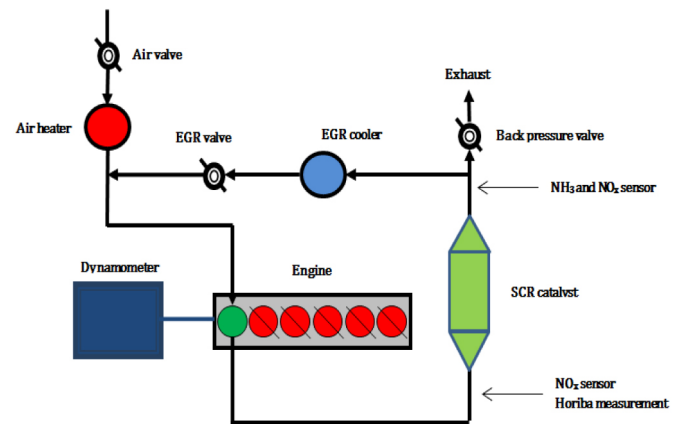


Figure 2. Engine setup used during the experimental phase. The engine is a 13 l Scania D13 with an extreme high pressure common-rail system (XPI) for the fuel injection. Additionally, an external pump system (maximum pressure 180 bar) is used for the AdBlue injection. The original six cylinder engine has been customized into a single cylinder engine (only the cylinder marked in green is used).

A total of three computers are utilized for data collection and engine control. A host computer is used with a graphical user interface (GUI) where target values and running conditions are defined. The host computer communicates with a logger through serial communication. The logger is collecting lambda, temperature and pressure data from the engine. A MEXA-9100EGR from Horiba measures engine emissions (NO_x, CO₂, HC, O₂ and CO). Emission measurements are transferred to the host computer using a dedicated emission computer. The computer is collecting emission data from the Horiba and sending it to the host through TCP/IP communication. A real time target PC from National Instruments is used for engine control and cylinder pressure collection. The computer used is a NI PXIe-8135 Core i7-3610QE 2.3 GHz with a LabVIEW 2012 Real-time module. Ethernet communication between the host PC and the PXI computer is used for transferring data. A NI PXI7854 FPGA card sets the control signals to the injector.

common-rail pump and other actuators. This is done with a D/A-converter (vice versa for cylinder pressure collection) between the FPGA and the engine. The system setup can be seen in Figure 3. The NI 7854 FPGA card is capable of extremely fast code executions. In this setup, the algorithm calculating temperature and NO_x concentrations executes a single calculation time step in only 3 μs [3]. At an engine speed of 1200 rpm this corresponds to approximately 0.015 crank angle degrees (CAD). The control and measurement setup can be seen below in Figure 3.

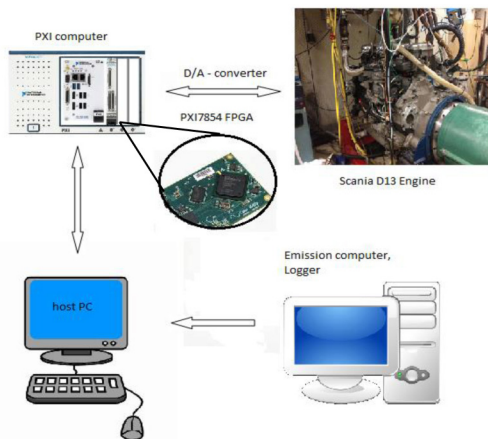
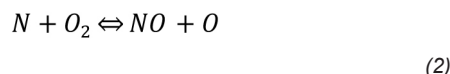
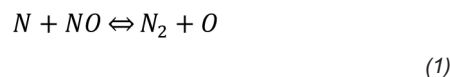


Figure 3. The final control and measurement system setup layout. The NO_x and NH₃ CAN-sensor measurement values (see position of the sensors in Figure 2) are collected on a separate computer independent from the above system layout.

NO_x FORMATION MODEL

The NO_x formation model, used in the experiments, is based on previous work in two-zone, zero-dimensional pollution modeling [3, 6, 7, 8, 9, 10]. Model inputs are cylinder pressure, EGR, lambda, inlet pressure and inlet temperature. The original Zeldovich mechanism is used in the model to describe the formation [11]:



This assumes that the NO_x production in a diesel engine is mostly NO and that the formation is dominated by the thermal mechanism, as described in [12]. Heat release calculations are based on equations presented in [13].

As a function of pressure and volume, the heat release (dQ) is calculated as:

$$dQ = \frac{\gamma}{\gamma-1} p dV + \frac{1}{\gamma-1} V dp \quad (3)$$

The cylinder volume (V) is tabulated and stored in memory while the cylinder pressure (p) is measured. The influence of EGR is accounted for in the calculation of local combustion temperatures. Exhaust gases will have an effect on the specific heat of the total gas content in the cylinder. The presence of EGR will increase the specific heat and thus reduce the peak combustion temperatures, as can be seen in:

$$dQ = mc_p dT \quad (4)$$

The specific heat (c_p) of the cylinder gas is calculated based on polynomial approximations [3] of the NASA Glenn tables [14]. The heated mass, m, corresponds to the mass of the products formed during combustion. Equation (4) states that the heat release (dQ) will result in a temperature increase, proportional to the inverse of the specific heat, c_p.

In the model, the cylinder is divided in two separate zones: burned and unburned zone. The burned zone contains all the products formed during the combustion of diesel. The unburned zone consists of fuel not yet combusted, air and EGR. One assumption in the model is that the temperature change in the unburned zone is due to polytropic compression and expansion. The temperature in the burned zone is calculated by addition of heat, as described in (4). The water-gas shift reaction [6] is added in the combustion chemistry to account the effect that dissociation of water and carbon dioxide has on the temperature:

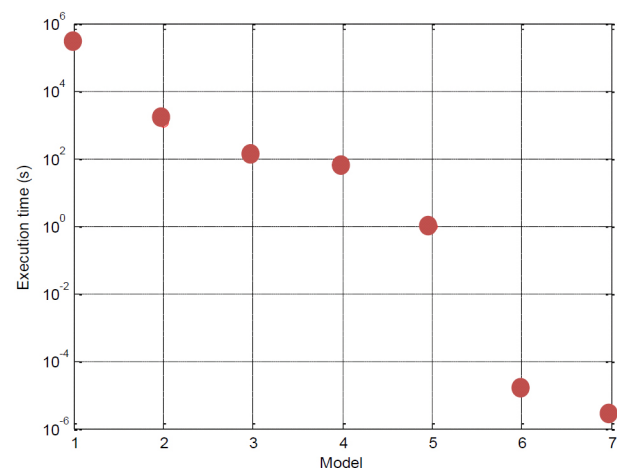
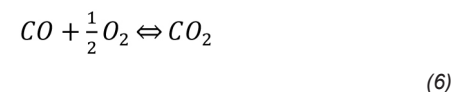
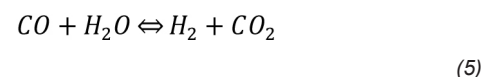


Figure 4. Execution times for models of NO_x formation. Model 1 = CFD model [12], model 2 = multi-zone zero-dimensional model [7], model 3 = zero-dimensional two-zone model on a PC [7], model 4 = improved multi-zone model [8], model 5 = empirical model in industry, model 6 = model implemented on a micro-processor [6], model 7 = zero-dimensional two-zone model implemented on FPGAs [3].

When the combustion temperature, combustion chemistry and combustion product mass is known, the Zeldovich mechanism is applied to get the NO concentration at each crank angle. A more in-depth description of the model is available in [3][15]. Calculation time of 3 μ s is achieved in real-time execution of the NO_x algorithm. The result can be compared to execution times of other formation models in Figure 4 (log-scale used on y-axis). In Figure 5 an example of the real-time calculation of the NO_x concentration is given at a 10 bar engine load point.

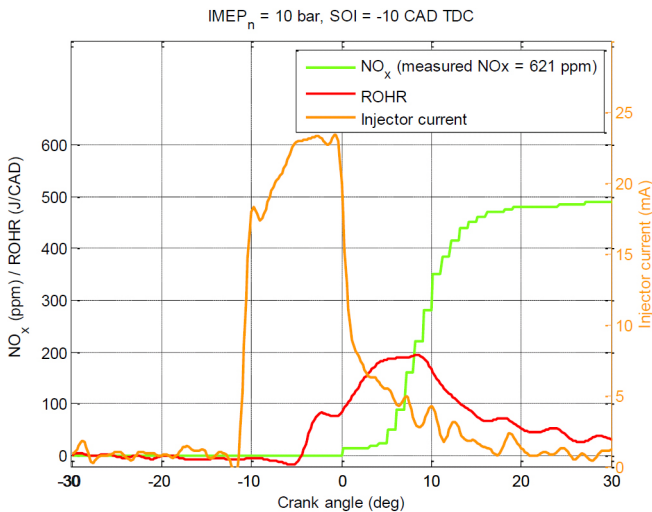
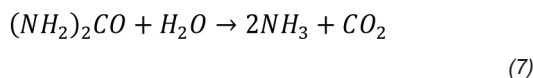


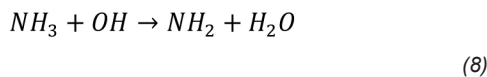
Figure 5. Results from the FPGA NO_x model at an engine load of 10 bar and start of injection (SOI) = -10 CAD TDC. The measured NO_x concentration is 621 ppm while the estimation gives approximately 490 ppm.

NOX REDUCTION MECHANISMS USING ADBLUE DIRECT INJECTION

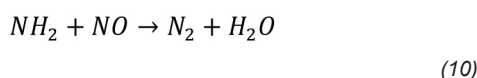
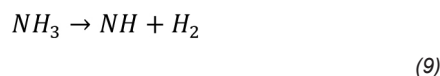
AdBlue is a liquid substance at room temperature, consisting of approximately 2/3 water and 1/3 urea (NH₂)₂CO. The urea is decomposed into ammonia and carbon dioxide according to the chemistry, assuming that water vapor is present [2]:



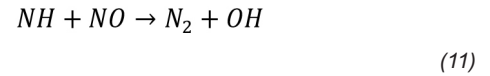
Furthermore, hydrogen abstraction results in the formation of the radical NH₂:



In turn the NH₂ will react with nitrogen oxide molecules, if such are present:



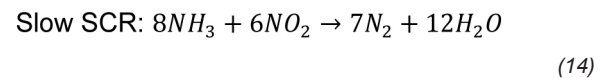
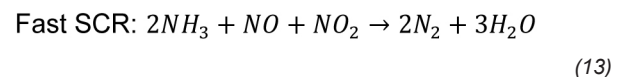
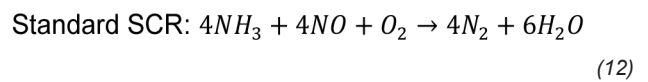
Another common reaction path in NO_x reduction consists of the radical NH, which decomposes the nitrogen oxide into nitrogen and hydro-oxygen:



As can be seen, both reactions (10) and (11) reduce the NO_x emissions. These are the NO_x reducing reactions sought when injecting AdBlue at a high temperature in the cylinder.

SELECTIVE CATALYTIC REDUCTION BASED NOX REDUCTION MECHANISMS

There are three major chemical reactions contributing to the reduction of NO_x in a commercial SCR-catalyst [16]:



The fast SCR reaction mechanism (equation (13)) is an exothermic reaction while the Slow SCR (equation (14)) is endothermic. In order for the reactions to take place, the exhaust gas temperatures needed passing the SCR is at least 470 K. In commercial applications the AdBlue is introduced through an injection before the SCR catalyst but after the DPF and oxidation catalyst, as can be seen in Figure 6. The exothermic fast reaction described by (13) may very well lead to a measurable increase in temperature after the exhaust gases leave the SCR-catalyst.

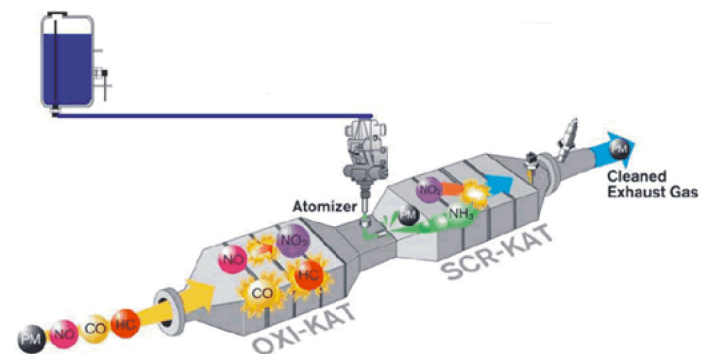


Figure 6. A schematic of an SCR setup to reduce NO_x in the exhaust pipe in a typical diesel engine setup. AdBlue (blue colored tank) is introduced by injection, after the oxidation catalyst, before reaching the SCR catalyst [16].

ADBLUE INJECTION STRATEGY

If one wants to obtain NO_x reduction already in the cylinder the gas temperature has to above a certain threshold value. There is also a upper limit to the temperature, when the urea instead