Directly actuated piezo injector for advanced injection strategies towards cleaner diesel engines

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Low fuel consumption is one of the greatest merits of the Diesel engine, emission of nitrous oxides, NOx, and particulate matter, PM, are its most prominent disadvantages. For modern passenger car diesel engines, to achieve low fuel consumption targets, i.e. CO_2 emissions, and to simultaneously fulfil the ambitious EU6 emissions legislation, a combination of intelligent injection strategies and high EGR rates with appropriate boost pressures is required.
Generally, NOx emissions can efficiently be decreased via exhaust gas recirculation, EGR. An unwanted consequence of this is an increase in smoke, HC and CO emissions. This can be alleviated by a suitable application of injection strategies. Injections strategies are also employed to curb excessive emissions of unburnt hydro-carbons, HC, and carbon monoxide, CO, particularly in conditions of cold start. These strategies may also be used to facilitate fast light-off of the oxidation catalyst.
In the current work the novel directly actuated piezo injector of Continental Automotive GmbH was used to evaluate the emissions potential not only of multiple injection patterns, but also of advanced rate shaping strategies.
The application of this wealth of technology puts further cost onto the already expensive Diesel engine. Nevertheless, there is a need to explore the benefits and the limits of such technology, since the fuel consumption and CO_2 emission target of 120g/km across the European passenger car fleet can only be achieved with a sufficiently high share of Diesel vehicles, also in the most dominant market segment of small and medium sized cars.
Cost in this respect needs to be considered from an overall engine system point of view. Higher cost for measures to reduce engine out emissions may be well invested if exhaust gas aftertreatment can be avoided or at least be minimised.

Introduction

The advent of the EU5 and EU6 [1] legislation marks the revision of ideas and methods to achieve ever lower emissions targets. Where hitherto the decrease of the "regulated four" - NOx, PM, CO and HC – was of prime importance, the request to lower CO_2 emissions – i.e. fuel consumption – slowly gains equal significance. Among the most prominent means to reduce fuel consumption is the decrease of engine size, generally termed "downsizing" [2], to reduce the level of friction at part load. Part load is the dominant operating condition of passenger car engines and plays a large role in all of the currently applied homologation cycles. The other simple but effective way to reduce fuel consumption is the reduction of the overall level of engine speed. This is termed "downspeeding" and denominates the application of very long gearing in six and even seven speed transmissions.

Both, downsizing and downspeeding, require the increase of engine torque to provide the desired power for pleasurable driving. As a consequence engine boosting has to be increased massively and, to limit the resulting NOx production, simultaneously EGR rates have to be raised [3, 4, 5].

The presence of large portions of more or less inert gas in the combustion chamber converts the conventional Diesel combustion process such that prolonged ignition delays allow for a more extended mixture preparation period before ignition [6]. In contrast to the predominantly premixed "homogeneous charge compression ignition", HCCI, the combustion initiation still is controlled by injection timing. This means, that at a desired time with respect to engine top dead centre at least the minimum critical mass of fuel, necessary to create loci of ignition, is introduced. Nevertheless, both techniques share to some extent a problem, also well known from premixed gasoline engine: the presence of premixed fuel and air close to the combustion chamber walls, where wall quenching leaves a layer of unburnt mixture. If additionally the mixture is overly lean, the problem of hydrocarbons leaving the engine unused is aggravated by flame quenching in mid air. This can be overcome to some extent by stratifying the in-cylinder charge by means of smart injection strategies [7, 8, 9]. These strategies have to respect both boundary conditions, that of the location of the fuel in the combustion chamber and the available time for mixture preparation before the onset of the main ignition.

Once ignition has occurred, the feeding of more fuel to the combustion has to be done such, that excessive peak temperatures are avoided, since this helps to reduce NOx.

At the end of the combustion process, in-cylinder pressure and temperature drop, and charge motion decays. There, a post injection introduces some additional momentum for mixing and some thermal energy for further oxidation of carbonaceous species [10].

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Conclusively, it can be summarised, that injection strategies serve the following purposes:

1. appropriate pilot injections facilitate an optimal mixture preparation before ignition of the main injection
2. the injection rate allows to some extent the control of cylinder temperature during combustion
3. an appropriate post injection enhances the oxidation of carbon based pollutants to CO_2

State-of-the-art injection systems allow for the application of multiple injections per working cycle of the engine. Beside conventional injection strategies, "Boot" and "Ramp" injections are discussed in recent publications [9, 11, 12] as appropriate means to control the injection rate. The purpose of these strategies is to further reduce any of the critical parameters, pollutant emissions, fuel consumption and combustion noise. Figure 1 gives an overview of the injection strategies, currently feasible on an industrial scale.

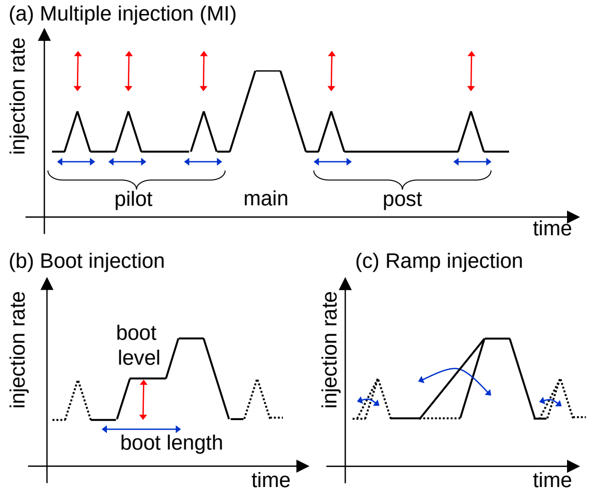

Figure 1: Overview of possible injection strategies

Obviously there are boundaries to the application of injection strategies, beyond which they do not work anymore.

Premixing before ignition is limited on the one hand by the local extension of the cloud of gaseous fuel, propagating from each injected jet into the combustion chamber. The proper distribution of the fuel cloud requires a suitable combination of injection pressure, charge movement and charge density, as well as a suitable shape of the spray plume. On the other hand injection timing is crucial, since the formation and propagation of the air fuel mixture is a function of time.

These temporal and spatial restrictions for mixture preparation and ignition are dictated by the operating condition of the engine. The time available for propagation and mixing of fuel shrinks linearly with increasing engine speed, and the ignition delay is determined by the pressure and temperature rise during the compression phase of the engine. Also, at higher engine speeds the heat loss to the walls will be smaller, i.e. the gas temperature for a given crank angle position will be higher, which shortens the ignition delay. Additionally, when the engine is boosted at higher loads, there will be a higher gas mass present in the cylinder. This increases compression pressure and, hence, the gas temperature. Therefore, there will be a limit in terms of engine speed and load up to which pre-main injection strategies can sensibly be applied. Figure 2 provides an overview of the boundary conditions for mixture formation and combustion at three engine operating points. Clearly visible is the drastic shortening of the ignition delay with increasing in-cylinder pressure and temperature.

N / rpm	1500	1500	2280
IMEP / bar	4.2	6.5	10.5
p_{Rail} / bar	750	900	1650
p_{Boost} / bar	1.06	1.16	1.7
Density_gas / kg/m³	12.7	13.5	20
mF_pilot / ms	1.0 (0.5+0.5)	1.0	1.0
Ignition delay / ms / °crk	**1.4 13**	**0.66 6**	**0.23 3.2**
T_{Gas_Max} / K	**1760**	**1890**	**1990**

Figure 2: Thermo-physical boundary conditions for mixture formation and chemical reaction at three engine operating points.

An additional limitation for the use of any injection strategy is engine power output. When high power output is demanded, then thermodynamics require the necessary amount of fuel to be injected within a sensible time window, unless a loss in engine efficiency, i.e. the deterioration in fuel consumption is accepted. Additionally the resulting extreme exhaust temperatures pose severe problems for engine and turbo charger.

The current paper will elucidate basic mechanisms of injection strategies, including multiple injection, MI, and rate shaping. For this the directly actuated Continental NG injector was applied in a single cylinder research engine, based on a 2 liter 4 cylinder and 4 valve engine. The influence of engine operating conditions on the use of injection strategies will be discussed.

Multiple injection

Pilot injections have different purposes depending on the operating point. At low load they serve for the reduction of HC and CO emissions (see Figure 3). At low engine speed, small pilot injections have time to mix well in the combustion chamber. Because the general temperature level is low at low load, the pre-ignition chemistry is slow. Therefore a relatively large amount of fuel can be introduced into the combustion chamber. In order to prevent early ignition of the pre-main injected fuel, it has to be introduced in several portions at sufficiently long time intervals. Otherwise the critical fuel concentration for ignition will be exceeded. If on the other hand the injection sequence starts too early before ignition, wall and mid-air quenching will be the result, which increases the HC and CO emissions massively.

Figure 3 depicts the effect of the number of pilot injections on HC and CO emissions. The curves show an EGR rate variation, with EGR rate increases from right to left in the diagram. PM emissions were on a very low level for all shown settings and far below EU6 engineering target.

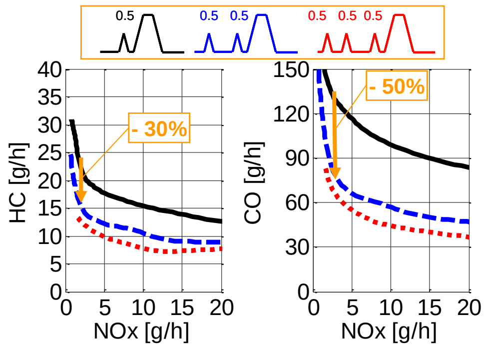

Figure 3: Minimising HC and CO emissions by means of multiple injections at n = 1500 rpm, IMEP = 4.2 bar

At higher part load PM and NOx emissions are of main concern. There, the local temperature is high enough for good oxidation of HC, but also is favourable for NOx generation. The equivalence ratio is locally rich, promoting soot production. Shown in Figure 4 is an EGR trade off. PM emission and combustion noise are plotted over NOx emission. It is clearly demonstrated, that the increase of the pilot fuel mass leads to a significant PM increase, but also to a reduction in combustion noise. Therefore, the trade off at this operating point is between PM and combustion noise. Both are a strong function of the gas temperature in the combustion chamber before the onset of the main combustion, T_{bm} [9]. In [9] it was also found - by means of 3D combustion simulation - that very small dwells between pilot and main injection would reduce PM emission further.

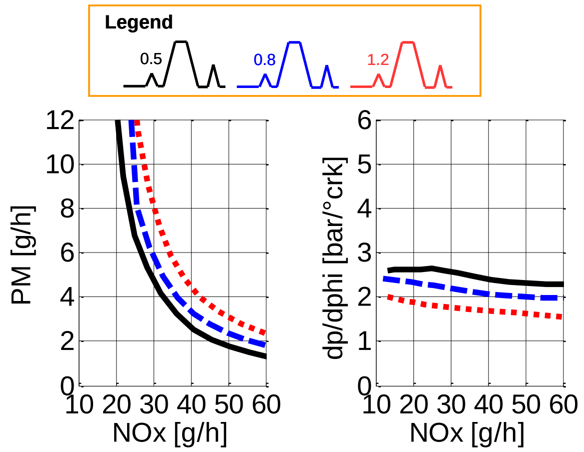

Figure 4: Effect of pilot injection fuel mass on pollutant emissions and combustion noise at n = 2280rpm, IMEP = 10.5 bar

Boot injection

The application of the so-called zero-dwell between pilot and main injection suggested, that an even closer coupling of the pre-main fuel mass to the main injection may offer further PM reductions. Figure 5 shows the application of boot injection strategies with different boot lengths and levels (see Figure 1). The pre-main fuel mass was app. the same for all shown injection patterns.

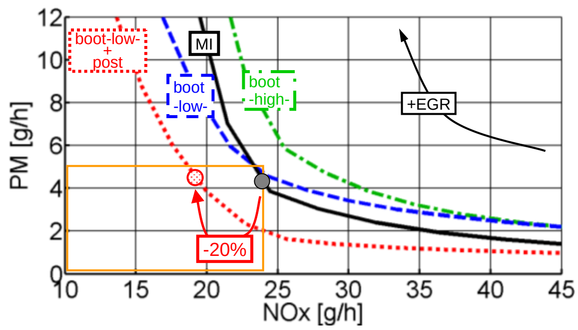

Figure 5: Effect of different boot settings on PM emission. Reference is a Multiple injection pattern. The orange box defines the EU6 engineering targets

Both boot patterns without post injection achieve about the same emissions level as the optimised MI pattern. However, the MI pattern also included a post injection. If a post injection is combined with the better boot strategy, the PM-NOx-trade off improves beyond that achievable with MI.

Ramp injection

A further option to modify the injection rate is the application of a ramp injection. This is the continuous increase of the initial injection ramp, rather then the stepped shape used in the boot injection. Shown in Figure 6 is the comparison of a slow injection rate increase (blue with circles) versus a fast one (black with triangles).

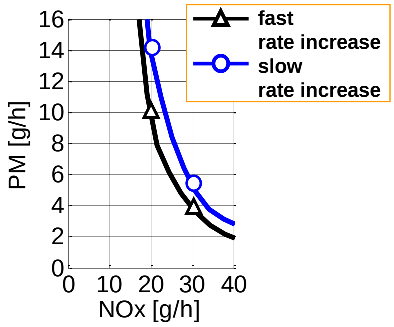

Figure 6: Effect of initial injection rate gradient ("opening ramp") on the PM-NOx-trade off at n = 2280rpm, IMEP = 10.5 bar

At higher part load the "fast ramp" offers an advantage in the PM-NOx-trade off. However, this effect is also dependant on the operating point and further work is required to fully exploit its benefits.

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