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EFFECTS OF PILOT INJECTION TIMING AND EGR ON A MODERN V6 COMMON RAIL DIRECT INJECTION DIESEL ENGINE

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ABSTRACT

Nitric oxide and smoke emissions in diesel engine can be controlled by optimising the air/fuel mixture and combustion temperature. Early in-cylinder diesel injection that produces premixed charge can simultaneously reduce NO_x and smoke emissions. However, there could be an increase in hydrocarbons and CO emissions due to fuel impinged to the cylinder wall. The focus of the present work is on the effects of a variation of pilot injection timing with EGR to NO_x and smoke level of a modern V6 common rail direct injection. This study is carried out at two different engine load conditions of 30 Nm and 55 Nm, at constant engine speed of 2000 rpm. Emissions of NO_x are measured from the exhaust sample line by an exhaust gas analyzer (Horiba MEXA-7100EGR). Smoke level is measured by using an AVL 415S smoke meter which provides results directly as a Filter Smoke Number (FSN) unit. The results show that the early pilot injection timing contributed to the lower smoke level and higher NO_x emissions. The higher level of NO_x is due to higher combustion temperatures resulting from the complete combustion. Meanwhile, the lower smoke level is due to complete fuel combustion and soot oxidation. The early pilot injection timing produces an intermediate main ignition delay which also contributed to complete combustion. The formation of smoke is higher at a high engine load compared with low engine load is due to the higher amount of fuel being injected, resulting in higher smoke formation.

***Keywords*: Pilot injection; Combustion strategies; Emissions control; Ignition delay; Premixed combustion.**

INTRODUCTION

In direct injection diesel and compression ignition engines, the start of fuel injection (SOI) influences the fuel-air reaction rates and combustion behaviour (Cenk Sayin and Canakci 2009; Cenk Sayin, Murat Ilhan et al. 2009). A number of studies have been carried out aiming to promote premixed lean charge and minimise diesel engine emissions (D. T. Montgomery and Reitz 2001; Cenk Sayin and Canakci 2009; Cenk Sayin, Murat Ilhan et al. 2009; Dec 2009). This is due to the improved premixed combustion leading to low combustion temperatures and condition favourable for low NO_x and PM emissions. Several studies have revealed that the pilot injection strategy produced a shorter ignition delay on the main injection thus contributing to the lower emissions (Zhang 1999; Keiichi Okude, Kazutoshi Mori et al. 2007; Gavin Dober, Simon Tullis et al. 2008) and cleaner combustion process (A. Vanegas, H. Won et al. 2008).

In diesel and compression ignition engines, ignition delay and combustion phasing are amongst the main parameters influencing emissions formation and engine performance. Long ignition delay promotes premixed uncontrolled combustion which can lead to knocking and high combustion noise (Nwafor 2000; Shuji Kimura, Osamu Aoki et al. 2001; Timothy J. Jacobs, Stanislav V. Bohac et al. 2005-01-0166, 2005; I.Nwafor 2007; Siddappa S. Bhusnoor, M. K. Gajendra Babu et al. 2007). Murari Mohon Roy and Hideyuki Tsunemoto studied the effects of injection pressure (200 - 1200 bar) and split injection on emissions and engine noise using a common rail four-stroke multi cylinder 7.7 L direct injection diesel engine. The results showed that the proper post-pilot injection strategy has a significant improvement in the emissions and engine noise (Murari Mohon Roy and Tsunemoto 2002). Keiichi Okude et al. investigated the effect of multiple injections of engine performance and emissions using a single-cylinder engine 0.744 L. The results showed that the multiple pilot injection substantially reduced HC and CO emissions (Keiichi Okude, Kazutoshi Mori et al. 2007). A. Vanegas et al. used a 4-cylinder common-rail diesel engine to study the effect of multiple injection on emissions. The overall results showed that the NO_x emissions from the split injection strategy were significantly lower compared to the single injection strategy (A. Vanegas, H. Won et al. 2008). D. T. Hountalas et al. demonstrated that the cooled EGR is favourable for NO_x reduction (D. T. Hountalas, G. C. Mavropoulos et al. 2008). Siddappa et al. utilised a single cylinder direct injection engine to study the performance and emissions at different injection pressures and injection timing fuelled with diesel and biodiesel. According to their experimental results the higher injection pressure produces improved engine performance and emissions in terms of smoke, HC and CO but NO_x emissions were slightly increased (Siddappa S. Bhusnoor, M. K. Gajendra Babu et al. 2007).

From the literature review, it was concluded that the effects of variation of pilot injection timing on engine performance and emissions of a diesel engine can be further investigated. Moreover, the influence of the pilot injection timing on the main ignition delay has not been extensively discussed. A number of research programs have been carried out at the University of Birmingham to investigate diesel engine performance and emissions (A. Tsolakis, A. Megaritis et al. 2004; A. Tsolakis and Megaritis 2004; A. Tsolakis and Megaritis 2005; A. Abu-Jrai, A. Tsolakis et al. 2007; A. Tsolakis, A. Megaritis et al. 2007; Hirotatsu Watanabe, Yoshikazu Suwa et al. 2007; S. Chuepeng, A. Tsolakis et al. 2007; A.Tsolakis, A. Megaritis et al. 2008; S. Chuepeng, H. M. Xu et al. 2008; Nik Rosli Abdullah, Rizalman Mamat et al. 2009). In present study, the variations of pilot injection timing were performed in order to investigate their effects on the emissions of $\mathbf{NO_x}$ and smoke level by using a common rail direct injection V6 diesel engine equipped with variable turbine geometry (VTG) turbochargers and cooled EGR. The pilot injection has a potential to control the pressure rise during the main combustion through a shorter main ignition delay. This experiment run with a split injection consists of 10 % pilot injection and 90 % main injection fuel quantity. The use of 10 % pilot fuel quantity is due to the large amount of pilot injection tends to increase the $\mathbf{NO_x}$ emissions due to higher rate of heat release (Mohammad Ghaffarpour and Noorpoor 2007).

EXPERIMENTAL SET UP

The experiments were carried out on a fully instrumented multi-cylinder V6 diesel engine, common rail multiple direct fuel injection system, twin water-cooled variable geometry turbochargers and cooled EGR. The engine specification is shown in Table 1. An eddy-current dynamometer type Schenck W230 and an engine starter motor, are used to load and start the engine respectively. The Schenck series 2000 controller is used to control the dynamometer. The exhaust gas of the engine is passed through the gas analyser via a sample line and $\mathbf{NO_x}$ and smokes were measured. The exhaust sample acquisition time is approximately 10 seconds at an operating temperature of 28 to 30 °C and the relative humidity is approximately 40-50 percent. The emissions presented are an average value from 10 reading samples. The smoke emissions were measured by using an AVL 415S smoke meter which provides results directly as a Filter Smoke Number (FSN) unit. Main injection quantity, timing, pressure and EGR rate were held constant throughout the experiment. The amount of fuel injected for both pilot and main injection was at a constant ratio of 10:90 for pilot and main respectively. All the tests were performed with ultra low sulphur diesel (ULSD) and the fuel properties are given in Table 2. The effects of pilot injection timing on the emissions of NO_x and smoke level were examined. These experiments consisted of three different regions of pilot injection timing (early, middle and late) at two different engine loads (30 Nm, 55 Nm) operating with a constant speed 2000 rpm. The details about the experimental conditions have been summarized in Table 3.

Table 1: Engine Specifications

Bore	81.0 mm
Stroke	88.0 mm
Displacement Volume	2720 cm^3
Maximum Torque	435 Nm @ 1900 rpm
Maximum Power	152 kW @ 4000 rpm
Compression Ratio	17.3 : 1
Connecting Rod Length	160.0 mm

Table 2: Fuel Properties

Properties	ULSD
Cetane Number	53.9
Density at 15 °C (kg/m^3)	827.1
Viscosity at 40 °C (cst)	2.5
50% Distillation (°C)	264
90% Distillation (°C)	329
LCV (MJ/kg)	42.6
Sulphur (mg/kg)	46
Mano-aromatics (% wt.)	21
Di-aromatics (% wt.)	3.1
Molecular Mass (eq.)	209
C (wt.)	86.5
H (wt.)	13.5
O (wt.)	-

Table 3: Summary of Test Conditions

Test	Injection Timing CAD Pilot Injection	Engine Load (Nm)	Notes
1	9 bTDC	30	
2	12 bTDC	Fixed	Late Injection
3	15 bTDC	Fixed	
4	19 bTDC	Fixed	Middle Injection
5	21 bTDC	Fixed	
6	24 bTDC	Fixed	
7	27 bTDC	Fixed	Early Injection
8	30 bTDC	Fixed	
9	9 bTDC	55	
10	12 bTDC	Fixed	Late Injection
11	15 bTDC	Fixed	
12	19 bTDC	Fixed	Middle Injection
13	21 bTDC	Fixed	
14	24 bTDC	Fixed	
15	27 bTDC	Fixed	Early Injection
16	30 bTDC	Fixed	
Constant Engine Speed:	2000 rpm		
Constant Main Injection Timing:	1.4 CAD aTDC		
Constant EGR Rate:	40%		

RESULTS AND DISCUSSION

The NO_x emissions are mainly influenced by the peak in-cylinder pressure and high combustion temperatures. It can clearly be seen from Figure 1 that the NO_x concentration increases monotonically with early and late pilot injection timing. The early pilot injection timing tends to produce intermediate main ignition delay resulting in a complete combustion process due to long residence time for the reaction of fuel-air (Guntram A. Lechner, Timothy J. Jacobs et al. 2005-01-0167, 2005). As a result, the early pilot injection timing produces the higher in-cylinder pressures leading to the higher temperatures and NO_x emissions (Cenk Sayin and Canakci 2009; Cenk Sayin, Murat Ilhan et al. 2009). The middle pilot injection produces longest main ignition delay that leads to the slower combustion and low NO_x emissions (K.Verbiezen, A. J. Donkerbroek et al. 2007).

Therefore, in general the reduction in NO_x can be controlled through the reduction of peak in-cylinder pressure by reducing the main ignition delay, the air temperature and combustion duration (Mohammad Ghaffarpour and Noorpoor 2007). The overall results show that the NO_x emissions increased with the early and late of pilot injection but decreased with the middle pilot injection timing in both engine loads.

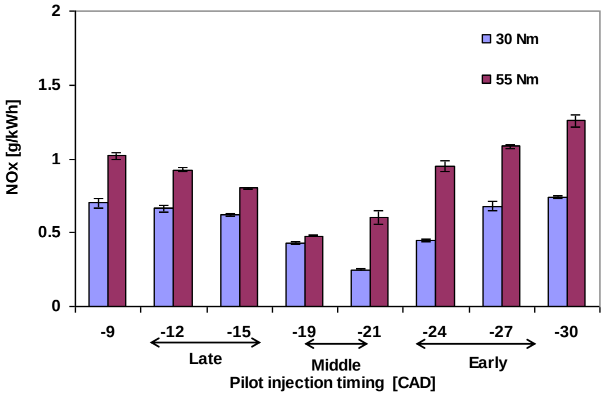

Figure 1: NO_x emissions as a function of pilot fuel injection timings (-9 to -30 CAD) at two different engine loads (30 Nm and 55 Nm) and constant engine speed 2000 rpm, error bars represent 95 percent confidence.

The effect of pilot injection timing on the smoke number (FSN) is shown in Figure 2 with the engine operating at two different loads at a constant engine speed of 2000 rpm. The amount of smoke formation is strongly related to the fraction of diffusive combustion phase (Ren, Huang et al. 2006). Smoke formation occurs at extreme local air deficiency. It increases as the air/fuel ratio decreases. The higher fraction of diffusive combustion phase will result in an increase in smoke formation due to insufficient of oxygen. The presented results are in a good agreement with Keiichi Okude et al. which showed that the smoke decrease as the pilot injection timing is advanced (Keiichi Okude, Kazutoshi Mori et al. 2007). It is strongly believed due to improvement in mixture formation with an early pilot injection. This in turn resulted in complete combustion due to better mixing process. The early pilot injection timing produces an intermediate main ignition delay which also contributed to complete combustion. The formation of smoke is higher at a high engine load due to the higher amount of fuel being injected, resulting in higher smoke formation. Complete combustion also resulted in higher combustion temperature leading to the higher soot oxidation during expansion and exhaust stroke (Nicolas Dronniou, Marc Lejeune et al. 2005). The most obvious finding to emerge from this study is that the early pilot injection timing is better for smoke reduction.

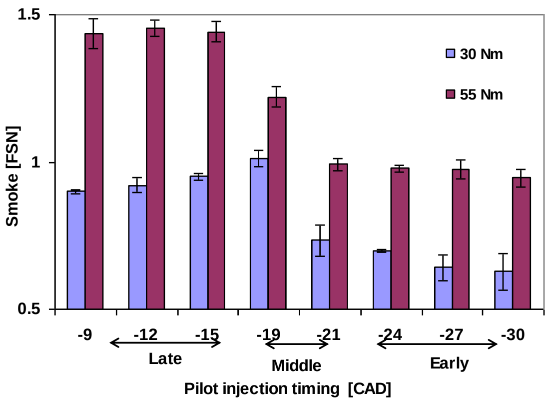

Figure 2: Smoke level (FSN) as a function of pilot fuel injection timings (-9 to -30 CAD) at two different engine loads (30 Nm and 55 Nm) and constant engine 2000 rpm, error bars represent 95 percent confidence.

CONCLUSION

In the present work, the emissions of NO_x and smoke level were measured for various pilot injection timings, operating with two different engine loads at a constant engine speed. As accepted, the pilot injection favoured for the main combustion behaviour. It has been shown smoke level were increased with retarded pilot injection and then decreased after an injection timing of 19 CAD onwards. Both engine loads produced similar patterns. However, the NO_x emissions were decreased with retarded pilot injection then increased after 19 CAD onwards in both engine loads. Therefore, it has been proven that advancing pilot injection timing of 24, 27 and 30 CAD are better for smoke. Conversely, the injection timings of 9, 12, 15, 19 and 21 are worse for this particular emission. In terms of NO_x emissions, the injection timings of 19 and 21 CAD are the best. In summary, advanced pilot injection has promising emissions reduction associated with it in terms of smoke but not for NO_x.

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