Reduction of Diesel Engine Emissions Performance – Further Steps Towards a Fast and Flexible Fuel Injection

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H. Tschöke, R. Marohn (Hrsg.), *10. Tagung Diesel- und Benzindirekteinspritzung 2016*, Proceedings, DOI 10.1007/978-3-658-15327-4_2

Abstract

Diesel engines remain the main powertrain concept in view of efficiency and robustness. On the one hand the emissions towards the future EU CO_2 limit of 95 g/km by 2021 further demands the reduction of the fuel consumption. On the other hand the new WLTP test cycle and RDE emissions tests demand to reduce the engine-out raw emissions. So far, the main development path of the fuel injection system is focusing on increasing the rail pressure. The increase of the no. of injection events is another approach that aims for phasing the combustion in the working process of the Diesel engine efficiently. This approach is limited by the needle opening speed and capability of closed-coupled injection events. Such features were so far restricted to Piezo injectors. Recently the solenoid injector was enhanced to close this gap and it was firstly tested on an hydraulic test bench and a 4 cyl. passenger car Diesel engine. The hydraulic and engine performance is compared against the solenoid injector G4S and the Piezo injector G4P. With increasing the injection rate steepness and reducing the hydraulic intervals, a triple pilot injection strategy is applied to control the ignition delay and rate of combustion. The steep injection rate reduces the soot emissions without compromising the combustion noise. On the other hand the short interval and fast needle actuation reduces the injection and combustion duration. Thanks to this improved hydraulic performance the BSFC could be improved by 1.7% and soot emissions reduced by 36% at engine part load conditions (2000 rpm, BMEP=6 bar).

1 Introduction

The scenario of future mobility is driven by the emissions legislation and challenges the automotive industry to reduce the CO_2 and NO_x emissions in view of new upcoming cycles as WLTP and RDE being introduced for new registered passenger car vehicles from the year 2017 on. The shift to higher engine load and higher vehicle accelerations increases firstly the NO_x and fuel consumption BSFC and hence CO_2 emissions. The efforts on the after-treatment side have the objective to increase the NO_x conversion efficiency but are restricted by the exhaust gas temperature. To achieve the challenging fleet CO_2 emissions target of 95 g/km in the year 2021, the Diesel engine will remain thanks to its superior efficiency. On the other hand this demanding target must be achieved by various technologies including the further efficiency improvement of the Diesel engine combustion process. In the past, the increase of rail pressure was the objective to achieve an improved spray mixture formation to reduce the soot emissions at high EGR rates or increase the specific power for engine downsizing. Introducing recently a rail pressure of 250 MPa for the passenger car application [1] and first demonstration with 300 MPa for HD Diesel engines [2,3] , the next improvement steps for the fuel injection system side is related to the flexibility of the injector to phase the combustion timing efficiently into the engine process without the restriction of the combustion noise. This flexibility is achieved firstly by the increase of the injection rate steepness and then second by the reduction of the minimum hydraulic interval. In the past such improvement steps were firstly introduced for Piezo servo valve injectors [4-6]. Now the performance of the solenoid injector G4S [7, 8] was improved for achieving a similar hydraulic performance. The performance of the improved injector named G4.5S is investigated on the hydraulic test bench and assessed from combustion point of view on a 4 cylinder, 2.2 l Diesel engine.

2 Improvements of Solenoid Injector Technology

The combustion process of Diesel engine depends directly on the performance of the fuel injection system. The speed of combustion is related to the speed of mixing and hence the related FIE performance in terms of rail pressure usage and injection rate steepness. The increase of combustion speed will increase first of all the combustion noise. This increase of combustion noise is balanced through the flexibility of the injection system by increasing the no. of injection events and achieving short, hydraulic intervals. Already such concept were developed and tested by using Piezo servo valve technology [4,6] and firstly studied by trial samples for solenoid injectors [9,10]. Now this technology is furthermore improved through the on-going development of new solenoid actuators.

The G4S injector function during start-of-injection and end-of-injection is displayed in Fig. 1.

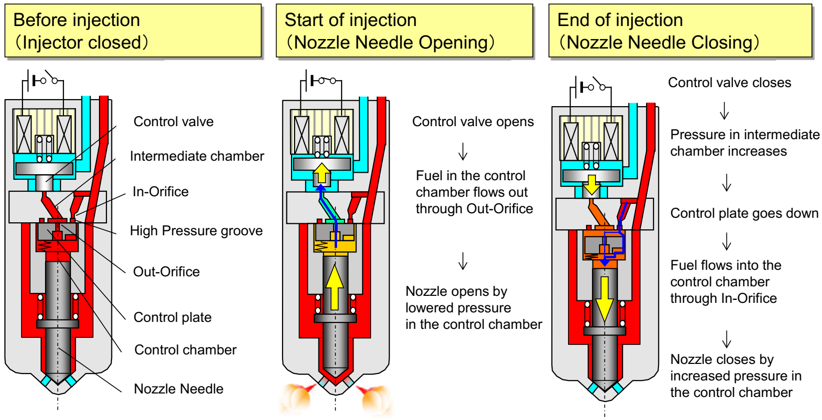

Fig. 1 Actuation principle of the solenoid servo valve of the G4S injector

The needle movement is indirectly controlled by the solenoid actuator indirectly. At the start of the actuation, the control plate remains at its position. The pressure in the control chamber is released through the opening of the control valve. By releasing the pressure in the control chamber, the force balance across the needle is changed. At closing, the control valve closes and the pressure is build up. During the first two phases, the control plate separates the high and the low pressure area. Only at closing, the control plate starts moving and supports to fill-up the fluid in the pressure chamber quickly. It has the function as a three way valve. The pressure decrease is defined by the flow rate characteristics of the out-orifice which is part of the control plate. It is therefore the flow characteristics of the out-orifice to define the needle opening speed. To improve the needle opening speed, this flowrate characteristics of the out-orifice was increased while maintaining the flowrate characteristics of the inlet orifice.

To avoid downstream a throttleing effect by the intermediate chamber, the volume and orifice diameter was therefore increased. To ensure that the control valve is safely closed at max. rail pressure of 250 MPa the spring set force of the control valve was increased. Therefore the magnetic force was increased by changing the solenoid material. Fig. 2 shows the resulting performance of the improved solenoid injector denoted as G4.5S in the following. As a result of these improvement steps the injection rate steepness could be increased while the closing speed was maintained constantly.

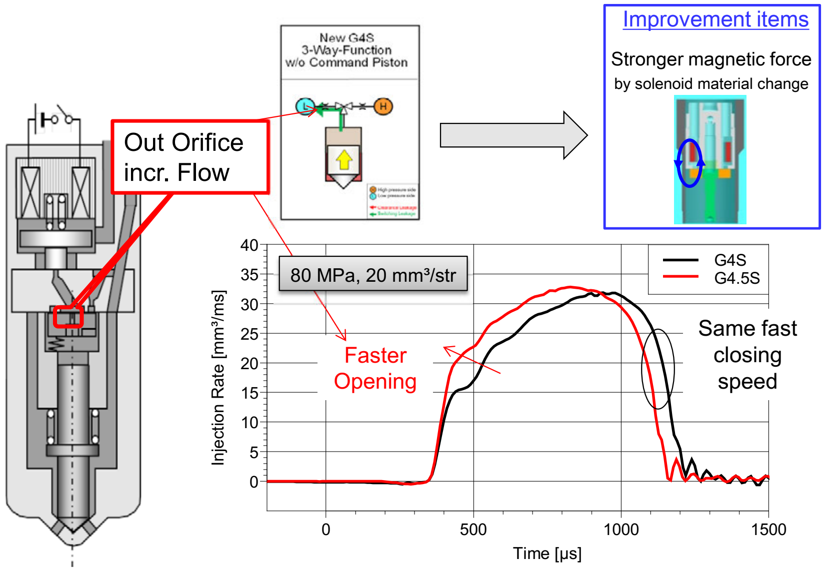

Fig. 2 Injection rate performance of the solenoid injector

In order to study the effect of the injection rate steepness, the Piezo actuator offers even higher forces to close the control valve. In this concept the fast opening speed with max. increase of injection rate steepness is presented in Fig. 3. Similar as for the solenoid injector technology, the out-orifice controls the steepness of injection rate but the closing behaviour can be independently adjusted thanks to the function of the 3-way control valve. As this concept was overtaken from the G4S injector both injector concepts have a zero static leakage and very small dynamic leakage thanks to the reduced control pressure volume and miniaturized design.

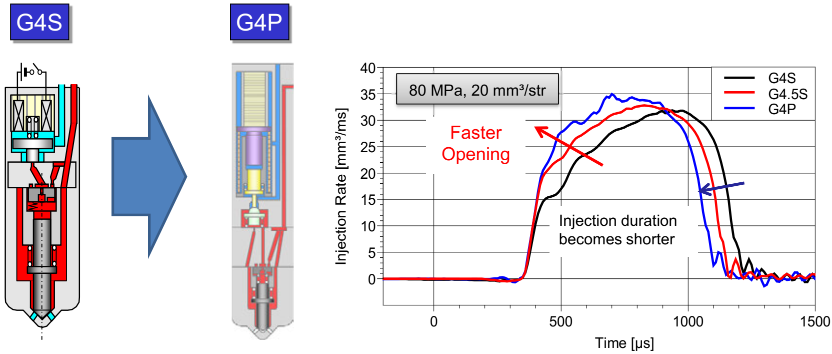

Fig. 3 Injection rate performance of the Piezo injector

In addition the increase of the out-orifice flowrate is beneficial for achieving a shorter hydraulic interval. The standard solenoid injector G4S achieves an hydraulic interval of 200 µs. This interval is a result of the time required for the movement of the control plate. After the injector actuation stops, the control valve closes and the pressure build-up in the intermediate chamber and control chamber starts. The control plate movement starts and supports the pressure build-up in the control chamber. As intermediate and control chamber are connected by the out-orifice, the control plate becomes pressure balanced. A small support spring pushes back the control plate to the original closed position and the pressure in the control chamber is restored. Now the conditions allow for actuating the injector for the next injection event. Thus the hydraulic interval mostly is defined by the time required for the lift of the control plate. This time duration is shortened if the out-orifice flowrate is increased because of the shortened time to pressure balance the control plate. In Fig. 4, the resulting hydraulic interval is presented. In this example, the G4.5S injector could achieve an hydraulic interval of 110 µs whereas the Piezo servo valve could achieve even an hydraulic interval of 60 µs. It is therefore possible to adapt the hydraulic performance through the specification of the out-orifice flowrate in the concept of the 3-way valve.

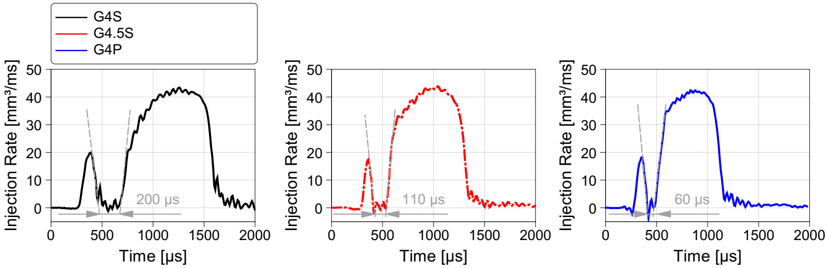

Fig. 4 Hydraulic interval performance (rail pressure of 120 MPa)

3 Improvement of Nozzle Technology

The injector actuation is on the macroscopic level controlling the timing of the fuel injection. On the other hand the soot emissions in particular are depending on the local mixing. Soot particles are formed at the locally fuel-rich conditions. Such mixing conditions can be controlled throughout the nozzle design itself. Especially the quality of fuel mixing depends strongly on the internal nozzle flow during the initial opening and closing phase of the needle. In the present study, two different nozzle concepts are compared and presented in Fig. 5. The objective of the design change is to improve the internal nozzle flow when omitting the chamfer at the tip of the needle. Therefore the internal nozzle flow is analysed by means of the CFD simulation. Here, two needle lift positions low and high are considered representative for the needle seat throtteling and non-throtteling position, respectively. In case of the nozzle Spec1, a strong vortex flow is attached to the needle chamfer when the needle starts to lift. This vortex flow changes its position and is relocated to the sac volume when the needle is lifted to the high position. The transitional flow phenomena could be avoided in case of the nozzle Spec2. Here the vortex flow remains stable in the sac hole during the needle movement from low to high position. As a result the flow re-circulation at the nozzle hole entrance could be omitted. The flow recirculation results in a local pressure drop and cavitation occurs if the pressure drop is below the vapour pressure. Such instability causes also a deterioration of the flow velocity distribution across the nozzle hole cross-section.

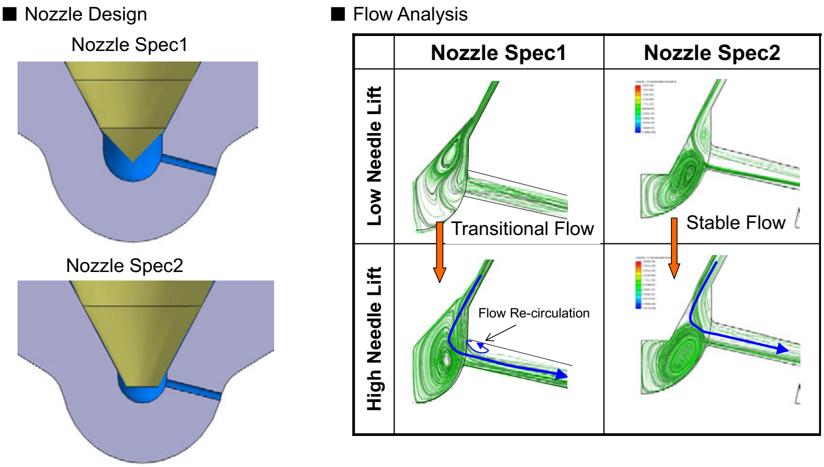

Fig. 5 Nozzle design and internal nozzle flow analysis

To verify the effect of the changes of internal nozzle flow between nozzle Spec1 and Spec2, the fuel spray was observed by shadowgraph imaging in a constant vessel filled with Argon gas at room temperature conditions and pressurized to 2 MPa as presented in Fig. 6. The comparison of the spray shadowgraph images indicates a faster spray penetration of the nozzle Spec2 and less width of the individual fuel sprays especially at the lower rail pressure conditions. Hence the internal flow of the nozzle Spec2 is more stable and generates a more uniform spray image than the nozzle Spec1. It is therefore pre-assumed that such improvement of the spray quality has a positive effect on the soot emissions.

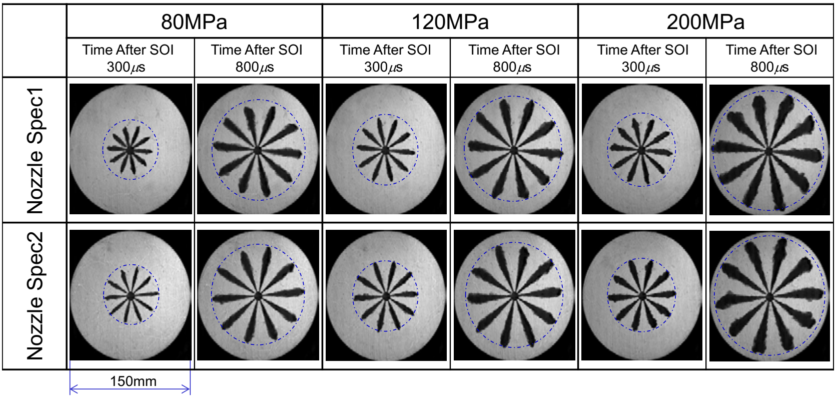

Fig. 6 Spray shadowgraphy: spray chamber with Argon gas at ambient temperature, pressure of 2 MPa

4 Engine Evaluation

4.1 Injector Evaluation

The improvements of the injector actuation and the nozzle design, are tested on a 4 cyl. passenger car engine of 2.2l engine displacement. The G4S solenoid injector with a conventional calibration of a double Pilot injection is here the reference to compare with. This double pilot injection strategy is calibrated at large hydraulic intervals through a DoE optimization. With the improved solenoid injector G4.5S it is now possible to reduce the hydraulic interval and apply a triple Pilot injection strategy including an After injection as discussed in [9-11] which is denoted as advanced injection strategy. Two different calibrations of the advanced injection strategy were investigated by changing the interval and the quantity of the Pre-injection. Fig. 7 shows the resulting engine performance at an engine speed of 2000 rpm and engine load of BMEP = 6 bar which is a typical part-load point. The centre of combustion and the rail pressure were kept constantly at 12°CA aTDC and 100 MPa, respectively. Beside the G4.5S injector also the performance of the Piezo injector G4P is presented which offers even more potentials to create a very compact phased injection of fuel.

Firstly it is evident that thanks to the steeper injection rates (cf. Fig. 4) the soot emissions could be reduced by 36% with the improved G4.5S solenoid injector. With even steeper injection rates of the Piezo injector G4P, an additional soot reduction by 25% is achieved. By applying conventional, long hydraulic intervals, the steep injection rate would result in an increase of the combustion noise. Thanks to the closed coupled injection events the premixed-amount of the combustion is not increasing and the combustion noise remains on a similar level. On the other the short hydraulic interval phases the combustion more closely to the engine TDC. The phasing of the combustion is analysed in Fig. 8 by the rate of heat release (RoHR) from the indicated cylinder pressure. The MFB10 is advanced to earlier timings as the analysis of the cumulative heat release rate shows. The RoHR indicates that the individual Pilot injection quantities are burning continuously together compared to the G4S where each Pilot injection quantity burns individually.

Overall such continuous combustion of burning Pilot and Main injection quantity results in a more efficient process that improves the BSFC up to 1.7%. Still the ultra-short hydraulic interval and steep injection rate of the G4P injector reduces the fuel consumption by 1.8%.

Injector	QPi2 [mg/str]	TINTPi2 [ms]	QPi3 [mg/str]	TINTPi3 [ms]	QPre [mg/str]	TINTPre [ms]	QAf [mg/str]	TINTAf [ms]	HRC50 [CA aTDC]	PFIN [MPa]	Injection
G4S	-	-	1	0.600	1.2	0.250	-	-	12°	100	Conventional
G4.5S	1	0.300		0.130	2	0.130	2.5	0.300			Advanced injection Strategy
G4.5S		0.150		0.150		0.150	3				
G4P		0.300		0.010		0.010	2.5				

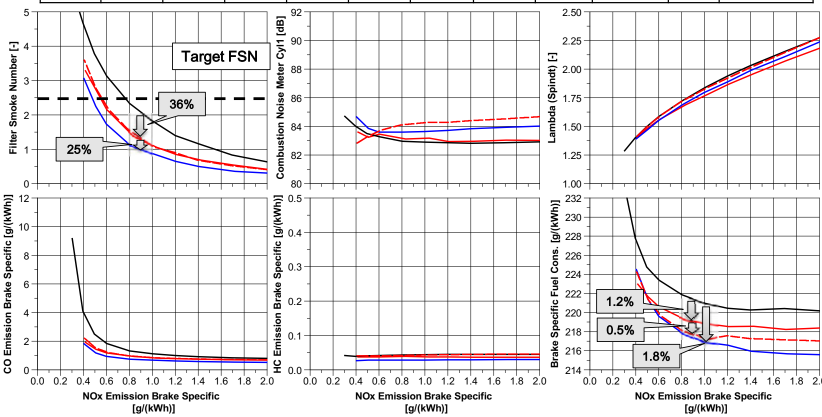

Fig. 7 Injector evaluation at engine operation ne=2000 rpm, BMEP = 6 bar

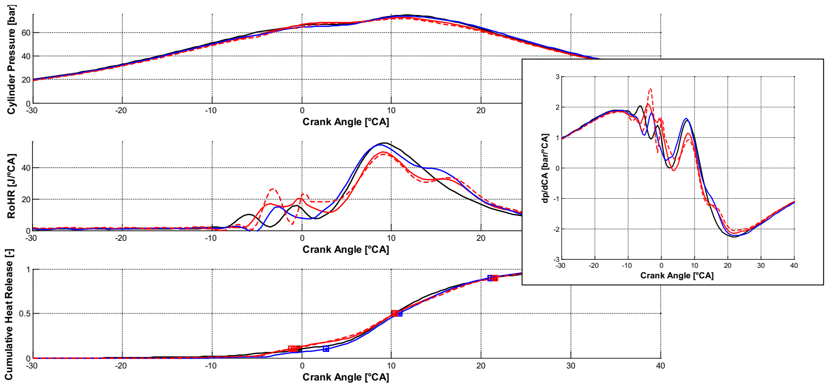

Fig. 8 Injector evaluation: analysis of the rate of heat release (RoHR) and pressure gradient at engine operation ne=2000 rpm, BMEP = 6 bar

4.2 Nozzle Evaluation

The nozzle performance was evaluated only for the G4.5S injector with a single Main injection applied while keeping the rail pressure and the centre of combustion constantly. By this approach the cross-influence of pressure waves from the multiple injection strategy is avoided. The engine performance of nozzle Spec1 and Spec2 is compared in Fig. 9. The effect of the improved fuel spray mixing of nozzle Spec2 becomes visible in the reduced soot emissions. The better mixing results in a more premixed combustion which results in the increase of combustion noise by 1 dB. Due to the improved internal nozzle flow of nozzle Spec2 the fuel consumption could be reduced by 0.8%.

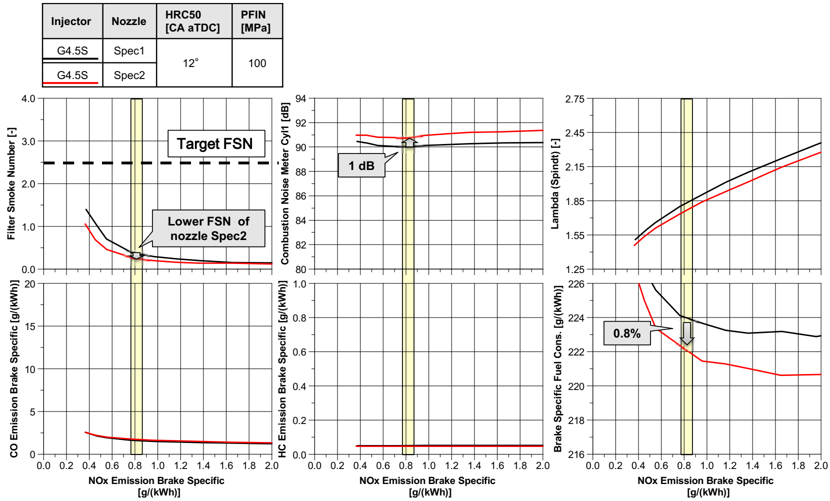

Fig. 9 Nozzle evaluation at engine operation ne=2000 rpm, BMEP = 6 bar with main injection only

In Fig. 10, the rate of heat release was analysed. Both nozzle concepts show a similar rate of heat release. The nozzle Spec2 has a slightly higher peak of the pressure gradient and of the heat release rate which explains the increase of combustion noise by 1 dB. The combustion timing and the cumulative heat release remain similar for both nozzles. It must therefore be assumed that the local mixing of the nozzle Spec2 improves the thermodynamic efficiency of the combustion process.

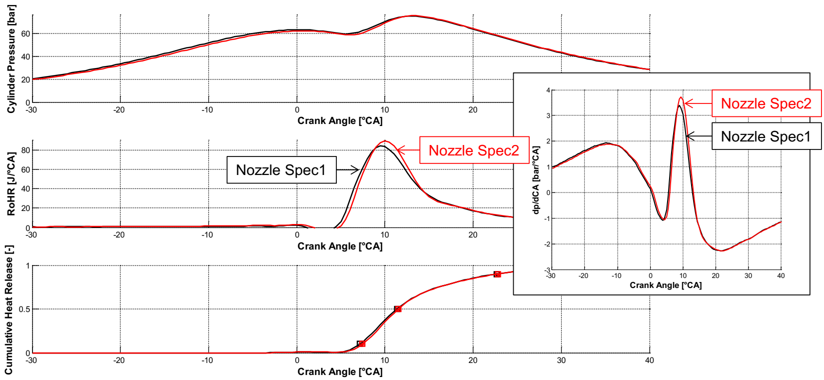

Fig. 10 Nozzle evaluation: analysis of the rate of heat release (RoHR) and pressure gradient at engine operation ne=2000 rpm, BMEP = 6 bar with main injection only

5 Summary

Future engine emissions legislation requires the improvement of the combustion process.

In the presented approach the injector actuation and the nozzle contribute to this objective. As reference, the solenoid injector G4S with a conventional double Pilot injection strategy is used here for comparison.

First, the combustion could be improved by a steeper injection rate and increasing the number of injection events. By reducing the hydraulic intervals such advanced injection strategy creates a compact combustion which is phased closely to the engine top dead centre without constraint in the combustion noise. The soot emissions could be improved by 36% for the G4.5S injector and 61% for the G4P injector. As the combustion noise is not deteriorated thanks to the avoidance of pressure peaks, the fuel consumption could be reduced simultaneously by 1.7% and 1.8%, for the G4.5S and G4P injector, respectively.

Second, the nozzle was improved with regard to the shape of the needle tip and the sac hole. The nozzle Spec2 results in a stable flow in the transition phase of the needle opening. Thanks to the improved spray mixture formation the soot emissions become reduced and the fuel consumption is improved by 0.8%.

6 Literature

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10. Tagung Diesel- und Benzindirekteinspritzung 2016
Inklusive Gaseinblasung
Tschöke, H.; Marohn, R. (Hrsg.)
2017, XV, 514 S. 345 Abb., Softcover
ISBN: 978-3-658-15326-7