EXPERIMENTAL STUDY OF POST-INJECTION FOR SOOT REDUCTION AT MEDIUM LOAD OF A LIGHT-DUTY DIRECT INJECTION DIESEL ENGINE

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Abstract: *This paper presents an experimental study on soot reduction by means of post injection. The post injection leads to higher temperature during the late combustion in the combustion chamber thus increases the oxidation rate of the soot previously formed. However, the optimization of the timing and quantity of the injection fuel is essential. The higher amount of injected fuel and retarded injection cause to lower thermal efficiency due to higher heat loses. The experiments were conducted on an automotive turbocharged diesel engine at typical operating points. The injection strategy consists of a pilot injection, main injection and a post injection. In order to assess the effect on post injection the pilot and main injection were constant. In-cylinder pressure was also recorder in order to evaluate the engine efficiency.*

Keywords: *soot, diesel engine, post injection*

INTRODUCTION

Diesel engines offer high thermal efficiency in conversation the fuel energy. Due to that they are widely used in the transport, power plants, etc. It was considered that implementing diesel engines in passenger cars would help the society to easily reduce CO_2 emission, thus to limit the greenhouse effect and global warming. However, diesel engines emit pollutant that are toxic, most important of them are NO_x and soot. Due to that, in Europe, it becomes very demanded the development and homologation to Euro 6d the passenger cars powered by diesel engine. Obviously, the diesel cars can comply to the new European emission standards implementing the very complex after treatment consists oxidation catalizator, diesel particulate filter and SCR. However, this complex after treatment increase the investments and makes the diesel cars less preferred by the customers.

Last decades many researches was performed on the possibilities to reduce NO_x and soot formation directly in the cylinder of diesel engines (Lakshminarayanan and Aghav, 2010; Zhao, 2010). One of the promising approach to reduce soot in the cylinder is multiple injection strategy (d'Ambrosio and Ferrari, 2015; Jeftić and Zheng, 2015; Wu *et al.*, 2019). The multiple injection strategy is implemented in modern diesel engines that are equipped with Common Rail injection system. The modern solenoid and piezo controlled injectors provide very short opening and closing time, thus the injection could be separate up to 8 single injections per cycle. Usually, the pilot injections (up to 3) are used to control the pressure rise and combustion noise (Punov *et al.*, 2018). The post injection strategy offers a possibility to emission reduction in particular soot reduction (Liu and Song, 2016). According to (O'Connor and Musculus, 2013) the post injection leads to soot reduction due to: enhanced mixture, increased temperature in late combustion and injection duration effect. The post injection strategy can be applied to dual fuel diesel engines operating in HCCI combustion process (Yoon and Bae, 2013; Jeftić and Zheng, 2015). (Wu *et al.*, 2019) reported that soot emission are very sensitive to post injection timing and duration.

Thus, the paper aims to study experimentally the influence of post injection parameters (injection timing and injection duration) on soot formation in a modern diesel engine operating at middle load.

EXPOSITION

Experimental set-up

The experimental study was conducted on a direct injection diesel engine with displacement of 2 l, which complies to EURO V emission standard. The engine is equipped with a Common-Rail injection system, variable geometry turbocharger, water cooled exhaust gas recirculation (EGR), oxidation catalytic converter, etc. The solenoid injectors offer a multiple injection per cycle thus pilot, main and post injection could be occurred. The engine rated power is 100 kW at 4000 min^{-1} as the rated torque is 320 Nm at 2000 min^{-1}. The boost pressure is limited to 1.3 bar. The engine main parameters are listed in Table 1.

Table 1. Engine data

Engine type	HDI
Number of cylinders	4
Displacement	2 l
Bore	85 mm
Stroke	88 mm
Compression ratio	17.6
Maximum Rail Pressure	1600 bar

An eddy-current engine dynamometer was directly coupled to the engine output shaft in order to control the engine operating point and output power measurement. It has a maximum power of 160 kW and maximum speed of 10000 rpm. In order to provide steady operating conditions, the engine brake is electronically controlled by means of a Schenck control box. The brake control system also offers the torque measurement thus a closed loop engine torque control could be carried out. Exhaust particulate matter are measured by means of a smoke meter – AVL 415. In order to study the combustion proces a piezoelectric pressure sensor was implemented in the first cylinder. The sensor was mounted on the place of glow plug thus it offers no modifications in the combustion chamber volume.

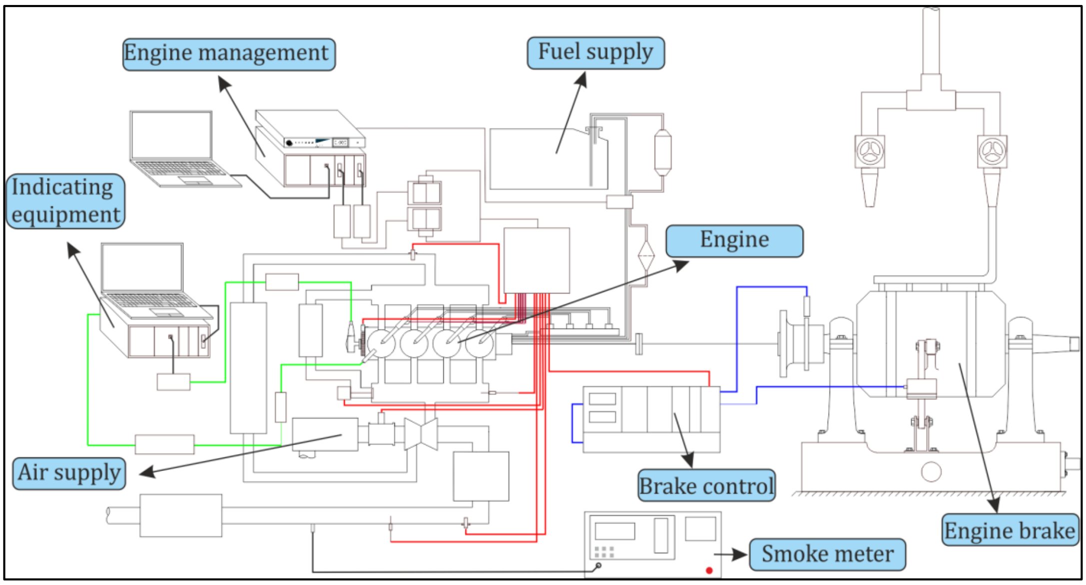

Fig. 1. Engine test bench

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Signal from the sensor is transmitted to a Kistler Type 5011 charge amplifier, then to the AVL indicating unit. The crankshaft angular position is registered by means of an optical encoder. The fuel consumption is measured by means of a volumetric flow meter Rotronics RCC101. Overall engine test bench is shown in Figure 1.

Table 2. Test equipment specification.

Eddy-current brake	Zöllner - 160 kW/10000 rpm
Brake control	Schenck
Pressure sensor	AVL GH13P
Signal amplifier	Kistler Type 5011
Angle encoder	AVL 364C - 0.1 CAD
Optical signal converter	AVL 364
Indicating system	AVL Indiscop 647
Smoke meter	AVL 415
Fuel flow measurement	Rotronics RCC 101

The engine management system is based on a National Instruments real-time controller. The hardware of the system consists of PXI chassis – NI PXI-1031, Real-Time Embedded Controller – NI PXI-8106 RT, FPGA module – NI PXI-7813R, two R Series Expansion Chassis – NI CRIO 9151 as well as the modules developed by Drivven. In our project we used four modules: DI Driver – 2 pcs., Low Side, AD Combo and O2 sensor module. All of these modules are based on NI C series interface.

The entire system provides a large functionality for real-time control and monitoring of the engine control parameters such as: injection control by up to five injections per cycle, injection pressure control, boost pressure control, exhaust gas recirculation (EGR) control, closed-loop control of injection by means of wide band oxygen sensor in exhaust gases, etc. A LabVIEW project was developed in order to determine the control logic of the management system. The real-time data were visualized by means of the software called CalView developed by Drivven. This software was also used to set the operating parameters in real-time.

Injection control strategy

Our study was conducted at steady operating point, which means constant engine speed and constant engine torque. As a result of that the engine output power was also constant. The operating point was determined as follows: engine speed – 1600 rpm and engine torque – 140 Nm. Moreover, the injection pressure and boost pressure were also constant – 800 bar and 0.3 bar, respectively. EGR valve was closed, thus the EGR rate was zero. We used the injection strategy that provide pilot, main and post injection. Here, the pilot injection was a part of injection strategy to reduce the maximum pressure rise and combustion noise. However, the pilot injection also leads to variation in pollutant formation especially NO_x and PM. Due to that, the pilot injection parameters (timing and duration) were set to be constant. The main injection timing was set to be a constant. The actual beginning of this injection was at 0° BTDC. Then, the main duration was varied in order to achieve the constant engine torque for each post injection strategy. Obviously, in order to study the influence of a post injection on soot formation their parameters were widely varied. Thus, the experimental study was conducted in two parts. Firstly, the duration of the post injection was constant as the injection timing was varied. Secondly, the post injection timing was set to a value that corresponds to the minimum soot in first study and the injection duration was varied. The injection strategy was presented in Figure 2.

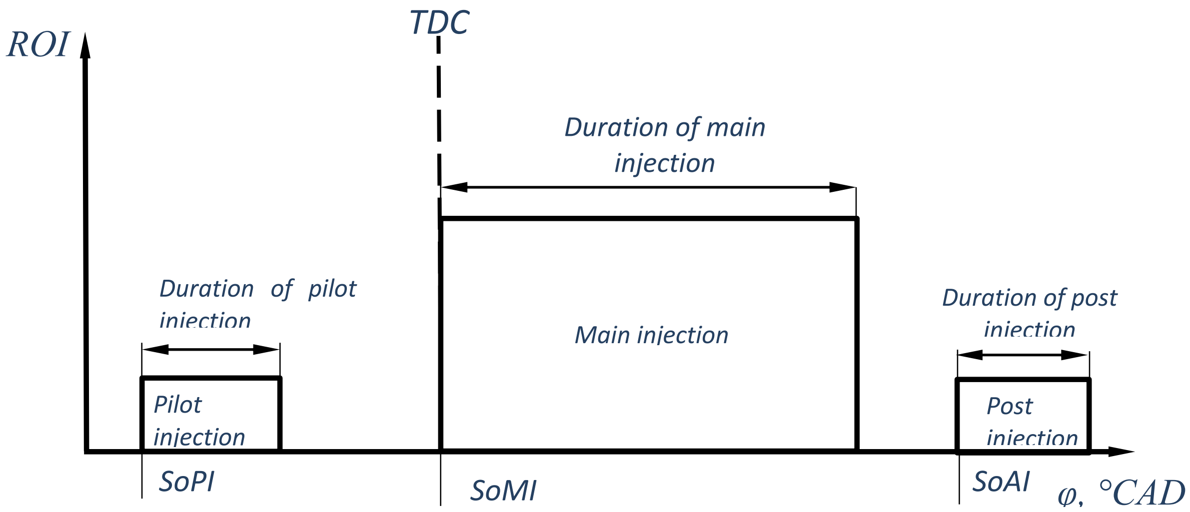

Fig. 2. Injection strategy

Experimental study

As it was explained above the experimental study was conducted in two steps. On the first step an influence of post injection timing was evaluated as the post injection duration was constant. Thus, the start of post injection was varied within the range of 10°ATDC to 25°ATDC. Then, the engine parameters were compared to that without post injection. The main injection parameters in the first study are listed in Table 3.

Table 3. Main injection parameters in first study

Start of main injection	0° BTDC
Duration of main injection	variable
Start of pilot injection	1
Duration of pilot injection	0.35 ms
Duration of post injection	0.2 ms
Start of post injection	10 to 25° ATDC

The combustion analysis is presented in Fig. 3 to 5. It consists of in-cylinder pressure, heat release rate as well as the in-cylinder temperature analysis.

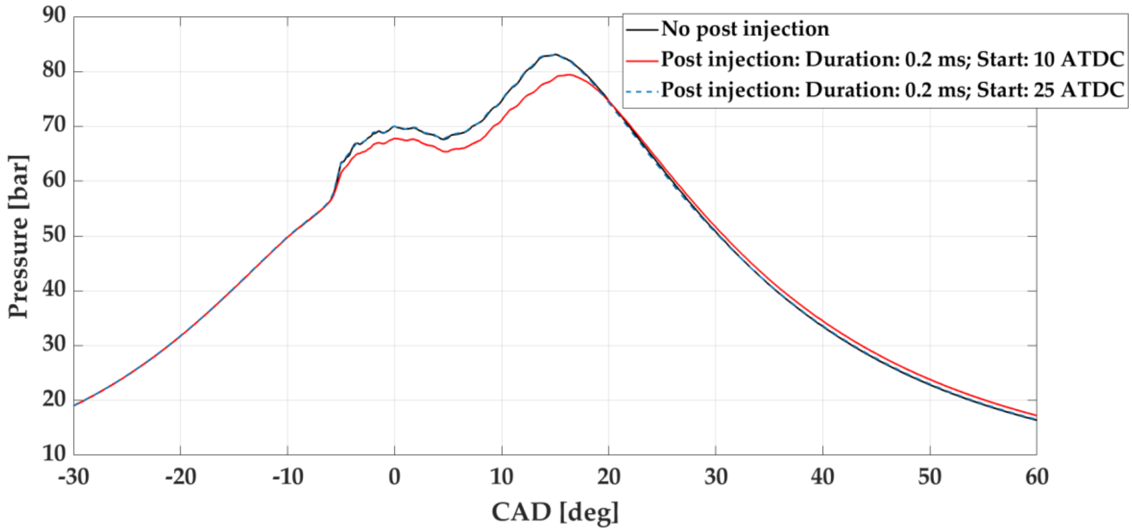

Fig. 3. In-cylinder pressure vs crank angle

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It was observed almost no influence of the post injection on cylinder pressure curve expect in case of early post injection (10° ATDC) in respect to the main injection. In this case the mixture formation is highly influenced as it leads to extended heat release (Fig. 4) and reduced main injection duration.

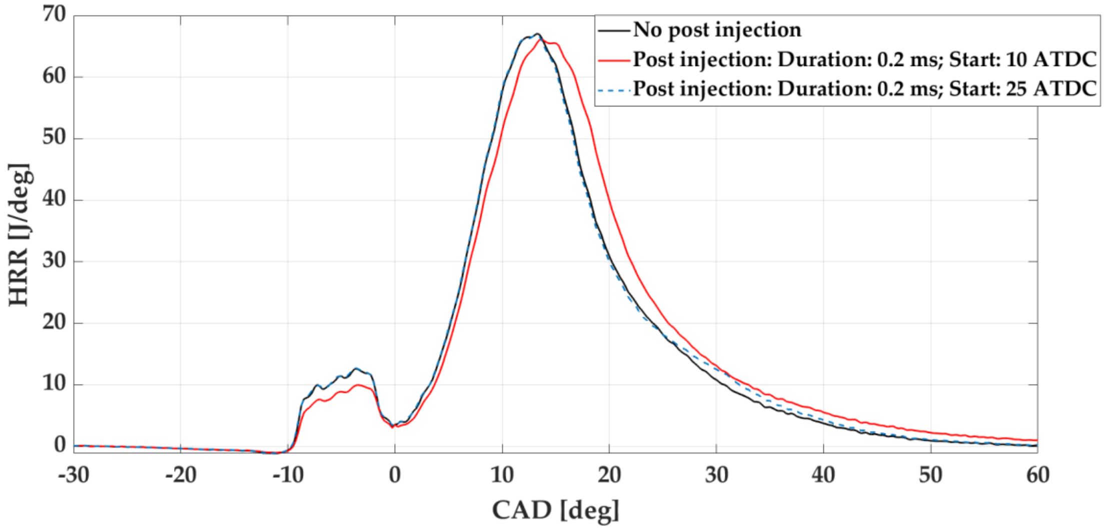

Fig. 4. HRR vs crank angle

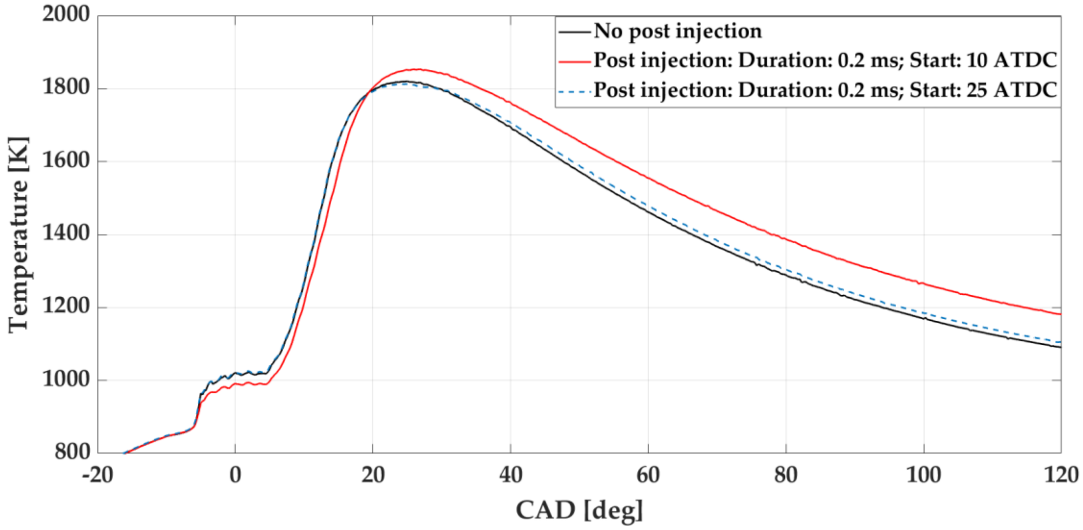

Fig. 5. Temperature vs crank angle

As a results of this poor mixture formation the maximum pressure is reduced and the maximum temperature is increased. However, the engine fuel consumption was the same as the injection strategy without post injection. Therefore, the reason for that poor mixture formation could be the injection quality due to very short period between the end of the main and the beginning of the post injection. This very early post injection leads to higher soot formation as it was observed by other researchers. In order to better understand the influence of post injection on the late combustion phase HRR and temperature curve evaluation need to be conducted. Here, only the results concerning the very late post injection (25° ATDC) are presented for better visualization. The late post injection leads to increased HRR at late combustion phase, thus, the in-cylinder temperature is higher as it allows to better soot oxidation in the cylinder.

Less soot formation was observed in case of post injection which starts at 15° ATDC. In that injection strategy the smoke accounted to 0.23 FSN or a reduction by 8% compared to strategy without post injection. Moreover, it leads to 1.1 % reduction in the fuel consumption. The results concerning the smoke and fuel consumption are summarized in Table 4.

Table 4. Soot formation and fuel consumption

Post injection start [CAD]	Post injection duration [ms]	Smoke [FSN]	Fuel consumption [kg/h]
No post injection	-	0.25	4.89
10 [ATDC]	0.2 ms	0.377	4.89
15 [ATDC]	0.2 ms	0.23	4.838
20[ATDC]	0.2 ms	0.25	4.824
25[ATDC]	0.2 ms	0.24	4.833

The second experimental study was conducted as the beginning of post injection was fixed while the post injection duration was varied within the range of 0.2 ms to 0.4 ms by a step of 0.05 ms. The start of post injection was chosen on the bases of first study: the value that offers lower soot formation - 15° ATDC. Thus, the main injection parameters are listed in Table 5.

Table 5. Main injection parameters in first study

Start of main injection	0° BTDC
Duration of main injection	variable
Start of pilot injection	1
Duration of pilot injection	0.35 ms
Duration of post injection	0.2 ms to 0.4 ms
Start of post injection	15° ATDC

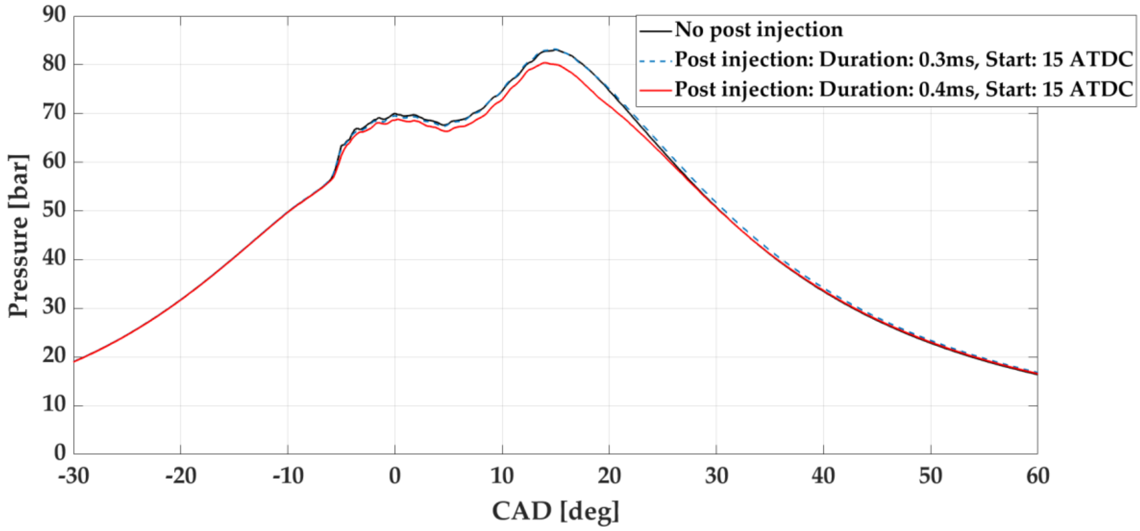

Fig. 6. In-cylinder pressure vs crank angle

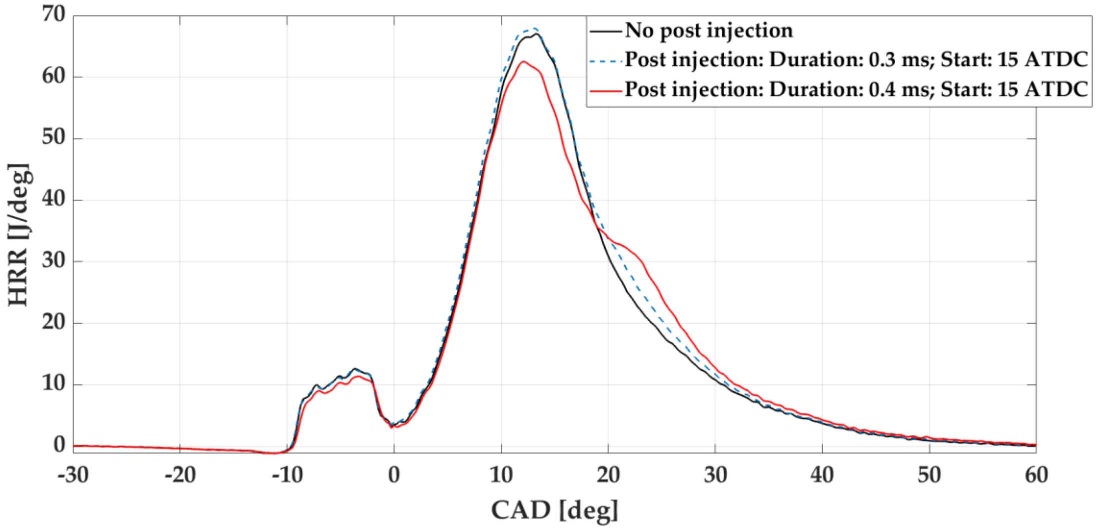

Fig. 7. HRR vs crank angle

In this study the combustion process analysis was conducted on the bases of in-cylinder pressure, heat release rate and in-cylinder temperature. The results are presented in Figure 6 to 8.

Post injected quantity mainly affects the late combustion phase but also the mixing combustion phase when quantity is higher. When post injected duration varied from 0.2 ms to 0.3 ms the in-cylinder pressure curve was without significant modification. However, the higher injection duration (0.3 ms) leads to increased HRR and temperature during late combustion (Fig. 7 and 8). Moreover, the maximum in-cylinder temperature increased. When post duration is higher than 0.3 ms it affects both late combustion and mixing control phase. Here, for better visualisation the curves corresponding to post injection duration 0.4 ms are presented. It was observed lower maximum heat release rate but higher value during late combustion. Taking into consideration the soot emissions post injection duration of 0.3 ms offers less FSN – 0.21 or reduction by 16% compared to the case without post injection. The lower soot quantity could be related to the higher maximum temperature as well as higher temperature during late combustion phase. Moreover, that post injection parameters lead to lower fuel consumption. The results concerning soot formation and fuel consumption are listed in Table 6.

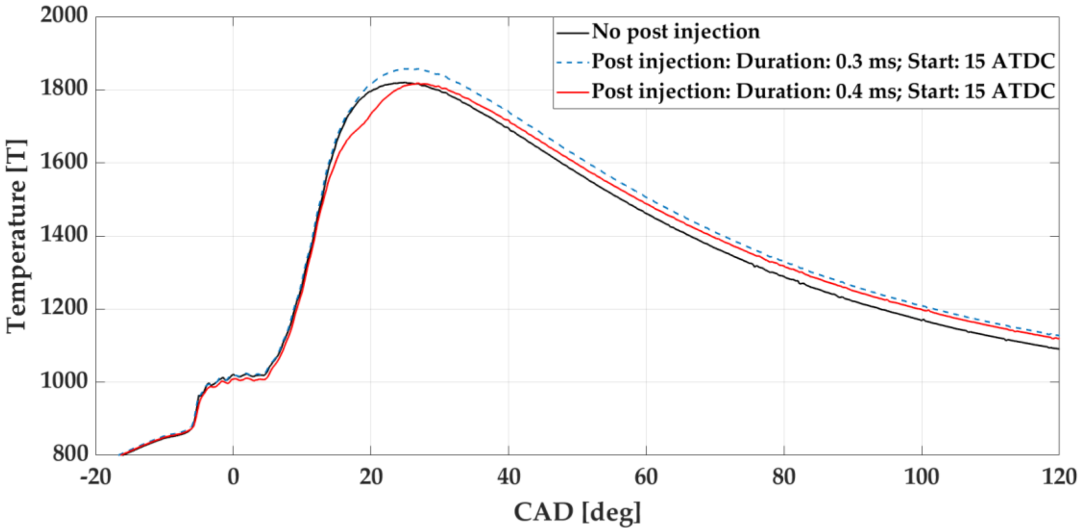

Fig. 8. Temperature vs crank angle

Table 6. Soot formation and fuel consumption

Post injection start [CAD]	Post injection duration [ms]	Smoke [FSN]	Fuel consumption [kg/h]
No post injection	-	0.25	4.89
15 [ATDC]	0.2 ms	0.23	4.838
15 [ATDC]	0.25 ms	0.25	4.854
15 [ATDC]	0.3 ms	0.21	4.82
15 [ATDC]	0.35 ms	0.25	4.883
15 [ATDC]	0.4 ms	0.39	4.901

CONCLUSION

An experimental study on the effect of post injection on soot reduction in a diesel engine was performed. It was conducted on a single engine operating point: engine speed of 1600 rpm and engine load – 140 Nm. The injection strategy included a pilot, main and a post injection. The pilot injection parameters were constant during the tests. The start of main injection was also constant - 0° BTDC. However, in order to achieve the same engine output torque, the main duration was varied for each test. In order to study the impact of post injection on combustion process and soot formation, the main post injection parameters (start of injection and injection duration) were varied. Thus, the experimental study was conducted on two step.

Firstly, the post injection duration was fixed to 0.2 ms and the start was varied within the range from 10° ATDC to 25° ATDC. The results then were compared to that obtained without post injection, also called basic results. It was found that early post injection leads to higher soot due to poor mixture formation in both mixing controlled and late combustion phase. The combustion duration was also increased. The minimum soot was observed when the post injection starts at 15° ATDC. It can be explained with enhanced mixing and higher temperature in late combustion phase. The soot reduction measured indirectly by FSN accounted to 8 % compared to injection strategy without post injection. Moreover, it offers a slide fuel consumption reduction by 1%.

Secondly, the effect of quantity of post injected fuel was studied. Thus, the post injection timing was fixed to the value that offers less soot in the first study - 15° ATDC. Then, the injection duration was varied within the range of 0.2 ms to 0.4 ms. When post injection duration increased from 0.2 ms to 0.3 ms it has very positive effect on the late combustion phase as a result higher temperature was observed. Higher value than 0.3 ms, however, leads to significant impact not only on late combustion but also on mixing controlled phase. Therefore, the maximum HRR is reduced as well as the maximum temperature. As a result, the soot increased. The post injection optimal parameters for studied engine operating point were found to be: start of post injection - 15° ATDC and post injection duration – 0.3 ms. It offers 16 % reduction of soot emissions and 1.4 % reduction of fuel consumption.

In order to better understand the soot reduction mechanism due to post injection strategy more complex analysis need to be performed over the whole engine operating range that soot formation is important.

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