

CARE – CAlytic Reformed Exhaust Gases in Turbocharged DISI-Engines

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ABSTRACT

Today's car manufactures inevitably have to focus on the reduction of fuel consumption while maintaining high performance standards. In this respect, the downsized turbocharged DISI (Direct Injection Spark Ignition) engine represents an appealing solution.

However, downsizing is limited because of knocking phenomena occurring at high- and full-load conditions due to autoignition of the unburned mixture ahead the flame front. A common way of reducing knock tendencies is provided by Exhaust Gas Recirculation (EGR). However, EGR modifies the chemical composition of the cylinder charge and recirculated species like nitric oxide (NO) or unburned Hydrocarbons (HC) particularly increase the reactivity of the unburned mixture. In other words, the EGR influences the Octane Number (ON) of the in-cylinder gases.

This paper proposes a new EGR concept in which a catalytic converter is introduced into the EGR system in order to minimize the NO and HC concentrations and thereby to reduce the reactivity of EGR.

Pressure trace and infrared-spectral measurements are carried out on an engine test bed including a standard three-way-catalyst in the high-pressure EGR pipe of a turbocharged DISI engine. Pressure trace measurements allow thermodynamic analysis, while IR-spectral analysis identifies the concentrations of EGR species in the EGR pipe. Furthermore, a zero-dimensional reactor-network modeling the EGR

pipe and the combustion chamber is used to numerically investigate the influence of EGR species on the autoignition processes.

Both experimental and numerical results show a potential benefit introduced by catalytic reformation of exhaust gases for turbocharged DISI engines in terms of reduced fuel consumption.

INTRODUCTION

An overview on current engine development trends points at turbocharged DISI-Engines as favored solution for mid-term future powertrains [1]. In comparison to alternative combustion processes these turbocharged downsized concepts show quite good cost efficiency in conjunction with increased fuel consumption efficiency. Nevertheless, this trend leads to increased cylinder pressures and thereby to increased knock tendency at high- and full-load condition. A possible countermeasure is represented by the use of cooled external EGR. Hereby, the specific heat capacity of the mixture is enhanced, resulting in a lowered unburned gas temperature at the end of the compression stroke. Consequently, the uncontrolled autoignition of the unburned gas can be delayed [17,18].

Because of incomplete combustion and high combustion temperature, the EGR composition (Figure 1) in a DISI-Engine shows significant amounts of HC and NO.

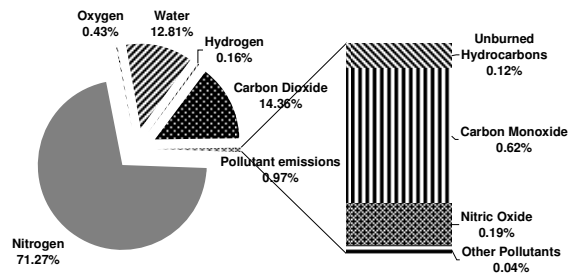
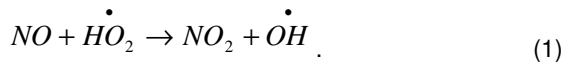


Figure 1: Measured component concentrations in EGR at a EGR rate of 10 % EGR for operating conditions at $n = 2500 \text{ min}^{-1}$, $imep = 17.5 \text{ bar}$, $\phi = 1$

Former publications already discuss the influence of increased NO concentrations in fresh gas mixtures on knock occurrence. Prabhu et al. [2] and Kawabata et al. [3] found a direct link between the NO concentration in the unburned gas mixture and knock occurrence during engine run. Stenlås et al. [4] numerically investigated the reaction paths leading to increased knock occurrence driven by NO. Depending on the temperature range, the initiating reaction leading to earlier autoignition is:



Knock occurrence is therefore directly linked to the NO concentration and the compression temperature. The sensitivity towards NO increases with increasing initial compression temperature [4]. Furthermore, the effect of HC on autoignition is extensively documented [15,25].

Based on this knowledge, the driving idea of this paper is to modify the EGR composition, using a catalytic converter in the EGR system. In this way, uncontrolled autoignition phenomena at high- and full-load conditions on a standard DISI-Engine can be delayed.

Similar investigations are focusing on the acceleration of combustion processes by generating hydrogen (H_2) and carbon monoxide (CO) enriched and simultaneously diluted gas mixture [5-8]. To date, no investigation using an on-engine EGR reformation with focus on the influence of HC and NO concentrations is known to the authors.

EXPERIMENTAL SETUP

Experiments are carried out on a 2.0 l turbo engine with a centrally mounted piezo injector and a waste gate exhaust turbo charger. The engine is equipped with an

external EGR route. The EGR route consists of a standard upstream three-way-catalyst based on a Palladium/Rhodium-Ratio of 9:1, an EGR cooler and an EGR valve just before the EGR inlet between the throttle and the intake manifold. The EGR route is built up on modular parts, allowing a quick exchange of the EGR catalyst with a standard EGR pipe.

Figure 2 shows the engine setup as well as the position of the temperature and pressure measurement points on the intake and exhaust side. Exhaust emissions are sampled just behind the turbine exit and analyzed using an SESAM System [9] and an AVL SmokeMeter [10]. Additionally, temperature and pressure measurement points are set in front of and behind the catalytic converter and the EGR cooler (Figure 2). The EGR is sampled in front and behind of the catalyst where the EGR component concentrations are measured. In this way, the EGR catalyst conversion rate can be controlled. Moreover, these measured concentrations are used as initial concentrations for later described numerical simulations.

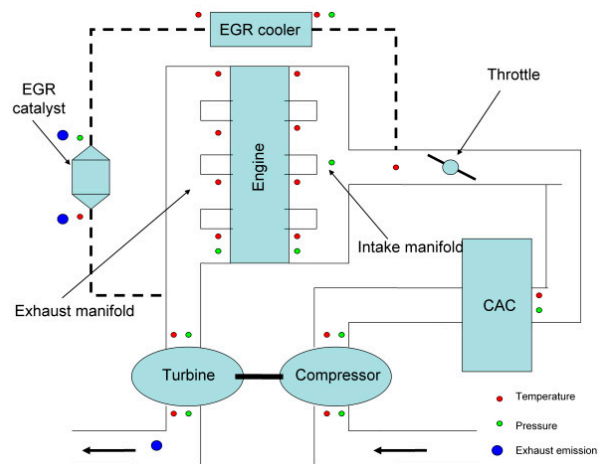


Figure 2: Engine setup and test bench measurement points (CAC: Charge Air Cooler)

For detailed combustion analysis, all cylinders are equipped with uncooled pressure transducers (Type AVL GU23D [10]). In addition, cylinder one is equipped with a pressure transducer just before the intake port and a cooled pressure transducer just behind the exhaust port (both Type KISTLER 4075 A5/10, cooling Type KISTLER 7531 [11]). The recorded pressure lines are analyzed using the software TIGER [12]. During the experiments, the engine runs with a CEC-Reference-Fuel Ref- O_2 -03 (RON 100) [13].

EXPERIMENTAL RESULTS

MEASUREMENT ROUTINE - For investigating the effect of the recirculated modified exhaust gas on high-load combustion, the amount of EGR is varied at constant load with constant fuel/air ratio (ϕ) as well as constant

exhaust gas temperature at 80 % of maximum brake torque (MBT) and two different engine speeds (Table 1).

Table 1: Investigated engine operating points

	IMEP [bar]	Eng. Speed [rpm]	ϕ [-]	T_{exhaust} [K]
1	17.5	2500	1	$\neq$ const.
2	19	3000	$\neq$ const.	1173

The ignition time is chosen using a standard knock criterion [14] calculated from the cylinder pressure. For both operating points, the engine runs without the EGR catalyst firstly. Successively, the same measurements are carried out with the EGR catalyst. Performing the tests on the same day excludes the influence of changing ambient conditions like ambient air density, humidity and pressure. In order to reduce the influence of cyclic fluctuations, the pressure signal is recorded for 200 consecutive cycles. Results of the test bench measurement systems are averaged over 45 seconds.

Following, the test bench results of the first operating point are presented. Since the investigation of the second operation point shows similar results, the detailed description will be neglected here.

RATES OF CONVERSION OF THE EGR CATALYST – In order to aim optimal conversion of the catalytic converter, a stoichiometric fuel-/air ratio is needed. Additionally, a specific exhaust gas temperature range is necessary during conversion. Here, the exhaust gas temperature is set between 1073 and 1173 K, depending on the EGR rate and operating point.

Figure 3 shows the measured conversion rates of the EGR catalyst for unburned HC's, CO and NO. Here, HC represents a sum of eleven different HC measured [9]. NO and HC are almost completely reduced by the EGR catalyst. At low EGR rates, the reduction of CO is rather poor, but with increasing EGR rates the rate of CO conversion downstream of the catalyst increases.

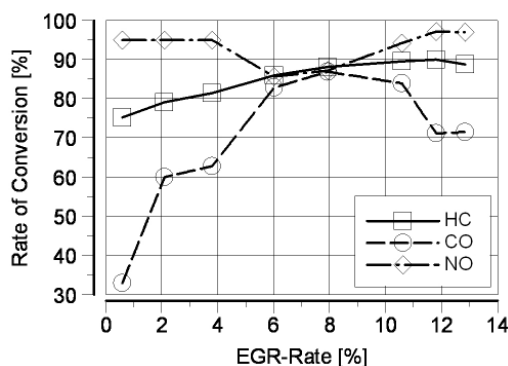


Figure 3: Conversion rates of the EGR catalyst for an EGR variation. $n = 2500 \text{ min}^{-1}$, $\text{imep} = 17.5 \text{ bar}$, $\phi = 1$

It needs to be pointed out, that the carbon dioxide (CO_2) concentration increases due to catalysis. This is important to keep in mind, since the external EGR rate is calculated through the measured CO_2 concentration in the intake manifold. The catalytic process introduces an error in calculating the external EGR rate, which is calculated to be less than 2 %.

EGR VARIATION AT 2500 MIN^{-1} / 80 % LOAD AND CONSTANT FUEL-/AIR RATIO - Figure 4 shows the measured indicated specific fuel consumption (a), the ignition time (b) as well as the crank angle ($^\circ\text{CA}$) time of 50 % mass fuel burned (MFB 50 %, c) during an EGR variation with and without the EGR catalyst. Starting at 0 % EGR, the fuel consumption decreases with increasing EGR rate due to improved thermodynamic efficiency in agreement to the results found in [18]. The ignition time can be moved forward because of lower knock occurrence. Consequently, the combustion process takes place earlier. The gap between ignition time and MFB 50 % increases with increasing EGR rate. The higher EGR concentration in the combustion chamber decelerates the heat release because of lower laminar flame speed [15].

The measured fuel consumption values with EGR catalyst are 2 % lower compared to the measurements without EGR catalyst. The effect of the EGR catalyst on knock occurrence is reflected by the earlier ignition time and the resulting earlier time of MFB 50 % between 1.5 and 3 $^\circ\text{CA}$. Therewith, a thermodynamically improved heat release in comparison to engine run without EGR catalyst is observed.