

Investigation of a New Injection Strategy for Simultaneous Soot and NO_x Reduction in a Diesel Engine with Direct Injection

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ABSTRACT

An important source for soot formation during the combustion of diesel engines with direct injection is the interaction of liquid fuel or a very rich air/fuel-mixture with the flame. This effect appears especially in modern direct injection engines where the injection is often split in a pre- and a main injection due to noise reasons. After the ignition of the pre-injected fuel a part of the main injection can interact with the flame still in liquid phase as the fuel is injected straight towards the already burning cylinder areas. This leads to high amounts of soot.

The injection strategy for this experimental study overcomes this problem by separating the injections spatially and therefore on the one hand reduces the soot formation during the early stages of the combustion and on the other hand increases the soot oxidation later during the combustion. In particular an injection configuration is used which gives the degree of freedom to modify the injection in the described manner. Therefore the cylinder head of a heavy duty single cylinder research engine is equipped with a second common-rail injector. This second injector is used for the pilot injection which is injected centrally in the combustion chamber while the main injection is done in a conventional manner using a seven-hole injector.

In the first step the mixture formation of the spatial separated pre- and main injection is simulated with the 3D-CFD code KIVA-3V to get a first impression on the mixture formation. Then the effects of the new injection strategy on the combustion process itself are investigated with the single cylinder engine in comparison to a conventional engine operation using cylinder pressure indication and exhaust gas analysis as well as the Two-Color-Method for observing the soot production and soot oxidation in the combustion chamber during the combustion process. This allows an assessment of the operating behaviour of the engine in comparison to the operation with a conventional injection pattern and the achievable emission reduction potential.

INTRODUCTION

Up to now Diesel engines with direct fuel injection are the propulsion systems with the highest efficiency for mobile applications. They can help significantly to meet future targets in CO₂ emissions with regard to global warming effects. A major disadvantage of Diesel engines are the high soot emissions which cannot be reduced completely with only engine measures today. Therefore highly complex exhaust gas after-treatment systems are required to meet future emissions regulations. Even with exhaust gas after-treatment it is of particular importance to reduce the engine-out soot emissions in order to increase filter regeneration intervals. In modern Diesel engines with direct fuel injection, the injection process itself is often split in a pilot injection, a main injection and possibly a post injection. Usually these part injections are done with the same injection hardware and injector and therefore the fuel is injected in the same cylinder areas. Hence, a strong interaction between the separate part injections depending on the combustion conditions is evident. With a small amount of fuel injected before the main injection significant reductions of combustion noise can be achieved compared to an engine operation without pilot injection. The pre-injected fuel starts to burn before the combustion of the fuel injected during the main injection and increases the temperature in the combustion chamber. This increased temperature reduces the ignition delay for the main fuel and the ratio of premixed to diffusion-controlled combustion is decreased. Consequently the maximum pressure gradient and peak temperature during the combustion decreases which lowers both the engine noise and the formation of nitrogen oxides. Unfortunately the larger fraction of diffusion-controlled combustion leads to higher soot emissions. This becomes even more apparent with an increasing amount of pre-injected fuel where the soot emissions rise disproportionately. But not only the larger part of diffusion-controlled combustion but also several other parameters are responsible for the higher soot emissions. The local air/fuel ratio λ for the main injected fuel is reduced due to the already burned pilot fuel, which both increases the soot formation and decreases the soot oxidation during the combustion.

Additionally a direct contact of injected and liquid fuel with the potentially still burning pilot fuel can take place and lead to an intense soot formation.

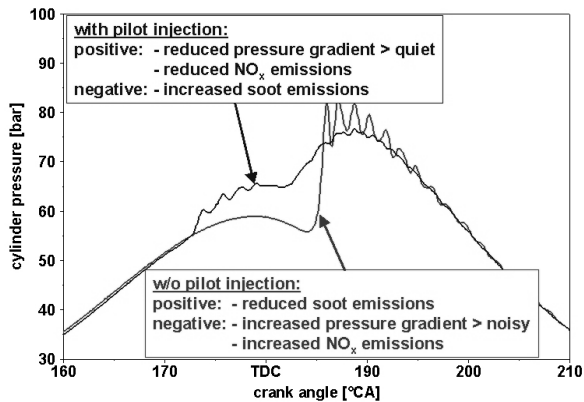


Figure 1: Cylinder pressure with and w/o pilot injection

Figure 1 shows an example of the cylinder pressure with and without pilot injection. The advantage of the pilot injection strategy in reducing the maximum pressure due to a smaller part of premixed combustion gradient during the combustion can be seen clearly. Nevertheless, a major disadvantage is the significantly increased soot emission [1, 2].

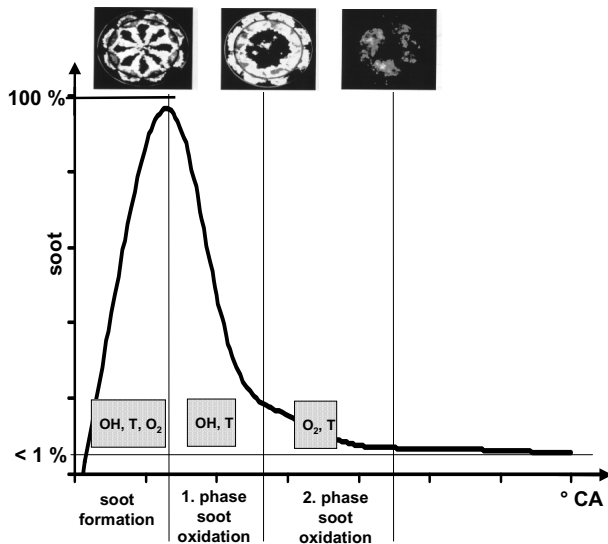


Figure 2: Qualitative characteristic process of the soot formation and oxidation [3]

In Figure 2 the characteristic progression of the soot concentration in the cylinder during the combustion process is shown. The whole process is divided into a first soot formation phase, where the in-cylinder soot concentration is rising, and afterwards two soot oxidation phases with decreasing in-cylinder soot concentration. Additionally, the corresponding main influencing parameters for the different phases are listed. It can be seen that for both the soot formation part and the second

oxidation phase the oxygen concentration is a main parameter to influence the final engine out soot emission. The small pictures on the top of the diagram show the soot radiation during combustion. It can be seen that the soot at the end of combustion is located near the cylinder wall. So in the centre of the combustion chamber there is an excess of oxygen which cannot be used in the soot oxidation phase. The effect of the local air/fuel ratio λ and the temperature on the amount of emitted soot is shown in Figure 3 [4]. Only a small increase in the local air/fuel ratio λ results in a significant decrease of the soot formation. Hansen et al. [5] also showed in extensive investigations that the soot formation could be suppressed completely when local air/fuel ratio λ can always be kept above $\lambda = 0.6$ to 0.7 during the combustion.

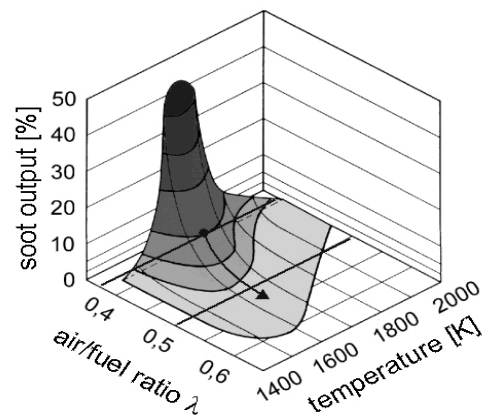


Figure 3: Temperature and air/fuel ratio λ conditions for soot formation [4]

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

THE NEW INJECTION STRATEGY (NIS)

The new injection strategy (NIS) separates the pilot and main injection not only temporally like in the conventional case but also spatially. So it is possible to avoid the negative interaction between pilot and main injection, in terms of liquid fuel and flame contact, and, even more, increase the local air fuel/ratio λ for the main injection and therefore reduce the soot emissions as already mentioned above.

The pilot fuel injection is directed towards the central area of the combustion chamber and so the excess of oxygen in the middle of the cylinder can be better used for the soot oxidation. Later, the main fuel is injected using a conventional spray pattern with an opening angle of 158°. With this spatial separation, the fuel, injected during the pilot injection phase, burns in a different cylinder area than the main fuel and hence does not reduce the local air/fuel ratio λ for the main combustion as it would be the case with a conventional pilot and

main injection strategy using the same injector and nozzle holes.

Figure 4 shows a schematic of the realisation of the spatial separation with two pilot injection sprays and seven main injection sprays. Because there is no mass production injector available which allows the spatial separation of pre and main injection in one unit, a second injector with two holes is adapted in the cylinder head.

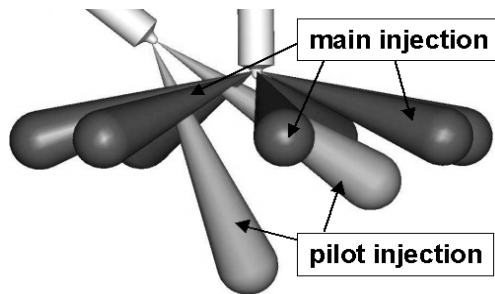


Figure 4: New injection strategy (NIS)

EXPERIMENTAL SETUP

For the investigations a single-cylinder heavy-duty research Diesel engine from Daimler is used which was significantly modified according the experimental requirements. This engine with its four valve low-swirl cylinder head represents the current engine technology but still offers enough space to integrate the additional equipment necessary to realise the proposed injection strategy (Figure 5).

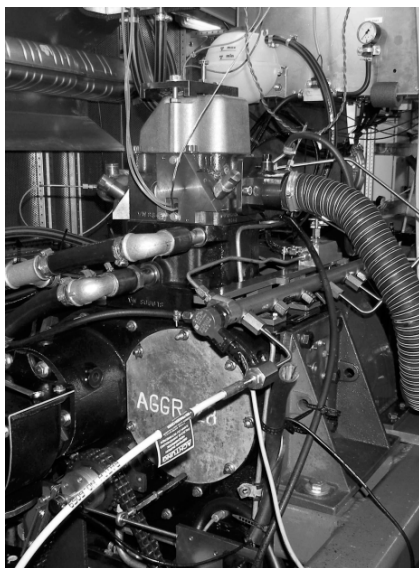


Figure 5: Single cylinder test engine

The test bench was equipped with an eddy-current brake and an electric dynamometer to either brake or motor the engine at a constant speed. Further an external electrically driven supercharger was installed together with a water-cooled intercooler to boost the engine independently from the operating point. The engine coolant and oil was conditioned to keep the engine temperature constant at a pre-set value. In Table 1 the main engine specifications and operating conditions for the investigations showed in this paper are listed.

Displacement	1827 cm ³
Stroke	142 mm
Bore	128 mm
Compression ratio	17.7:1
EGR	external
Boost pressure	1.1 bar
Engine speed	1175 rpm
Injection pressure	1600 bar
Max. injection pressure	1750 bar
Coolant / oil temperature	80° C

Table 1: Engine specifications and operation conditions

To achieve the necessary degree of freedom concerning the injection parameters the original unit pump injection system was replaced by a common rail system which enables a free adjustment of the injection pressure (max. 1750 bar) and the injection timing. The high pressure fuel pump of the engine was also electrically driven to be able to choose the rail pressure independently from the engine operation. The second injector for the pilot injection was connected to the same high pressure fuel rail as the main injector so the injection pressure was constant for both part injections but the timing was freely adjustable.

Cylinder head modifications

The cylinder head of the test engine was a conventional four valve head with a centrally located injector. This injector position was maintained for the main injection, but the production injector was replaced by a commercially available common rail injector with a heavy-duty nozzle. For the pilot injection a second injector was additionally integrated in the cylinder head. This injector was a production light-duty injector with a specially manufactured two-hole nozzle. This smaller injector is sufficient for the pilot injection due to the significantly smaller amount of fuel for the pilot injection than for the main injection.

Figure 6 shows the CAD-model of the cylinder head in two different views with the two mentioned injectors, the schematic fuel sprays and two additional optical accesses to the combustion chamber. The pilot injector can be rotated so that it is possible to investigate the effect of pilot injection into different cylinder areas. For these investigation a very central and steep injection of