Performance and Emission Investigation of the Common Rail Injectors in Single Cylinder Research Engine

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Abstract— Diesel engines currently are the main stream application choice for heavy duty vehicle industry in advantage of the high thermal efficiency of compression ignition combustion engines and they possibly will remain their position for a long while. One of the most critical elements of the engine is fuel injector. Mixing properties of the injector determines the combustion and emission formation of the compression ignition combustion. In this study, common rail injectors with different flow capabilities are investigated in terms of fuel efficiency, NOx and soot emissions for heavy duty engine on non-EGR strategies.

***Keywords*— Combustion, diesel engine, common rail injector, exhaust emissions, single cylinder engine, NOx, soot, thermal efficiency**

I. INTRODUCTION

Flow characteristics and nozzle design are the most significant parameters related with performance and formation of emissions [1][2]. In this paper, four different injectors with different flow numbers are investigated on 2.1L single cylinder engine. This study covers one part load, one full load operation condition in order to evaluate the combustion properties, performance analysis and formation of the exhaust emissions of NOx and soot. These part and full load operating points represent the most of the operating points of the WHTC (World Harmonised Transient Cycle) homologation test. Engine behaviour is characterized by performing a DoE (Design of Experiment) including rail pressure, start of injection (SOI) and air to fuel ratio (AFR) sweeps [3]. Purpose of the tests is to investigate both fuel economy and exhaust emissions of heavy duty truck engine on non-EGR operation with high flow injector options.

II. EXPERIMENT

A. *Single Cylinder Engine*

Experiments are conducted on a single cylinder research engine which is designed and manufactured by Ford Otosan. The engine was developed based on Ecotorq 13lt Heavy Duty Commercial Engine. The engine is 2.1 litre, four strokes, and four valves engine. Engine head, cylinder liner and injection system carried over from multi-cylinder engine. Table 1 summarizes the most specifications of the single cylinder research engine.

TABLE I

SPECIFICATION S OF THE SINGLE CYLINDER RESEARCH ENGINE

Models	**Size (nm)**
Bore x stroke [mm]	130 x 160
Connecting rod [mm]	310
Compression ratio	17:1
Squish [mm]	1.2
Displacement [lt]	2.1
Swirl ratio	1.2
Number of valves	4
Intake valve closing	140 degCA BTDC

The engine consists of external boost pressure system which is capable to run up to 6 bars with variable EGR system and boost temperature controller. Water cooling, lube oil and fuel injection systems are also external and electrically driven with a control system. Fig. 1 shows the photographs of the single cylinder engine developed by Ford Otosan.

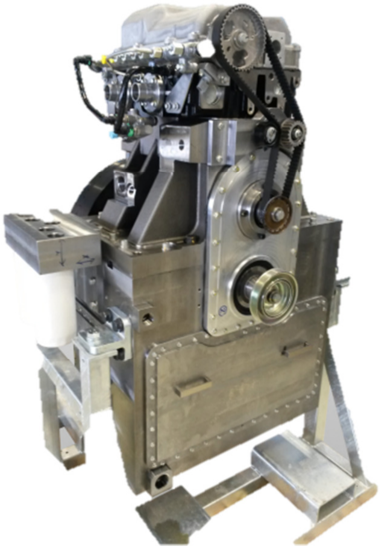

Fig. 1 Single Cylinder Research Engine

B. *Measurement Systems*

AVL Indicom device is used to measure in-cylinder pressure and indicated based calculations as IMEP (Indicated Mean Effective Pressure) and ISFC (Indicated Specific Fuel Consumption). AVL Puma is used to control engine, all auxiliary conditioning systems and data logging. At the exhaust side of the engine, NOx emission measurements are performed by NOx sensor which is currently used in serial production engine. Smoke mass concentrations (FSN) are measured by AVL 415 Smoke meter.

Injectors are solenoid type common rail injectors, supplied by Bosch. Three common rail injectors with different flow rate and injection cone angles are tested on the measurements. The main specifications of the common rail injectors are shown in Table 2.

TABLE II

SPECIFICATIONS OF THE COMMON RAIL INJECTORS

Injector	**Flow rate [cc/30sec/100bar]**	**Hole Diameter [µm]**	**Spray Cone Angle [°]**
A	850	181	*150*
B	1000	179	*146*
C	1000	179	*150*

In the experiments, injector A is the reference injector which is currently used in the serial production engine. Injector B and C are the alternatives of the proposed high flow injectors. The difference between injector B and C is the spray angle. Injectors have similar nozzle geometry and each injector have 8 cylindrical holes in the nozzles. A Bosch CRIN 3.25 fuel system which is capable of 2500 bars maximum rail pressure, driven by an electric motor is used in the experiments. In the experiments a low sulphur EN590 standard fuel is used.

III. RESULTS

Engine is operated on one part and one full load operating conditions. All tests are performed on non-EGR operation. In order to investigate the performance of the combustion system, SOI, rail pressure and AFR sweeps are performed. The aim is to compare combustion performance on ISFC-NOx, ISFC-Soot trade off curves. First operating point (Part load) is selected as cruising speed of the heavy duty truck on maximum pay load condition. Second full load operation is represent the average full load condition on common driving cycles.

C. *Part load results*

In part load operating condition, engine is running @ 1100 rpm and 10.6 bar BMEP (Brake Mean Effective Pressure). Fig. 2 shows the ISFC – NOx trade- off curves for different boost pressure variation. In this operating point, fuel rail pressure is 680 bars and a SOI sweep is performed from 400 mbar up to 900 mbar boost pressure. This figure shows that, high boost pressure reduces the fuel consumption up to 4 g/kWh compared to reference point.

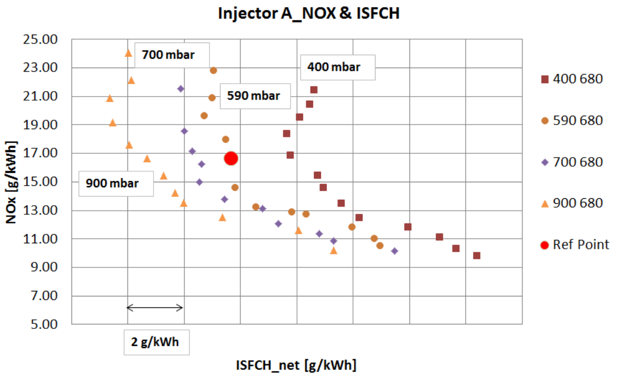

Fig. 2 ISFC – NOx trade-off for boost variation of part load conditions

Fig. 3 shows the NOx soot trade off curve on different boost pressure values. As it is shown, in the late injection case, NOx formation reduces up to 10 g/kWh. Besides, soot emission values increase up to 0.15 to 0.25 FSN values. Moreover, high boost pressure reduces the soot emissions on up to 0.05 FSN. However, further boost increase cannot reduce the soot emissions below 0.05 FSN.

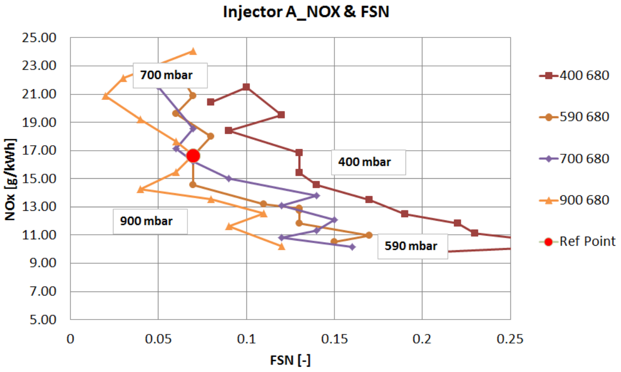

Fig. 3 NOx – soot trade off curves for boost variation

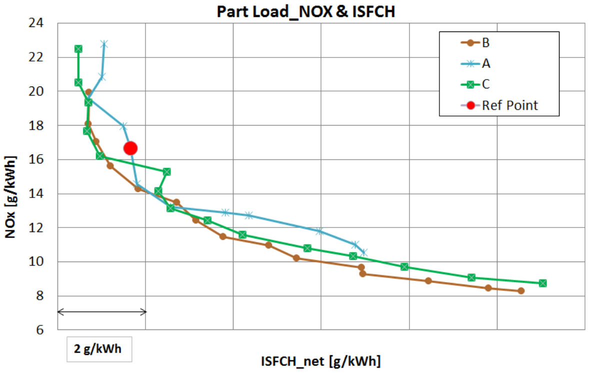

Fig. 4 NOx – ISFCH trade off curves

Indicated specific fuel consumption – NOx curves are shown in the Fig. 4 to compare the three injector options in part load conditions. Tests are performed on 590 mbar boost and 680 bar rail pressure as a reference condition. The mass burnt 50% (MFB50) value is set to 4° crank angle (CA) after top dead centre (TDC) in the reference point. A SOI sweep is performed to investigate the effect of ISFCH and NOx trade-off. Results show that negligible fuel consumption benefit can be possible by using high flow injectors. In addition, there is negligible difference on ISFC values between 146 to 150° spray cone angle injectors. On the other hand, soot emissions will be higher on high flow injectors with 150° cone angle (Injector C).

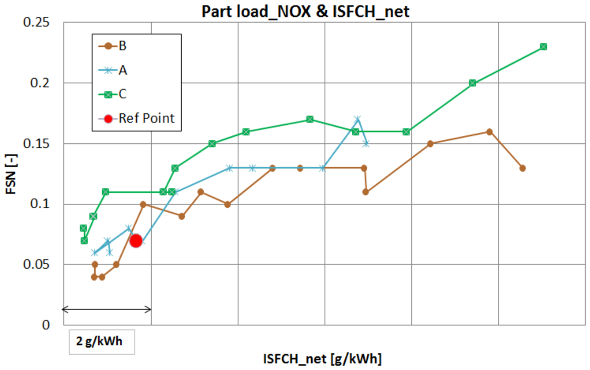

Fig. 5 Soot – ISFCH trade off curves

Three injectors are compared in terms of heat release rate and in-cylinder pressure. In Fig. 6, Injector A (black), Injector B (red) and Injector C (blue) are shown. It can be seen that, Injector B and C combustion has higher burn rate compared to low flow injector (A). In-cylinder pressure comparison, not very significant difference is obtained.

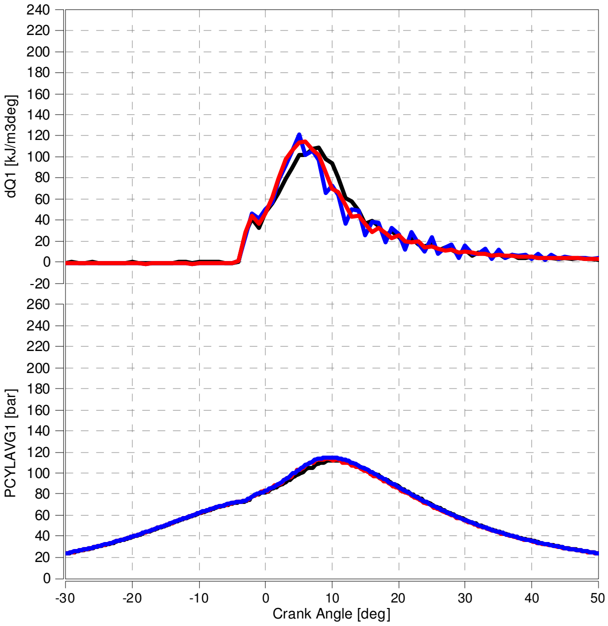

Fig. 6 Heat Release Rate and In-cylinder pressure curves of part load conditions of three injector variants – NOx trade-off for boost variation of part load conditions

D. *Full load results*

In full load condition, engine is also running @1100 rpm and 24.7 bar BMEP. In the first experiment, boost pressure sweep is performed to investigate combustion performance @1200 bar rail pressure. SOI sweeps are performed between 1500 up to 2100 mbar boost pressure. Fig. 6 shows the ISFC – NOx trade-off of different boost levels with a SOI sweep. Operating range of the SOI sweep is limited with maximum in-cylinder pressure limit (advanced SOI) and MFB50 limit for retarded combustion (retarded SOI) [4]. Engine operating condition is limited between 230 bar in-cylinder pressure and MFB50=18° CA limit. Fig. 7 shows the ISFCH – NOx trade off curves for boost variations of full load conditions. In low boost condition, it is able to decrease the NOx emissions about 20% compared to reference operating point. On the other hand, better ISFC values are obtained in high boost operating conditions. Up to 1 to 2 g/kWh ISFC gain can be possible with high boost operation. However, high boost option cannot reduce the NOx emission.

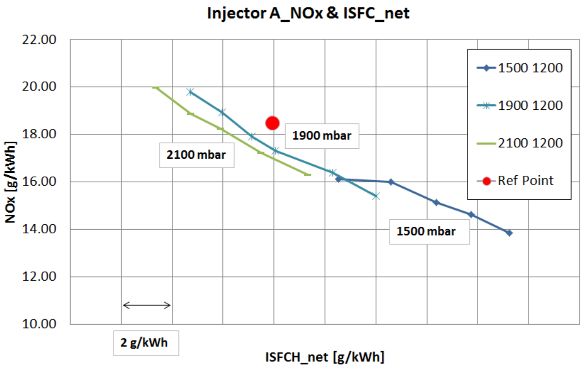

Fig. 7 ISFC – NOx trade-off for boost variation of part load conditions

Fig. 8 shows the NOx soot trade off curve on different boost pressure values. As it is shown, NOx formation reduces up to 4 g/kWh on retarded combustion on the other hand, soot emission values negligibly increased. Moreover, increasing boost pressure reduces the soot emissions on up to near zero FSN values.

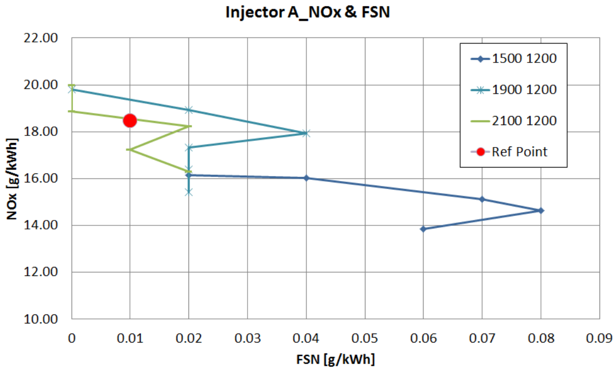

Fig. 8 NOx – soot trade off curves for boost variation

Three injector options are investigated in full load conditions. The tests are performed on 1900 mbar boost pressure and 1200 bar rail pressure as reference conditions. The mass burnt 50% (MFB50) value is set to 16° crank angle (CA) after top dead centre (TDC) in the reference point. A SOI sweep is performed to investigate the effect of ISFCH and NOx trade-off. The results are shown in Fig. 9; fuel consumption benefit up to 8 g/kWh can be achieved with high flow with narrow cone spray angle injectors. Moreover, there is more than 4 g/kWh fuel benefit can be possible with 146° spray angle rather than to 150° spray angle injectors.

Soot emissions are very low in all injectors and FSN values are extremely low in full load conditions. Soot emissions are shown in Fig. 10 below.

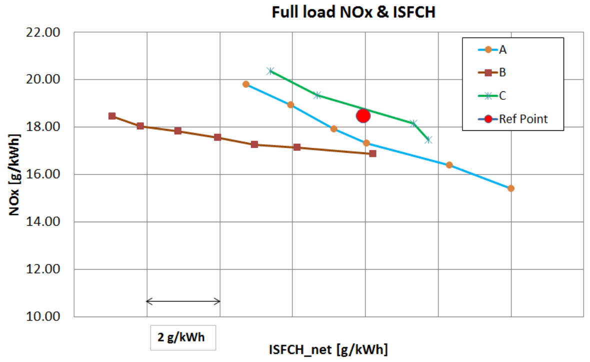

Fig. 9 NOx – soot trade off curves for boost variation

Heat release rate and in-cylinder pressure values are compared for three injectors. In Fig. 11, Injector A (black), Injector B (red) and Injector C (blue) are shown. It is seen that, Injector B and C combustion has higher burn rate compared to low flow injector (A). In addition, Injector B has better burn rate than the other high flow injector. This is enabler for better fuel economy. More than 6 bars in-cylinder pressure difference is obtained between high flow and low flow injectors.

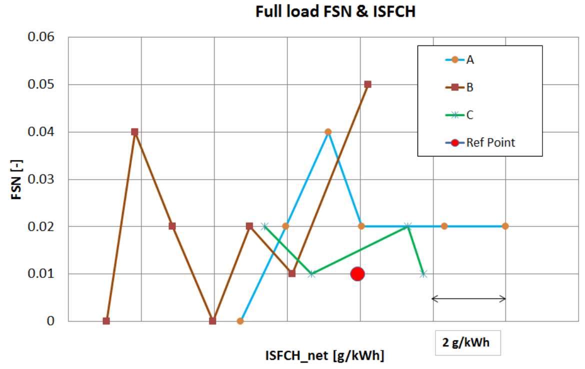

Fig. 10 Soot – ISFCH trade off curves

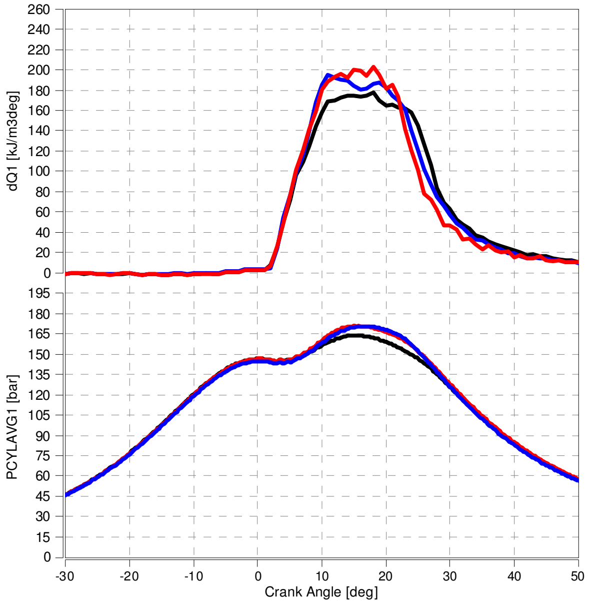

Fig. 11 Heat Release Rate and In-cylinder pressure curves of part load conditions of three injector variants – NOx trade-off for boost variation of full load conditions

IV. CONCLUSIONS

In this study, effects of the nozzle flow and spray angle of common rail injector has been investigated to represent heavy duty Euro6 diesel engine in single cylinder research engine.

At part load operating condition, high flow injectors (B, C) has no benefit in terms of fuel consumption. On the other hand, high flow, narrow cone injector (B) can reach the soot levels as low flow injectors. As a result, engine performance and emission trends are very similar in the part load operating conditions. However, boost pressure increase is significant to reduce the fuel consumption. Therefore, turbocharger matching becomes more critical on non-EGR engine to satisfy the high boost pressure values.

At full load conditions, boost pressure increase has minor effect on fuel consumption. On the other hand, boost pressure can be selected for the NOx capacity of the after-treatment system of the engine. In high boost conditions, combustion system cannot reduce the NOx emissions even in retarded combustion. Moreover, soot emissions in reference operating conditions in full load operation are rarely too low to compare. In addition, high flow narrow cone angle injector (B) has better ISFCH - NOx trade off curve in the comparison.

As a result, high flow injectors with optimum spray cone angle injector can achieve better fuel economy without increasing soot emissions at full load conditions on for non-EGR engines. Moreover, no drawbacks of the high flow injector with optimum spray cone angle are seen in part load engine operating conditions.

Finally, the present study has shown injector flow rate and spray cone angle variations on fuel consumption and exhaust emissions. In the combustion system design, these parameters are always taken account for the development phase of the engine design and calibration activities.

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